ESTIMATING EXTERNALITIES OF BIOMASS FUEL CYCLES

OAK RIDGE NATIONAL LABORATORY
AND
RESOURCES FOR THE FUTURE

Report No. 7 on the
EXTERNAL COSTS AND BENEFITS OF FUEL CYCLES:
A Study By The
U.S. Department of Energy
And The
Commission of the European Communities

January 1998

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6205
is manged by
LOCKHEED MARTIN ENERGY RESEARCH CORP.
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-96OR22464

This report is one of seven in a series published by Utility Data Institute (UDI) and the Integrated Resource Planning Report (IRP Report), business units of McGraw-Hill Companies, under subcontract to Lockheed Martin Energy Research Corp.

Printed in the U.S.A.

UDI-5119-98

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PREFACE

Some analysts think that biomass offers great potential as a renewable fuel for electricity generation. Biomass' emissions of greenhouse gases, over its whole fuel cycle, are relatively insignificant when compared to even the "cleanest" of the fossil energy technologies — natural gas. Yet, the external costs (and benefits) of biomass fuel cycles, which stem from impacts other than those associated with greenhouse gases, are not necessarily trivial. Some of these impacts are similar to those that result from the combustion of fossil fuels. Other impacts are unique to biomass fuel cycles. This report describes methods to estimate many of the more important external costs (and benefits) of biomass fuel cycles.

As with the other reports in this series, this report has benefitted greatly from reviews by the panel commissioned by the Secretary of Energy's Advisory Board, which Chris Bernabo chaired; and by Hilary Smith and others of the U.S. Department of Energy's (DOE) staff. We are also grateful to Vito Stagliano, then of DOE; Pierre Valette of the European Commission; and Bob Shelton of Oak Ridge National Laboratory (ORNL) for championing this study. I am also personally grateful to my colleagues at Oak Ridge, particularly Meg Eady, Bob Perlack and Cindy McIlvaine; at Resources for the Future, especially Alan Krupnick and Dallas Burtraw; and others, for their vitally important contributions to this report. I am also thankful for the steadfast backing that my previous supervisors, Charles Kerley and Randy Curlee, gave me. And I am especially grateful to my family for their enduring support.

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January 1998

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ACRONYMS

A	assessment
ac	acres
ai	active ingredient
AIRS	Aerometric Information Retrieval System
ANC	acid neutralizing capacity
bhp	brake horsepower
BIG/STIG	biomass gasifier steam-injected gas turbine
BIG/ISTIG	biomass gasifier intercooled steam-injected gas turbine
BIG	biomass gasifier
BPA	Bonneville Power Administration
Btu	British thermal unit
bu	bushels
C	carbon
CEC	California Energy Commission
CFR	Code of Federal Regulations
cfs	cubic feet per second
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
COHb	carboxyhemoglobin
CRBR	Clinch River Breeder Reactor
CV	contingent value
D	data inputs
DFA	Damage Function Approach
DOE	U.S. Department of Energy
E	estimation methods
EC	European Community
EIA	Environmental Impact Statement
EJ	10^{18} Joules (work done by the force of 1 newton acting through a distance of one meter)
EPA	Environmental Protection Agency
EV	expected value
F	fahrenheit
fps	feet per second
g	gram
G	generalizability
gal	gallon
gals	gallons
GNP	Gross National Product

GWh	gigawatt hour
h	hour
H	existence of other posterior plausible values does not matter
ha	hectare
HAV	hand-arm vibration
HC	hydrocarbons
hp	horsepower
hr	hour
Hz	Hertz
I_1	value of information based on spread
I_2	value of information based on the foreseen application for the entry
ISCLT	Industrial Source Complex Long-Term
ISTIG	intercooled steam-injected gas turbine
J	joules
K	potassium
K_2O	potassium
kg	kilogram
kg/km^2-hr	kilograms/square kilometers per hour
km	kilometer
kWh	kilowatt hour
L	existence of other posterior plausible values matters for application
lb	pound
LB	lower bound
lbs	pounds
LC_{50}	concentration which is lethal to 50 percent of test animals
LD_{50}	dose which is lethal to 50 percent of test animals
m	meter
M	estimation metric
M	existence of other posterior plausible values matters marginally
MBtu	Million British thermal units
MD	mode
ME	mean
Mg	milligram
mi	mile
MJ	megajoule
MMBtu	Million British thermal units
MN	median
MSW	Municipal Solid Waste
MW	megawatt
MWe	megawatts electric

MWh	megawatt hour
N	Numerical entry
N	nitrogen
N/A	not applicable
N_2O	nitrous oxide
NAAQS	National Ambient Air Quality Standards
NAPAP	National Acid Precipitation Assessment Program
NCLAN	National Crop Loss Assessment Network
ND	no distribution
NEPA	National Environmental Policy Act
ng	nanogram
NIOSH	National Institute for Occupational Safety and Health
NMHCs	non-methane aromatic hydrocarbons
NMOC	non-methane volatile organic compound
NO	nitrogen oxide
NO_2	nitrogen dioxide
NOAA	National Oceanic and Atmospheric Administration
NO_x	nitrogen oxide
NRI	Natural Resources Inventory
NSPS	New Source Performance Standard
NUSAP	Numerical Unit Spread Assessment Pedigree, a notation scheme for summarizing information on the uncertainty and quality of data.
NYSPSC	New York State Public Service Commission
°C	degrees Centigrade
°F	degrees Fahrenheit
ORNL	Oak Ridge National Laboratory
OSHA	Occupational Safety and Health Administration
OZIPM4	Ozone Isopleth Plotting with Optional Mechanisms
P	phosphorous
P	pedigree
P_2O_5	phosphorous
PAH	polycyclic aromatic hydrocarbons
PAN	peroxyacetyl nitrate
pH	notation that refers to hydrogen ion concentration
PIC	product of incomplete combustion
PM	particulate matter
PM	particulate matter
PM-10	particulates under 10 microns
ppb	parts per billion
ppm	parts per million
R	robustness

RAD	Restricted Activity Day
RFF	Resources for the Future
S	Spread
S_1	Degree of confidence of the spread
S_2	entry for upper or lower bound % range, standard deviations range, or factor of variation of the spread
SCAQMD	South Coast Air Quality Management District
SCREEN	model used to predict pollutant concentrations
SCS	Soil Conservation Service
sec	seconds
SEPA	Swedish Environmental Protection Agency
SMSA	Standard Metropolitan Statistical Area
SO_2	sulphur dioxide
SO_x	sulphur oxide
SO_x	sulphur dioxide
SRIC	Short-Rotation Information Culture
SRIC	short-rotation intensive culture
STAR	summaries that tabulate joint frequency of occurrence of wind speed and wind direction categories
STIG	steam-injected gas turbine
STORET	a water quality databases for surface and ground water
T	theoretical basis
TNMHC	total non-methane hydrocarbons
TRIS	Toxic Release Information System
TSP	total suspended particulates
TVA	Tennessee Valley Authority
U	Unit
U_1	Unit of measure entry
U_2	Statistic entry
UB	upper bound
UCS	Union of Concerned Scientists
USDA	U.S. Department of Agriculture
USDOE	U.S. Department of Energy
USGS	United States Geological Survey
VOC	volatile organic compounds
wk	week
WTA	willingness to accept
WTB	Whole Tree Burner
WTE	waste-to-energy
WTP	willingness to pay
yr	year

EXECUTIVE SUMMARY

ES.1 INTRODUCTION

Social cost accounting is of interest to many institutions worldwide as a means of assisting in energy and environmental decision making. Social cost accounting seeks to make explicit all of the social costs and benefits that result from production and consumption decisions. Social cost accounts have two components: private costs such as capital, operating and maintenance costs; and costs and benefits that are not reflected in market transactions. The latter are called *external* costs and benefits—or externalities. They include environmental quality, health, and non-environmental considerations.

The U.S. Department of Energy and the Commission of the European Communities agreed in 1991 to "develop a comparative analytical methodology and to develop the best range of estimates of costs from secondary sources" for eight fuel cycles and four conservation options for electricity generation. The fuel cycle approach accounts for the major stages of activities and engineering processes involved in generating electricity. These stages begin with the development and extraction of a resource and end with the disposal of all wastes or residuals from the various activities and processes.

ES.2 PURPOSE OF STUDY

This report documents the analysis of the biomass fuel cycle, in which biomass is combusted to produce electricity. The major objectives of this study were:

(1) to implement the methodological concepts which were developed in the Background Document (ORNL/RFF 1992) as a means of estimating the external costs and benefits of fuel cycles, and by so doing, to demonstrate their application to the biomass fuel cycle;

(2) to develop, given the time and resources, a range of estimates of marginal (i.e., the additional or incremental) damages and benefits associated with selected impact-pathways from a new wood-fired power plant, using a representative benchmark technology, at two reference sites in the United States; and

(3) to assess the state of the information available to support energy decision making and the estimation of externalities, and by so doing, to assist in identifying gaps in knowledge and in setting future research agendas.

The demonstration of methods, modeling procedures, and use of scientific information was the most important objective of this study. It provides an illustrative example for those who will, in the future, undertake studies of actual energy options and sites.

As in most studies, a more comprehensive analysis could have been completed had budget constraints not been as severe. Particularly affected were the air and water transport modeling, estimation of ecological impacts, and economic valuation.[1] However, the most important objective of the study was to demonstrate methods, as a detailed example for future studies. Thus, having severe budget constraints was appropriate from the standpoint that these studies could also face similar constraints. Consequently, an important result of this study is an indication of what can be done in such studies, rather than the specific numerical estimates themselves.

In fact, there are several reasons why ***it is not appropriate to apply the numerical results of this study to compare different fuel cycles:***

(1) All of the potentially important impacts were not necessarily addressed because of limitations in the state of quantitative knowledge or in the time and budget for this study.

(2) Impacts are project-specific. Different power plant specifications will change the magnitude of the residual damages and benefits.

(3) Impacts are generally site-specific. It would be erroneous to extrapolate, without appropriate analysis, the numerical estimates for the two sites analyzed in this study to other sites. In particular, the two sites are not intended to be representative of all sites in the country, nor even to be economically viable alternatives. Of the two biomass sites, one (the Northwest Reference site) is a likely option, while the other (the Southeast) is economically marginal. These sites were selected so as to compare individual impacts across fuel cycles using a common environmental baseline. The sites are plausible from a physical standpoint, though not necessarily from an economic or regulatory one. They were selected

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[1]While the phrase "economic valuation" is redundant to economists, it is used in this study to be clear that residual damages and benefits are valued in economic terms.

primarily because data was available for those sites to facilitate the demonstration of the methodology.

(4) Limitations in knowledge preclude quantitative estimates of many ecological impacts. The effect of these limitations on the ability to derive quantitative estimates might vary for different fuel cycles.

(5) Aggregation errors might arise from adding estimates of damages that are estimated separately for individual impacts.

(6) This study is primarily a demonstration of methods, rather than a conclusive comparison of alternative energy technologies.

ES.3 METHOD OF ANALYSIS

The fuel cycle that was considered in this study involved the construction and operation of a new biomass-fired power plant. The public transportation and other infrastructure that would be required to supply biomass feedstock to the power plant were assumed to exist already — except for the plantations which would be dedicated to the conversion facility. Other options such as adding units to an existing plant, purchasing power from other power producers, or integrated resource planning to meet systemwide or regionwide needs were not addressed.

The Damage Function Approach (DFA) was the methodology that was used to estimate the social costs and benefits of the biomass fuel cycle. The DFA combines science, engineering and economics to estimate the changes in both environmental and nonenvironmental conditions that stem from an incremental investment (to build and operate a biomass-fired power plant). The DFA is the most detailed and thorough approach for this purpose.

Figure ES-1 is a flowchart that illustrates the DFA. It begins with an estimate of the residual emissions from each fuel-cycle activity and considers (1) the transport, deposition, or chemical transformations of these emissions, and the resulting change in the geographical concentrations of these pollutants; (2) the changes in ecological, human, and social resources which are caused by the changes in concentrations; (3) the economic value that is placed on these impacts; and (4) the distinction between the social costs and benefits which are internalized within the market and the remaining externalities.[2]

[2]In this document, the terms "economic valuation" and "economic damages" are used—even though for economists, the "economic" part of the phrases is redundant.

The concept of impact-pathways is used within the context of the DFA to define a sequence of physical cause-and-effect linkages. An impact-pathway begins with a given activity or process of the fuel cycle (such as electricity generation). The impact-pathway then includes a particular emission from an activity; the transport and the possible chemical and physical transformation of that emission; the resulting change in its concentration in the environment; and the effect of that change, which results in a specific ecological impact or effect on health. This impact is the endpoint of the pathway and the starting point for an economic valuation of that impact.

Something has value to the extent that individuals are willing to pay for it—the so-called willingness to pay (WTP) criterion in economics that underlies modern benefit-cost analysis. Emissions or other residuals from the biomass fuel cycle result in health, environmental, and other impacts. These impacts have a monetary value in that people may be willing to pay to avoid negative impacts or to obtain positive impacts. In this study, the valuation of these impacts generally utilizes the results of past economic studies which have estimated the WTP to avoid different types of impacts.

Whether damages or benefits are counted as a social cost of the fuel cycle that is external to the private costs of delivering electricity from biomass is a complicated issue. It depends on the type of policy in place to address these impacts. The current study estimates the marginal damages and benefits from a new biomass-fired plant and from its supporting fuel cycle activities, that are thought to be externalities of the fuel cycle, but a more thorough analysis is needed to confirm that these damages and benefits are completely externalities.

An overwhelming conclusion from the discussions in Sections 4 to 10 is that while the approach is simple in concept, it is not in its implementation. Rather, it consists of a considerable amount of analysis characterizing the fuel cycle, the technologies, and their emissions; data collection; the application of atmospheric transport models; and the analysis and utilization of the ecosystems, environmental impacts, epidemiology, public health, and economics literatures. The procedure can be summarized as consisting of the following steps:

(1) Select a particular technology(s) and site (including sites of the "upstream" activities which are the plantations growing the biomass feedstocks for the power plant).

(2) Characterize the nature of the major activities and processes of the total fuel cycle in terms of the potentially (or known) major sources of emissions. Obtain estimates of the major emissions or other residual output from each type of activity. The type of activity could be defined as a general category such as biomass feedstock transportation.

(3) Select the higher priority impact-pathways on which the analysis is to focus.

(4) Identify and use the appropriate atmospheric (and aquatic, if appropriate) transport models to estimate the change in concentrations and deposition in the surrounding area.

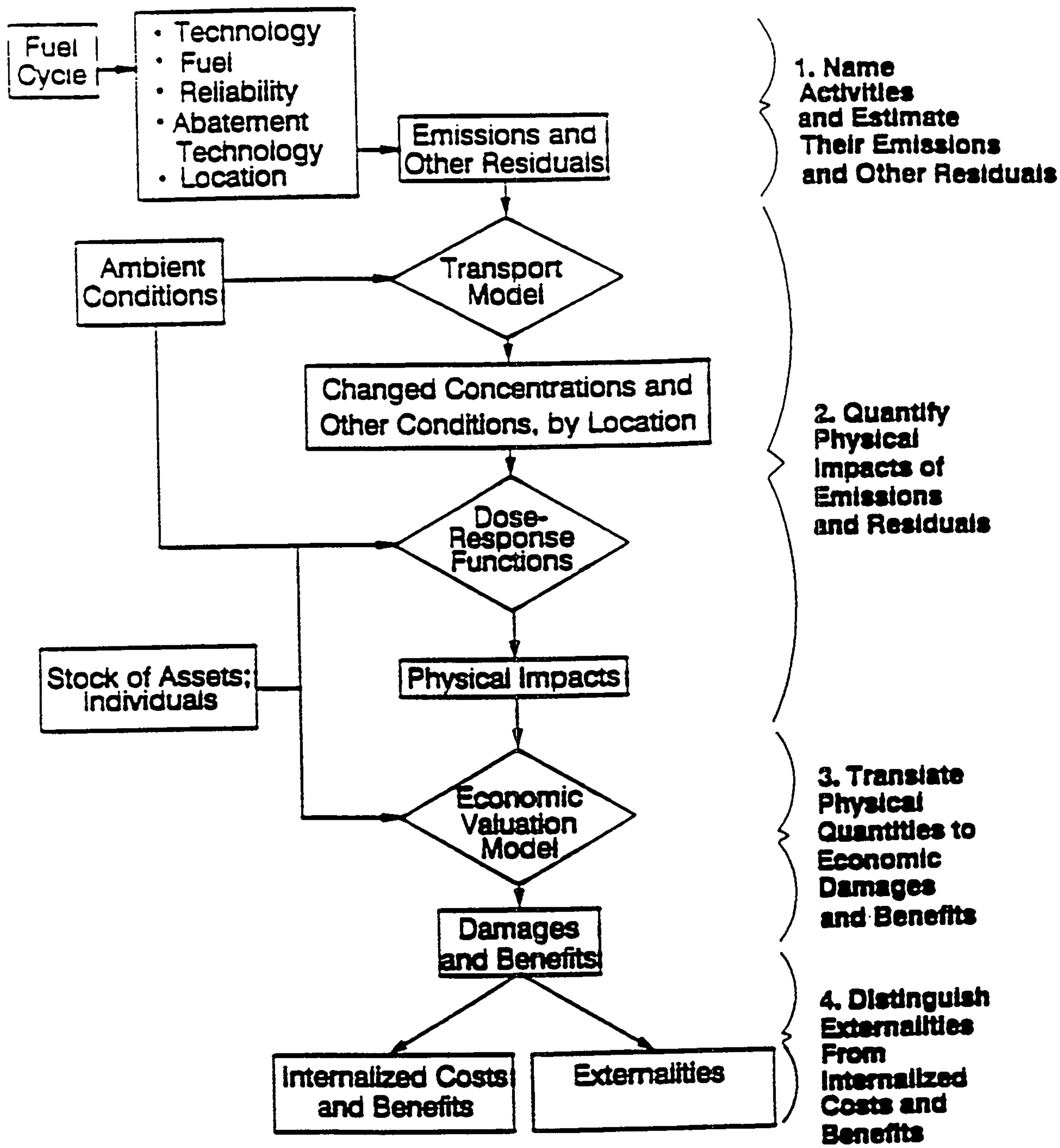
(5) Identify the types of ecological, health and other impacts that potentially arise from exposure to the changed conditions; and identify appropriate dose-response relation ships, as permitted by the scientific literature.

(6) Scale or adjust the estimates of changes in concentrations into the spatial and temporal units required by the dose-response relationships.

(7) Use the dose-response relationships to estimate the impact(s) of the changes in concentration or changed condition of the environment (with environemnt interpreted in the broadest sense).

(8) Use the economic valuation functions obtained from the literature to estimate the marginal economic damages and benefis of the fuel cycle, and express these values as mills/kWh on an annual (levelized) basis.

Figure ES-1. Impact-pathway for damage function approach.



ES.4 BIOMASS-TO ELECTRICITY TECHNOLOGIES AND EMISSIONS

The biomass-to-electricity fuel cycle was assumed to begin with the production of wood energy feedstocks that utilize short-rotation intensive culture (SRIC). SRIC is a silvicultural system that uses fast-growing hardwood trees, short rotations or cutting cycles, densely spaced trees, and fertilizers and pesticides to accelerate biomass growth. For both time periods a 6-year rotation was assumed. In general, construction and operation of the power plant would require new plantations. Thus, the (set) impacts of the plantation are part of the fuel cycle's impacts. (By contrast, a new coal fired power plant would generally not require opening a new coal mine).

Two conversion technologies were considered. A conventional steam turbine represents a current technology (1990 timeframe). A biomass gasifier gas turbine represents a future technology (2010 timeframe). Two sites were used in the demonstration of the Damage Function Approach methodology: a Southeast Reference site near Oak Ridge, in East Tennessee and a Northwest Reference site at Camas, Washington which is about 20 miles east of Portland, Oregon (Figure ES-2). The tree species at the Southeast Reference site were sycamore and sweetgum, mixed with black locust. The species in the Northwest Reference site were hybrid poplars mixed with red alder.

Total acreage required at the Southeast Reference site was 25,000-40,000 acres, depending on the conversion technology. Total acreage required at the Northwest Reference site was 17,000-30,000 acres. This acreage will supply a 30 MW plant in 1990 and a 40 MW plant in 2010. Plantations replace existing land uses: pasture, corn, soybeans and hay in the Southeast; and closecrop and pasture in the Northwest. Other changed conditions and emissions of interest include emissions from exhaust of diesel farm tractors, tractor accidents, applications of agricultural chemicals, changes in soil erosion from the changes in land use, transportation of feedstock to the conversion facility, and emissions from biomass combustion to generate electricity. Two key sets of data are summarized in Tables ES-1 (changes in erosion) and ES-2. (air emission factors for wood-fired power generation).

ES.5 SELECTED IMPACT-PATHWAYS

There are many activities, processes, and emissions associated with the biomass fuel cycle. Due to time and resource constraints, only a subset can be addressed in any detail. Three major factors guided this setting of priorities: (a) impacts that were considered to be most important in terms of their potential damages or benefits (based on the existing literature and informed assessments); (b) impacts that spanned all of the major stages of the fuel cycle; (c) and impacts and damages (or benefits) that were more likely to be quantified.

The impact-pathways that were selected were identical for both sites. Due to data limitations, and time and resource constraints interest in these types of studies, all of the impacts and damages (or benefits) could not be quantified. The selected impact-pathways are listed in Tables ES-3 (Southeast) and ES-4 (Northwest). Letter designations are used to summarize the limitations that precluded quantitative estimates of many of the impacts.

ES.6 MARGINAL ECOLOGICAL IMPACTS OF A BIOMASS FUEL CYCLE

Tables ES-3 and ES-4 summarize the ecological impacts that were examined. For each emission examined, this table identifies ecological endpoints that: (1) are believed to be negligible, (2) can be quantified from the existing knowledge base, or (3) cannot currently be quantified.

There are two important qualifications in interpreting the table and, by implication, any estimates of ecological impacts associated with the biomass fuel cycle.

First, site-specific impact calculations are sometimes not generalizable to other sites. For example, erosion and its impacts are highly dependent on local topography, meteorology, and geology. Study results for a plantation in East Tennessee cannot be extrapolated to sites in the Midwest. Results for the impacts of ozone on crop production, on the other hand, can be at least approximately extrapolated to other sites where the same crops are grown.

Second, impacts that are distributed over large regions are inherently difficult to quantify. Quantitative regional impact assessments have been performed for only a few ecological resources and stress types.

It should also be noted that impacts of all stresses on biodiversity cannot be quantified at this time, principally because there is no consensus among ecologists on operational definitions of biodiversity that are suitable for assessment purposes. Endangered species and legislatively protected ecosystem types (e.g., wetlands) provide some regulatory tools for environmental protection but are inadequate as a basis for quantifying environmental externalities.

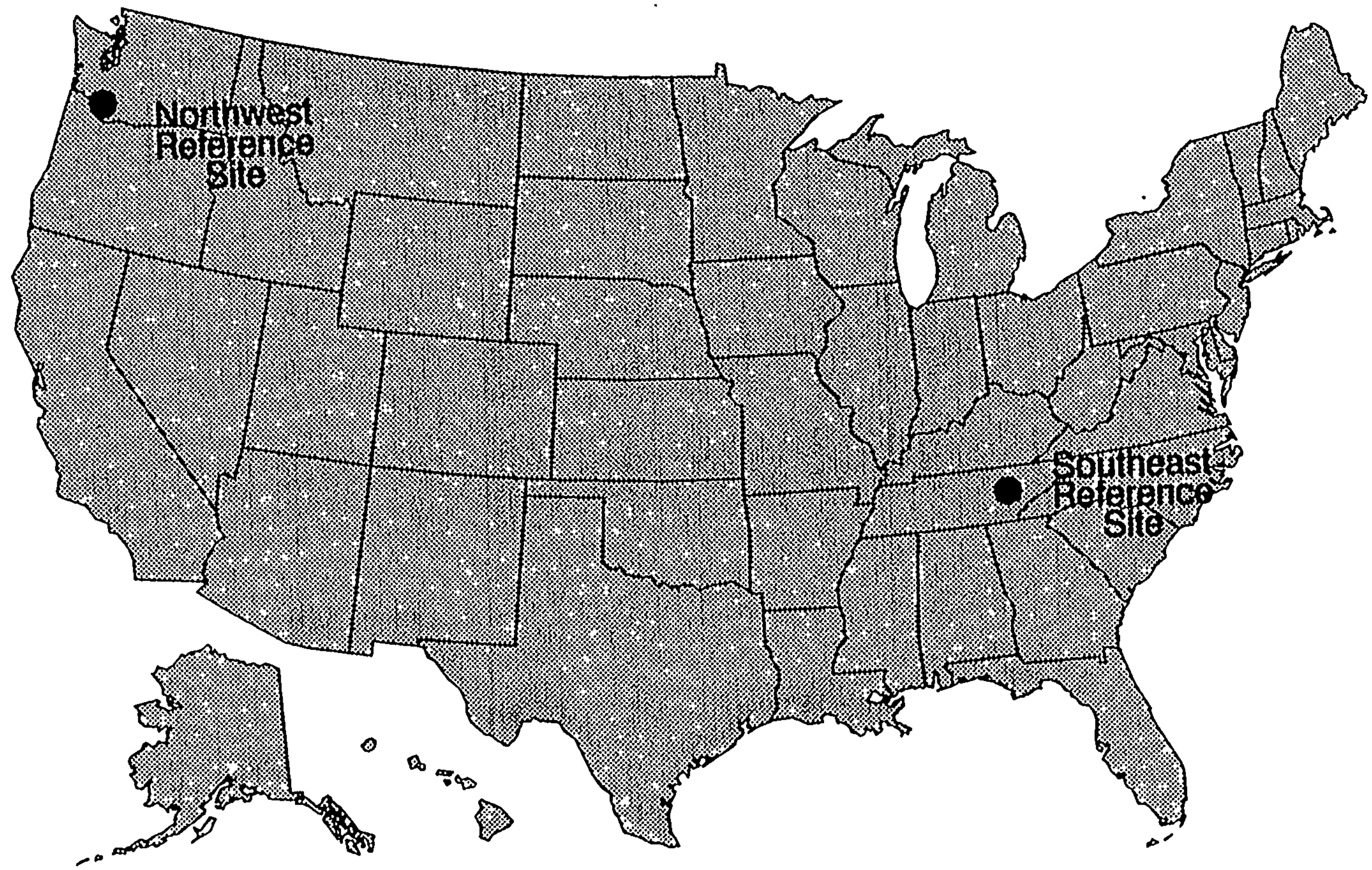


Figure ES-2. Northwest and Southeast Reference Sites

Table ES-1. Annual Erosion (tons)

	Years after Establishment											
	1	2	3	4	5	6	7	8-18	19	20-24	25	26-36
						1990 Southeast						
Plantation	47,863	71,795	76,581	81,368	86,153	90,940	47,863	28,718	71,795	90,940	47,863	28,718
Prev. use	19,808	39,616	59,424	79,232	99,040	118,848	118,848	118,848	118,848	118,848	118,848	118,848
Net loss	28,055	32,179	17,157	2,136								
Net gain					12,887	27,908	70,985	90,130	47,053	27,908	70,985	90,130
						2010 Southeast						
Plantation	29,863	44,794	47,781	50,767	53,753	56,739	29,863	17,918	44,794	56,739	29,863	17,918
Prev. use	12,385	24,770	37,155	49,540	61,925	74,310	74,310	74,310	74,310	74,310	74,310	74,310
Net loss	17,478	20,024	10,626	1,227								
Net gain					8,172	17,571	44,447	56,392	29,516	17,571	44,447	56,392

Note: For tree plantations, erosion rates estimated to be equal to that of corn in the first year after establishment, one-half that of corn in the second year, and one-tenth that of corn in the third through 18th year. One-sixth total acreage planted in each of the first six years. For years 8-18, 20-24, and 26-36 values given are for each year; in year 37 the cycle begins again with the values for year 19.

Table ES-2 Air emission factors for wood-fired power generation -- 1990 and 2010 reference technologies

Emission factors	NSPS	AIRS	UCS (1992)	
			Conventional wood	BIG/STIG
Particulates	0.51	7.2	--	--
PM-10	NA	6.48	--	--
TSP	--	--	0.09	0.19
SO_2	20.40	0.15	0.14	0.14
NO_x	10.20	2.8	1.72	1.02
VOCs	NA	1.4	1.31	0.05
CO	NA	4.0	3.76	0.03

Notes: Tests of the whole tree burner technology indicate SO_2 and NO_x emissions of 0.0068 and 0.731 lbs/dry ton, respectively. Particulate emissions of 14.79 lbs/dry ton were measured without collection devices.

Table ES-3. Health and environmental impacts for the Southeast Reference site: 1990 biomass fuel cycle

Fuel cycle stage and impact pathway	Inform. quality	Annual impact: Quantity	Unit	Comments
		Tree Plantations		
Occupational health:				
Fatal accidents	●	4.25	Fatalities/GWe-y	Data not directly applicable
Injuries	●	5,625	Work days lost and restricted activity days/GWe-y	Data not directly applicable
Biodiversity	Δ[b,c]	b,c		Biodiversity discussed in terms of local and regional changes in wooded habitat
Erosion Impacts-1990 - 2010	⊖			Net changes relative to previous use calculated
Erosion Impacts-suspended sed.	Δ[a]	a		Modeling of runoff, and concentrations in receiving water body needed to assess impacts
Ecological and health effects from herbicides	○[a]	a		Modeling of runoff, and concentrations in receiving water body needed to assess impacts
Ecological and health effects from fertilizers K and P N	○[a]	a		Modeling of runoff, and concentrations in receiving water body needed to assess impacts
Ecological and health effects from insecticides Non-N fixing spp. N-fixing species	○	b		No impacts expected due to infrequent use
Ecological and health effects from VOCs	○[b]	b		Potential effects on ozone formation

Table ES-3. Health and environmental impacts for the Southeast Reference site: 1990 biomass fuel cycle

Fuel cycle stage and impact pathway	Inform. quality	Annual impact: Quantity	Unit	Comments
Transportation				
Occupational fatalities	⊖	a	Deaths/GWe-y	
Publicfatalities	⊖	a	Deaths/GWe-y	
Occupational injuries	⊖	a	Injuries/GWe-y	
Public injuries	⊖	a	Injuries/GWe-y	
Road damage	⊖	a	Miles of road resurfacing/year	
Generation				
Occupational health:				
Fatal accidents	○	0.2	Deaths/GWe-y	National Safety Council General industry 1990 data distributed over 25 sites each 30 MWe
Injuries	○	450	Work days lost and restricted activity days/ GWe-y	
CO_2—global warming potential	●	0	Degrees Celcius	No impacts due to recycling of carbon
SO_2—morbidity:				
Children cough-days	⊖	27	Symptom days	
Adult chest discomfort	⊖	15	Symptom days	
SO_2—ecological impacts	●[c]	0		Resulting ambient concentrations below threshold levels for ecological impacts
Acid deposition	Δ	0		Minimal impacts due to low level of sulfur in wood

Table ES-3 (continued)

Fuel cycle stage and impact pathway	Information quality[a]	Annual impact		
		Quantity	Unit	Comments
NO_X-ecological impacts	⊖[c]	0		Resulting ambient concentrations below threshold levels for ecological impacts
NO_2—morbidity:				
Phlegm days	⊖	1,105	Symptom days	No economic valuation
Particulates (PM_{10}) mortality	⊖	0.028	Deaths	
Particulates (PM_{10})—morbidity:				
Respiratory hospital admissions	⊖	0.527	Admissions	
Emergency room visits	⊖	1.22	Visits	
Restricted activity days	⊖	212	Days	
Respiratory symptoms	⊖	7,940	Symptoms	
Chronic bronchitis in children	⊖	2.10	Added children	
Chronic cough in children	⊖	2.42	Symptoms	
Asthma attacks	⊖	86.4	Days	
Chronic bronchitis in adults	⊖	0.351	Adults	
Particulates—material damage	Δ			May be catalyst for other degrading pollutants
Particulates-visibility	⊖	a		Modeling required to determine effects on visibility
Ozone - morbidity:				
Total respiratory restricted activity days	⊖	2,690	Symptom days	
Any-symptom day	⊖	5,700	Symptom days	
Asthma-attack day	⊖	308	Symptom days	
Eye-irritation day	⊖	7,710	Symptom days	

Table ES-3 (continued)

Fuel cycle stage and impact pathway	Information quality[a]	Annual impact		
		Quantity	Unit	Comments
Days of coughing	⊖	3,090	Symptom days	
Cough incidence	⊖	17,900	Symptoms	
Shortness of breath	⊖	10,300	Symptoms	
Pain upon deep inspiration	⊖	2,460	Symptoms	
Ozone—crops	⊖	0.06-0.12	Percent	Lost productivity in major crops
Hydrocarbons	Δ[d,c]	c		Insufficient data on specific compounds (i.e., PAHs), conc. and dose-response functions
Water vapor	Δ[a]	a		Modeling required to determine effects on visibility
Peroxyacetyl nitrate (PAN)	Δ[d,c]	c		Field data and modeling needed to assess impacts
Inorganics	Δ[c]	c		Conc. of heavy metals in wood are relatively low, and no significant impacts expected
Cooling system - blowdown	Δ[c]	c		Modeling required to determine concentrations
Wastewaters	Δ[c]	c		Modeling required to determine concentrations
Ash -	⊖	c		Potential benefit as a soil conditioner

Legend: ▬ no data; Δ qualitative information; ○ marginal quality of quantitative information; ⊖ quality could be improved; and ● good quality.

a. Data can be improved with near term inputs, such as application of appropriate models.
b. Data limited by state of the science; i.e, new models needed.
c. Data limited by lack of site specific studies
d. Maximum application rates
e. Maximum annual average

Table ES-4. Health and environmental impacts for the Northwest Reference site: 1990 biomass fuel cycle

		Annual impact		
Fuel cycle stage and impact pathway	Inform. quality	Quantity	Unit	Comments
		Tree Plantations		
Occupational health:				
Fatal accidents	●		Fatalities/GWe-y	Data not directly applicable
Injuries	●		Work days lost and restricted activity days/GWe-y	Data not directly applicable
Biodiversity	Δ[b,c]	b,c		Biodiversity discussed in terms of local and regional changes in wooded habitat
Erosion Impacts-1990 - 2010	⊖			Net changes relative to previous use calculated
Erosion Impacts-suspended sed.	Δ[a]	a		Modeling of runoff, and concentrations in receiving water body needed to assess impacts
Ecological and health effects from herbicides	○[a]	a		Modeling of runoff, and concentrations in receiving water body needed to assess impacts
Ecological and health effects from fertilizers K and P N	○[a]	a		Modeling of runoff, and concentrations in receiving water body needed to assess impacts
Ecological and health effects from insecticides Non-N fixing spp. N-fixing species	○	b		No impacts expected due to infrequent use
Ecological and health effects from VOCs	○[b]	b		Potential effects on ozone formation

Table ES-4. Health and environmental impacts for the Northwest Reference site: 1990 biomass fuel cycle

Fuel cycle stage and impact pathway	Inform. quality	Annual impact Quantity	Unit	Comments
		Transportation		
Accidents:				
Deaths:				
Occupational	⊖	a	Deaths/GWe-y	
Public	⊖	a	Deaths/GWe-y	
Injuries:				
Occupational	⊖	a	Injuries/GWe-y	
Public	⊖	a	Injuries/GWe-y	
Road damage	⊖		Miles of road resurfacing/year	
		Generation		
Occupational health:				
Fatal accidents	○	0.2	Deaths/GWe-y	National Safety Council General industry 1990 data distributed over 25 sites each 0 MWe
Injuries	○	450	Work days lost and restricted activity days/ GWe-y	
CO_2—global warming potential	ΔΔ	0	Degrees Celcius	No impacts due to recycling of carbon
SO_2—morbidity:				
Children cough-days	⊖	a	Symptom days	
Adult chest discomfort	⊖	a	Symptom days	
SO_2—ecological impacts	●[c]	0		Resulting ambient concentrations below threshold levels for ecological impacts
Acid deposition	Δ	0		Minimal impacts due to low level of sulfur in wood

Table ES-4. (continued)

Fuel cycle stage and impact pathway	Information quality[a]	Annual impact		
		Quantity	Unit	Comments
NO_X-ecological impacts	⊖[c]	0		Resulting ambient concentrations below threshold levels for econological impacts
NO_2—morbidity:				
Phlegm days	⊖	a	Symptom days	No economic valuation
Particulates (PM_{10}) mortality	⊖	a	Deaths	
Particulates (PM_{10})—morbidity:				
Respiratory hospital admissions	⊖	a	Admissions	
Emergency room visits	⊖	a	Visits	
Restricted activity days	⊖	a	Days	
Respiratory symptoms	⊖	a	Symptoms	
Chronic bronchitis in children	⊖	a	Added children	
Chronic cough in children	⊖	a	Symptoms	
Asthma attacks	⊖	a	Days	
Particulates—material damage	Δ	c		May be catalyst for other degrading pollutants
Particulates-visibility	⊖	a		Modeling required to determine effects on visibility
Ozone - morbidity:				
Total respiratory restricted activity days	⊖	a	Symptom days	
Any-symptom day	⊖	a	Symptom days	
Asthma-attack day	⊖	a	Symptom days	
Eye-irritation day	⊖	a	Symptom days	

Table ES-4. (continued)

Fuel cycle stage and impact pathway	Information quality[a]	Annual impact		
		Quantity	Unit	Comments
Days of coughing	⊖	a	Symptom days	
Cough incidence	⊖	a	Symptoms	
Shortness of breath	⊖	a	Symptoms	
Pain upon deep inspiration	⊖	a	Symptoms	
Ozone—crops	⊖	a	Percent	Lost productivity in major crops
Hydrocarbons	Δ[d,c]	c		Insufficient data on specific compounds (i.e., PAHs), conc. and dose-response functions
Water vapor	Δ[a]	a		Modeling required to determine effects on visibility
Peroxyacetyl nitrate (PAN)	Δ[d,c]	c		Field data and modeling needed to assess impacts
Inorganics	Δ[c]	c		Conc. of heavy metals in wood are relatively low, and no significant impacts expected
Cooling system - blowdown	Δ[c]	c		Modeling required to determine concentrations
Wastewaters	Δ[c]	c		Modeling required to determine concentrations
Ash - 1990 2010	⊖	c		Potential benefit as a soil conditioner

Legend: ▬
no data; Δ
qualitative information; ○
marginal quality of quantitative information; ⊖
quality could be improved; and ● good quality

a. Data can be improved with near term inputs, such as application of appropriate models.
b. Data limited by state of the science; i.e, new models needed.
c. Data limited by lack of site specific studies
d. Maximum application rates
e. Maximum annual average

ES.7 MARGINAL EFFECTS OF A BIOMASS FUEL CYCLE ON HEALTH

The emissions and impact-pathways which were evaluated in this study probably represent the greatest proportion of adverse health effects related to the biomass fuel cycle. Data presented in Tables ES-3 and ES-4 indicate, however, that only a small proportion of both health and ecological impacts are rated as having a high quality of information about them.

These impact-pathways represent a partial listing of potentially important sources of adverse impacts. For human health impacts, only the air inhalation pathway was considered (except for a lead uptake factor which considers the oral pathway for dust). Consideration in the future should be given to transport through the environment to and through the food chain. Likewise, effluent releases to the aquatic pathway were not fully addressed because of the lack of a sufficient knowledge base.

ES.8 MARGINAL ECONOMIC DAMAGES AND BENEFITS

Table ES-5 summarizes the damages (in total annual damages and in mills per kilowatt-hour in 1989 dollars) associated with the operation of the specified biomass plant in the Southeast Reference environments. The list of impact-pathways presented is limited to those identified. Low, midpoint, and high estimates are presented where such estimates can currently be made with the existing base of knowledge.

The main goal of the study was to demonstrate methods for estimating damages. Thus, in some instances, methods relevant to *additional* pathways were demonstrated, rather than to duplicate analyses for both reference environments. However, in several cells no estimates are possible, either because of missing knowledge base or an effect too small to estimate or value.

Discount rates were used in very few cases because almost all of the effects are for each year of the 40-year life of the plant. Where effects were not the same each year, a 5% interest rate was used to levelize the damages and benefits.[3] This interest rate is within the generally accepted range of 2%–10%. Other users of the methodology will wish to use their own appropriate rates.

The damage estimates are for the biomass fuel cycle. For planning assessments, the salient damage estimates are those for *differential damages*

[3]A levelized cost is the value which, when summed annually over the life of the power plant, will sum to the present value of the total cost, expressed in real dollars.

between fuel cycles (including conservation). This distinction is crucial in light of the rather large employment benefits associated with a new biomass plant. Yet, any project to generate an equivalent amount of electricity will result in significant employment benefits. Thus, when estimating differential damages between the biomass and any other similarly sized fuel cycle, the employment benefits registered for the former will tend to be canceled out by employment benefits in the latter, leaving environmental and other damage differentials largely determining external cost differentials among the alternative fuel cycles.

ES.9 CONCLUSIONS

ES.9.1 Scope of the Study

It cannot be over-emphasized that the primary objective of the study was to ***demonstrate methodology***. Thus, the numerical results are in no respect definitive, universal estimates of total fuel cycle externalities. The sites considered were for illustrative purposes. They are not representative of all, or even likely, sites in the U.S. The idea of the study was **not** to estimate damages and benefits that could be applied throughout the U.S., or even to other sites in the same region. Nor are these sites actual options. They are so numerous and different in their site characteristics that no single study could pretend to encompass all options.

ES.9.2 Usefulness of the Damage Function Approach

This study has demonstrated that the damage function approach is an operational method for estimating many of the damages and benefits of a biomass fuel cycle. Insofar as many countries are considering ways of internalizing the external damages of fuel cycles, it seems all the more important to invest in thorough assessments. Regulatory burdens imposed on utilities and others are very costly. They should be justified by thorough study. By the same token, the external damages to health and to the environment should be accounted for and reflected in energy prices. The method demonstrated in this study represents an important step in this direction. Thus, ***in spite of its limitations and the gaps in the base of scientific knowledge, the results gained from studies using this approach would add to the base of knowledge*** to support informed decisions about energy.

Table ES-5. Aggregation of priority pathway damages for 1990 biomass-to-electricity coal fuel cycle in the Southeast Reference site

Stages	Pathway	Damages (1000s of 1989 dollars			Damages (mills/kWh)		
		Low	Med	High	Low	Med	Hi
Tree Plantations	Occupational health: Fatal accidents		a			a	
	Occupational injuries		a			a	
	Biodiversity		b,c			b,c	
	Erosion Impacts	-175	-110	-60	-0.950	-0.596	-0.3
	Erosion Impacts-suspended sed.		a,c			a,c	
	Ecological and health effects from herbicides		a,c			a,c	
	Ecological and health effects from fertilizers K and P N		a,c			a,c	
	Ecological and health effects from insecticides Non-N fixing spp. N-fixing species		a,b,c			a,b,c	
	Ecological and health effects from VOCs		a,b,c			a,b,c	
Transportation	Occupational accidents-fatalities		a			a	
	Public fatalities		a			a	
	Occupational injuries		a			a	

Table ES-5. Aggregation of priority pathway damages for 1990 biomass-to-electricity coal fuel cycle in the Southeast Reference site

Stages	Pathway	Damages (1000s of 1989 dollars			Damages (mills/kWh)		
		Low	Med	High	Low	Med	High
	Public injuries		a			a	
	Road damage					0.122	
Generation	Occupational health: Fatal accidents		a			a	
	Occupational Injuries		a			a	
	CO_2-global warming potential	0	0	0	0	0	0
	SO_2-morbidity	0.0260	0.760	1.50	0.0014	0.0014	0.0082
	SO_2-ecological impacts	0	0	0	0	0	0
	Acid deposition	0	0	0	0	0	0
	NO_X-ecological impacts	0	0	0	0	0	0
	NO_2-morbidity: Phlegm days						
Generation (continued)	particulates (PM_{10})-mortality (VSL approach)	25	78	160	0.14	0.42	0.88
	Total particulates (PM_{10})-morbidity:	49	82	130	0.27	0.44	0.69
	Particulates respiratory hospital admissions	0.82	3.4	7.0		part of total	
	Particulates emergency room visits	0.017	0.22	0.41		part of total	
	Particulates restricted activity days	2.4	11	19		part of total	
	Particulates respiratory sysmptoms	22	51	94		part of total	

Table ES-5. Aggregation of priority pathway damages for 1990 biomass-to-electricity coal fuel cycle in the Southeast Reference site

Stages	Pathway	Damages (1000s of 1989 dollars			Damages (mills/kWh)		
		Low	Med	High	Low	Med	Hi
	Particulates chronic bronchitis in children	0.0045	0.28	0.52		part of total	
	Particulates chronic cough in children	0.0019	0.013	0.052		part of total	
	Particulates asthma attacks	0.4	2.6	5.3		part of total	
	Particulates-bronchitis adults	2.7	15	26		part of total	
	Particulates-material damage	c	c	c	c	c	c
	Particulates-visibility	a	a	a	a	a	a
	Total ozone-morbidity	16	27	41	0.085	0.15	0.
	Ozone total respiratory restricted activity days	0.13	10	23		part of total	
	Ozone any-symptom day	0.62	6.4	14		part of total	
	Ozone asthma-attack day	0.46	1.6	3.1		part of total	
	Ozone eye-irritation day	4.2	9	16		part of total	
	Ozone days of coughing	0.78	28	64		part of total	
	Ozone cough incidence	1.2	6.5	18		redundant	
	Ozone shortness of breath	1.4	9.8	29		redundant	
	Ozone pain upon deep inspiration	2.3	11	25		redundant	

Table ES-5. Aggregation of priority pathway damages for 1990 biomass-to-electricity coal fuel cycle in the Southeast Reference site

Stages	Pathway	Damages (1000s of 1989 dollars			Damages (mills/kWh)		
		Low	Med	High	Low	Med	High
	Ozone-crop					0.088	
	Hydrocarbons		c			c	
	Water vapor		a			a	
	Peroxyacetyl nitrate (PAN)		c			c	
	Inorganics		c			c	
	Cooling system-blowdown		c			c	
	Wastewaters		c			c	
	Ash		c			c	
	Employment benefits	-196	-83	-46	-0.80	-0.35	-0.19

a. Data can be improved with near term inputs, such as application of appropriate models.
b. Data limited by state of the science; i.e, new models needed.
c. Data limited by lack of site specific studies
d. Maximum application rates
e. Maximum annual average

ES.9.3 Marginal Damages and Benefits

The biomass fuel cycle has benefits in at least two areas. One benefit is from the ***reduced erosion***: 0.60 mills/kWh in the year 1990 and 0.29 mills/kWh in 2010 for the Southeast, and 0.20 mills/kWh in 1990 and 0.08 mills/kWh in 2010 in the Northwest. The differences stem from the different feedstock requirements for the different technologies and the different soil and land uses in the different regions. The second benefit is the ***employment benefit***: 0.35 mills/kWh in the Southeast and 0.27 mills/kWh in the Northwest. Both benefits are significant in size. As stressed throughout this report there is considerable uncertainty and wide confidence intervals for all of the estimates. Furthermore, these estimates should **not** be interpreted as being the total benefits of the biomass fuel cycle.

Of the impacts that were quantified, the ***major source of damage from the biomass fuel cycle is particulates, especially in areas with high baseline concentrations***. Premature mortality damages were estimated to be 0.42 mills/kWh and morbidity damages 0.44 mills/kWh.

Based on inspection of data on ambient ozone concentrations in the rural Southeast, high ozone concentrations are not uncommon. High ozone concentrations are associated with elevated rates of respiratory illnesses. A second significant source of damages were the ozone-related ***health effects from the*** NO_x emitted by the plant. For the Southeast Reference site, these damages amounted to 0.15 mills/kWh.

For comparison, the average total cost to generate electricity from coal-fired power plants in the United States in 1990 was about 3 cents/kWh (EIA 1992). The cost of producing electricity from biomass is widely held to be greater then that from coal. USDOE (1992) reports costs ranging from about 6.3 to 7.4 cents/kWh. This range is much higher than the estimate provided by the ERIP (1991). ERIP reports wood-fired generation to be about 13% higher than coal.

Damages to public roads from the feedstock-hauling trucks were also significant: 0.12 mills/kWh. These road impacts are the *net* damages. Road use related to the replaced agricultural activities also cause road damage. Other damages were estimated to be at least an order of magnitude less.

Since most of the damages were health-related, if the biomass plant were situated in a region with 10 million people nearby, rather than only one million, as in the Southeast Reference site, then the damages would be about an order of magnitude greater -- assuming that meteorological conditions, topography, population density, and demographic characteristics are comparable at the two sites. This approximation follows directly from: (a) the near-linear relationships between emissions and changes in concentrations, and (b) the linear (or linear approximation) dose-response functions that were used throughout our analysis. In general, the ***size of the nearby population is a major determinant of the level of damages from the biomass plant.***

Estimates of damages are highly uncertain, and are project- and site-specific. The estimates should not be summed and then compared, either between the two regions or technologies, or among alternative fuel cycles. There was generally a lack of quantitative information on ecological exposure-response functions. Also, some impacts were quantified at one site, but not at the other. The same differences are true among the different fuel cycle studies (e.g. biomass and coal). It **is**, however, informative to compare **individual** impact-pathways -- between sites, or technologies, or fuel cycles.

The results show that there are ***significant differences in damages, and thus externalities, among different sites (for example, benefits from erosion reduction differ by a factor of three) and for different biomass technologies (for erosion, by a factor of two).***

The use of advanced biomass conversion technologies could reduce ***NO_x emissions significantly compared to conventional wood burners (Table ES-2). The resulting reduction in the risks of morbidity caused by exposure to ozone is not as great proportionately as the reduction in emissions.***

The biomass fuel cycle has ***near-zero net emissions of CO_2***. Thus, compared to fossil fuel cycles, biomass is not burdened with the problems regarding its impacts on global climate change.

ES.9.4 Information Need

A major conclusion of this study is that while the scientific base of knowledge is reasonably good in some areas, it is certainly lacking in others. The paucity of quantitative estimates of ecological impacts is particularly striking, all the more so for regional and global impacts that extend well beyond the local site of a biomass plant. The many interacting factors in ecological systems make it difficult to identify well-defined functions describing the impacts of changes in pollutant concentrations on ecosystems. ***Given the current state of knowledge, it will generally be very difficult to develop quantitative estimates of ecological damages caused by fuel cycles.***

In the health effects area, the air inhalation pathway was considered in some detail. However, some of the more important health-effects estimates rely on a few or sometimes individual studies. The ***lack of health-effects studies is an obvious weakness which can be overcome with additional research.*** The lack of information about the effects of effluents on aquatic ecosystems and effects related to solid wastes have not been addressed. The ingestion of pollutants through the food-chain is another area where the knowledge base is lacking. Also, priorities should be established to ***develop better atmospheric transport models*** that are reasonably accurate and that are also inexpensive to use in terms of their data demands.

In economics, a major issue in this area of research is the accuracy and precision of estimates of individuals' willingness to pay (WTP) to avoid certain ecological impacts or health risks. In using estimates of ***WTP, significant issues arise in the transferability issue*** — the application of results obtained in one location or context to another. Other major issues are aggregation and non-use value. Aggregation refers to the practice of how to best add damages and benefits to obtain an overall measure. Non-use value refers to individuals' willingness to pay for certain environmental conditions, even though the individuals may never experience those conditions themselves.

Finally, all of the caveats regarding the interpretation of the numerical results bear repeating:

- The analyses were performed on a number—but not all—of the possible effluents and impacts.

- Limitations in the knowledge base precluded quantitative estimates on most ecological impacts.

- The analyses are project- and site-specific.

- Because of these and related limitations in the analyses, the numerical results should not be used in any definitive comparison of externalities from alternative sources of energy.

Notwithstanding the above caveats, this study has successfully ***demonstrated the application of the Damage Function Approach to estimate the damages and benefits of biomass fuel cycles***. The study has ***identified important limitations in the quality of scientific information***, that preclude a quantification of all damages and benefits. Finally, the study has ***developed a range of estimates of the damages and benefits of many of the important impacts*** of a new biomass-fired power plant at two reference sites in the United States.

1. INTRODUCTION

1.1 BACKGROUND

The social accounting concept is of interest to many institutions in the United States and elsewhere as a means of assisting in energy and environmental decision making. Social accounting seeks to make explicit all the social costs and benefits resulting from production and consumption decisions. Ideally, a system of social accounts reflects two components: private costs (e.g., capital, operating, and maintenance costs); and externalities (incremental costs and benefits that, for various reasons, are not reflected in market transactions but, nevertheless, have value). External costs and benefits include environmental quality, health, as well as nonenvironmental considerations.

Estimating the externalities of energy production and consumption requires information about many complex factors. Information is needed about: (1) the total fuel cycle for each energy source, beginning with the development and extraction of the energy resource and ending with the disposal of its wastes; (2) the production processes and technologies at each stage of the fuel cycle, particularly about emissions and other residuals; (3) changed concentrations and deposition in the environment that result from the emissions and residuals; (4) the incremental consequences, or impacts, that result from these changed concentrations, or from other physical changes, in the environment; (5) how these impacts are valued by individuals to derive the economic damages, as well as benefits, associated with these impacts; and (6) distinguishing between externalities and the costs and benefits that are already "internalized" within market prices. This series of information needs corresponds to the identification of "impact-pathways," in which the effect of an emission is traced from its source to its ultimate damage or benefits. The term emission is used here to mean any residual or altered chemical or physical condition. Further discussion on these concepts is provided in the Background Document for this study (ORNL/RFF 1992).

The lack of high-quality information about external costs and benefits is a handicap to making good decisions about energy. Consequently, in 1991 the U.S. Department of Energy (DOE) launched a major initiative to provide a foundation for better decision making. The European Communities had come to much the same realization—that the external costs and benefits of fuel usage could not be understood, estimated, and correctly applied given the current state of knowledge. Thus DOE and the Commission of the European Communities (EC) signed a joint statement regarding the externalities of fuel cycles. This agreement committed their respective organizations to "develop a comparative analytical methodology and to develop the best range of estimates of costs from secondary sources" for eight fuel cycles and four conservation options. Lead responsibilities for the fuel cycles were distributed between the two research teams as follows:

- both teams were to undertake the coal fuel cycle and conservation options;
- the United States was to lead on biomass, oil, natural gas, and small hydroelectric energy; and
- the EC was to lead on the uranium, photovoltaic energy, and wind cycles.

A study team was created in the United States by bringing together research staff at Oak Ridge National Laboratory (ORNL) and Resources for the Future (RFF). A similar study team was organized for the EC effort. Given time and budget constraints, the U.S. and EC study teams, with the full agreement of the principals, moved to construct the foundation for improving our information about the external costs and benefits of energy fuel cycles. The study teams did not address the purely private-cost component of social costs. This activity is appropriately covered by individual DOE and other programs and involves a very different body of literature and analysis.

This foundation phase concentrated on the first five of the six areas of information needs presented in the preceding portion—all except a complete distinction between externalities and internalized costs and benefits (discussed further in Section 1.4). Furthermore, complete analysis of the external costs and benefits ultimately requires an equally balanced assessment of abatement technology and costs; this latter assessment is beyond the scope of this study.

1.2 STUDY PRIORITIES

The major objectives of this biomass-to-electricity fuel cycle study were three-fold:

(1) to implement the methodological concepts which were developed in the Background Document (ORNL/RFF 1992) as a means of estimating the external costs and benefits of fuel cycles, and by so doing, to demonstrate their application to the biomass fuel cycle;

(2) to develop, given the time and resources, the best range of estimates of marginal damages and benefits associated with selected impact-pathways from a biomass project, using two benchmark projects at two reference sites in the United States; and

(3) to support the continued development of the National Energy Strategy by assessing the state of the information available to support energy decision making and the estimation of externalities, and by so doing, to assist in identifying gaps in knowledge and in setting future research agendas.

The demonstration of methods, modeling procedures, and use of scientific information was the most important objective of this study. It provides an illustrative example for those who will, in the future, undertake "actual" studies of "real" options at "real" sites.

A more comprehensive study could have been completed had the time and budget constraints not been as severe. Particularly affected were the estimation of ecological impacts, and economic valuation. However, the most important objective of the study was to demonstrate methods, as an example for future studies. Thus, having severe time and budget constraints was appropriate from the standpoint that these studies could also face similar time and budget constraints. Consequently, a more important result of the study is an indication of what can be done in such studies, rather than the specific numerical estimates themselves.

In fact, there are several reasons why ***it is not appropriate to apply blindly the numerical results of this study to compare different fuel cycles:***

(1) All of the potentially important impacts were not necessarily addressed because of limitations in the state of quantitative knowledge or in the time and budget for this study.

(2) Limitations in knowledge preclude quantitative estimates of many ecological impacts. The effect of these limitations on the ability to derive quantitative estimates may vary for different fuel cycles.

(3) Impacts are generally site-specific. It would be erroneous to extrapolate, without appropriate analysis, the numerical estimates for the two sites analyzed in this study to other sites. In particular, the two sites are not intended to be representative of all sites in the country, nor even to be economically viable alternatives. Of the two biomass sites, one (the Northwest site) is a likely option, while the other (the Southeast) is economically marginal. Rather, the sites were selected so as to compare individual impacts across fuel cycles using a common environmental

baseline. The sites are plausible from a physical standpoint, though not necessarily from an economic or regulatory one.

(4) While the damages and benefits that were estimated are candidates for externalities, a comprehensive study has not yet been completed to take into account regulatory, taxation, and other factors that may internalize some portion of those damages.

(5) Aggregation errors may arise from adding estimates of damages that are estimated separately for individual impacts.

(6) This study is primarily a demonstration of methods, limited by time and budget constraints, rather than a conclusive comparison of alternative energy technologies.

This study, like any other study, established a set of priorities in order to best reach its objectives. All studies must decide how much of the world is critically necessary to include and how much can be held fixed or beyond the scope of the study. Given the relatively unexplored territory faced by this study, many choices had to be made. These are summarized in the following section.

Study Approach:

- The Damage Function Approach (DFA) was selected by the study teams as the basic methodology. The DFA attempts to combine natural science and economics to identify the changed conditions which stem from an incremental investment. In our study the investment is building and operating an biomass power plant. Figure 1.2-1 shows a flow chart that illustrates the DFA process. It is described further in Section 1.3 and in the Background Document (ORNL/RFF 1992).

- A major departure from other approaches, which provide information about residual emissions and impacts, is the use of economic valuation approaches to monetize the physical impacts. Resources or impacts have economic value only because they affect ***individual welfare***, not because they represent so many energy units, labor units, or land units or even health or the ecology *per se*. The assessment of damages and benefits, as defined by the theory of welfare economics, reflects both location-specific impacts and the monetary *value* of these impacts.

- Given the extreme challenges posed by dynamic modeling at the given level of knowledge, in terms of both data and the understanding of the physical and economic processes, the U.S. and EC teams chose to develop a static set of data and relationships. The term "static" describes the lack of feedback and other interactive channels that would normally be active in any systems approach for a given incremental change in generating capacity. For instance, we ignore the effect of more impaired health on wage rates and on demand for commodities.

Fuel-Cycle Assumptions:

- The U.S.-EC studies are based on the fuel cycle concept, emphasizing fuel conversion (or more broadly in the context of certain renewable energy sources, resource use) for the generation of electricity.

- Fuel cycle stages encompass all of the activities involved in: (1) primary resource extraction (or growth) and preparation, (2) transport and storage of resources and materials, (3) conversion and processing, (4) distribution of electricity or products, and (5) disposal of wastes. End-use activities are highly varied and will be addressed in future phases of the study program. For the biomass fuel cycle, the study considered the following stages of activities: growing and harvesting trees, transportation of the feedstock, and electric power generation.

- The fuel cycle considered in this study was the construction and operation of a new generating plant located at a particular site. The source of the biomass is a new plantation of trees, which replaces marginal agricultural and other land uses. The plantations developed solely for the purpose of serving a wood fired power plant. The transportation, and other infrastructure required to supply the power plant were assumed to exist already-unless they were unlikely to exist without the biomass plant. Other options-such as adding units to an existing plant, purchasing power from other power producers, or integrated resource planning to meet system-wide or region-wide needs-were not addressed. Our goal was to make a contribution to knowledge about how to estimate damages under a specific set of conditions.

- The U.S. and EC teams have adopted, for simplicity, an incremental investment view of the problem, leaving the operations view to be applied in further extensions of the work. Investment and operation activities are not mutually exclusive but do involve a substantially different perspective on the required information base necessary to examine pollution emissions and other effects. The operations view, which is preferred, requires a complete characterization of the existing production system's activities to capture the change in emissions and other effects from an increase in electricity output associated with bringing a new plant on line. The investment view, however, limits the analysis to characterizing emissions, impacts, and damages associated with the increment to output, holding the rest of the power system constant.

- Similarly, it is more consistent with existing literature to frame the incremental needs of a new power plant than those of a new extraction process. Thus, incremental activities performed within other stages are assumed to reduce underutilized capacity.

Scenario Assumptions:

- Two benchmark technologies were considered. One technology represents a current technology. The other technology represents a future technology, one available in the year 2010. For the 1990 timeframe, a whole-tree burner is assumed. For 2010, a biomass gasifier steam-injected gas turbine (BIG/STIG) is assumed. These two technologies are generally considered to be the most likely for the two respective timeframes.

- The scale set for the benchmark biomass plant was a 30 MWe capacity. The benchmark plant was assumed to achieve a 70% capacity factor producing about 184 GWh of electricity per year for 30 years. Power plants come in many sizes, which influences their use in an existing electricity system. A review of current United States utility expansion plans suggested that, for commercial feasibility, coal, nuclear, oil, and gas plants corresponded to medium- to large-scale investment needs; and that hydro, biomass, photovoltaic and wind might satisfy smaller-scale needs. Medium to large scale is 300 megawatts electric (MWe) or larger, while smaller scale is under 50 MWe.

- Since impacts may have varied temporal distributions, the corresponding damages and benefits must reflect their placement in time: conventionally, this is done either by using a discount rate to derive present values or by using an interest rate for "levelization." The levelized cost is the amount which, when summed annually, equals the total present value of the cost over the life of the coal plant. This study used a 5% interest rate, which falls within the commonly considered range of 2% to 10%; and puts all damages and benefits in levelized terms, that is, in mills/kWh.

1.3 OVERVIEW OF IMPACT-PATHWAYS DAMAGE-FUNCTION APPROACH

The general methodological approach consists of three related concepts: total fuel cycles, the damage function approach, and impact-pathways.

The first concept, the total fuel cycle refers to the approach in which all stages of the fuel cycle are explicitly considered, beginning with the development and extraction of a resource, and ending with the disposal of all wastes or residuals. Section 4.1 describes a fuel cycle accounting framework that was developed to illustrate the stages of the coal fuel cycle and the subsequent impacts of fuel-cycle activities.

The second key concept is the damage function approach (DFA). This approach uses the existing scientific literature on ecological and health impacts associated with fuel cycle to identify impact categories, exposure processes that link emissions to impact endpoints, dose-response information to quantify endpoint changes, and various measurement and quantification issues. A detailed discussion of the literature supporting the analysis of ecological impacts from the biomass fuel cycle can be found in Appendix F.

For estimates of incremental damages, the DFA considers each major fuel cycle activity and estimates: (1) the residual emissions or the altered physical conditions (such as soil erosion); (2) the transport, deposition, or chemical transformations of these emissions and other residual, and the resulting changed concentrations of pollutants and other materials that are spatially and temporally distributed; (3) the physical response of ecological, human, and social resources (which are also spatially and temporally distributed) to these changes in concentrations; (4) the value that is placed on these impacts by the individuals affected; and (5) the distinction between externalities and social costs and benefits which are internalized within the market.

In practice, analysis of every fuel-cycle activity, emission, and impact is impossible. Practical implementation of the damage function approach requires that the more important impacts be selected for more detailed analysis.

These more important impacts are analyzed using the third key concept, impact-pathways. This concept is used to define the sequence of linkages or "mappings" for a given activity or process of the fuel cycle (such as electricity generation). Defining an impact-pathway begins with an emission or other residual from an activity, the transport and/or chemical and physical transformation of that emission, the resulting changes in its concentration in the environment, and the effect of that change that results in a specific ecological impact or health effect. This impact is the endpoint of the pathway and the startpoint for an economic valuation of the impact, what we call a damage, or benefit of that impact. Table 1.3-1 illustrates some general impact and valuation pathway mappings, both at the broad level and at the more specific level.

Impacts are quantified using the available natural science literature to describe a pathway that may consider any or all of the following steps: the transport and chemical transformation of residual emissions, the deposition or changed concentrations of these emissions to these conditions, the exposure of environmental resources and people, and the biological and ecosystem responses. Responses may be positive or negative. The physical responses are then matched to endpoints that can be valued.

Impact Scope:

- The scope of impacts includes local, regional, and global consequences. The U.S. and EC teams agreed to examine local and regional impacts first. However, there is considerable interest in the association between fuel cycles and the problem of global warming. This report contains a discussion of CO_2 emissions and sequestration. However, there is extreme uncertainty and scientific disagreement about the linkage between emissions and measurable physical changes. Thus, no economic valuations are suggested for global warming damages or benefits.

- Impacts are generally site specific. In this study, impacts were considered in two different regional reference environments reflecting the importance of how differences in location affect impact and damages. For the biomass fuel cycle analysis, regional reference environments were defined for the Southeast (Clinch River site, Tennessee) and Northwest (Camus, Washington area). See Section 4.2 for the description of the regional reference environments.

1.4 ECONOMIC VALUATION

Value is intimately connected to opportunity costs: the concept that there is no free lunch, that something must be given up to gain something else. Thus, values are determined in the context of constraints, be they money, time, health, or something else that is valued. These constraints imply that something has value to the extent that individuals are willing to pay for it - the so-called willingness to pay criterion in economics that underlies modern benefit-cost analysis. Emissions or other burdens imposed by the biomass fuel cycle result in health and environmental impacts (which may be positive or negative). These impacts have a monetary counterpart in that people may be willing to pay to avoid such negative impacts (or to obtain positive impacts). Whether these "marginal damages" (or benefits) are counted as a social cost of the fuel cycle external to (and therefore additive to) the private costs of delivering electricity from coal depends on the type of policy in place to address these impacts and even on details of its design. Because of these complexities (see Freeman, Burtraw, Harrington, and Krupnick, 1992), the purpose of the current effort, insofar as health and environmental impacts are concerned, is to estimate marginal damages/benefits from a new plant and its supporting fuel cycle. It is not to estimate the extent to which such damage has already been internalized in the cost of building the plant or the electricity it produces.

Table 1.3-1. Impact-pathway mappings

Broad-Level Mappings		
Fuel cycle stages	→	activities
Activities	→	emissions and other residuals
Emissions	→	transport and change concentration
Transport and changed concentration	→	physical impacts
Impacts	→	economic damages and benefits
Damages and benefits	→	external costs and external benefits
More Specific Mappings		
Emissions	→	source terms
Source terms	→	concentrations
Concentrations	→	exposures
Exposures	→	doses
Doses	→	responses
Responses	→	physical impact endpoints
Impact endpoints	→	valuation startpoints
Valuation startpoints	→	damages and benefits
Damages and benefits	→	external costs and external benefits

The practical and conceptual problems of economic valuation are discussed fully in the Background Document. However, some general remarks about the valuation process are worth noting here:

- The concept of value is based on decades of research in neoclassical microeconomic analysis. At the core of this notion is consumer sovereignty—i.e., that each individual in society is the best judge of his or her value for a good or resource.

- When damages show up in nonmarketed commodities, values are estimated as the individual's willingness to pay (WTP) for an improvement in the state of nature (in terms of reductions in pollution or its physical consequences) or by the individual's willingness to accept (WTA) compensation to tolerate a worsening of the state of nature.

- Standard economic methods to valuing changes in welfare may be used when damages show up in marketed products, such as using demand and supply models to derive price and quantity changes, which, in turn, provide the basis for damages.

When impacts occur in non-marketed commodities, two broad approaches have been developed to estimate damages: the contingent value (CV) and indirect approaches. Both of these approaches have been developed over decades and continue to evolve and improve, although significant problems remain and significant types of impacts have yet to be credibly valued.

Even with all of this research activity, effort has been unevenly distributed among the benefit categories. The most effort has clearly gone into the theory and estimation of recreation and mortality benefits. Mortality benefit studies have derived values for reducing risks of accidental death that are quite consistent with one another. However, very few studies have obtained values for reducing mortality risks arising from environmental improvements. Substantial research has also addressed the valuation of pollution effects on health, visibility, and economic production, particularly on the effects of ozone exposure on field crops. Valuation of damages to materials and to ecosystems (including endangered species) is largely unexplored, although much effort has recently been placed on the natural resources damage assessment process particularly applied to the Exxon Valdez oil spill.

The CV methods involve asking either open- or closed ended questions to elicit their willingness to pay in response to hypothetical scenarios involving reductions in health or environmental risks or effects.[1] The major advantages of these approaches are that they can be designed for *ex ante* situations,[2] the good being valued can be specified exactly to match other information available to the analyst (such as the endpoint specified in a dose-response function), and the survey can be administered to a sample appropriate for the good being valued (whether representative of the general population or of some other group, such as older people. Further, for some types of values, such as existence values, there are no other means of obtaining values. On the other hand, the hypothetical and often complicated nature of the scenarios raises serious concerns about whether individuals can process the information provided and have enough motivation and familiarity with the "goods" being valued to respond as if they were in a real situation. Concern over strategic bias[3] appears to have been overcome and much recent research has attempted to systematize and standardize the development and conduct of these surveys (Mitchell and Carson 1989; Cummings, Brookshire, and Schulze 1986), in terms of payment vehicle, treatment of risk in the scenarios, open versus closed-ended questions, and other issues such as how questions are phrased. Additional research has attempted to compare values elicited from CV surveys to values obtained by indirect methods (see below), generally finding close agreement. It should be recognized, however, that such comparisons are possible only for certain classes of nonmarketed goods. For obtaining existence values, for instance, CV methods are the only available approach.

The indirect approaches (sometimes called revealed preference approaches) seek to uncover values for the nonmarketed environmental goods by examining market or other types of behavior related to the environment as substitutes or complements. For example, treating money (in the form of a wage premium) as a substitute for on-the-job safety, the relationship between wage rates and accidental death rates in different occupations has been statistically examined, with the finding that such premia do exist. These premia represent a value for reducing risks of premature death that can be used to value occupational health and safety risks posed by alternative fuel cycles and, with appropriate caveats (see below), to value risks to life posed by environmental pollution. As another example, environmental quality and recreation are complementary in the sense that more visits will be made to recreation sites with better environmental quality. Observing behavior in the choice of recreation sites and the frequency of visits to sites of different levels of

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[1]Open-ended questions ask individuals for their WTP, either in a bid format, on a payment card, or some other method that seeks a best estimate from the individual. Closed-ended questions involve asking individuals whether they would be willing to pay as much or more than a given amount. This latter approach is less demanding of individuals, while still permitting recovery of values for the group.

[2]This means that WTP for some future change in the state of nature can be elicited. This is the appropriate perspective for valuation. In contrast, other methods must rely on realized (or *ex post*) information to infer *ex ante* values.

[3]This is the term for the act of willfully offering misleading answers in the hopes of influencing the outcome of the survey and, ultimately, of policy.

water quality and relating this behavior to miles and time for travel to the site has revealed willingness to pay for improvements in water quality at recreation sites.

As a third example, when costs are incurred to avoid impacts, these goods may be viewed as substitutes for environmental quality. By tracking spending on goods used to avoid pollution or its effects, one can gain some idea of WTP. For instance, if people buy bottled water solely to protect themselves from toxics in their tap water, we know that their willingness to pay for avoiding health risks from these toxics is at least equal to the cost differential between bottled and tap water. As pain, suffering, and other non-pecuniary costs are omitted from consideration, this approach provides underestimates of willingness to pay, assuming the other problems with this approach have been avoided. Unfortunately, if the substitute good provides other benefits, the estimates could be too large.

Aside from the problems and successes in applying valuation techniques to nonmarket commodities, there are special issues associated with valuing health and environmental damages in the context of the fuel cycle study: transferability of benefits/damage estimates and functions from one location or context to another; aggregation of damages across endpoints, locations, stages of the fuel cycle, and individuals; treatment of nonlinearities in damage functions; matching physical endpoints with economic startpoints; and treatment of the temporal perspective, including discounting/levelization. These issues are addressed in some detail in the Background Document.

Because of both conceptual and empirical difficulties raised by these special issues, the reader should be cautioned about the interpretation of the estimates of damages contained in this report. While reasonable attempts were made to estimate damages specific to the reference environments, some "short-cuts" were taken and strong assumptions made to address these special issues, particularly transferability, aggregation, and nonlinearities.

Transferability particularly becomes a difficult issue particularly for assessing recreation damage, because the quality and availability of recreation assets varies greatly across locations. Had recreation impacts been estimated for the biomass cycle as part of this study, these difficulties would have received much attention. As it was, we could not estimate any noticeable impacts. Therefore, the "benefit transfer" issues remain largely unexplored. Where benefits transfers could be made, for health pathways in particular, we assumed direct transferability of health dose-response functions and unit values (or valuation functions) from the setting and location in which they were derived to the reference environment. This assumption is reasonable where income and socioeconomic characteristics are not much different across locations. Even if such characteristics were different, this would be unimportant for the transfer unless these characteristics affected marginal responses or valuations. In general, dose-response and valuation functions are not specified to admit any marginal influences of these characteristics.

The aggregation issue was not dealt with in a sophisticated way, either, primarily because of lack of empirical studies to guide a more satisfying treatment. We summarize the economic damages for each impact pathway for each emission or residual. This sum should **not** be interpreted as an overall estimate of damage. One reason is that not all impact-pathways were valued. However, another reason is that in reality, individuals in the reference environment would be confronted with (offered) a package of impacts (both positive and negative) associated with the new plant. Their WTP to avoid or obtain this package may not necessarily equal the sum of their WTP for each impact, depending on complementarity or substitutability of impacts (as well as physical interdependencies not picked up in the modeling of emissions to concentrations or concentrations to physical response).

The nonlinearity issue arises because many damage functions are non-linear, in that the estimate of damage depends on baseline emissions, concentrations, or physical impacts. This issue is handled reasonably well for the assessment of the ozone-morbidity damage pathway and the lead-morbidity pathway. For the ozone-morbidity pathway, for instance, the non-linearity in concentration-response functions is addressed by estimating impacts using a frequency distribution of daily peak ozone concentrations, rather than using the annual average of the daily peak readings. This issue does not even arise with some important pathways. Most notably, the concentration-response functions for the particulate-mortality pathway fit the linear model very well. Thus, the strategy of using temporally disaggregate air quality data to estimate this damage function is not necessary. For other functions, however, practical considerations have dictated that we use linear versions of non-linear functions. Note here that we do use a nonlinear valuation function for estimating WTP to avoid increased risks of premature death, where the nonlinearity is related to the size of the risk change.

The issue of non-use values, while not an issue special to this project, is nonetheless particularly controversial. One side in the debate over whether such values can be credibly estimated asserts that lack of familiarity with the "goods" at issue (such as an ecosystem, an endangered species, or a wilderness area) and the embedding effect (i.e., where WTP is sensitive to whether a good is valued by itself or as part of many other goods) make it inherently impossible to reliably estimate the WTP for such goods through hypothetical questioning. It is asserted (Kahneman and Knetch, 1992) that observed WTP values are for the purchase of "moral satisfaction" not a WTP for marginal changes in the good. The other side suggests that the studies relied upon for these conclusions are faulty and that normal economic behavior can explain most of the observed alledgedly inconsistent patterns of WTP responses (Smith, 1992). Similar conclusions have also been reached about an Exxon-funded effort that concluded CV was an unreliable tool for eliciting non-use values. For example, one of the studies purporting to show that individual bids for saving ducks were insensitive to the number of ducks being saved (i.e., from 2,000 to 200,000 ducks annually (Desvousges et al. 1992)) has been criticized for defining scenarios that involve, in fact, a very nearly identical percentage of ducks being saved (from 1 to 2% of ducks on the flyway). In such a case, it may be unremarkable that WTP estimates for a group of individuals responding to one scenario are very similar to those from a group responding to a different scenario. One reason for our sparse treatment of non-use values is that the literature primarily addresses major changes in special ecosystems or species elimination whereas the changes to environmental assets associated with a single power plant are likely to be very small and the assets themselves may not be unique enough to generate substantial non-use values.

1.5 REPORT OUTLINE

This report summarizes the collection, assessment and application of existing literature to estimate selected damages and benefits from the biomass fuel cycle. In Section 2, a brief review of other recent attempts to accomplish this goal is provided for contextual background. Section 3 provides a discussion of the organization of the results that is critical to interpreting the analysis which follows in Sections 4 through 10. Section 4 provides a technical characterization of the biomass to electricity fuel cycle. Section 5 summarizes the major emissions and other residuals of the biomass fuel cycle. Section 6 presents the priority pathways selected for more in-depth analysis, discussed in greater detail in Sections 7 to 10. Section 7 presents analysis of some of the major impacts and damages associated with growing the biomass. Section 8 discusses an impact from the biomass feedstock transportation stage of the fuel cycle. Section 9 presents impacts and damages from biomass combustion. Section 10 provides an estimated of employment benefits.

Appendices A through G provide additional discussion. Appendix A gives information on the benchmark technologies and their emissions. Appendices B and C present details of the atmospheric transport modeling and the results. Appendix D reports on health effects related to the biomass fuel cycle. Appendix E discusses erosion effects of the biomass fuel cycle. Appendix F is a discussion of possible ecological impacts. Appendix G presents information on the quality of some of the data used in the analysis.

2. PRIOR STUDIES OF DAMAGES AND BENEFITS FROM THE BIOMASS FUEL CYCLE

Several studies share similar characteristics with this study. These studies include *Environmental Costs of Electricity* by the Pace University Center for Environmental Studies (1990), *Valuation of Environmental Externalities for Energy Planning and Operations* by the Tellus Institute (1990), *Estimating Environmental Costs for Five Generating Resources* written by ECO Northwest (1986) for the Bonneville Power Administration, papers from an ongoing study in the Australian state of Victoria, and *America's Energy Choices* published by the Union of Concerned Scientists (1992). The following sections briefly summarize these reports.

2.1 PACE REPORT

The intent of this study is "to review the literature on the methodologies used to assign monetary costs to environmental externalities and to present the results of studies which have applied these methodologies" (Pace 1990). Unlike our study, which addresses the total fuel cycle, Pace (1990) focuses on only the electricity generation stage. Estimates in the Pace (1990) report are drawn from previous studies; modeling was limited. Lack of economic valuation information for certain impacts caused these impacts to be excluded from the computations of economic damages. Notwithstanding its limitations, the Pace (1990) report stands as a comprehensive, path-setting, often-cited reference on the environmental costs of electricity.

The Pace study follows a five-step procedure in valuing environmental damages. The first step ascertains "the pollution sources, the quantity of...emissions and the constituents of the emissions that can cause environmental damages" (Pace 1990). The second step determines the dispersal of the emissions. Step three determines the populations (including people, flora and fauna) and the materials exposed to the pollutants. The fourth step determines the impacts on those populations and materials exposed to the pollutants. The fifth step estimates the economic value of that exposure. The economic value of risk involved with an environmental good or service was measured in terms of willingness to pay, the amount society would be willing to pay to avoid the environmental risk, and in terms of willingness to be compensated, the amount society would have to be compensated in order to incur the damage.

For the biomass-to-electricity fuel cycle, Pace bases their analysis on the Bonneville Power Administration's *Estimating Environmental Costs and Benefits for Five Generating Resources*, written under contract by ECO Northwest (see Section 2.3 for a full discussion). The technology is a generic 12 megawatt (MW) cogeneration plant located at a mill site or near lumber, wood products, or pulp or paper industries. The feedstocks are mill wastes, waste liquor, and forest residue (rotten or flawed wood or wood that is too small to harvest for milling). Being wood residues, these feedstocks differ from those considered in our study--in which short-rotation wood plantations provide a dedicated source of feedstocks. The reason for considering wood energy crops rather than residues is that wood residues are generally already used for energy to their fullest potential. Most of this use is in the pulp and paper and lumber industries, generating electricity and process heat for on-site use in their mills. Most of the potential for any significant increase in the use of biomass is in the availability of low-cost energy crops. The U.S. Department of Energy is funding research programs whose objective is to achieve that end.

Emission levels are given in Pace (1990) for particulates, nitrous oxide, volatile organic compounds, carbon monoxide, and polycyclic organic matter. Table 2.1-1 gives these emissions. The plant produces steam as well as electricity for on- and off-site use. However, ECO Northwest, and therefore Pace attributes all emissions to electricity production. Pace and ECO admit that this assumption could seriously overstate the environmental costs associated with electricity production itself.

Table 2.1-1. Emissions of air pollutants from a generic biomass cogeneration plant (units = tons/year)

Emission	Amount
Particulates	18.7
N_2O	286
Volatile organic compounds	143
CO	220
Polycyclic organic matter	0.002

Source: Pace University Center for Environmental Legal Studies 1990. *Environmental Costs of Electricity*, Oceana Publications, Inc., N.Y.

The ECO Northwest study is said to identify four "potentially environmentally important effects." These include: (1) facility emissions of particulates and potential health hazards associated with these emissions, (2) improved visibility due to replacement of open burning of slash with the fueling of cogeneration, (3) water consumption and surface water pollution, and (4) occupational accident potential. According to Pace, ECO Northwest dismisses occupational accidents, saying they are not externalities. Water use and pollution are said to be short term and reversible. This leaves only health hazards from particulates and visibility improvement as being of concern to Pace (1990). Table 2.1-2 lists the levelized costs for the environmental impacts.

Table 2.1-2. Levelized cost (1989 dollars using a 3% discount rate) of the environmental effects of biomass electricity generation in mills/kWh

Impact	Low	Expected	High
Health	0.00	1.28	6.68
Visibility	–0.12	–0.94	–1.26
TOTAL	–0.12	0.31	5.42

Source: Pace University Center for Environmental Legal Studies 1990. *Environmental Costs of Electricity*, Oceana Publications, Inc., N.Y.

No explanation was given in Pace (1990) of how these numbers were computed. The low-cost scenarios are based on the assumption that existing air quality standards completely protect human health. The expected risk scenario uses linear dose-response functions and assumes that no safe threshold of exposure exists (see Section 2.3 for a full explanation).

Carbon monoxide accounts for approximately two-thirds of the health effects ECO computes. The health effects from biomass cogeneration are not specifically defined in Pace (1990). The values are not listed as "morbidities" or "mortalities," merely "health effects." The value of a statistical life used to compute the health costs is $3 million. The value of a statistical illness is assumed to be one-tenth the value of a statistical life.

Comparisons of results and methodologies will be carried out in Section 2.3 because Pace uses the ECO Northwest (1986) report as its basis.

2.2 TELLUS REPORT

The Tellus report (1990) develops damage estimates for air emissions using an abatement cost approach. This method is different from the approach followed in this report and in ECO Northwest (1984, 1986, 1987) and Pace (1990). Abatement costs are viewed as an indicator of revealed political preference.

The report analyzes existing and proposed regulations in order to "estimate the value that society implicitly places on specific environmental impacts" (Tellus 4-5). This method identifies the cost of implementing the technology required to meet the standards set by the regulations. This value is then taken as the value that the regulators, and thereby society, have placed on air emissions. The standards are regarded as the "revealed preference" of the regulators. The current study methodically identifies emission-impact-damage pathways and costs those pathways. These studies contrast the two methods for costing the damages involved in electricity production--revealed preference and damage costing. Tellus identifies two reasons for avoiding the damage costing approach. First, estimating the physical impacts of emissions can be a complex task with a high degree of uncertainty. There can also be significant non-physical damages. Second, the valuation of damages can be difficult and controversial. Significant uncertainties arise when attempting to place a dollar value on non-market goods such as health and visibility.

The use of abatement or control costs is not compelling either, as is readily admitted by Tellus. Abatement or control costs do not necessarily reflect the costs of environmental risks faced by society. In order for a regulation-based cost to represent the cost of that risk, it must be assumed that legislators choose optimal control technologies--those equating costs and marginal benefits, rather than those based on a political, health, or distributional basis. Another limitation of the abatement cost approach is temporal. Past or current regulations may bear little resemblance to current damage costs. See Krupnick and Burtraw (1992) for a full discussion.

The revealed preference approach is used to estimate the damages of eight air pollutants: (1) oxides of nitrogen (NO_X); (2) oxides of sulfur (SO_X); (3) particulates, both total suspended particulates (TSP) and particulates under 10 microns (PM_{10}); (4) volatile organic gases, volatile organic compounds (VOCs), and reactive organic gases (ROGs); (5) carbon monoxide (CO); (6) carbon dioxide (CO_2); (7) methane (CH_4); and (8) nitrous oxide (N_2O). The first five are under federal regulation standards. The basis for the revealed preferences are federal standards and the South Coast Air Quality Management District (SCAQMD) regulations.

Different fuel cycles are used to estimate the abatement costs. Cost estimates for controlling NO_X emissions are based on control technologies for new natural gas turbines in the northeast United States, but on afterburner controls in southern

California. SO_X estimates for the Northeast are based on control technologies for coal-fired electricity generating plants, while southern California estimates are based on oil refinery cracking. Cost estimates are based on an electrostatic precipitator in a high sulfur coal plant for particulates in the United States, and estimates are based on oil refinery cracking units for southern California. VOC and ROG costs are based on control technologies not defined in Tellus for non-attainment areas in the United States and on automobile assembly coatings in southern California. Carbon monoxide estimates were not figured outside of southern California. Estimates for southern California are based on the control measure T-7, which requires an increase in oxygenation of gasoline. Carbon dioxide costing is based on sequestration by tree planting.

The pollutants CO_2, CH_4, N_2O, CO, and NO_X are referred to as the greenhouse gases because increased atmospheric concentrations of these pollutants can contribute to global warming and associated local and regional climate change. Since no regulations exist for these greenhouse gases, estimates are made for regulations which may result in the future. Externality costs for CO_2 are based on the mitigation cost of tree planting [as in Pace (1990)]. The costs of CH_4 and N_2O, and the greenhouse effects of CO and NO_X are based on the value of a global warming potential (GWP) index that weights each greenhouse gas relative to CO_2 with respect to its global warming impact. These weights are applied to the CO_2 costs to derive the costs of the other greenhouse gases. This methodology is based on the premise that because CO_2 and the other greenhouse gases all contribute to the greenhouse effect, it is reasonable to assume that the effects of the other gases could be offset by CO_2 controls. The valuations from Tellus are given in Table 2.2-1. Because the methodologies of the current study and the Tellus study are fundamentally different, comparisons regarding their accuracy and differences can be made only in the methodology stage.

2.3 ECO NORTHWEST FOR THE BONNEVILLE POWER ADMINISTRATION

Estimating Environmental Costs and Benefits for Five Generating Resources was written for Bonneville Power Administration (BPA) by ECO Northwest (1986). Their main purpose is to develop a "*generic* model of environmental costs for each resource which will allow BPA to estimate for each resource the future environmental costs,..., for different facility types, sizes, and locations" (p. viii). BPA will use the assessments of environmental costs and benefits for all resources considered for future acquisition of power plants. In this report, ECO Northwest reviews cogeneration of municipal solid waste and biomass, geothermal, solar central stations, and wind. We will only review ECO's treatment of biomass.

Table 2.2-1. Tellus valuation of emissions based on abatement costs

Emissions	Abatement Costs (constant 1989 dollars per pound)		
	Area-specific	Southern California	Global
Nitrogen oxides (NO_X)	3.25 (Northeast U.S.)	131.00	*a*
Sulfur oxides (SO_X)	0.75 (Entire U.S.)	37.50	*a*
Volatile organic compounds (VOCs)	2.65 (Non-attainment areas)	14.50	*a*
Particulates	2.00 (Entire U.S.)	22.00	*a*
Carbon monoxide (CO)	(Not figured)	0.41	*a*
Carbon dioxide (CO_2)	*a*	*a*	0.011
	Greenhouse gases		
CO_2	*a*	*a*	0.011
CO	*a*	*a*	0.024
Methane (CH_4)	*a*	*a*	0.11
Nitrous oxide (N_2O)	*a*	*a*	1.98

Source: Tellus Institute 1990. Valuation of Environmental Externalities for Energy Planning and Operations.

[a]No figures given in report.

ECO utilizes a six-step approach: (1) characterization of generating resources; (2) identification and description of potential environmental effects associated with each phase of the fuel cycle; (3) determination of significant effects; (4) description and estimation of magnitude of significant effects; (5) estimation of the economic value of the physical effect; (6) calculation of the present value of the expected effect. It is stressed that the estimates arrived at in the ECO report are *generic*, actual effects and costs could vary greatly with plant size and location. ECO Northwest defends the use of *generic* sites, saying that generic numbers do not account for site-specific differences in the fuel cycles, but they do offer some guidance in estimating numbers for site-specific studies, and can be used in long-range planning in which the absence of site certainty eliminates the use of site-specific data. The uncertainty surrounding the impacts associated with emissions could also cause variation in estimates. Significant effects are those with economic values of greater than or equal to one mill per kilowatt hour.

ECO uses two facility sizes, 12 and 22 megawatts (MW), operating at 80% minimum capacity and 85% assumed annual capacity. The facilities are located at mill sites, adjacent to or near lumber, wood products, and pulp and paper industries. The plants are located in the Coast Range, the Cascades, western Montana, and the Idaho panhandle. Construction time is 12 to 24 months and lifetime is 30 years. The facilities are cogenerators, generating electricity and providing process steam for on- and off-site use. Fuel is assumed to be mill wastes and waste liquor, with logging residues being used as a supplement and eventually as a replacement. The facilities will require 25 acres of land. Although the process is cogeneration, it is said to be impossible to separate the environmental effects between electricity generation and steam production.

By comparison, the current study uses a facility size of 40 MW, operating at 70% capacity. The sites are located at Camas, Washington and the Clinch River Breeder Reactor site in east Tennessee. No construction time is specified and lifetime is 40 years. The technology is a whole tree burner with feedstock grown as an energy crop, strictly for use in the plant. No mill wastes or logging residues will be used.

No significant environmental effects were found with construction in ECO Northwest (1986). Because the main fuel used is mill wastes (rather than wood energy crops), no significant effects are found in the "extraction" stage of the fuel cycle. The current study finds significant effects at the tree production and extraction level; however, no comparison can be made between the two reports because the fuels are from different processes. ECO Northwest ignores transportation of the feedstock while the current study considers road deterioration, noise, diminished aesthetic quality, and air emissions from the trucks as priority impacts. Operation of the plant provides the basis of costs in ECO Northwest. Economically significant effects are determined to include the net changes in air quality—including health, visibility and material damage, and changes in land productivity. The current study finds similar priority pathways.

In determining the magnitude of air quality changes on health, the quantity of emissions from the generating facility are estimated. A simplified Gaussian plume model and population densities are used to estimate population exposures. Dose-response functions are used to estimate the fraction of the population suffering a response, and dollar values are assigned to these physical effects using the value of increased risk of morbidity or mortality. The available information on health effects is said to be crude and in the future could prove to be quite different than those calculated in the report. The simple calculations of concentration multiplied by population multiplied by dose-response coefficient ignores the population density and the pollutant dispersion, and could overstate the damage done by the pollutants. The current study adjusts the pollutant concentration for the effects of pollutant dispersion and population density in the vicinity of the plant, thus being less likely to overstate the damages. Visibility is valued using contingent-valuation studies. A similar method is used in the current study.

Human exposures are estimated at low, high, and expected populations at the level of concentrations estimated for the pollutants. No safe threshold is assumed to exist and dose-response relationships are linear. Results show that carbon monoxide accounts for two-thirds of the health effects of biomass cogeneration. Morbidity and mortality are taken as an aggregate, with the value of an 1/100,00 increase in the risk of death equal to 30 dollars. The calculated value of health effects for biomass cogeneration is about 1 mill per kilowatthour.

Visibility loss is calculated by multiplying the lost visibility in kilometers by the number of residents around each source. The aggregate visibility loss is 300 person-kilometers per year. According to contingent-valuation studies, the value of a kilometer of visibility to equal $0.30 per day for recreationists and $10 per year for residents of the area. Because the visibility improves when waste is burned in the cogeneration plant rather than as slash, the value is a net benefit for visibility (levelized benefit of between 0.1 mills/kWh and 1.1 mills/kWh, with the expected value at 0.9 mills/kWh). Because the current study does not use mill wastes as feedstock, the visibility effects are not benefits.

Material-damage valuing is attempted; however, the effects are said to be too small to distinguish. Table 2.3-1 shows the results from ECO Northwest's study.

2.4 VICTORIAN PROJECT

At the time of this writing, the state of Victoria, Australia, was working on a similar study. Their study seems to have broader coverage but less depth. The scope of the project included five main tasks:

(1) identification of the environmental and socioeconomic impacts associated with the range of energy supply and demand side options plausible for development in Victoria;

(2) identification of appropriate methodologies for quantifying the environmental and socioeconomic costs and benefits of these impacts in the short and long term;

Table 2.3-1. Results of the biomass fuel cycle in ECO Northwest

	Low	Expected	High
Health effects			
Annual (1986 dollars)	0	104,000	532,000
Mills/kWh[a]	0.00	1.16	6.04
Visibility			
Annual	–10,000	–75,000	–100,000
Mills/kWh[a]	–0.11	–0.85	–1.14
TOTAL			
Annual	–10,000	–22,000	432,000
Mills/kWh[a]	–0.11	0.31	4.90

[a]Levelized using a 3% discount rate.
Source: ECO Northwest 1986. Estimating Environmental Costs and Benefits for Five Generating Resources, prepared for Bonneville Power Administration, Portland, Oregon, April.

(3) measurement or estimation of the costs and benefits of the environmental and socioeconomic impacts associated with particular energy resource options;

(4) identification of methods of incorporating environmental and socioeconomic externalities in the energy sector (e.g., taxes, pricing, weightings, etc.); and

(5) recommendation to Government of the most appropriate method(s) for incorporating environmental and socioeconomic externalities in energy planning and the decision making process.

2.5 UNION OF CONCERNED SCIENTISTS

America's Energy Choices is a report on a study undertaken by the American Council for an Energy-Efficient Economy, the Alliance to Save Energy, the Natural Resources Defense Council, and the Union of Concerned Scientists (UCS) with the objective of examining the role that energy efficiency and renewable energy technologies can play in meeting America's energy and environmental needs and problems over a forty-year period from 1990 to 2030. For each of four alternative energy scenarios the researchers evaluate the impact on energy use of such factors as energy prices, technological change, and structural shifts in the economy to determine both the roles that various energy sources would play in the nation's energy mix and the magnitudes of those sources' air pollutant emissions.

The study deals with four possible energy futures for the U.S.: the "reference" scenario, the "market" scenario, the "environmental" scenario, and the "climate stabilization" scenario. The reference scenario, developed by drawing upon many of the assumptions and projections of the Department of Energy's *1990 Annual Energy Outlook* study, is, as *America's Energy Choices* puts it, that of a "business-as-usual" energy future in which current policies and trends prevail. It takes into account expected GNP growth, changes in population and energy prices, and the impact of the Clean Air Act Amendment. The market scenario is that of a situation in which policies such as the allocation of research and development funds to least-cost energy technologies are implemented to spur a more rapid introduction of cost-effective technologies and efficiency measures into the energy market. The environmental scenario is one in which the environmental costs of air pollutants are incorporated into energy prices by political regulations such as pollution taxation. The climate stabilization scenario ascribes a monetary value to carbon dioxide emissions to account for the possible consequences of global warming.

For each of the scenarios the researchers attempt to determine the make-up of the underlying energy mixes that would prevail in the residential and commercial, industrial, and transportation sectors. With that aim in mind, the costs of investments in an array of technologies and efficiency measures are compared to the cost of energy saved (i.e. to the cost avoided by not having to generate the saved energy) by each of those investments to determine their respective cost-effectiveness. In the case of the environmental and climate stabilization scenarios the emissions of nitrogen oxides (NO_x), sulfur dioxide (SO_2), methane (CH_4), carbon monoxide (CO), total suspended particulates (TSP), and volatile organic compounds (VOC) for various energy sources are estimated and the corresponding monetary costs added to the market energy prices.

America's Energy Choices' reported emission values for wood combustion technologies, for example, based upon data from the EPA's National Emissions Data System, are listed in Tables 2.5-1 and 2.5-2 below. Table 2.5-1, taking into account regional differences in such factors as environmental constraints and control technologies, lists the current average emissions of wood combustion utilities in lb/MMBtu for the north central, northeastern, southern, and western regions of the U.S. Table 2.5-2 lists the emissions values for the biomass gasifier steam-injected gas

Table 2.5-1. Current average wood utility emissions factors (lb/MMBtu)

Region	NO_X	SO_2	CO_2	CH_4	CO	TSP	VOC
North Central	0.345	0.023	212	0.033	0.299	0.328	0.103
Northeast	0.270	0.015	212	0.033	0.365	0.007	0.124
South	0.168	0.017	212	0.033	0.234	0.317	0.084
West	0.365	0.021	212	0.033	0.470	0.210	0.153

Source: Union of Concerned Scientists 1992. America's Energy Choices. Cambridge, MA.

Table 2.5-2. New power plant emissions factors (lb/MMBtu)

	NO_X	SO_2	CO_2	CH_4	CO	TSP	VOC
Wood	0.101	0.008	212	0.033	0.221	0.005	0.077
BIG/STIG	0.06	0.008	226	0.0015	0.002	0.011	0.003

Source: Union of Concerned Scientists 1992. America's Energy Choices. Cambridge, MA.

turbine (BIG/STIG) technology, as well as for wood combustion based upon newer combustion and control technologies.

In a table reproduced below (Table 2.5-3), *America's Energy Choices* lists monetary values for air emissions externalities developed by the Tellus Institute, the California Energy Commission, the New York State Public Service Commission, the South Coast Air Quality Management District, PACE University Center for Environmental Legal Studies, and the Swedish Environmental Protection Agency. The report does not discuss the CEC, NYSPSC, SCAQMD, PACE, BPA, or SEPA values other than to offer them as a comparison to the Tellus values, which the UCS study uses as a basis for its air pollutant costs. The report states that "since we have employed a real discount rate of 3% (and a real levelized fixed charge factor of 5% for thirty year investments), we have modified the capital cost component of the marginal control costs used as air pollutant values by a factor of one-half (Technical Appendixes p. F-9)." The modified Tellus values are listed in Table 2.6-4. The Tellus Institute developed the original values by using the "revealed preferences" approach.

Table 2.5-3. Monetary values for air emissions externalities (1990 $/lb)

	Tellus	CEC	NYS	SCOQMD	Pace	BPA	Sweden
SO_2	0.78	9.07	0.43	39.2	2.12	0.20-1.80	1.19
NO_X	3.40	4.65	0.96	137.0	0.86	0.03-0.40	3.18
CO_2	0.012	0.004	0.0006	—	0.007	0.003	0.02
CH_4	0.12	0.04	—	—	—	—	—
CO	0.45	—	—	0.43	—	—	—
TSP	2.09	6.11	0.17	23.0	1.24	0.08-0.8	—
VOC	2.77	2.61	—	15.2	—	—	—

Source: The Union of Concerned Scientists 1992. *America's Energy Choices*, Cambridge, MA.

Table 2.5-4. Air pollutant values with modified capital cost (1990)

Pollutant	Cost
SO_2	0.40
NO_X	2.92
CO_2	0.006
CH_4	0.06
CO	0.41
TSP	1.05
VOC	1.38

Source: The Union of Concerned Scientists 1992. *America's Energy Choices*, Cambridge, MA.

That is, it studied existing and proposed environmental regulations to estimate values that society places on environmental impacts. It should be noted, however, that the UCS study does not use the CO_2 values listed in the tables below. Rather, a cost of $25 per ton, developed from estimates of the costs of pursuing a significant tree planting program, is used to mitigate atmospheric CO_2 levels for the climate stabilization scenario.

2.6 COOK ET AL.

Various types of biomass--farm and forest waste, low-quality wood, and dedicated energy crops (the latter being the feedstock considered in our study)--have been promoted as renewable energy sources. James H. Cook, Jan Beyea, and Kathleen H. Keeler suggest in their paper, *Potential Impacts of Biomass Production in the United States on Biological Diversity*, that without some regulation, biomass production could be hazardous to natural ecosystems.

According to Cook et al., the U.S. Environmental Protection Agency has projected that biomass could become the world's largest single source of energy due to intervention in the market to protect the climate. This increase in demand for biomass will cause an increase in the demand for arable land on which to produce biomass. There will be competition for land with other human needs such as food and fiber production.

Cook et al. define four potential impacts of the production of biomass. These include: (1) competition for arable land with food production; (2) water pollution; (3) loss of soil fertility; and (4) spread of bio-engineered organisms. The push to maximize production and to minimize costs has routinely led to monoculture agroecosystems that significantly reduce biodiversity.

Three sources of biomass exist: natural ecosystems, existing forests--including forest industry residues and waste, and dedicated energy crops. Managing forests more intensely for increased wood production and conversion of natural lands to dedicated energy farms are of particular concern from a biological standpoint and to this paper. Approximately 200 million hectares of commercial forest land and approximately 100 million hectares of either uncultivated or potential cropland in the United States exist. Utilizing 80 to 200 million hectares of the commercial cropland could increase total biomass production from 47 EJ (10^{18} joules) per year to 51 to 79 EJ per year, while utilizing uncultivated or potential cropland could increase biomass production to 59 to 96 EJ per year. The authors state that it is most likely that a combination of these two production processes and that an increase in demand for biomass equivalent to 20% the current use of fossil fuels could place tremendous pressure on biomass production through forests, demanding the removal of wood at nonsustainable rates until adequate supplies of energy crops are available. The authors figure that although dedicated energy crops might be able to replace fossil fuels, the area would be quite vast and the effects on biodiversity would be great.

Improvements in biotechnology may strengthen the use of biomass for energy purposes. The negative aspect of such improvements is that genetically engineered organisms may spread through the ecosystem, destroying its natural integrity. If the bioengineered technologies propel the industry into economic success, the side effects of the technologies could become a serious problem of the environment.

The conclusion is stated that "for biomass cultivation to affect large areas of the United States, and thereby potentially threaten biodiversity, demand for biofuels must be so high that they displace a large share of the current energy market (p. 409). Market forces and policy pressure to eliminate the climatic effects of energy production may make biofuels an attractive energy."

3. ORGANIZATION AND INTERPRETATION OF RESULTS

This section describes the organization of the results that follow, particularly in Sections 6 through 10. Section 3.1 discusses the *types* of results that the reader should look for in studying this report. Section 3.2 discusses their *interpretation* and the most important caveats. These caveats should always be borne in mind in order that the report *add* to our base of knowledge, rather than provide "disinformation." Section 3.3 describes how our uncertainty about our estimates are explicitly portrayed in reporting the results of the study. Section 3.4 summarizes a notational system which was used to provide information on that uncertainty and on the quality of the some of the existing base of knowledge that was used for the calculations.

3.1 TYPES OF RESULTS

This section identifies the most important types of results that are presented in this report, and describes the format for their presentation. There are three general types of results. Each type corresponds to one of the objectives of the study.

3.1.1 A Demonstration and An Account of the Methods

The first type of result is a demonstration of the damage function approach to the biomass-to-electricity fuel cycle. Whereas Cantor et al. (1992) provided a general discussion of the approach and of the issues in estimating the externalities of fuel cycles, this report presents an actual application for a specific fuel cycle. The description of this application provides an account of the types of data sources and methods that can be used in other studies of fuel cycle externalities.

Section 4 gives information on the reference sites, biomass feedstock operations, and conversion technology. Section 5 identifies the major emissions and other residuals from the biomass-to-electricity fuel cycle. Section 6 summarizes the major impact pathways and identifies those addressed in greater detail in this study.

Sections 7 through 10 provide an account of the methods that were used to calculate the damages and benefits for each of the impact-pathways that was selected for detailed analysis. Section 7 is on the feedstock operations stage of the fuel cycle. Section 8 is on the feedstock transportation stage of the fuel cycle. Section 9 is on the electricity generation stage and Section 10 is on some of the nonenvironmental externalities of providing electricity from biomass.

3.1.2 Numerical Estimates of Damages and Benefits

The second type of result, numerical results, are estimates of the marginal damages or marginal benefits associated with specific fuel-cycle activities or processes. These estimates are specific to the particular technology(s) that were analyzed, as well as to the specific sites. The nature and the magnitude of residual impacts depend on the power plant project and on the characteristics of the specific site.

Presentation of these results is in Sections 7 through 10. Each section presents material on a separate stage of the fuel cycle. Each sub-section describes a distinct impact-pathway. Parts within each sub-section give estimates of emissions and changed concentrations, the ecological or health impacts, and the economic damages (or benefits) for each of the impact-pathways.[1] The dose-response and valuation functions are presented in shaded tables.

Estimates of impacts are in the physical units appropriate for the particular impact-pathway. Estimates of damages and benefits are expressed in terms of mills/kWh, and as the dollar damages or benefits for each impact-pathway (in 1989 dollars, adjusted for inflation). Where possible, the numerical values are presented as low, mid, or high estimates. These ranges do not necessarily represent a specific (say 90%) confidence interval. The reason is that these ranges are based on estimates from other studies and these other studies are not consistent in their definition of "low" and "high."

In most instances, the numbers used in, or stemming from calculations, are reported "as is," with many digits. The number of digits in these numbers does *not* reflect the actual precision of the calculations.

3.1.3 Identifying Information Quality and Gaps

The third type of result is the identification of where important quantitative information does not exist, or is highly imprecise. These information gaps are generally in the data on reference sites, which are required as inputs for some of the modeling; in the relationships between specific pollutants and their ecological and health impacts; and in the economic value of these impacts. Identifying these information gaps provides a research agenda for the future.

[1]The terms "economic damages" and "economic valuation" are generally used throughout this report, even though for economists, the "economic" descriptor is redundant.

Section 11 includes tables that summarize the quality of the information that was available on the emissions, impacts and economic damages (and benefits) of the biomass-to-electricity fuel cycle. Visual inspection of these tables provides a quick assessment of information needs. Sections 7 through 10 discuss the data and analytical methods used in this study -- providing additional insight about data quality and the lack of information. Sections 3.3 and 3.4 discuss the methods used to describe systematically the uncertainty in calculations and the quality of the knowledge base.

3.2 INTERPRETATION OF NUMERICAL RESULTS

While demonstration of methodology is the most important objective of this study, many readers of this report will be drawn more to the numerical results. It is important to have the correct perspective in viewing these results.

3.2.1 Caveats in the Interpretation of the Results

The numerical results should *not* be interpreted as being *the* externalities of the biomass-to-electricity fuel cycle. There are several reasons for this caution and all are important:

(1) The estimates do not include every emission, or impact. A limited number of impact-pathways were considered in detail. While the selected impact-pathways were regarded as being among the most important, others may be important as well. The lack of information is one of the main reasons why these other impact-pathways were not fully addressed.

(2) Only two particular biomass conversion technologies were analyzed in detail for each of the two timeframes. The biomass feedstock was assumed to be from tree plantations.

(3) Ecological and health impacts, and thus economic damages and benefits, are generally site-specific. The estimates pertain only to the two reference sites selected for the study. Analysis of other reference sites, including those in the same geographical region, could result in very different estimates. A corollary to this statement is that comparisons among alternative fuel cycles could vary, depending on the particular site.

(4) In many cases there is considerable uncertainty about the dose-response functions, the ecological and health impacts, and the relationships between impacts and their economic value.

(5) Adding the externalities of individual impact-pathways to estimate a total externality for the fuel cycle would likely overestimate it. Estimates of externalities for individual impacts are usually obtained in isolation, without taking into account a collection of impacts simultaneously and without any explicit constraints on individual or household income.

(6) It is not always clear when damages are in fact externalities. Some damages are reflected in higher prices paid for electricity, and are thus internalized. This issue is discussed in Cantor et al. (1992). The economic values derived in this study should be interpreted as the marginal damages and marginal benefits associated with the addition of the biomass plant and of the feedstock operations needed to support the biomass plant.

Notwithstanding, the results are still informative. Comparisons can be made among different impact-pathways within a single fuel cycle. Comparisons can also be made between similar impact-pathways in different fuel cycles, keeping in mind that they pertain to only the specific sites studied. The sums (really the partial sums) may also be informative in terms of their general order of magnitude, keeping in mind the particular site, the missing impacts that were not studied, as well as the likelihood of overestimation in adding estimates of damages. In any comparisons, the above-stated caveats should always be kept in mind.

3.2.2 Valuation Approach

Damages and benefits may be aggregated both within and across major impacts (keeping in mind the caveats above). For example, within the morbidity endpoints, both ozone and particulates affect symptoms and restricted activity days (RADs). Within an ozone analysis, adding symptoms to RADs double counts some of the symptoms (since one must have a symptom to have a RAD). However, considering both ozone and particulates, there is not necessarily any double counting when two different pollutants are linked to the same health endpoint, as long as the dose-response functions contain variables for both pollutants.

Discount rates are used to aggregate over time. The timing of damages and benefits is tracked for appropriate use of discounting techniques. Attention is paid to whether a damage is annualized, one-time only, or periodic. All damages and benefits are discounted to the present. They are expressed in "levelized" terms. The levelized cost (or benefit) is the constant annual payment (in real dollars, adjusted for inflation) that if paid over the life of the biomass plant would sum up to the total present value of the damage or benefit.

Damage to field crops, for instance, occurs annually. Thus, no further levelization is needed other than to divide by annual kWh. Mortality risks from, say, exposure to radon from coal mining operations occur over a worker's lifetime, and deaths generally occur only after a long latency period. However, the willingness to pay for risk reductions may be estimated by using a study that asks how much a person would be willing to pay today to reduce the risk of future mortality risks. In this case, the economic value of the expected reduction in risk would be credited to the current period, even though the actual risk would be experienced in the future. (Hedonic wage studies provide a value for the wages given up to reduce the risk of annual accident risk. In this context, annual wage differentials reflect willingness to pay for a current year's risk reduction and not for risk reductions beginning in 20 or 30 years.) Medical costs of morbidity experienced in the future would be credited to the future, however, and discounted to the present.

3.3 CONSIDERATION OF UNCERTAINTY

Uncertainties are taken into account in several ways. For this study, a standard approach to propagate uncertainties was applied by defining information as being low, mid, or high estimates. These estimates were used to construct an overall low, mid, and high estimate. The low estimate was computed by using the low estimates at each step in the pathway. The mid and high estimates were similarly computed. It can be shown that this approach results in confidence intervals on the endpoint of the analysis exceeding the confidence intervals used at each step in the pathway.

In addition to uncertainties about functions and parameter values at each link in the impact-pathway, there is uncertainty with regard to the baseline level of environmental quality. For instance, where dose-response functions are strongly nonlinear, the assumptions one makes about future baseline pollution levels is obviously important for determining where calculations should begin on the dose-response functions.

4. CHARACTERIZATION OF THE BIOMASS-TO-ELECTRICITY FUEL CYCLE

This chapter provides an overview of the boundary assumptions required for estimating emissions and impacts for a biomass-to-electricity fuel cycle. The study encompasses two time periods and two reference sites. The use of two time periods provides an opportunity to examine technological advances for both production and biomass-to-electricity conversion technologies. The use of two reference sites allows a comparison between the Northwest and the Southeast, between a relatively urban and rural site, and between a site with very favorable biomass growing conditions and one that is economically marginal for biomass production.

This chapter is organized along the stages of the fuel cycle. Section 4.1 provides a brief overview of the fuel cycle and potential emissions, pathways, and impacts. Section 4.2 discusses the reference sites and the availability of land for growing wood feedstocks. Section 4.3 describes wood feedstock production and harvesting operations. These aspects include the selection of species and the annual productivity (dry tons/acre) at each reference site. Section 4.4 summarizes the approach used to calculate the amount of land required for production operations and the average haul distances to the conversion facility. The final section (4.5) discusses the conversion technology assumed in each time period. More details on the characterization and emissions from each stage of the fuel cycle is contained in Appendix A.

4.1 OVERVIEW OF BIOMASS FUEL CYCLE, EMISSIONS, PATHWAYS, AND IMPACTS

The biomass-to-electricity fuel cycle involves three major stages—wood feedstock production and harvesting operations, handling and transport logistics, and electricity generation. Feedstock production is from hardwood tree plantations that are developed for, and dedicated to, a specific conversion facility. Thus, the net impacts of plantations contribute to the marginal damages and benefits of the biomass fuel cycle. As shown in Fig. 4.1-1, land, labor, equipment, diesel fuel, fertilizers (nitrogen, phosphorous, and potassium), and pesticides are used in producing and harvesting wood feedstocks. Carbon dioxide (CO_2) is also an input to tree growth through photosynthesis. With the exception of the agricultural chemicals

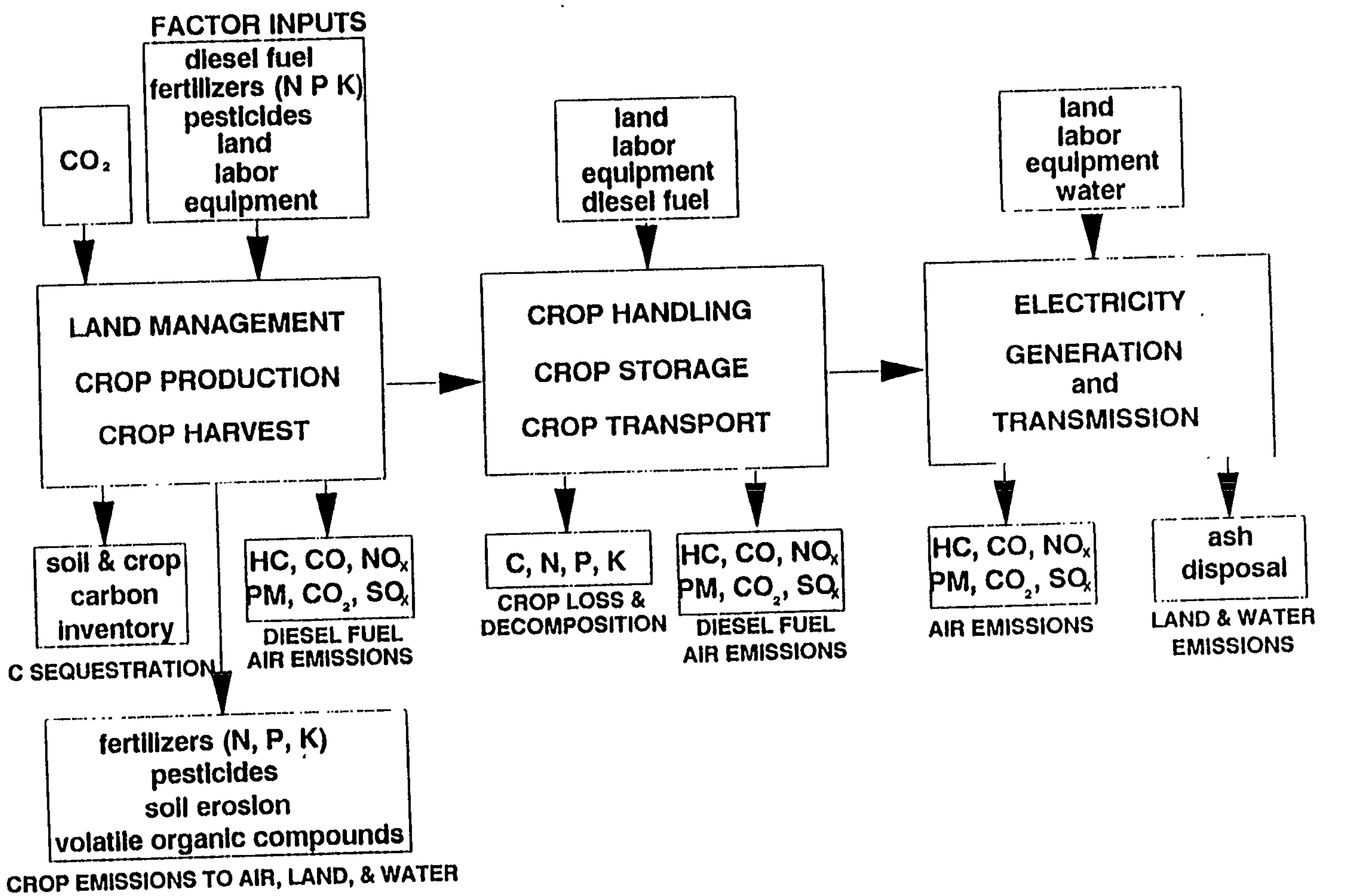

Fig. 4.1-1. Schematic of the biomass-to-electricity fuel cycle showing major inputs and environmental emissions

and CO_2, the same inputs are used for handling and transport operations and for electricity conversion.

These factor inputs create a wide variety of emissions. Fuel used in operating tractors and trucks releases hydrocarbons (HC), carbon monoxide (CO), nitrous oxides (NO_x), particulate matter (PM), carbon dioxide (CO_2), and sulfur dioxide (SO_2) to the air. Agricultural chemicals applied to the land release nitrogen (N), phosphorus (P), potassium (K), and pesticides to surface and ground water, air, and soils. The disturbance of soils also creates erosion. Of course, the significance of these impacts depends greatly on quantity applied, timing of application, site conditions (e.g., erosivity), and weather.

The growing of biomass feedstocks also produces biogenic emissions. Biogenic emissions broadly include the sequestering of carbon and the release of hydrocarbons during biomass growth. Production of wood feedstocks may also raise environmental issues related to biodiversity and habitat change.

All of these impacts directly attributable to the growing of wood energy feedstocks are ***relative to the net displacement of existing land uses and crops***. For example, the displacement of certain agricultural row crops (e.g., corn and soybeans) with trees may result in a positive net change in environmental impacts, especially on erosive sites. The production of wood in managed plantations is much less erosive than row crop production and the amount of fertilizers and pesticides used is much less. Some estimates of these factors are shown in Table 4.1-1. The conversion of pasture land to tree production may increase soil erosion as trees are being established. However, runoff containing nutrients from animal wastes is not present. All of these changes, as well as those linked to biodiversity and habitat change, depend on the assumption that the displaced crops represent marginal production which will not re-locate elsewhere.

Land, labor, capital, water, and wood feedstocks are all used to generate power. Environmental emissions released to the air are CO, NO_x, SO_x, PM, and CO_2. Relative to coal and other primary fossil-fuel sources of electricity, wood-fired electricity generation has very low levels of SO_x emissions because wood contains very little sulfur. There are also reduced emissions of NO_x. CO_2 emitted from wood combustion is merely carbon that was sequestered from biomass growth. The major emissions from wood-fired generation involve the release of PM. However, these emissions are controlled effectively with existing technology, though of course at increased cost.

Emissions to land and water resources are associated with soil disturbance and runoff and the disposal of ash. However, ash disposal is not a major concern from wood combustion and may be beneficial as a fertilizer and soil conditioner (provided the pH is not excessively high).

Table 4.1-1. Fertilizer use, pesticide use, and erosion for various crops

Approximate fertilizer levels applied to various crops (lb/acre)			
Crop Type	Nitrogen	Phosphorous	Potassium
Corn	121	54	71
Sorghum	80	54	54
Soybeans	18	40	62
Wheat	54	31	40
Hay land	18	36	36
Alfalfa	0	67	134
Pasture	13	36	36
Set-aside	4	18	18
Switchgrass	45	54	54
Woody crops	54	13	13
Mean annual pesticide use on various crops (lb a.i./acre)			
Crop Type	Herbicides	Insecticides	Fungicides
Corn	2.73	0.34	0.001
Soybeans	1.63	0.14	0.001
Wheat	0.16	0.021	0.009
Switchgrass	0.22	0.018	0.0009
Woody crops	0.35	0.009	0.0001
Mean annual erosion rates for various crops (tons/acre)			
Crop Type		Soil erosion	
Average cropland		8.1	
Corn		9.7	
Soybeans		18.3	
Wheat		6.3	
Hayland		0.09	
Switchgrass		0.9	
Woody crops		0.9	

Note: a.i. denotes active ingredient.

Sources: Fertilizer and pesticides—Ranney, J. W. and L. K. Mann, 1993. "Environmental Considerations in Energy Crop Production", *Biomass and Bioenergy*, in press, (1993). Erosion rates—Pimental, D. and J. Krummel, (1987). "Biomass Energy and Soil Erosion: Assessment of Resource Costs", *Biomass*, 14: 15-38.

The above emissions have potential for ecological impact. Some of the emissions also have health and safety impacts, specifically NO_x as a precursor to ozone and PM as a contributor to increased respiratory illnesses. There may also be potential for spores and moulds to grow on the harvested and stored biomass and to cause health effects. Accidents could also be associated with biomass production and harvesting. Finally, there are potential socioeconomic impacts with a biomass-to-electricity fuel cycle. These impacts would include employment and income growth, and changes in recreation opportunities from habitat.

Table 4.1-2 shows the biomass fuel cycle emissions, and the potential resource categories that may be impacted. Table 4.1-3 lists the emissions, pathways, resource categories, and impact evaluations that are *not* discussed in detail and gives the reasons why these are not evaluated in this study.

4.2 DESCRIPTION OF REGIONAL REFERENCE SITES

Two sites were chosen as regional reference environments for biomass plants. One site is in the southeastern United States and the other is in the northwest. Two sites were chosen to illustrate the differences in the analyses that result from different socioeconomic and environmental conditions. This study uses a 80-mile radius from the plant site to define the boundaries of the local reference environment.

4.2.1 Reference Plant and Biomass Production Sites

The site of the biomass plant in the southeast region is what was to have been the location of the Clinch River Breeder Reactor (CRBR) in Roane County, Tennessee. This location is on the north side of the Clinch River and is approximately 25 miles west of Knoxville and 9 miles south of Oak Ridge. The site of the biomass plant in the northwest region is along the Columbia River in Camas, Washington. Camas is approximately 20 miles east of Portland, Oregon. Figure 4.2-1 is a map showing the locations of these two reference sites.

The National Resources Inventory (NRI) was used to identify land surrounding the reference sites to produce wood energy feedstocks (SCS 1987). The NRI is a data base that provides detailed county-level information on current land uses by capability class and subclass, the potential cropland, soil erosion, the extent of flood-prone areas, and other conservation related data. The identification of the specific types of land that could be used for biomass production was based on a screening analysis by Graham (1992). Graham applied a series of filters to eliminate land that is not compatible or suitable for biomass production. Examples of the types of land excluded include riparian land, forest land, government owned land, land in horticulture, and land with severe environmental limitations (land classes V, VI, VII, and VIII). Essentially, land identified for growing wood feedstocks is land that is classified by the SCS as existing cropland or land that has a potential for conversion

Table 4.1-2. Emissions of the biomass-to-electricity fuel cycle and potential resource categories that may be impacted

Emissions	Pathways	Resource Categories
	Air Emissions:	
Carbon dioxide Carbon monoxide	Releases from mechanical equipment, trucks, and power plant stack; greenhouse gases	All impact categories
Carbon dioxide	Biogenic emissions and sequestration	All impact categories
Nitrogen oxides Sulfur dioxides	Releases from mechanical equipment, trucks, and power plant stack	Human health; biodiversity; crop production; tree growth
Acid aerosols	Secondary formation in the atmosphere	Human health; biodiversity; recreational fishing; crop production; tree growth
Particulates	Releases from mechanical equipment, trucks, and power plant stack	Human health
Particulates, Hydrocarbon, Sulfur dioxide	Releases from mechanical equipment, trucks, and power plant stack; formation of haze	Recreational use of parks
Water Vapor	Drying and combustion of wood feedstock; formation of fog	Recreational use of parks
Peroxyacetyl nitrate (PAN)	Secondary formation in the atmosphere from NO_x and hydrocarbons	Biodiversity
Ozone	Secondary formation in the atmosphere from NO_x and hydrocarbons	Human health; crop production; biodiversity

Table 4.1-2 (continued)

Emissions	Pathways	Resource Categories
Spores, moulds, pollen	Storage of wood feedstocks, tree growth	Human health
Fertilizers	Volatilization at tree plantations	Biodiversity; crop production
Herbicides	Volatilization at tree plantations	Biodiversity; crop production
	Water Emissions:	
Fertilizers	Runoff from tree plantations; groundwater	Biodiversity; water quality
Suspended solids	Erosion from tree plantations	Recreational uses; biodiversity; water quality
Herbicides	Runoff from tree plantations	Biodiversity; water quality
Cooling water	Power plant cooling system blowdown	Biodiversity; recreational fishing
Wastewater	Power plant boiler blowdown and other waste streams	Biodiversity; recreational fishing
	Other Factors:	
Land use	Siting of tree plantations and power plant	Biodiversity; crop production
Organic carbon	Buildup of soil carbon from leaf fall, etc.	Biodiversity
Erosion	Runoff from plantations	Soil loss
Wood ash	Power plant fly ash and boiler ash	Biodiversity
Road use	Feedstock transportation	Road deterioration
Road use	Feedstock transportation	Truck noise
Worker safety	Accidents	Human health

Table 4.1-3. Emissions, pathways, resource categories and impact evaluation linked to the biomass fuel cycle and considered to be low priority

Emissions	Pathways	Resource Categories	Impact Evaluation
	Air Emissions:		
Particulates, Acid aerosols, Ozone from NO_x	Primary emissions and secondary formation in atmosphere; reduction in visibility	Recreational use of parks	Insufficient data; modeling not conducted
Hydrocarbons	Natural tree emissions, drying of feedstock, combustion products; long range transport; haze formation	Recreational use of parks	Insufficient data; modeling not conducted
Water vapor	Drying and combustion of feedstock; fog formation	Recreational use of parks	Insufficient data; modeling not conducted
Peroxyacetyl nitrate (PAN)	Formation in the atmosphere from NO_X hydrocarbons	Biodiversity	Insufficient data
Inorganics	Emissions from power plant stack	Biodiversity	Not ecologically significant
	Water Emissions:		
Erosion	Runoff from tree plantations	Decreased land productivity	Not quantifiable
Insecticides	Runoff from tree plantations	Biodiversity	Infrequent use

Table 4.1-3 (continued)

Emissions	Pathways	Resource Categories	Impact Evaluation
Cooling water	Blowdown	Recreational fisheries; biodiversity	Insufficient data, high dilution minimizes impacts
Wastewater	Boiler water blowdown and other waste streams	Recreational fisheries; biodiversity	Insufficient data, high dilution minimizes impacts
Other Factors:			
Wood ash	Combustion product	Crop productions	Potential benefit, not significant
Noise	Truck traffic	Biodiversity	Not ecologically significant

to cropland.[1] (More details on the screening analysis used to identify land can be found in Appendix A.)

4.2.1.1 Southeast Reference Site

The available cropland for growing wood feedstocks for the Southeast site is summarized in Fig. 4.2-2. The data show that most of the land (nearly 56%) is class II erosive. That is, the land may have an erosion hazard or may have substantial damage from previous erosion. About 13% of the suitable cropland is class I having no major restrictions for growing tree crops. Nearly 30% of the suitable land base is subclass w for classes II, III, and IV. This land has excess water that may be caused by poor drainage, wetness, a high water table, or flooding. Class III and IV land having erosive or shallow soils is not included because this land cannot not support wood production in excess of 4 dry tons/acre (see Appendix A).

[1]The screened NRI data provide an indication of how much land is potentially available and suitable for growing wood feedstocks. However, this cropland inventory may not necessarily coincide with land availability based on purely economic considerations. For example, a landowner's decision to grow wood energy feedstocks would depend on risk-adjusted net returns from producing energy crops, how tree crops impact traditional agricultural operations (e.g, labor and equipment complementarity and crop rotation restrictions), and the influence of government policy (e.g., crop support payments, soil srosion limits, and specific programs such as the Conservation Reserve Program).

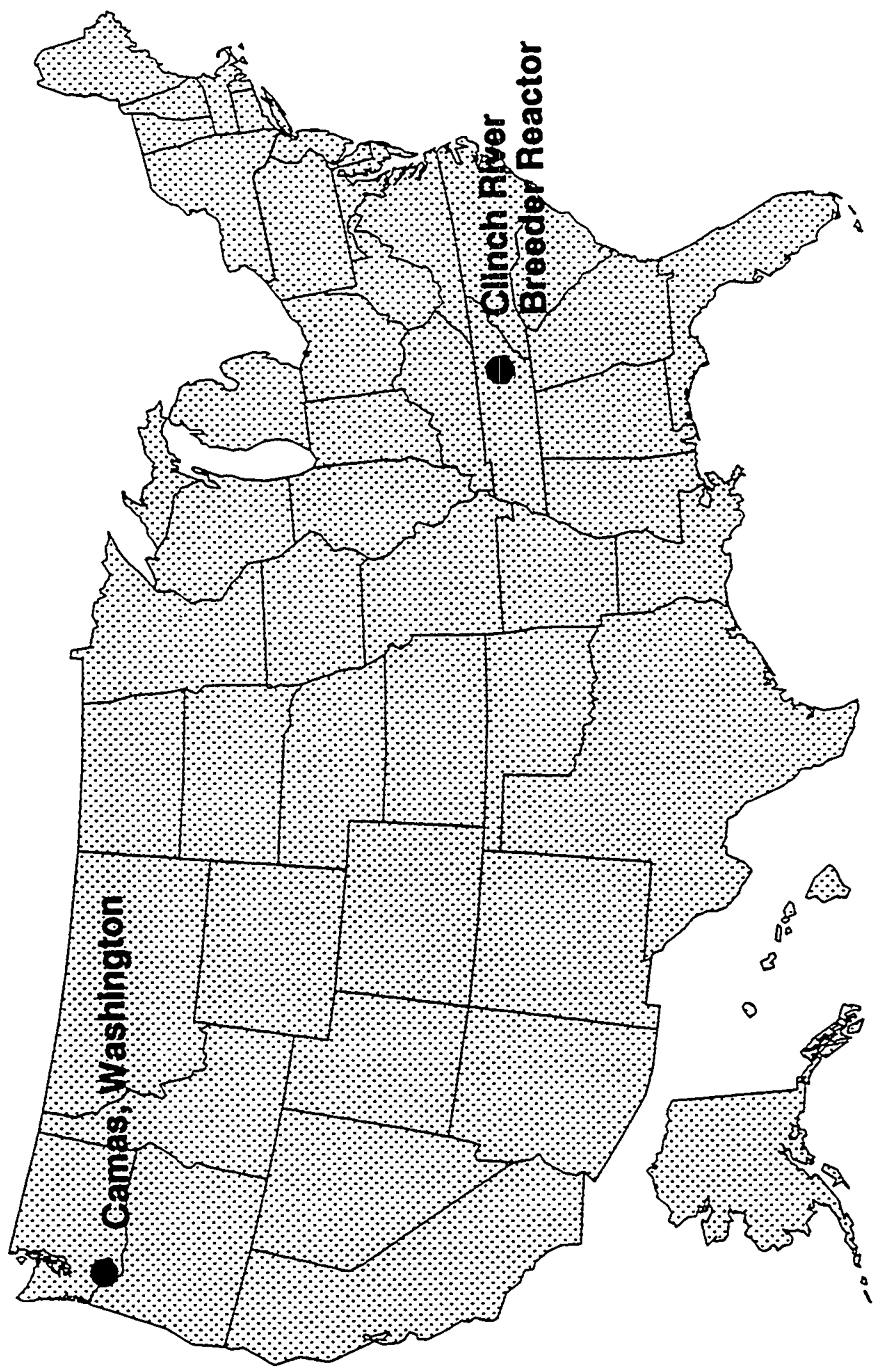

Fig. 4.2-1 Locations of the Southeast and Northwest Reference sites

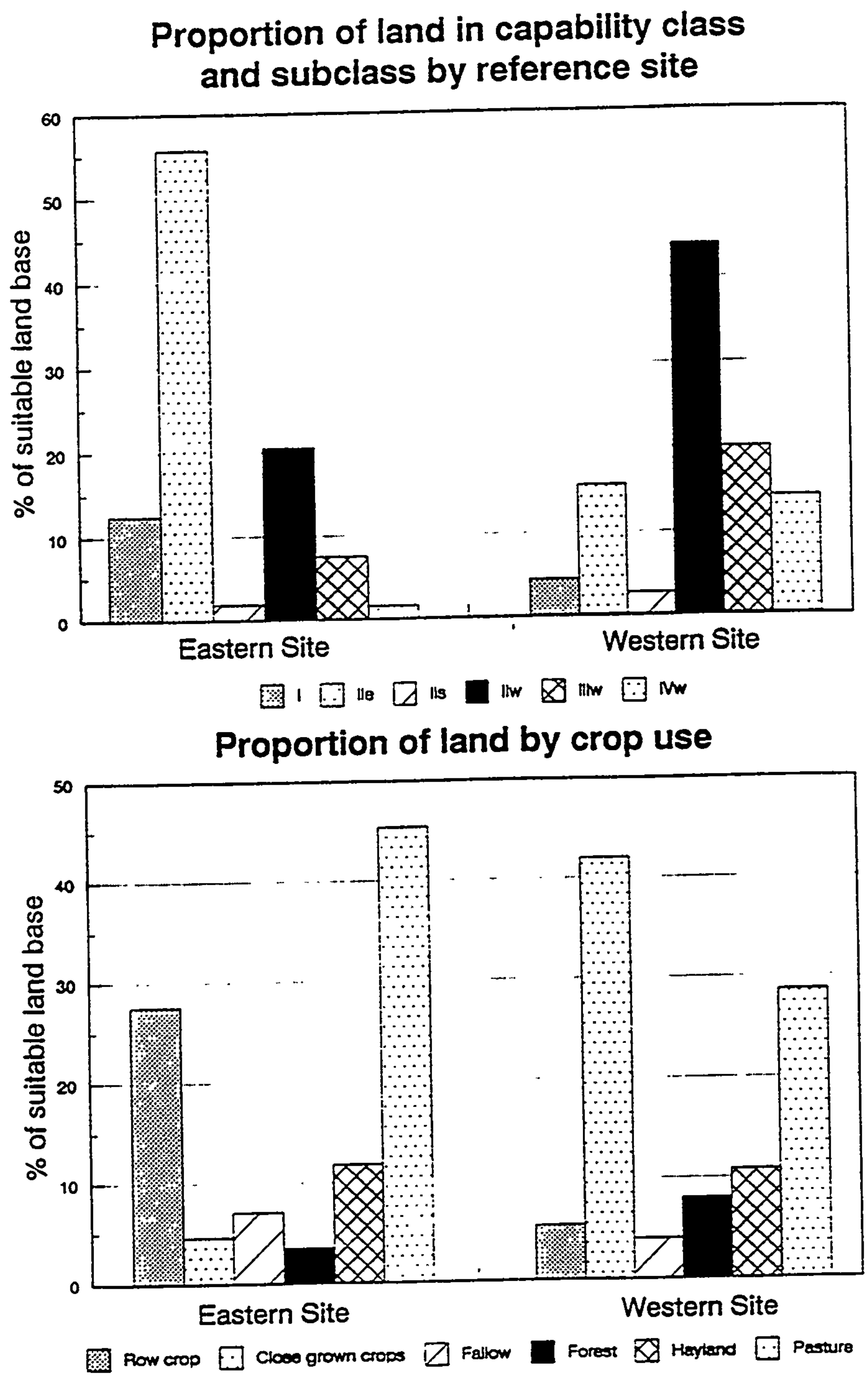

Fig. 4.2-2. Summary of land capability classes and current cropland land use for the Southeast and Northwest Reference sites

Figure 4.2-2 also summarizes current crop land uses. The dominant land uses are pasture (45%) and row crops (28%). The row crops are mostly corn and soybeans. About 12% of the current land use is classified as hayland. Less than 4% of the land base is open forest land (closed forest land having a canopy cover greater than 55% is **not** considered appropriate for tree crops). Small percentages of land in close grown crops (e.g. wheat) and land that is currently fallow is also potentially available for energy crop production.

4.2.1.2 Northwest Reference Site

The Northwest Reference site is different from the Southeast Reference site in that only 15.5% of the land is class II erosive (Fig. 4.2-2). Most of the suitable land base is class II with a wetness limitation, which is beneficial for tree production. Relative to the Southeast Reference site there is a smaller percentage of class I land but a much higher percentage of lower class land having wetness limitations. Erosive and shallow land in capability classes III and IV are not included because of low tree growth.

Current land use for the Northwest Reference site is similar to the Southeast Reference site in that there are two dominant uses. However, instead of row crops the Northwest Reference site has close grown crops (wheat, barley, etc.) and pasture. These two crops account for over 70% of current use. There is less fallow land and a higher percentage of open forest land (i.e., forest with less than a 55% canopy closure) relative to the Southeast Reference site.

4.3 WOOD FEEDSTOCK PRODUCTION OPERATIONS

This section discusses the selection of tree species, biomass productivity, and operations that are used to produce wood energy feedstocks. Additional characterization of this part of the fuel cycle is provided in Appendix A.

4.3.1 Species Selection and Productivity

4.3.1.1 Southeast Reference Site

In the Southeast, sycamore (*Platanus* occidentalis) and sweetgum (*Liquidambar* styraciflua) have been identified as desirable species because they combine the traits of rapid juvinile growth, wide site adaptability, pest resistance, and disease resistance (Wright et al., 1991). Although sycamore grows better on bottomland sites, it can be grown successfully on upland sites that have good fertility, moisture, and drainage . Sweetgum has greater tolerance to drought and weed competition and can tolerate seasonally wet soils. These tree species have been the focus of much of the genetic improvement studies focused in the Southeast. Black locust (*Robinia* pseudoacacia) is another promising species. Black locust is a nitrogen-fixing tree that can be intermixed with sycamore and sweetgum or grown alone on upland sites that are low in nutrients.[2]

Annual productivity (dry tons/acre) is expected to be highest on the class I and IIw sites and lowest on class IIe and IIs. Productivity on class IIIw and IVw sites should exceed class IIe and IIs. Table 4.3-1 summarizes the assumed productivity levels for each capability subclass. These estimates are based on Graham (1992) and English et al. (1992) and reflect the use of currently available clones and seed sources. The range in productivity estimates (4 to 5.5 dry tons/acre) compares with estimates from current production research trials of 4 to 7 dry tons/acre (Wright and Ehrenshaft, 1990). Also shown in Table 4.3-1 is an estimate of the long-term potential of the sites. These estimates of potential productivity reflect the use of improved species (i.e., advances in the selection and breeding of desirable traits). The potential productivity estimates are used for the 2010 reference time period. The potential for increasing productivity beyond current levels on Southeast upland sites is modest because the overall growing conditions are marginal for intensive wood feedstock production.

4.3.1.2 Northwest Reference Site

In the Pacific Northwest region, hybrid poplars have consistently produced high yields on high-moisture, high-fertility bottomlands (Wright et al. 1990). These hybrid poplars are crosses of native black cottonwood (*Populus* trichocarpa) and eastern cottonwood (*Populus* deltoids). On upland sites acceptable productivity has been obtained from Populus spp. provided there is adequate moisture and soil fertility. A nitrogen-fixing tree, red alder (*Alnus* rubra), has also performed well on some low fertility upland sites (Wright et al. 1990).

Table 4.3-1 shows the assumed productivity levels for each capability subclass. Higher productivity is associated with higher capability classes and the availability of moisture. Relative to the Southeast Reference site, overall productivity is greater in the Pacific Northwest. Productivity is assumed to be 7 dry tons/acre on class I sites and wet class II and class III sites. On wet class IV sites productivity is placed at 5.5 dry tons/acre. The erosive and shallow class II sites are the lowest producing with only 4.5 dry tons/acre. In the future, productivity gains are likely to be greater on the better sites.

[2]Supply management and risk considerations lead to decisions to mix tree species. Risks of crop losses from pests, diseases or climate can be minimized by having a variety of species and clones including those that can fix nitrogen.

Table 4.3-1. Land use classes and subclasses for the Southeast and Northwest Reference sites

Agricultural class/subclass	Productivity (tons/acre)	
	1990	2010
Southeast Reference site		
I	5.5	8.0
IIe	4.5	5.0
IIs	4.5	5.0
IIw	5.5	8.0
IIIw	4.0	6.0
IVw	4.0	6.0
Northwest Reference site		
I	7.0	10.0
IIe	4.5	5.0
IIs	4.5	5.0
IIw	7.0	10.0
IIIw	7.0	10.0
IVw	5.5	8.0

Notes: Subclasses e, s, and w denote erosive, shallow soils, and wet sites, respectively.

4.3.2 Production and Harvesting Operations

The establishment of wood feedstock plantations requires effective site preparation and weed control. This includes herbicide spraying, mowing, and plowing (and/or disking) prior to planting. After planting, weeds are controlled with a selectively applied pre-emergent herbicide. During the summer, weeds are mowed and an application of a broad-kill herbicide applied. Mowing and a herbicide spray are also used during the second growing season. After two years of growth, canopy closure occurs and further herbicide use is not required. Following establishment, the management of a woody crop is not intensive, requiring only an application of nitrogen ($N_2H_4O_3$ and urea), phosphorous (P_2O_5) and potassium (K_2O). An insecticide is also applied once during each rotation.

Harvesting operations are assumed to take place in year 6 followed by two additional coppice (or regrowth) cycles of six years each. The total life of any tree is 18 years. Based on the assumed harvest or rotation age, one-sixth of the total acreage required to meet the needs of the conversion facility is planted each year. This sequenced production assures that each year equal feedstock amounts will be available to fuel the conversion facility.

The harvesting system used is one in which trees are severed during the dormant season (between the months of November and March), field dried, moved, chipped, loaded, and hauled to the conversion site. Dormant season harvesting of trees will lead to better coppice regrowth and leaves more nutrients on the site than would non-dormant season harvesting.

When trees are severed, handled, chipped, and loaded/unloaded feedstock losses occur. Decomposition also occurs when the feedstocks are stored long-term. Losses due to harvesting, handling, and field storage (pre-haul losses) are assumed to be 12%. Additional losses of 4% are assumed once the trees are delivered to the conversion facility. Total wood feedstock losses are 15.5% of the dry weight standing yield.

For the 2010 time period, establishment, management, and harvesting operations are assumed to remain unchanged. The major technology difference between time periods is the use of improved and much higher yielding species and clones. Higher productivity will result in the need to have less land in production to fuel the conversion facility.

4.3.2.1 Southeast Reference Site

The factor inputs (chemicals and diesel fuel) used to produce sycamore, sweetgum, and black locust are summarized in Table 4.3-2. Maximum chemical application amounts are 90 lb/acre for N, 80 lb/acre for P, 80 lb/acre for K, 3 lb/acre for herbicides, and a small quantity of insecticide. These maximum amounts when multiplied by the number of acres undergoing treatment are the basis for calculating impacts. On a life-cycle basis, chemical use is much less than that for agriculture (Table 4.1-1). Annual nitrogen requirements average 15 lb/acre for sycamore and sweetgum and 13 lb/acre for phosphorous and potassium. Herbicides average only 0.2 pounds per acre reflecting application in just the first two years of tree life. Insecticide use is minimal for non-nitrogen fixing trees. Black locust does not require nitrogen but may require more insecticide use.

Table 4.3-2. Factor input requirements for SRWC

Activity	Material	Amount/acre
Crop Establishment (year 1)		
Herbicide spray	Broad-kill Diesel	1.0 lb 0.4 gals
Mow	Diesel	0.6 gals
Plow (or disk)	Diesel	1.4 gals
Plant	Diesel	2.8 gals
Herbicide spray	Preemergent Diesel	1.0 lb 0.4 gals
Mow (mid-year)	Diesel	0.6 gals
Herbicide spray (mid-year)	Broad-kill Diesel	1.0 lb 0.4 gals
Crop maintenance (years 2–18)		
Fertilizer spread (one application during each rotation)	N P_2O_5 K_2O Diesel	90 lb 80 lb 80 lb 0.3 gals
Insecticide/fungicide spray (one application during each rotation)	Pesticide Diesel	0.06 lb 0.4 gals
Mow (in year 2 only)	Diesel	0.6 gals
Herbicide spray (in year 2 only)	Broad-kill Diesel	1.0 lb 0.4 gals
Harvesting operations (years 6, 12, and 18)		
Harvesting and handling	Diesel	1.9 gals

Notes: Pesticides amounts are given in terms of active ingredient. Amounts are derived from Ranney and Mann (1991). There are two exceptions for N-fixing trees (black locust and red alder). First, fertilization does not include nitrogen. Second, insecticide use is 2.7 lb/acre.

There is no difference in chemical use between the 1990 and 2010 time periods on a per acre basis. However, total use in 2010 is much less for two reasons. First, the use of more efficient conversion technology reduces feedstock requirements and lowers the number of acres in production. Second, the use of improved species means that each acre produces more feedstocks.

In addition to the chemical emissions, tractors used for the various field operations will emit a number of pollutants—HC, NO_x, PM, CO_2, and SO_2. These emissions can be calculated knowing the amount of time required to perform an opration (e.g., spraying) and the total fuel used (see Appendix A). Fuel use was estimated at approximately 11 gals/acre and 12.0 gals/acre for 1990 and 2010 time periods, respectively. The increase in fuel use on a per acre basis is due to the greater amount of standing biomass at harvest and the need for more equipment for harvesting operations. However, total fuel consumption declines by about 30% because there are fewer acres in production.

4.3.2.2 Northwest Reference Site

Chemical use is the same as the Southeast Reference site on a per acre basis. However, total chemical use is lower at the Northwest site because there are fewer acres in production (i.e., the land is capable of producing more biomass per unit area). The Northwest Reference site has more favorable growing conditions and has a higher percentage of land that is classified as wet and more appropriate for wood production.

Fuel use is about 4 gals/acre (14 gals/acre in 1990 and 17 gals/acre in 2010) higher at the Northwest site. Higher per acre fuel use is due to productivity differences and greater fuel use in harvesting (i.e., higher standing yields). Total fuel use is slightly lower at the Northwest site.

4.4 ACREAGE AND HAUL DISTANCE REQUIREMENTS

Identifying the location and type of land to use to grow the wood feedstocks was accomplished by assuming that 5% of the suitable land base is converted to wood production (see Appendix A). The 5% conversion assumption was applied uniformly across land capability classes I, IIe, IIs, IIw, IIIw, and IVw.

A disproportionately higher percentage of class III and IV land might appear to be more economically justified because of the presumption of lower land cost. However, such land produces lower yields and may not necessarily result in positive economic returns. Moreover, results from a recently completed study indicate that row and close grown crops are displaced more than non-intensive uses such as pasture (Graham et al. 1992). This is explained by the fact that returns from row and close grown crops are not high and the costs of converting pasture are greater than conversion of row and close grown crop land. Given that the cultivation of row and close grown crops is more intensive (both equipment and chemicals) than tree crops, the use of the 5% assumption over all classes is likely conservative and tends to overstate the impact of tree crops with respect to their potential effects (soil erosion and chemical run off).

4.4.1 Southeast Reference Site

As shown in Table 4.4-1 about 39,930 acres are required to fuel the 1990 conversion facility. (Feedstock requirements come from assumptions about the conversion facility—heat rate, capacity factor, and plant size—discussed in the next section of this chapter.) Most of this production is from IIw and I land (see Appendix A). This land can produce over 191,100 dry tons of feedstock each year. After accounting for pre- and post-haul losses, 161,450 dry tons are actually supplied to the conversion facility. Also shown in Table 4.4-1 are the feedstock flows and losses computed as wet or field tons. The standing wet yield is 382,225 tons having a moisture content of 200% computed on a dry basis.[3] The moisture content in the cut trees is assumed to decline to 125% after field drying. The haul tonnage (210,220 tons) reflects a 125% moisture content. The average haul distance is computed at 44 miles (one-way).

For a year 2010 facility, only 24,910 acres are required to supply the conversion facility. Total wood feedstock production is 151,660 dry tons with 128,120 dry tons delivered to the conversion hopper after accounting for handling and decomposition losses. The lower feedstock requirements mean a shorter average haul distance—35 miles (one-way).

4.4.2 Northwest Reference Site

Fueling the conversion facility from the area surrounding the Northwest Reference site requires about 30,150 acres (Table 4.4-1). Higher productivity relative to the Southeast site means that less land is required to fuel the facility. For the 2010 time period, the amount land required declines to about 17,200 acres. The haul tonnage for the Northwest Reference site is the same as the Southeast Reference site. Computed average haul distances (one-way) are 37 miles and 28 miles for the 1990 and 2010 time periods, respectively.

[3]Moisture content can be computed in two ways—wet basis and dry basis. Moisture content on a wet basis is the amount of water in a tree divided by the total weight of the tree. Moisture content on a dry basis is the weight of the water in a tree divided by the total dry weight of the tree.

Table 4.4-1. Land available for wood energy production, feedstock tonnages, losses, and haul distance requirements

Acres, Production, Feedstock Flows, Haul Distances and Fuel Use	Southeast		Northwest	
	1990	2010	1990	2010
Total acres	39,928	24,911	30,154	17,203
Annual productivity (Dry tons)	4.8	6.1	6.3	8.8
Annual production (Dry tons/acre)	191,110	151,660	191,110	151,660
Feedstock flows (Dry tons)				
Standing yield	191,130	151,660	191,130	151,660
Pre-haul losses	22,930	18,200	22,930	18,200
Haul tonnage	168,180	133,460	168,180	133,460
Post-haul losses	6,730	5,340	6,730	5,340
Conversion hopper	161,450	128,120	161,450	128,120
Haul distances (miles)				
Maximum distance	66	52	56	42
Average distance	44	35	37	28
Total annual fuel use (gallons)	176,860	97,550	149,360	78,790

Notes: Moisture content is 200% on dry basis for standing yield. Moisture content is 125% for computing tons hauled and tons at the conversion hopper.

4.5 BIOMASS-TO-ELECTRICITY CONVERSION TECHNOLOGY

In the U.S., there are about 9 gigawatts of biomass-fired electric generating capacity (Williams and Larson 1992). Most of this capacity is a direct result of PURPA legislation introduced in the late 1970s. This legislation along with favorable purchase contracts helped to encourage the development of biomass and other renewable fuels for electric power production.

Biomass-fired power generation can be an economically viable alternative to fossil-fired generation provided biomass feedstocks can be obtained at low cost. EPRI (1991) reports that electricity from wood-fired power plants costs about 13% more than power from a coal-fired plant. However, they note that biomass power is competitive with coal provided wood feedstocks can be obtained at less than $12/wet ton (50% moisture). EPRI also notes that wood-fired power generation is viable where there is an need to reduce SO_x and NO_x emissions from power plants.

Most installed biomass-to-electricity conversion facilities have a readily available supply of low-cost wood or waste product. The availability of low-cost feedstocks tends to favor conversion facilities with lower capital costs and lower operating efficiencies (high heat rates). These systems are designed to convert biomass to energy at minimal cost without taking into consideration the use of more efficient technology. With the growing scarcity of biomass feedstocks, more efficient equipment is now being installed. Typical efficiencies of plants currently being installed range from about 20 to 25% (USDOE 1992). Conversion efficiencies up to 34% are now possible with current technology; however, the relatively small-scale of most plants and the low cost of biomass waste feedstocks have not justified such investments (Wright et al. 1991). For biomass to be economically attractive for power generation with higher priced feedstocks requires the development of conversion technologies that offer both high efficiency and low capital costs at modest scales (Williams and Larson 1992).

The type and cost of biomass feedstocks also influence the scale of biomass-fired conversion facilities. Biomass has a fairly low energy density and transportation and handling costs can become prohibitively expensive if feedstocks have to be hauled long distances. High transportation costs have effectively limited the size of biomass-electric facilities to under 50 MW with most of the construction in the 15 to 30 MW size (Hollenbacher 1992). The largest operating biomass electric plant is the McNeil facility located in Burlington, Vermont. This plant has a nameplate capacity of 50 MW. In the future, the use of dedicated biomass feedstocks grown on plantations in relatively close proximity to higher efficiency conversion facilities may mean larger-scale plants.

The quality of the rural environment is also a factor in the design and scale of a biomass conversion facility. There has been public opposition to proposed biomass facilities when the hauling of large quantities of feedstocks are required (Frankena 1987). This opposition stems to a considerable degree from truck traffic and the deteoriation of aesthetic quality of the rural environment. Wood-fired plants in the very small scale range may be the most feasible in terms of social and political acceptability (Frankena 1987). For both the 1990 and 2010 time periods conversion technologies are assumed to be built at modest scales. This assumption recognizes hauling limitations and costs as well as the potential problems associated with the siting of large-scale facilities.

4.5.1 1990 Reference Conversion Technology

A conventional steam turbine (spreader-stoker) technology is assumed for the 1990 time period. It is sized at 30 MW operating at a heat rate of 14,920 Btu/kWh.

This heat rate (net plant efficiency) is about average for plants currently being installed. The quantity of feedstock required for the facility is based on a 70% capacity factor (baseload operation) and a higher heating value of wood of 17 MMBtu/dry ton. The 1990 conversion facility needs approximately 161,450 dry tons of feedstock each year net of losses to handling and decomposition (Table 4.5-1).

Table 4.5-1. Technical assumptions for biomass conversion technology

Technical parameter	Conversion technology: 1990 Conventional steam turbine cycle	Conversion technology: 2010 Biomass-gasifier gas turbine
Plant size	30 MW	40 MW
Capacity factor	70%	70%
Net heat rate (Btu/kWh)	14,920	8,890
Dry tons/year	161,450	128,270
Annual generation (MWh)	183,960	245,280

Notes: The higher heating value of wood is assumed to be 17 MMBtu/dry ton.

4.5.2 2010 Reference Conversion Technology

A biomass-gasifier ISTIG power plant is assumed for the 2010 time period. The ISTIG is expected to be tested with natural gas firing by 1997 and a gasifier should be optimized for biomass by 2010 (USDOE 1992). In contrast to conventional steam turbine cycles, gas turbines are relatively insensitive to scale and offer low capital costs. The gas turbine also offers high efficiency.

A 40 MW plant operating with an annual capacity factor of 70% is assumed for the 2010 period. Larson et al. (1989) provide a conservative estimate of conversion efficiency of 38.4% (or net heat rate of 8,890 Btu/kWh). As summarized in Table 4.5-1, this plant requires approximately 128,100 dry tons of wood feedstocks each year.

5. BIOMASS-TO-ELECTRICITY EMISSIONS AND OTHER RESIDUALS

This chapter presents the main activities and emissions from each major stage of the fuel cycle—feedstock production, transport, and generation of electricity. Emissions are calculated for each reference site and time period. The chapter is organized into three major parts. The first section presents a discussion of land-use change associated with feedstock production as well as estimates of emissions from the growing, harvesting, and transport of feedstocks to the conversion facility. The second section discusses biogenic emissions that are associated with feedstock growth including volatile hydrocarbons. This section also discusses CO_2 sequestration. The final section presents emissions from electricity generation.

5.1 FEEDSTOCK PRODUCTION, HARVESTING, AND TRANSPORT

5.1.1 Changes in Land Use

In assessing the emissions and impacts from growing wood feedstocks, it is important to account for the specific land uses to be displaced. Several important fuel cycle impacts depend on the ***change*** in land use (e.g., effects of erosion and biodiversity). As discussed in the previous chapter, it is assumed that wood feedstocks displace existing land uses proportionately. These changes by land class (and subclass) and land use (i.e., crop type) are shown in Table 5.1-1 for both reference sites.

5.1.1.1 Southeast Reference Site

In the southeast most of the land (55.7%) for growing wood energy crops comes from class IIe (erosive) land. Only 12.6% is assumed to come from class I land. Very little of the land is in the lower level classes (III_w and IV_w). The crops that are displaced by trees are also shown in Table 5.1-1. Pasture, row crops (corn and soy beans), and some hay land are the major displaced crops for both time periods.

Table 5.1-1. Summary of land use change by land class/subclass and crop type for each reference site and time period

Land Class/ Subclass	Southeast Reference Site			Northwest Reference Site		
	Acreage			Acreage		
	1990	2010	(%)	1990	2010	(%)
I	5,023	3,134	12.6	1,291	736	4.3
II_e	22,234	13,872	55.7	4,662	2,660	15.5
II_s	775	484	1.9	792	452	2.6
II_w	8,241	5,141	20.6	13,205	7,532	43.8
III_w	3,027	1,889	7.6	5,985	3,415	19.8
IV_w	627	391	1.6	4,219	2,407	14.0
TOTAL	39,928	24,911	100	30,154	17,203	100
Land Use						
Closecrop	1,588	991	4.0	12,706	7,249	42.1
Corn	5,353	3,340	13.4	1,086	620	3.6
Fallow	2,642	1,648	6.6	1,201	685	4.0
Open Woodland	1,579	985	4.0	2,418	1,379	8.0
Hayland	4,712	2,940	11.8	3,249	1,853	10.8
Pasture	17,652	11,013	44.2	8,846	5,047	29.3
Row crop, other	682	426	1.7	529	302	1.8
Soybeans	5,720	3,569	14.3	0	0	0
Range	0	0	0	119	68	0.4
TOTAL	39,928	24,911	100	30,154	17,203	100

5.1.1.2 Northwest Reference Site

In contrast to the southeast, most of the land for the Northwest Reference site is classified as II_w (wetness limitation). The lower level classes (III_w and IV_w) are also used for growing wood energy crops. Very little of the land available for wood production is classified as erosive land (15.5%). Close grown crops (e.g. wheat) and pasture are the major displaced crops at the Northwest Reference site.

5.1.2 Equipment Operations

Diesel-fueled farm tractors give off a variety of airborne emissions—exhaust VOCs, CO, NO_x, particulates (PM), CO_2, and SO_2. These emissions were computed as the product of average annual power requirements, acres in production, and emission factors for VOCs, CO, NO_x, PM, CO_2, and SO_2. The emission factors are based on g/bhp-hr (grams per brakehorsepower-hour) or the amount of emissions that are released for each unit of energy delivered by the tractor engine. The emission factors for the 1990 reference time period are 1.7, 3.34, 9.39, and 1.28 grams/bhp-hr for exhaust VOCs, CO, NO_x, and PM, respectively. For the 2010 reference time period, tractor emissions are assumed to reach levels of current high-speed diesel truck engines. These assumed future emission factors are: 1.1, 4.8, 4.8, and 0.5 g/bhp-hr for exhaust VOCs, CO, NO_x, and PM, respectively.

Emissions of CO_2 and SO_2 from equipment operations are a function of the amount of fuel used (gallons). CO_2 and SO_2 emission factors are in units of g/lb of fuel (grams per pound of fuel combusted). The assumed emission factors are 1,448 and 0.45 g/lb-fuel for CO_2 and SO_2, respectively. These emission factors are assumed not to change between the 1990 and 2010 reference time periods.

5.1.2.1 Southeast Reference Site

Table 5.1-2 summarizes emissions for equipment operations used to grow and harvest tree feedstocks. Emissions are presented both in terms of yearly totals and on a dry ton basis. These emissions are not insignificant, being about one-quarter of those from the power plant. However, emissions from equipment are essentially from an area source. As such, they contribute orders of magnitude less to changes in ambient concentrations compared to the point source emissions from the power plant.

5.1.2.2 Northwest Reference Site

Emissions from tractor operations are approximately the same as those for the Southeast Reference site for both time periods.

Table 5.1-2. Annual air emissions from equipment operations

	Units	Emission factor					
		VOCs	CO	NO_x	PM	CO_2	SO_2
Southeast Reference Site							
1990	lb/year	22,848	44,890	126,203	17,203	9,730,689	3,024
	lb/dry ton	0.142	0.278	0.782	0.107	60.27	0.019
2010	lb/year	11,661	50,884	50,884	5,300	6,754,000	2,099
	lb/dry ton	0.091	0.397	0.397	0.041	52.72	0.016
Northwest Reference Site							
1990	lb/year	22,567	44,327	124,648	16,991	9,610,778	2,987
	lb/dry ton	0.140	0.275	0.772	0.105	59.53	0.018
2010	lb/year	11,462	50,017	50,017	5,210	6,638,958	2,063
	lb/dry ton	0.090	0.390	0.390	0.041	51.82	0.016

Notes: Fuel consumption is 0.50 and 0.44 lb/bhp-hr for 1990 and 2010, respectively. Emissions of CO_2 are based on 0.87% C/lb fuel (22.57 lb CO_2/gal of fuel). CO_2 equivalence based on the ratio of molecular weight of CO_2 to the atomic weight of C (3.664). SO_2 emissions are based on a factor of 0.45 grams/lb fuel. Emission expressed in lb/dry ton reflect total delivered wood feedstocks at the conversion hopper (after handling and storage losses).

5.1.3 Agricultural Chemical and Soil Emissions

When agricultural fertilizers and pesticides are applied some of the material applied will leach into groundwater, some will leave the site as runoff and erosion, some will be volatized, and some of the applied chemical will be taken up by the plant. Table 5.1-3 shows the fate of applied agricultural chemicals to groundwater, surface water, and air as a percentage of the total application amount. For example, for every unit of phosphorous applied 5% is assumed to leach into groundwater, 5% is assumed to leave the site as runoff, 10% is assumed to be lost to erosion, and the remainder (80%) is assumed to be plant uptake.

The product of these rates and the maximum annual application amount provide an upper limit on the emissions. Table 5.1-4 summarizes the maximum impact amounts for agricultural chemicals. These maximum amounts are used to assess potential impacts of fertilizers and pesticides.

Table 5.1-3. Agricultural chemical emission rates

Agricultural Chemical	Allocation of Applied Chemical (%)				
	Groundwater	Runoff	Air	Plant Uptake	Erosion
N-fertilizer	5	5	10	75	5
P-fertilizer	5	5	–	80	10
K-fertilizer	5	5	–	85	5
Herbicides	8	10	75	2	5
Insecticides	8	10	75	2	5

Notes: Emission rates are derived from a number of sources: Ahuja (1986), Alberts et al. (1978), Haith (1986), Hon et al. (1986), Isensee et al. (1990), McLaughlin et al. (1985), and Ranney and Mann (1991). Estimates are non-point emissions as a percent of chemicals applied to fields. These estimates do not include handling, transport, and storage of biomass, chemical spills and drift, container cleanup wastes, or fuel emissions.

The establishment of wood energy crops disturbs the soil. Disturbing the soil and removing existing cover crops will cause erosion. However, once the trees are planted and become established and leaf litter layers are deposited, soil erosion declines. Because there are no data on soil erosion from wood energy plantations, it is assumed that erosion during the tree crop establishment year (first year only) is the same as corn (a row crop). During the second year it is assumed that erosion is one-half of the erosion rate for corn. Thereafter, the site is stabilized and erosion is assumed to be the same as pasture or forest. For example, on class I land near the Southeast Reference site annual erosion from corn is about 2.5 tons/acre and erosion from pasture is 0.2 tons/acre. Based on the above assumptions, annual erosion from a tree plantation on this land would be equal 0.7 tons/acre (i.e., 2.5 tons/acre + 0.5(2.5 tons/acre) + 16(0.2 tons/acre))/18) assuming a tree life of 18 years. This calculation is repeated for each land class and subclass using the appropriate NRI erosion rates for corn and pasture. Table 5.1-5 summarizes the calculated erosion rates for each land class and subclass for the Southeast and Northwest Reference sites.

Table 5.1-4. Estimated fate of agricultural chemicals

Time period-site and fate	Maximum impact amount (lb/year)				
	N	P	K	Herbicides	Insecticides
1990 Southeast					
Groundwater	23,957	26,619	26,619	1,597	313
Surface water	23,957	26,619	26,619	1,996	391
Air	47,913	0	0	14,973	2,935
Soil	23,957	53,237	26,619	998	196
2010 Southeast					
Groundwater	14,946	16,607	16,607	996	195
Surface water	14,946	16,607	16,607	1,246	244
Air	29,893	0	0	9,342	1,831
Soil	14,946	33,214	16,607	623	122
1990 Northwest					
Groundwater	18,092	20,103	20,103	1,206	236
Surface water	18,092	20,103	20,103	1,508	296
Air	36,185	0	0	11,308	2,216
Soil	28,092	40,205	20,103	754	148
2010 Northwest					
Groundwater	10,322	11,469	11,469	688	234
Surface water	10,322	11,469	11,469	860	292
Air	20,644	0	0	6,451	2,193
Soil	10,322	22,938	11,469	430	146

Table 5.1-5. Assumed erosion rates

Land class/subclass	Reference Site (1990 and 2010 time periods)	
	Southeast (tons/acre)	Northwest (tons/acre)
I	0.39	0.16
IIe	0.93	0.52
IIs	0.13	0.11
IIw	0.45	0.21
IIIw	0.43	0.17
IVw	0.37	0.34
Weighted Average	0.70	0.27

5.1.3.1 Southeast Reference Site

Average annual emissions of fertilizers (N, P, and K) and pesticides (herbicides and insecticides and fungicides) are summarized in Table 5.1-4 for the 1990 and 2010 time periods. This summary table shows that chemical usage is reduced considerably between the 1990 and 2010. This reduction is due to fewer acres in production (higher efficiency of the 2010 conversion facility and higher productivity from improved species). Table 5.1-6 summarizes soil erosion at the Southeast Reference site. The fewer acres in production reduces erosion by over 10,000 tons/year.

Table 5.1-6. Estimated annual soil erosion

Time period	Total erosion	
	tons/year	lb/dry ton
Southeast Reference Site		
1990	27,947	347
2010	17,436	272
Northwest Reference Site		
1990	8,029	100
2010	4,580	71

5.1.3.2 Northwest Reference Site

Similar conclusions can be made when comparing between time periods at the Northwest Reference site. Chemical emissions and erosion are reduced. Comparisons between reference sites shows that chemical emissions are lower at the Northwest Reference site. This difference is due primarily to the higher assumed productivity. Because of differences in land classes (erosive sites) and in the existing crops grown between sites, erosion is about 2.5 times lower at the Northwest Reference site.

5.1.4 Feedstock Transport

High speed diesel engines used in trucks give off exhaust VOCs, CO, NO_x, particulates, CO_2, and SO_2. Emissions of VOCs, CO, NO_x, and particulates from diesel trucks were computed as the product of annual load-miles and an emission factor. Total annual load miles are a function of the haul tonnage, the average round trip distance, and an assumed 20 ton load. The haul tonnages and distances are from Chapter 4. The haul tonnage for each site and time period is based on a 25% moisture content on a dry weight basis.

The emission factors are based on g/bhp-hr (grams per brakehorsepower-hour) or the amount of emissions that are released for each unit of energy delivered by the truck engine. The emission factors for the 1990 reference time period are 1.1, 4.8, 4.8, and 0.5 grams/bhp-hr for exhaust VOCs, CO, NO_x, and PM, respectively. For the 2010 reference time period, truck emissions are assumed to decline and reach the following levels: 0.5, 2.0, 2.0, and 0.08 g/bhp-hr for exhaust VOCs, CO, NO_x, and PM, respectively. This decline is due to more efficient and clean burning diesel engines. (These factors were converted to lb/mile by an assumption of 2.69 bhp-hr/mile and 454 grams/lb.)

Emissions of CO_2 and SO_2 from feedstock transport are assumed to be a function of the amount of fuel used (gallons). CO_2 and SO_2 emission factors are in units of g/lb of fuel (grams per pound of fuel combusted). The assumed emission factors are 1,448 and 0.45 g/lb-fuel for CO_2 and SO_2, respectively. These emission factors are assumed not to change between the 1990 and 2010 reference time periods.

5.1.4.1 Southeast Reference Site

Table 5.1-7 summarizes emissions from feedstock transport. Emissions decline for the 2010 time period because haul distances are shorter. These emissions are much lower than those for equipment operations. This difference is due primarily to the fact that emissions from tractors are unregulated.

5.1.4.2 Northwest Reference Site

Emissions for the Northwest Reference site are somewhat lower than those for the Southeast Reference site. This difference reflectsshorter transport distances because fewer acres are required for biomass production.

5.2 BIOGENIC FEEDSTOCK EMISSIONS

Known biogenic emissions from woody feedstocks would include the CO_2 that results from decomposition of biomass during storage and from that left on the ground after harvest. Actively growing trees also produce volatile organic compounds (VOCs) that can mix with other air pollutants to generate higher tropospheric ozone conditions (Ranney and Mann 1991).

Table 5.1-7. Annual air emissions from feedstock transport

Annual emissions		Emission factor					
		VOCs	CO	NO_x	PM	CO_2	SO_2
Southeast Reference Site							
1990	lb/year	6,073	26,500	26,500	2,760	3,997,149	1,242
	lb/dry ton	0.037	0.164	0.164	0.017	24.758	0.008
2010	lb/year	1,730	6,921	6,921	276.8	2,204,814	685.2
	lb/dry ton	0.014	0.054	0.054	0.002	17.209	0.005
Northwest Reference Site							
1990	lb/year	5,129	22,381	22,381	2,331	3,375,785	1,049
	lb/dry ton	0.032	0.139	0.139	0.014	20.909	0.006
2010	lb/year	1,397	5,590	5,590	223.6	1,780,636	553.4
	lb/dry ton	0.011	0.044	0.044	0.002	13.898	0.004

Notes: Fuel consumption is 0.50 and 0.44 lb/bhp-hr for 1990 and 2010, respectively. Emissions of CO_2 are based on 0.87% C/lb fuel (22.57 lb CO_2/gal of fuel). CO_2 equivalence based on the ratio of molecular weight of CO_2 to the atomic weight of C (3.664). SO_2 emissions are based on a factor of 0.45 grams/lb fuel. Emission expressed in lb/dry ton reflect total delivered wood feedstocks at the conversion hopper (after handling and storage losses).

5.2.1 CO_2 Emissions and Sequestration

Carbon dioxide is taken up by plants in the growth process and emitted during decomposition or conversion to energy. Once CO_2 is absorbed by the plants, the carbon is incorporated into plant tissues and the oxygen is released through respiration. The production of wood energy crops, the transport of the feedstock, and the conversion of biomass to electricity, contributes a small net amount of CO_2 to the atmosphere, but only to the extent that fossil fuels are used in equipment operations and feedstock transport and handling. The vast majority of the carbon released from the conversion of biomass is merely CO_2 that has been sequestered from the atmosphere by tree growth (above and below ground biomass.)

5.2.2 Volatile Organic Compounds

The growing of energy crops will contribute VOCs to the atmosphere. These are mostly non-methane aromatic hydrocarbons (NMHCs), primarily isoprenes and terpenes. Other compounds may be present, but data on their rates of evolution are virtually nonexistent. In fact, more than one-hundred NMHCs have been identified. Ranney and Mann (1991) note that the kinds and quantities of compounds vary considerably by species with the level of emissions highly dependent on local temperature. These emissions are known to combine with fossil fuel NO_x to produce ozone and peroxyacetyl nitrate.

As summarized by Ranney and Mann (1991), the large-scale planting of trees in areas that currently do not have significant emissions of NMHCs has the potential to change atmospheric chemistry. However, the magnitude and importance of this change will be impossible to determine with current data. In areas that are forested, the growing of trees will probably have little net effect.

Given the availability of data, emissions of isoprene and terpene are the only biogenic hydrocarbons that are estimated from the growth of biomass feedstocks. Estimates are based on the foliage of woody plants. Data are essentially unavailable for emissions from bark, forest floor, and soil surfaces. Although it would seem likely that the steps involved in the operation of a biomass plantation (e.g., site preparation, growth, harvest, and storage) might lead to different rates of emissions per unit land area over time, the data are insufficient to allow this detail to be resolved.

Table 5.2-1 summarizes emission rates for isoprene and terpene estimated from limited laboratory data. Isoprene emissions are assumed to take place only during daylight hours of the growing season. Whereas, terpene emission rates are assumed to take place as a function of temperature throughout the frost-free period, and are not subjected to the diurnal patterns of evolution that appear to function in the case of isoprene. Rates of isoprene and monoterpene emissions from plant foliage are species specific with *Populus* having the highest biogenic emissions. Greater annual levels of emission in the Southeast are primarily a function of the length of the growing season and a higher average temperature (emissions increase with temperature). Except for the high rates of isoprene emissions from *Populus* (Sharkey et al. 1991; Monson and Fall 1989), emission rates for biomass plantations should not exceed those of surrounding forested areas. For comparison, emission from pines and oaks are included in Table 5.2-1.

5.2.2.1 Southeast Reference Site

Table 5.2-2 provides the estimated emissions of isoprenes and monoterpenes for each time period. Emission are based on the same unit rates. The differences among time periods reflect the number of acres in production. These emissions are highly uncertain and should be considered in the context of background emissions from natural vegetation and the from the land uses that are assumed to be displaced by tree crops.

Table 5.2-1. Estimated annual emissions for isoprene and monoterpene for selected locations

Species	Location	Annual rates of emissions	
		Isoprene (lb/acre)	Monoterpene (lb/acre)
Sweetgum	GA	82	13
Sycamore	GA	125	nd
Hybrid Poplar	PNW	272	nd
	NB	438	nd
	NY	438	nd
	IL	550	nd
	GA	169–1428	nd
Pine	GA	nd	10–17
Oak	NY	90	nd
	IL	112	nd
	Ga	66-299	nd

nd = no data.

5.2.2.2 Northwest Reference Site

Emissions for the Northwest Reference site are also summarized in Table 5.2-2. These emissions are lower due to fewer acres in production. The same caveats apply here.

5.3 ELECTRICITY GENERATION

This section presents air and land and water emission factors for the 1990 and 2010 reference technologies.

5.3.1 1990 Reference Conversion Technology

The most significant air emissions from the combustion of wood feedstocks in uncontrolled boilers are particulate matter (PM) and NO_x (Tilman, 1987). Emissions of SO_x are very low since wood contains little sulfur by weight (less than 0.1%). Emissions of CO and organic compounds are usually not a concern unless the

Table 5.2-2. Estimated annual biogenic emissions of volatile organic compounds

Time period		Isoprene 103.5 lb/acre	Monoterpene 13 lb/acre
Southeast Reference Site			
1990	lb/year	4,135,529	519,062
	lb/dry ton	25.60	3.21
2010	lb/year	2,578,268	323,840
	lb/dry ton	20.12	2.53
Northwest Reference Site			
1990	lb/year	3,120,915	391,999
	lb/dry ton	19.33	2.43
2010	lb/year	1,780,539	223,642
	lb/dry ton	13.90	1.75

plant is operated under poor conditions. For example, the use of excessively wet or high moisture feedstocks can lower combustion temperatures and increase emissions.

Large wood-fired facilites normally reinject flyash into the boiler. This has the effect of increasing fuel efficiency and reducing particulate emissions. In addition, wood-fired generation facilites use a variety of control devices to further reduce particulate emissions. These devices reduce particulate emissions by 95% and more. Electrostatic precipitators have been observed to have collection efficiencies as high as 99.8% operating on wood-fired boilers (EPA, AP-42).[1]

NO_x emissions can come from two sources—the fuel itself (fuel NO_x) or from the atmosphere (thermal NO_x). Emissions of fuel NO_x from wood-fired combustors are relatively low because wood contains little nitrogen. For example, the percentage of nitrogen in poplar, black locust, and red alder, three of the species used in this study, is 0.13, 0.57, and 0.47%, respectively (Kitani and Hall 1989). By contrast, coal may contain from 1.4 to 2% nitrogen by weight.

Thermal NO_x formation is a function of combustion temperature, residence time, and concentrations of N_2 and O_2 in the furnace (Ostlie 1990). Because wood combustion takes place at lower temperatures than does coal combustion thermal

[1]Reports by Hewitt and High (1978), Envirosphere (1980) and Mitchell (1990) also indicate collection efficiencies of 99% and higher using fabric filter baghouses or electrostatic precipitators.

NO_x is lower. However, the lower combustion temperatures mean less efficient combustion, higher boiler heat rates, and larger boilers for a given level of output relative to coal. Overall, EPRI (1991) state that wood-fired power plants emit about 45% less NO_x than coal.

The other major emission from the combustion is CO_2. However, net emissions of CO_2 in the fuel cycle are negligible if one considers that any released carbon in the stack is merely carbon that has been recently sequestered during tree growth. The production of wood feedstocks contributes only a small fraction of CO_2 to the atmosphere. This small fraction is equal to the fossil fuel used to grow, harvest, and haul the feedstock.

Air emission factors for the 1990 conversion technology are summarized in Table 5.3-1. The factors listed (in bold) are used in determining the fate of air releases discussed in subsequent sections of this report. These emission factors are from EPA (1993).

The combustion of wood will produce moderate quantities of ash. The ash from wood combustion is relatively benign containing inorganic alkaline compounds, magnesium, silicon, calcium, potassium, and sodium. Wood ash has potential as a low-cost soil fertilizer and conditioner. Because of its relatively high pH it is particularly appropriate for the acidic soils found in the Southeast. The ash makes the soils more alkaline, eliminates the need for lime, and provides some nutrients. However, the fine particle size of the ash can create fugitive dust problems. To minimize fugitive dust, ash must be wet down or plowed into the ground soon after spreading.

The amount of ash generated is a function of the ash content of the wood, the portion of the ash in the flue gas, the collection efficiency, and the ash remaining in the stack gases. For the sycamore, sweetgum, and black locust, the ash contents (dry basis) are 0.56%, 0.32%, and 0.82%, respectively. The average ash content is slightly more than 0.5%. Given an annual feedstock requirement of 161,500 dry tons, the amount of ash in the fuel is about 830 tons. This would mean that about 817 tons would require disposing assuming a combined collection efficiency of 98%. The plant would generate about one truck load of ash during each week of operation.

There are some potential water emissions from a wood-fired combustion facility. These include runoff from wood chip and ash storage piles, boiler cooling water, blowdown from boilers and cooling towers, and wash water. However, this runoff water can be routed and collected in a recycle basin and used to meet other plant needs such as ash sluicing.

Table 5.3-1. Air emission factors for wood-fired power generation—1990 reference technology (lb/MMBtu)

Wood/bark-fired boilers	PM	PM_{10}
Uncontrolled	0.800	0.720
Mechanical collectors		
with flyash reinjection	0.667	0.611
without flyash reinjection	0.589	0.189
Wet scrubber	0.053	0.052
Electrostatic precipitator	0.004	–
Collection efficiency of 98%	**0.016**	
Ash production (actual)	**0.595**	–

Boiler type	NO_x	SO_x	CO	TOC	CO_2
Dutch-oven boiler	0.042	0.008	0.733	0.020	233
Stoker boiler	**0.167**	**0.008**	**1.511**	**0.024**	**233**
FBC boiler	0.222	0.008	0.156	–	233

Notes: Emission factors converted from lb/ton (as fired wet with 50% moisture and 4500 Btus/lb) to lb/MMBtu.

Source: U. S. Environmental Protection Agency (EPA), *Chief (Clearinghouse for Inventories and Emission Factors), AP-42*, "Wood Waste Combustion in Boilers," Research Triangle Park, North Carolina, July 1993.

5.3.2 2010 Reference Conversion Technology

For the 2010 reference conversion technology wood feedstocks would first be gasified in a pressurized air-blown reactor. The gas would then be cleaned of particulates before being combusted in a gas turbine. As noted by Larson et al. (1989) gas cleaning is required to avoid damage to turbine blades and to meet emission regulations. The major gas contaminants are NO_x and particulates. Other gas contaminants, such as tars/oils and alkalai compounds, are not expected to be a problem provided high temperatures are maintained and particle removal is effective.

As with conventional wood-fuel cycles, NO_x can be produced from the fuel (fuel NO_x) and from the combustion air (thermal NO_x). Larson et al. (1989) state that thermal NO_x should be low because of the low heating value for biomass. Moreover, appropriate control mechanisms (steam-injection) can be developed to handle this source of NO_x. Fuel NO_x is produced from the nitrogen in biomass. Although there are few measurements of fuel NO_x from biomass gasifiers there are estimates of emissions from coal gasifiers. Larson et al. (1989) report that fuel NO_x are around

0.3 g/MJ for coal gasifiers. Fuel NO_x should be much less for wood feedstocks because of the lower nitrogen content.

Cleaning the raw fuel gas of particulates is critical to prevent damage to turbine blades. High efficiency cyclones are available to clean the raw gas of particles larger than 5 to 10 microns. About 83% of the particles in raw fuel gas from fluidized reactors are larger than 5 microns. Advances that are likely to be made in filter technology should be able to remove the smaller particles. Final stack gases are expected to be relatively free of particulate loadings.

The only complete reporting of emission factors for biomass gasifier gas turbine technology are from UCS (1992). They report emission factors in lb/MMBtu for TSP, NO_x, SO_x, VOCs, CO, and CO_2 at 0.011, 0.06, 0.008, 0.003, 0.002, and 226, respectively.

The bottom ash and fly ash from gasifiers are similar in content to that from conventional wood combustion technology. The disposal of this ash is not expected to be a problem, as wood contains few toxics and could be used as a fertilizer and soil conditioner. However, a potential emission concern is tar handling and tar contaminated wastewater.

6. PRIORITY PATHWAYS

This section provides an overview of the impact-pathways for the biomass-to-electricity fuel cycle. From this overview the priority impact-pathways are identified. The priority impact pathways are the basis for impact estimation and economic valuation in subsequent sections of this report.

6.1 OVERVIEW OF IMPACT-PATHWAYS

The production and harvesting of wood feedstocks, the transport of these feedstocks to the conversion facility, and the conversion of wood feedstocks to electricity are three major stages of the biomass-to-electricity fuel cycle. The primary factor inputs that give rise to ecological and health impacts in the first stage of the fuel cycle are diesel fuel, agricultural chemicals and changes in existing land uses. The major air emissions that occur during this stage of the fuel cycle are from the use of diesel fuel and from biogenic emissions (hydrocarbons and CO_2 sequestration). The major land and water impacts are from the application of agricultural chemicals and from physical changes in land-use.

During the second stage of the fuel cycle the use of diesel fuel in trucks is the source of air emissions. The use of trucks for biomass transport also contributes to road deterioration, noise, traffic, and diminishes aesthetic qualities of the rural environment.

The final stage of the fuel cycle is electricity generation. It produces air emissions from the conversion facility. Land and water emissions are related to ash disposal. For many of the emissions from the biomass-to-electricity fuel cycle the resultant ecological impacts could be either adverse or beneficial.

For each stage of the fuel cycle, there are potential health and safety impacts. There are potential health impacts from long-term handling and exposure to biomass feedstocks and accidents primarily from equipment operations during biomass production and harvesting. As with other fuel cycles, there are potential employment impacts.

Table 6.1-1 lists the emissions, environmental pathways, impacts and evaluations that are discussed in detail in Appendix B or D. Impacts which are assessed in further detail are marked in bold italics. Table 6.1-2 lists the emissions,

Table 6.1-1. Primary emissions, pathways and ecological impacts linked to the biomass fuel cycle

Emissions	Environmental Pathway	Impact	Impact Evaluation
	Air Emissions:		
Carbon dioxide Carbon monoxide	Atmospheric dispersion	Global warming	Impacts minimal due to recycling of carbon
Carbon dioxide	Biogenic emissions and sequestration as organic carbon	All impact categories	Quantified
Nitrogen oxides Sulfur dioxide	Deposition on plant surfaces and soil	Effects on plant growth	Minimal impacts due to low concentration
Acid aerosols form NO_X and SO_2	Land range transport, acid deposition	Effects on plants	Minimal impacts due to low concentrations
Ozone	Secondary formation in the atmosphere	***Effects on crop yield***	Quantified
	Water Emissions:		
Herbicides	Runoff from tree plantations into aquatic system	***Effects on aquatic organisms***	Continuing evaluation
Fertilizers	Runoff from tree plantations	***Effects on aquatic organisms***	Continuing evaluation
Suspended solids	Erosion from tree plantations	Effects on aquatic organisms; recreational uses; drinking water	Continuing evaluation
	Other Factors:		
Land use	Tree plantations	***Changes in biodiversity***	Qualitative evaluation
Erosion	Runoff from plantations	***Soil loss***	Quantified
Road use	Truck traffic	***Road deterioration***	To be quantified

Table 6.1-2. Emissions, pathways, and impacts of biomass fuel cycle not examined in detail

Emissions	Environmental Pathways	Impacts	Impacts Evaluation
	Air Emissions:		
Particulates, Acid aerosols, Hydrocarbons, Ozone	Primary emissions and secondary formation in atmosphere	Reduction in visibility	Additional modeling required to assess impacts
Water vapor	Evaporation from wood feedstock	Fog formation	Additional modeling required to assess impacts
Peroxyacetyl nitrate (PAN)	Formation in the atmosphere from NO hydrocarbons	Effects on plants	Insufficient data on ambient and increased concentration
Inorganics	Combustion emissions	Effects on plants and animals	Minimal impacts due to low expected concentration
	Water Emissions:		
Erosion	Runoff from tree plantations	Decreased land productivity	Not quantifiable
Insecticides	Runoff from tree plantations	Effects on aquatic organisms	Minimal impacts due to infrequent use
Cooling water	Releases from power plant cooling system	Effects on aquatic organisms	Minimal impacts due to closed cycle and high dilution
Wastewater	Boiler water blowdown and other waste streams	Effects on aquatic organisms	Minimal impacts due to high dilution
	Other Factors:		
Wood ash	Combustion product	Crop production	Potential benefit as soil conditioner
Noise	Truck traffic	Effects on wildlife	No impacts identified

environmental pathways, and impacts that were not discussed in detail in Appendix D and gives the reasons why these were not evaluated.

Table 6.1-3 summarizes the emissions, impacting health and safety from a biomass-to-electricity fuel cycle. Table 6.1-4 lists health impact-pathways that were not discussed in detail, and gives reasons why these were not evaluated.

Table 6.1-3. Primary emissions, burdens, pathways and human health impacts linked to the biomass fuel cycle

Emissions/ Burden	Environmental Pathway	Impact	Impact Evaluation
	Air Emissions:		
Carbon monoxide	Atmospheric dispersion	Human health	Minimal impacts due to below threshold concentrations
NO_X SO_x	Atmospheric dispersion	Human health	Quantified
Particulates	Atmospheric dispersion	Human health	Quantified
Ozone	Ozone Model + dispersion	Human health	Quantified
	Occupational Accidents:		
Production	Direct effect	Days of work lost or restricted activity days/fatalities	Quantified
Transportation	Direct effect	Days of work lost or restricted activity days/fatalities	Quantified
Generation	Direct effect	Days of work lost or restricted activity days/fatalities	Quantified

Table 6.1-4. Emissions, burdens, pathways and human health impacts of biomass fuel cycle not examined in detail

Emission	Environmental Pathway	Impact	Impact Evaluation
		Air Emissions:	
Diesel exhaust during production	Atmospheric dispersion	Human health	Minimal impacts due to low expected concentrations
Hydrocarbons during generation	Atmospheric dispersion	Human health	Lack of knowledge on specific effluents
Inorganic particulates during generation	Atmospheric dispersion	Human health	Minimal impacts due to low expected concentrations
Pesticides, fertilizer	Atmospheric dispersion	Human health	Minimal impacts due to low expected concentrations
Spores, moulds	Inhalation	Human health	Additional information needed to make evaluation
		Water Emission:	
Pesticides, fertilizer	Runoff from tree plantations	Human health	Minimal impacts due to low expected concentrations
		Other Factors:	
Wood Ash	Air/water	Human health	Anticipated low toxicity of ash
Noise	Tractors/truck	Human health	Expected to be small

6.2 PRIORITY IMPACT PATHWAYS

This section lists the priority impact-pathways from a biomass-to-electricity fuel cycle. All were selected based on an assessment of the emission and boundary assumptions in Sections 4 and 5 of this report, and on a preliminary review of the literature. In general, the priority impact-pathways are among those thought to be the most significant in terms of their potential for externalities.

Impacts from tree production and harvesting:

- soil loss due to erosion of top soil (during the 1-2 yr tree plantation establishment period)
- potential surface water contamination with inorganic nutrients and pesticides
- changes in biodiversity from altered land uses

Impacts from feedstock transportation:

- road deterioration
- morbidity and mortality from air emissions of combustion products

Impacts identified at the power plant include:

- potential reduced visibility from SO_x HC, PM, and water vapor into the atmosphere
- morbidity and mortality from air emissions of combustion products
- morbidity from ozone formation from emissions of HC and NO_X

Impacts which extend across all stages of the fuel cycle include:

- changes in air quality due to combustion of fossil fuels and wood feedstocks
- CO_2 cycling and carbon sequestering.

Of the impacts listed above, the ones that have the greatest potential for more significant environmental and health impacts are those on biodiversity, erosion, herbicide contamination of surface waters, and increases in atmospheric ozone and other air pollutants.

7. IMPACTS AND DAMAGES FROM TREE PLANTATIONS

The priority impact-pathways in this state of the fuel cycle are changes in biodiversity, erosion of topsoil, possible surface water contamination with agricultural chemicals, and occupational health risks.

7.1 CHANGE IN HABITAT FROM ALTERED LAND USES

7.1.1 Acreage Replaced by Tree Plantations

The short-rotation woody crop scenario created for the 1990 reference technology requires that 39,928 acres of land be utilized for tree plantations at the Southeast Reference site and 30,154 acres at the western site. In 2010, acreage requirements decrease to 24,911 acres at the Southeast Reference site and 17,203 acres at the Northwest Reference site. This decline in land requirements is due to increased biomass productivity and greater efficiency associated with the 2010 conversion technology.

For the Southeast Reference site, suitable land for growing wood feedstocks will be available within 66 miles of the facility for the 1990 time period. This distance is the maximum haul distance to the conversion facility and is based on the type of land available and the assumed productivity. For the 2010 time period, the maximum haul distance declines to 52 miles because less feedstock is required to fuel the conversion facility and biomass production on each acre is assumed to be greater. For the Northwest Reference site, the maximum haul distances are 56 and 42 miles for the 1990 and 2010 time periods, respectively.

Recent studies suggest that tree plantations will displace proportionally more row crop acreage than other types of land (i.e., pasture or hayland). The actual acreage used would vary from site to site and would be dependent on land availability, economic considerations (costs and value of row crop compared to cost and value of tree crop), and distance from power plant (i.e., a greater proportion of plantations would be situated closer to the power plant (Graham per. com). In the absence of more site-specific data, the assumption used here is that tree plantations will displace lands in proportion to current land use patterns (but excluding forests with a canopy cover of more than 55%, riparian areas, and environmentally sensitive areas). (Appendix A provides more details.)

Perhaps the most contentious issue associated with the acreage replaced by tree plantations is the issue of biodiversity. Potential changes in biodiversity are discussed in the Section 7.2.

7.1.2 Impact of New Land Use on Habitat

As indicated in Table 7.1-1, for the Southeast Reference site more than half of the land for the plantations would come from pasture and hayland and about one-fourth from row crops. At the Northwest Reference site about 40% of the land would be displaced from pasture and hayland, about the same amount from closecrops, but only about 5% from row crops. The major impact on resource categories would be the lost productivity from lands previously used for agriculture. This would amount to about a 4.6% decrease in acreage in 1990 and 2.9% in 2010 at the Southeast Reference site, about 1.9% in 1990 and 1.2% in 2010 at the Northwest Reference site. These impacts, however, are not externalities—farmers having made the decisions to switch "crops" based on the economics of alternative crops.

Table 7.1-1. Land utilized for tree plantations (acres)

Previous land use	Southeast Reference Site			Northwestern Site		
	1990	2010	%	1990	2010	%
Closecrop	1,588	991	4.0	12,706	7,249	42.1
Corn	5,353	3,340	13.4	1,086	620	3.6
Fallow	2,642	1,648	6.6	1,201	685	4.0
Open woodland	1,579	985	4.0	2,418	1,379	8.0
Hayland	4,712	2,940	11.8	3,249	1,853	10.8
Pasture	17,652	11,013	44.2	8,846	5,047	29.3
Row crop, other	682	426	1.7	529	302	1.8
Soybeans	5,720	3,569	14.3	0	0	0
Range	0	0	0	119	68	0.4
TOTAL	39,928	24,911	100	30,154	17,203	100

The increase in wooded habitat represented by the tree plantations may have positive impacts on recreational resources of an area if populations of woodland game birds and animals increase and are made accessible to hunters. There is little field data to determine to what extent this might actually occur. Although preliminary data from tree plantations in Canada suggest that bird diversity can be relatively high on hardwood plantations (Ranney, per. com.), there is little information available to indicate whether populations of game birds would be significant. Initial establishment of the tree plantations with the maintenance of weed strips or groundcover between the rows of tree seedlings could provide grazing areas for local deer populations (if the deer are not intentionally excluded to avoid damage to the seedlings). Studies on pine plantations have shown that deer populations may initially benefit after plantation establishment or after a controlled burn and thinning; however, after canopy closure and subsequent reductions in deer forage (loss of shade intolerant grasses and forbs) there is a decrease in the carrying capacity of the ecosystem and adverse impacts on the physical health of the deer (Johnson 1987). Populations of other potentially valuable game animals such as squirrels and turkeys may be limited by the age, size and types of trees grown on the plantations. The absence of mast-producing trees will limit food supplies and the relatively small size of the trees may limit the number of nesting cavities. These limitations may be compensated for by the establishment of the plantations near natural wooded areas or by using plantations as buffer zones around forest preserves. In addition, the use of habitat corridors of native vegetation may improve the value of the plantations as habitat for woodland species (Ranney, per. com.).

7.1.3 Economic Valuation of Changes in Biodiversity

Estimates of impacts are not sufficiently quantitative to allow an economic valuation of changes in habitat.

7.2 CHANGE IN BIODIVERSITY

7.2.1 Changes in Biodiversity

The impacts of tree plantation on biodiversity are difficult to quantify, but can be evaluated qualitatively in terms of altered land use and changes in habitat. Such changes can have impacts on both the local and regional scale depending on the types of habitats affected and the amount of land utilized.

The greatest negative impacts would arise if tree plantations displaced forests or other environmentally sensitive habitats (e.g., riparian areas); however, in the scenario created for this study, such lands are specifically excluded from use for tree plantations. However, wooded lands containing less than 55% canopy coverage were included, and such open woodland, with a greater variety of trees of mixed age would very likely support a higher level of biodiversity than tree plantations; therefore, a negative impact would accrue if such lands were converted to tree plantations. Assuming that the acreage used for tree plantations would be apportioned according to current land usage, then 985 to 2,418 acres of open woodland would be displaced at the two sites evaluated in this study. At the Southeast Reference site about 1,579 acres of open woodland would be converted to tree plantations for the 1990 technology and 985 acres for the 2010 technology but 32,000 acres would not be affected. Even at a higher rate of usage, the overall regional impact would still be small in relation to the total acreage of forest in the East Tennessee area (approximately 3.4 million acres, TVA 1984). At the northwestern site, of the 129,000 acres of open woodland available, only 2,418 acres would be used for the 1990 technology and 1,379 acres for the 2010 technology.

Most of the land used for the tree plantations will come from acreage previously used for closecrops, row crops, pasture and hayland. It was estimated that about 96% of the required plantation acreage would be derived from such lands at the Southeast Reference site and 88% at the Northwest Reference site. Displacement of these lands might generally be viewed as a net positive impact on biodiversity because the greater structural diversity of a wooded habitat is likely to support a greater variety of species. For example, preliminary studies indicate that hardwood tree plantations may support a rich insect fauna which, in turn, would allow for a greater diversity of bird life. However, at same time, the establishment of the plantations would result in negative impacts on species that are directly or indirectly dependent on open fields and grasslands for survival. One study revealed a decline in a hawk population following extensive conversion of open areas to trees and this was thought to be due to the decrease in populations of the species' prey, such as rabbits and grouse which are primarily open field species (Kavanagh, 1991).

On a regional scale the establishment of tree plantations would have a far greater impact on biodiversity in areas where forests are limited in size and distribution than in areas where they comprise a significant portion of the landscape. For the Southeast Reference site evaluated in this study, the plantations needed to support one 30 MW power plant would represent about a 50% increase in open woodland type habitat in a 75-mile radius of the site. In addition, the edge habitat defined by the individual plantations (parcels 20–100 acres) may also be of ecological value depending on the status of the adjoining lands. However, in a wider regional analysis, changes in habitat diversity at the Southeast Reference site, by the conversion of 38,000 acres of agricultural lands to wooded habitat, would represent only a small change (about 1%) in total acreage of wooded land in the East Tennessee area.

7.2.2 Economic Valuation of Changes in Biodiversity

Estimates of changes in biodiversity cannot be quantified for the purpose of economic valuation.

7.3 EROSION OF TOPSOIL

7.3.1 Estimates of Soil Loss

Soil erosion on tree plantations will be highest during the 1-2 year establishment period after the tree seedlings are planted. Erosion rates during this time may be as high as those for corn or soybeans (Ranney et al. 1991). Erosion and runoff into streams can result in increased water turbidity, stream scouring, siltation and increased concentrations of nutrients or pesticides. For small clear-water streams, such changes may have adverse impacts on aquatic fauna depending on stream size and background environmental parameters.

Because field data for erosion on hardwood tree plantations were not available, total soil loss was calculated by assuming that erosion rates would be equivalent to those for corn during the first year. [Several thousand acres of hybrid poplar are currently being planted in Western Minnesota, and studies are underway (in 1996) to assess soil erosion and the potential water quality benefits (Downing, per. com.)]. Maximum rates of erosion would therefore occur on those parcels of land planted each year (i.e. one sixth of the total required or 6,655 acres at the 1990 Southeast Reference site, 4,152 acres at the 2010 Southeast Reference site; 5,026 acres at the 1990 Northwest Reference site and 2,867 acres at the 2010 Northwest Reference site). Total soil loss for the first year, as well as soil loss for the equivalent acreage of displaced land, is shown in Tables 7.3-1 to 7.3-4. Soil loss on the tree plantations is about twice as high as that on the displaced lands. Differences between the two locations in the net change is erosion are due to differences in the amount and type of land displaced for the tree plantations.

For the following years, total soil loss for the plantations was calculated by assuming that erosion rates would be one-half that of corn in the second year and one-tenth that of corn in the 3rd through 17th year. As more acreage is added to the tree plantations, soil loss increases, but net changes relative to that for the displaced lands decrease. Consequently, there is a decreasing net soil loss in the first four years at the Southeast Reference site and in the first three years at the Northwest Reference site followed by a net gain in each succeeding year at both sites (Table 7.3-5 and 7.3-6).

Table. 7.3-1. Erosion in year 1 on tree plantations and displaced lands (1990 Southeast Reference site)

Year/land class	Acres[a]	Erosion rate[b] (tons/acre)	Total annual erosion (tons)		
			Tree plantation	Previous use	Net change
I	837	2.5	2,093	620	+1,473
IIe	3,706	10.1	37,427	15,745	+21,682
IIs	129	1.0	129	222	–93
IIw	1,374	4.3	5,906	2,180	+3,726
IIIw	504	4.1	2,068	768	+1,300
IVw	105	2.3	240	272	–32
TOTAL:			47,863	19,808	+28,055

[a]Acreage is based on one-sixth of the total required.
[b]Erosion rates based on those for corn.

Table. 7.3-2. Erosion in year 1 on tree plantations and displaced lands (2010 Southeast Reference site)

Year/land class	Acres[a]	Erosion rate[b] (tons/acre)	Total annual erosion (tons)		
			Tree plantation	Previous Use	Net change
I	522	2.5	1,306	393	+913
IIe	2,312	10.1	23,351	9,845	+13,506
IIs	81	1.0	81	137	–56
IIw	857	4.3	3,684	1,359	+2,325
IIIw	315	4.1	1,291	487	+804
IVw	65	2.3	150	164	–14
TOTAL:			29,863	12,385	+17,478

[a]Acreage is based on one-sixth of the total required.
[b]Erosion rates based on those for corn.

Table. 7.3-3. Erosion in year 1 on tree plantations and displaced land (1990 Northwest Reference site)

Year/land class	Acres[a]	Erosion rate[b] (tons/acre)	Total annual erosion (tons)		
			Tree plantation	Previous use	Net change
I	216	0.9	194	116	+78
IIe	777	2.0	1,554	999	+555
IIs	132	1.3	172	48	+124
IIw	2,201	1.5	3,301	1,550	+1,751
IIIw	998	1.0	998	290	+708
IVw	703	0.9	634	214	+421
TOTAL:			6,853	3,217	3,636

[a]Acreage is based on one-sixth of the total required.
[b]Erosion rates are based on those for corn.

Table. 7.3-4. Erosion in year 1 on tree plantations and displaced land (2010 Northwest Reference site)

Year/land class	Acres[a]	Erosion rate[b] (tons/acre)	Total annual erosion (tons)		
			Tree plantation	Previous use	Net change
I	123	0.9	110	66	+44
IIe	443	2.0	887	570	+317
IIs	75	1.3	98	27	+71
IIw	1,256	1.5	1,883	888	+995
IIIw	569	1.0	569	165	+404
IVw	401	0.9	361	122	+239
TOTAL:			3,908	1,839	+2,069

[a]Acreage is based on one-sixth of the total required.
[b]Erosion rates are based on those for corn.

Table 7.3-5. Southeast annual erosion (tons)

	Years after establishment											
	1	2	3	4	5	6	7	8-18	19	20-24	25	26-36
	1990 Southeast											
Plantations	47,863	71,795	76,581	81,368	86,153	90,940	47,863	28,718	71,795	90,940	47,863	28,718
Previous use	19,808	39,616	59,424	79,232	99,040	118,848	118,848	118,848	118,848	118,848	118,848	118,848
Net loss	28,055	32,179	17,157	2,136								
Net gain					12,887	27,908	70,985	90,130	47,053	27,908	70,985	90,130
	2010 Southeast											
Plantations	29,863	44,794	47,781	50,767	53,753	56,739	29,863	17,918	44,794	56,739	29,863	17,918
Previous use	12,385	24,770	37,155	49,540	61,925	74,310	74,310	74,310	74,310	74,310	74,310	74,310
Net loss	17,478	20,024	10,626	1,227								
Net gain					8,172	17,571	44,447	56,392	29,516	17,571	44,447	56,392

Table 7.3-6. Northwest annual erosion (tons)

	Years after establishment											
	1	2	3	4	5	6	7	8-18	19	20-24	25	26-36
						1990 Northwest						
Plantations	6,853	10,279	10,965	11,650	12,335	13,021	6,853	4,112	10,279	13,020	6,853	4,112
Previous use	3,217	6,434	9,651	12,868	16,085	19,302	19,302	19,302	19,302	19,302	19,302	19,302
Net loss	3,636	3,8454	1,314									
Net gain				1,218	3,750	6,281	12,449	15,190	9,023	6,282	12,449	15,190
						2010 Northwest						
Plantations	3,908	5,862	6,253	6,644	7,034	7,425	3,908	2,345	5,852	7,425	3,908	2,345
Previous use	1,839	3,678	5,517	7,356	9,195	11,034	11,034	11,034	11,034	11,034	11,034	11,034
Net loss	2,069	2,184	736									
Net gain				712	2,161	3,609	7,126	8,689	5,182	3,609	7,126	8,689

For tree plantations, erosion rates estimated to be equal to that of corn in the first year after establishment, one-half that of corn in the second year, and one-tenth that of corn in the third through 18th year. One-sixth total acreage planted in each of the first six years.

For years 8-18, 20-24, and 26-36 values given are for each year; in year 37 the cycle begins again with the values for year 19. Previous land use erosion is from the National Resources Inventory (SCS, 1987) and is based on average erosion rates for specific crops and land capabilities classes and subclasses.

7.3.2. Economic Valuation of Soil Erosion

The major distinguishing feature of the biomass-to-electricity fuel cycle, from an environmental point of view, is the possibility of environmental damage related to the production of the wood feedstock. As this production process is more like farming than forestry, the traditional concerns about damages from agricultural pollution are germane here, including effects from soil erosion (both those related to the soil itself and the nutrients, herbicides, and pesticides that it carries), from groundwater infiltration, and from blowing soil. Of these, the most research, and probably the largest effects, are those associated with soil erosion. Accordingly, this section presents estimates of the damages associated with soil erosion.

The basic measure of the damage from off-farm soil erosion is the willingness-to-pay (WTP) of individuals to avoid these effects. Appendix E details the literature on estimating these damages and makes the point that this literature leave much to be desired for providing conceptually correct measures of marginal damages.

Regionalized estimates of average damage per ton of soil erosion are derived from Ribaudo (1989). These estimates are obtained by first building up total damage estimates for a wide variety of damage categories, including flood control, clogged drainage ditches, dredging, recreation effects, etc., and then dividing these estimates of the total yearly regional off-site damage by tons of soil eroding annually. Ribaudo provides low, mid, and high estimates for farm producing regions (FPR) in the U.S. The two relevant regions for our study are Appalachia and Pacific. These estimates of unit values are the following (Table 7.3-7).

These estimates of erosion loss (reduction) are multiplied by the unit values provided above and compounded or discounting as appropriate and summed to obtain an estimate of the present discounted value of damages (benefits) in the start-up year period. As biomass farms require a six-year lag time before they can yield wood for use in electricity generation, we start the farm six years before 1990 or 2010, respectively. The net erosion damages (benefits) in these six years are compounded up to the respective base years above. Then net damages in the years following the

Table 7.3-7. Unit values used for estimating soil erosion damage

	Damage per ton of soil erosion ($1989)		
Area	Low	Mid	High
Appalachia (Southeast)	$0.90	$1.63	$2.60
Pacific (Northwest)	1.77	2.87	5.52

start-up of the generation plant are discounted back to the base year. The sum of 40 years of compounded and discounted values yields the present discounted value of erosion damage (benefit). This value is levelized over the 40 year life of the generation plant and divided by annual kWh to arrive at an estimate of net damage (benefit) in mills/kWh.

Table 7.3-8 provides the resulting net damage (benefit) estimates by reference environment, base year, and for low, mid, and high estimates of unit damages (benefits). The present discounted values are all negative, meaning that the biomass farms are **beneficial** in reducing soil erosion. In levelized terms, benefits range from 0.05 mills/kWh to 0.71 mills/kWh. The benefits are larger in the southeast than in the northwest for each base year because, although the benefits of a given amount of soil erosion are somewhat higher in the northwest, soil in that area is much less erosive than in the southeast. As a result, the biomass farms result in less of a reduction of soil loss in the northwest. Erosion reduction benefits of biomass farming with 2010 technologies are less than with 1990 technologies. Less acreage is needed to support the 2010 technology. Land not needed for plantations would experience erosion at their current higher rates. Midpoint estimates of levelized benefits are, for the Southeast, 0.60 mills/kWh with 1990 technologies and 0.29 mills/kWh and 2010 technologies. For the Northwest, midpoint benefits are 0.20 mills/kWh and 0.08 mills/kWh, respectively.

Other estimates of damages are rejected for various reasons. Clark et al. (1985) provides national estimates of soil erosion damage which Ribaudo regionalizes and improves upon to some degree. Thus, the latter are superior for our purposes. Several analysts estimate the benefits of Conservation Reserve Program (CRP) projects, which are projects carried out on highly erosive farmland and other land types to reduce soil erosion. These analyses have the advantage of being based on scenarios involving incremental investments, as opposed to the Ribaudo estimates, which are based on the total off-site damages from *all* soil erosion. Yet, the CRP estimates are problematical because they are very site-specific, making benefit transfer difficult and are dependent on how well the particular CRP project

Table 7.3-8. Damages (benefits) from changes in soil erosion from biomass production: Southeast and Northwest; 1990 and 2010

Area	Year	Present discounted value (1989 $'s)	Annual levelized (1989 $'s)	Levelized mills/kWh
		Low estimate		
Southeast	1990	−1,037,904	−60,487	−0.3288
	2010	−664,178	−38,707	−0.1578
Northwest	1990	−381,320	−22,223	−0.1208
	2010	−218,430	−12,730	−0.0519
		Mid estimate		
Southeast	1990	−1,879,759	−109,549	−0.5955
	2010	−1,202,901	−70,103	−0.2858
Northwest	1990	−618,298	−36,033	−0.1959
	2010	−354,178	−20,641	−0.0842
		High estimate		
Southeast	1990	−2,998,389	−174,741	−0.9499
	2010	−1,918,737	−111,820	−0.4559
Northwest	1990	−1,189,200	−69,304	−0.3767
	2010	−681,206	−39,700	−0.1619

Annual generation in 1990 is 183,860 Mwh and 245,280 Mwh in 2010.

is conceived and implemented. One very recent study (Alexander and English 1991) provides damage estimates, but it is in per ton of sediment delivered or deposited.[1] Finally, there are some quite good studies of average damages for particular regions, e.g., the Willamette Valley, but these estimates are also very site-specific (Moore and McCarl 1985).

[1] The Alexander and English's (1991) estimates cannot be used because appropriate sediment delivery ratios are unavailable. This study generally supports the Ribaudo estimates, however, in that (1) unit damage estimates are higher for the Pacific FPR than the Appalachian FPR; and (2) the unit damage estimates in sediment terms are higher per ton of sediment than the estimates per ton of erosion.

Estimates of levelized damages (benefits) per kWh are obtained by starting with year by year estimates of the net soil erosion resulting from the replacement of various land uses by biomass farms, as provided in the preceding section. According to this section, the working assumption is that land meeting productivity requirements will be placed into use for growing biomass in proportion to the percentage of land available in various land categories (cropland, pasture, etc.). It is recognized that this assumption is in lieu of an economic analysis to obtain an estimate of land conversion based on land prices and productivity in various uses, as well as the offer price for biomass. This assumption yields the conclusion that after several years of net increases in erosion, based on startup activities at the biomass farms, erosion will fall on net.

7.4 SUSPENDED SEDIMENTS

7.4.1 Impacts on Aquatic Organisms

While a comparison of long-term average erosion rates between different land uses and biomass plantations provides for an overall perspective to impacts, it does not provide direct data for the assessment of impacts to aquatic organisms. Impacts to aquatic organisms occur from episodic events.

Biomass plantations can generate non-point source pollution in the form of sediments and pesticides. If the actual location of the plantations were known, more accurate quantitative modeling of the impacts to surface waters could be done. In the absence of site-specific information, a screening level approach to modeling (EPA 1982) impacts to surface water was performed using average stream characteristics (Table 7.4-1). For this study pollutants were considered to be conservative (not reactive and remain in solution or suspension). All of the pollutant is assumed to enter the stream at one point and undergo complete mixing in the water column. It is also assumed that no concentration of the pollutant occurs in the stream within the mixing zone (this is probably true for pesticides, but not for sediments) and that the overland flow carrying the pollutants to the stream doubles the average flow of the stream (this is more likely to happen for small streams than for large streams). The concentration of the pollutant in the stream following mixing is then a function of the pollutant mass emission rate divided by the sum of the discharge rate of the overland flow carrying the pollutant and the flow rate of the stream above the point of entry (EPA 1982).

A suspended sediment concentration greater than 100 mg/L is likely to have adverse effects on aquatic organisms (EPA 1982). Suspended sediments adversely affect fish and their food populations by:

Table 7.4-1. Average stream characteristics for the United States by stream order

Stream order	Drainage area (acres)	Mean flow (ft^3/sec)
1	640	0.65
2	3,008	3.1
3	14,720	15.0
4	69,760	71.0
5	331,520	340.0
6	1,600,000	1,600
7	7,680,000	7,600

- acting directly on the fish swimming in the water by killing them, reducing their growth, resistance to disease, etc;
- preventing the successful development of fish eggs and larvae;
- modifying natural movements and migrations of fish; and
- reducing the abundance of food available to the fish (EPA 1976).

Estimated sediment concentrations are listed in Table 7.4-2 by stream order for the southeastern and northwestern sites in 1990 (6,655 acres planted). Using 100 mg/L as a guide to impacts, adverse effects can be expected to occur to aquatic organisms in 4th order and smaller streams in the southeast and 3rd order and smaller streams in the northwest. Erosion rates throughout the life of the biomass plantation would stress aquatic organisms in streams of these sizes if the conditions outline previously occur.

At the southeastern reference site most of the large rivers are impounded. These impoundments act as sediment traps so that the suspended sediment concentrations are low. Data for the Clinch River at Melton Hill dam and the Holston River near Knoxville illustrate this point (Table 7.4-3). These are 6th order streams and could easily contain all of the 40,000 acres of biomass plantations in their drainage areas. The estimated erosion rate (249 tons/day) for year six of the plantings (full implementation) could range from an additional contribution of 44% of the 1990 suspended sediment discharge at Melton Hill during high flow periods to almost the

Table 7.4-2. Evaluation of suspended sediment loads

Erosion[a] (tons/day)	Erosion (lb/day)	Stream order	Estimated sediment conc. (mg/L)
Southeastern Site (1990, year 1)			
131	262,263	1[b]	375
		2[c]	3,391
		3	1,625
		4	343
		5	72
Northwestern Site (1990, year 1)			
19	38,000	1[b]	543
		2[c]	570
		3	235
		4	50

[a]Mass per year divided by 365 days.
[b]Assumes 1/10th of erosion rate would enter stream of this size based on drainage area (Table 7.4-1).
[c]Assumes 1/2 of the erosion rate would enter stream of this size based on drainage area (Table 7.4-1).

Table 7.4-3. Water chemistry data for southeast rivers (Flohr et al. 1990)

Parameter[a]	Clinch River[b]	Holston River[c]
Suspended sediment discharge (T/day)	≤1–564	88–724
Suspended sediment (mg/L)	3–10	7–17
Total phosphorus (mg/L)	0.01–0.03	0.02–0.04
Nitrogen $NO_2 + NO_3$) dissolved (mg/L)	0.32–0.7	0.2–0.9

[a]Water year October 1989 to September 1990. Minimum and maximum values reported for six samples during period.
[b]Tailwater at Melton Hill dam, USGS 03535912.
[c]At Knoxville City limits, USGS 03495500.

total load during low flow periods. However, on the average, the estimated erosion rates would not significantly increase the concentration of suspended sediments to levels of concern for aquatic organisms in streams the size of the Clinch River unless they already had high concentrations.

7.5 HERBICIDES IN SURFACE WATERS

7.5.1 Impacts on Aquatic Organisms

Herbicides are used on tree plantations for weed control during the first two years of establishment of the seedlings. Surface waters may become contaminated as a result of atmospheric drift, surface runoff, erosion, and/or direct spills. Estimated rates of herbicide use on tree plantations for both the 1990 and 2010 scenarios are 3 lb/acre during the first year of establishment of the seedlings and 1 lb/acre during the second year, but none thereafter until the lands are replanted after 18 years (Appendix A).

A broad-kill herbicide (1 lb/acre) is used before planting and a pre-emergent (1 lb/acre) after planting. The third application occurs six months later and the fourth in the second year. Therefore, the greatest potential for surface water contamination will occur within the first few months of establishment of the tree plantations. An application rate of 1 lb/acre equates to about 112 mg/m^2 of soil surface. Emissions to surface water are expected to average 10% of application rate (Appendix A). Based on this estimate, approximately 0.1 lb/acre will enter surface water during each application. For an average size tree plantation of about 50 acres, the amount lost per application would be about 5 lb. The resulting concentration of the herbicide in a stream transversing that parcel will be dependant on rates of input (which is a function of rainfall, and subsequent runoff), length of stream affected, rates of degradation, and average stream flow and volume.

Using a simple dilution model, and assuming rapid runoff due to heavy rains immediately after application, the concentration in a first-order stream (640 acre drainage) was calculated to be about 5 mg/L. This concentration is sufficiently high to cause adverse effects on fish fry and the larval stages of aquatic invertebrates (see Appendix C). More refined modeling, taking into account soil types, rainfall patterns, stream sizes, and flow rates, is needed to develop a more site-specific assessment of this impact.

7.5.2 Economic Valuation of Herbicide Contamination

Estimates on impact endpoints, such as reduced fish population, are insufficient for any quantitative estimate of damages.

7.6 OCCUPATIONAL HEALTH RISKS

7.6.1 Injury Potential

Short rotation woody crops (the feedstock considered in this study) utilize systematic plantings, thus permitting more mechanization, in the harvesting of woody biomass. By contrast primary timber cutting and logging workers who are placed at considerable risk of unintentional injuries by their occupation include tree fellers, choker-setters (who attach cables to logs), and mobile equipment operators. In that industry the terrain, weather conditions, the wide geographical dispersion of the trees, and the close working proximity to heavy equipment and to cutting equipment are major factors increasing the risks of injury. Also, cutting injuries are likely to occur due to worker fatigue. Factors contributing to worker fatigue during chain saw usage in commercial logging include increased physical exertion, noise, heat stress and vibration exposure (NIOSH 1990b; Paulozzi 1987).

Watson and Etnier (1981) emphasized the significant potential for occupational injuries and fatalities in this industry. They noted that the high incidence of lost workdays among workers was principally due to injuries associated with shifting logs, falling trees, chain saw kick backs and falls during entry or exit from equipment (Watson and Etnier 1981). The substantial risk of physical harm associated with logging has influenced the conclusion by the Occupational Safety and Health Administration (OSHA) and the National Institute for Occupational Safety and Health that logging is "inherently dangerous" (NIOSH 1989).

The potential severity of injury may be illustrated by a study of injury to 51 loggers in the Northwest who required treatment at a level-I trauma center (Holman, Olszewski and Maier 1987). Falling or rolling trees or logs produced the injuries for 67% of the cohort. Two loggers (4%) died of massive head injuries and 25 workers received permanent disabilities sustained from head injuries, orthopedic injuries or spinal injuries (Holman, Olszewski and Maier 1987).

A study of fatal logging injuries in Washington State revealed an annual injury mortality rate of approximately 2/1000 workers, assuming the average worker worked 2000 hours/year (Paulozzi 1987). Falling trees were cited for 34% of the fatalities and equipment for an additional 24% of the fatalities. Those at greatest risk were tree fellers and choker-setters. Company size was noted as a significant variable for risk of injury. For companies employing five or fewer loggers, mortality ratios were nearly ten times higher than those of the largest companies (Paulozzi 1987).

Equipment rollovers in the traditional logging industry are calculated to produce a fatality rate of 15 deaths per 100,000 workers per year (NIOSH 1989). Due to the development of biomass energy plantations, fatal farming injuries involving tractors may be relevant. The National Safety Council (1991) reported an annual rate of 9.9 deaths per 100,000 tractors for 1990. Tractor overturns were cited for 52% of all on-the-farm tractor fatalities reported, with an additional 33% due to run over. On the basis of a tractor harvesting at a rate of 2 tons/h, it is estimated that approximately 50 tractors will be needed to harvest the approximately 191,000 dry tons of biomass at the Southeast Reference site each year. Further, about 50 more tractors are assumed to be required for agricultural related activities. Thus, using the recent death rate for tractor accidents, the production of woody biomass would be expected to result in 0.01 tractor related deaths per year. The basis for this estimate is experience with farm tractor use, but handling 6–8 in. diameter trees may not fit the farm use definition. General farm accidents would increase this figure to 0.04.

Approximately 1×10^{-7} accidental deaths per GJ wood has been estimated for whole tree removal (IAEA 1982). For the 30 MWe 1990 technology, this rate would result in about 0.3 deaths per year. It is anticipated that the adapted agricultural procedures will result in mortality rates somewhere between the rate based on numbers of tractors (i.e., 0.04 and the IAEA figure (0.3). For this study, a mean value of 0.17 is used for an upper limit.

Data by the Bureau of Labor Statistics, presented in Table 7.6-1, reveal the dramatically higher incidence rates of occupational injuries per 100 full time workers in the agriculture, forestry and logging industries for 1988 compared with all private sector workers (BLS 1990). The lost workday cases cited in Table 7.6-1 are those which resulted in days away from work or days of restricted work activity, or both. Total lost workdays for the logging industry are approximately three times higher compared to the other two industries and five times higher than that experienced in the private sector. Assuming 100 people are required to support a 30 MWe biomass plant, and assuming a mean value between agriculture and logging of 225 work days lost per 100 employees, it is estimated that the 30 MWe biomass plant will contribute to 225 work days lost per year (Table 7.6-2).

An estimated 16,500 compensable injuries occur to logging workers per year (NIOSH 1990a). Based on this estimate, approximately one in every five loggers will experience a compensable injury each year, with over half of the injuries involving cuts, fractures, or contusions (NIOSH 1990a).

Overall, relevant data for the 1990 and 2010 alternatives is unavailable because there are no biomass plants operating yet using the types of harvesting techniques proposed. Consequently, occupational health effects summarized in Table 7.6-2 are subject to much uncertainty.

Table 7.6-1. U.S. occupational injury incidence rates for agriculture forestry and logging industries, 1988

Workdays	Incidence rates per 100 full-time workers		
	Total cases	Lost workday cases	Total lost workdays[a]
Agricultural production	11.7	6.1	107.8
Forestry	11.9	6.3	136.0
Logging camps and logging contractors	19.6	12.7	345.4
Private	8.3	3.8	72.5

Source: BLS 1990.
[a]Lost work days or restricted days.

Table 7.6-2. Annual occupational health impacts associated with biomass production for a 30 MWe plant[a]

Health impact	Southeast		Northwest	
	1990	2010	1990	2010
Work days lost	225	225	225	225
Deaths	0.17	0.17	0.17	0.17

[a]Data are too imprecise to distinguish between site and year.

7.6.2 Micro-Organisms

Storage of biomass in preparation for biochemical or thermochemical conversion processes presents some problems. These include odors, fugitive dusts, loss of volatiles, spontaneous combustion and leachates. Of importance as a hazard to health is the growth of microorganisms and fungi utilizing lignocellulosic plant material as a substrate. Egneus and Wallin (1984) consider the spore and microorganism production to be a serious problem associated with handling biomass. They did not provide details regarding the length of storage time as a factor or suggest precautionary techniques.

Several health complaints were identified which have been associated with etiologic agents growing on grain, straw and wood (Egneus and Wallin 1984). The primary route of entry is by inhalation of the spores. Regarding mouldy wood chips, *Rhizopus sp., Mucor sp.*, and *Aspergillus fumigatus* are specified as agents giving rise to "chip boiler's complaint." *Aspergillus* is a group of fungi of low pathogenicity for the human unless other factors impact natural resistance. Aspergillosis may become localized to the lungs, ear or parinasal sinuses or be disseminated to other parts of the body (brain, heart, kidney, and spleen) by the blood stream where abscesses or granulomas may form (NIOSH 1977). For mouldy wood, *Pullaria pullulans* and *Peacilomyces sp.* are cited in relation to "sauna bather's disease" (Egneus and Wallin 1984). Because of lack of information it was not possible to relate the presence of microorganisms to numbers of persons affected or the degree of effect.

7.6.3 Limitations of Biomass Health and Safety Effects Review

A lack of information specific to biomass-generated electricity introduced substantial limitations to this review of associated health implications. The majority of available data on the end use of biomass is directed to alcohol fuels used in transportation. Data related to harvesting, transporting and storing of woody biofuels generally are aggregated for the total logging and forest products industries. Although suggestive of implications for biomass combustion technologies, these data do not permit the development of an adequate health and safety profile of biomass converted thermochemically for the production of electricity.

As Smith (1987) has noted, few studies of ill health produced by biofuel smoke exposures have been reported in the literature. Anecdotal accounts of exposures in industrial countries which are described are more often related to wood-fired heating stoves and combustion products of gas-fired cook stoves (Smith 1987).

More systematic data collection efforts will be needed to characterize the various occupationally health related factors associated with the biomass fuel cycle. Discrete data on occupational injuries associated with harvesting and transporting that biomass intended specifically for use in generating electricity are needed to improve understanding of this cost. Additional quantification of emissions from biomass-fueled power plants is needed especially for hydrocarbon emissions. Also, the limited research and development which has been directed to biomass-fired gas turbines to date (Williams 1990) should be expanded.

The major related health impact of the biomass fuel cycle is occupational injury associated with the forestry and logging industries. Again, the data are not collected at a level which enables unintentional injuries to be defined specifically for the harvesting and transporting of biomass subsequently used for power generation.

7.7 HEALTH RISKS TO MEMBERS OF THE PUBLIC

Potential impacts to members of the public from the production and harvest of biomass are limited to airborne pesticide drift and waterborne pesticide and nitrates. Present projections suggest that these materials will be used less intensively than for the crops which are displaced. Further, absolute rates are small. Because of these indications of small effects, this issue is not considered to be of great significance.

8. IMPACTS AND DAMAGES FROM TRUCK TRAFFIC

The main impact from transporting the wood from the plantation to the nearby conversion facility are those associated with the truck traffic.

8.1 TRUCK TRAFFIC

The feedstock requirements for both reference sites are 161,452 dry tons for the 1990 reference time period. This is based on a 40 MW plant operating with an annual capacity factor of 70%. The actual haul amount is 210,224 tons after accounting for the moisture content of the wood and pre-haul losses. Because of the higher assumed conversion efficiency, feedstock requirements for the 2010 time period decline to 128,280 dry tons or 166,826 wet or haul tons.

It is assumed that wood bombs will be transported by log hauling carriers to both the Southeast and Northwest conversion facilities. These trucks will be capable of hauling on average about 20 wet tons. This assumed load is well within the gross vehicle weight restrictions of the interstate highway system. The actual amount that can be transported is more constrained by volume considerations that by weight. The length of tractor trailer combinations is usually set at 65 feet. (Overhang of additional 10 feet is usually allowed for log hauling provided the logs are in single-piece lengths.) The sitting of a wood-fired conversion facility will cause an increase in local road traffic and could cause damages to roads and reduce the aesthetic quality of the rural environment with increased noise and road congestion. The economic damage from increased noise and road congestion are difficult to quantify. The knowledge base is lacking and these impacts are not quantified in our study.

8.1.1 Southeast Reference Site

Table 8.1-1 summarizes the number of loads and the total load miles for each reference time period. Approximately 10,510 loads will be required each year to supply the conversion facility in 1990. With a higher assumed conversion efficiency for the 2010 technology only 8,340 loads will be required to service the facility with wood bombs. On average about 4.2 loads will be delivered each hour in 1990 and 3.3 loads per hour in 2010. The number of load miles (round trip loaded and return

Table 8.1-1 Wood feedstock loads and deliveries

Reference site/time period	Average haul distance (one-way miles)	Total annual loads	Total annual load miles (round trip)	Number of truck deliveries per hour
Southeast 1990	44	10,510	924,906	4.2
Southeast 2010	35	8,340	583,890	3.3
Northwest 1990	37	10,510	777,830	4.2
Northwest 2010	28	8,340	467,110	3.3

Notes: Truck load is 20 wet tons. Deliveries made are 250 days per year on a 10 hour per day schedule.

empty) is more disparate because the haul distance is greater and the assumed biomass productivity is less for the 1990 time period.

8.1.2 Northwest Reference Site

For the Northwest Reference site the same number of hourly deliveries will be required as for the Southeast Reference site. However, the number of load miles are less because of the higher assumed biomass productivity in the Northwest and the shorter transport distance.

8.2 ECONOMIC VALUATION OF TRUCK TRAFFIC

This section gives results of the analysis of road damage that results from heavy truck traffic in the transportation of biomass feedstock on public highways. The passage of heavy trucks on public highways accelerates the deterioration of roadway surfaces. This necessitates earlier resurfacing than would otherwise occur. In addition, other drivers are exposed more often to impaired driving conditions and delays due to road construction. Finally, the presence of trucks themselves may contribute to congestion and worsened driving conditions. [For an introduction to the theory that is presented in this section, see Report 2, Estimating Fuel Cycle Externalities: Analytical Methods and Issues (ORNL/RFF 1994a).]

8.2.1 Burden

The biomass-fired power plant in the Southeast Reference environment would require annually 161,450 dry tons of wood. Wood biomass is typically transported by truck in a haul of 40,000 pounds, with the sum of vehicle and payload equaling 70,000 pounds. The biomass requirements at the facility would require 10,510 hauls of biomass from the farm to the power plant per year.

The burden from the addition of truck traffic hauling biomass would be offset to some degree by a decrease in truck and machinery traffic from previous agricultural land uses. The volume of traffic and the weight of the trucks would vary, depending on the previous land use. We assume traffic associated with close crops, corn, hay, row crops and soybean production would be equivalent in both the weight of the vehicles and frequency of passage on average to traffic from biomass production and hauling. These land uses represent about 45% of acreage that would be brought into biomass production in the Southeast Reference environment. Consequently we net these out against new truck traffic from biomass production, and we ignore traffic associated with other previous land uses. Under these assumptions, we estimate the net burden from truck traffic to be 5,758 new truck passages annually.

In the Northwest, about 58% of the acreage to be brought into biomass production would previously have been in close crops, corn, hay, row crops and soybean production. Accordingly, we estimate that 4,386 net new truck passages would result annually from the production of biomass.

8.2.2 Impacts

To determine the impacts that result from this burden we estimate the injury to roadway surfaces that occur due to each passage of a biomass truck. This impact is calculated in terms of the effect of each passage on the life of a road surface.

Road overlays define the endpoints of a pavement's life. The configurations and number of axles on a vehicle matter—as a rule, the more axles a vehicle has to distribute its weight the less damage it will cause.[1] The life of a road surface (i.e., the interval between road overlays) is affected by the number and type of the axles that pass over it.

[1]Many state laws, however, penalize trucks with a greater number axles. Many state turnpikes charge more for a given weight if it is carried on a vehicle with many axles. From: Clifford Winston, "Efficient Transportation Infrastructure Policy," *J. Econ Perspectives*, Vol. 5, No. 1, Winter 1991, pg. 116

The following equation yields the number of axle passages for each type of axle (j) on the truck that the road will withstand before requiring an overlay: [2]

$$Nj = \frac{A_0 \, (D+1)^{A1} \, (L_2)^{A3}}{(L_1 + L_2)^{A2}}$$

where:

L_1 = the total weight of the vehicle divided by the sum of its axles

L_2 = the type of axle weight. $L_2 = 1$ for single axles, $L_2 = 2$ for tandem axles (two axles close together)

D = the road's durability. (For rigid pavements, D equals the pavement's thickness in inches. For flexible pavements, D is a linear combination of pavement, base and subbase thicknesses with coefficients 0.44, 0.14 and 0.11 [i.e., D = 0.44(pavement) + 0.14(base) + 0.11(subbase)].

A_j = structural coefficients that describe the durability of rigid and flexible pavements, derived from an empirical study by the American Association of State Highway Officials.[3]

For rigid pavements,

A_0 = $e^{13.505}$ or 733,073;
A_1 = 5.041;
A_2 = 3.241;
A_3 = 2.270.

For flexible pavements,

A_0 = $e^{12.062}$ or 173,165;
A_1 = 7.761;
A_2 = 3.652;
A_3 = 3.238.[4]

[2]Kenneth A. Small, Clifford Winston and Carol A. Evans, *Roadwork: A New Highway Pricing and Investment Policy*, The Brookings Institution, Washington D.C., 1989, p.24

[3]The study evaluated 264 rigid and 284 flexible experimental pavement sections, using previously estimated values of N as dependent variables. Cited in *Roadwork*, Small, Winston and Evans, p. 25, from Highway Research Board, *The AASHO Road Test: Report 5, Pavement Research*, Special Report 61E (Washington, D.C.: National Research Council, 1962) pp. 36–40.

[4]Small, Winston and Evans, *Roadwork*, p. 27. The authors reanalyzed and revised figures from the AASHO report.

The surface type under consideration in the Southeast Reference site is flexible pavement. Table 8.2-1 reports the characteristics of axles on a fully loaded biomass truck. The final row of the table reports the numbers N_j representing the number of passages the roadway surface will withstand for each axle type j for a fully loaded truck. Appropriately transforming these numbers into comparable units and summing across all five axles yields an estimate of the number of passages for a biomass truck that the roadway will withstand before resurfacing is needed.

Table 8.2-1. Characteristics of axles on a fully loaded biomass truck

Axle	Single steering	Tractor tandem	Trailer tandem
L_1: weight (1000 lb)	10.5	14.875	14.875
L_2: axle type (1 = single 2 = tandem)	1	2	2
N_j: number of passages (D = 3.3)	2,016,388	4,689,035	4,689,035
(D = 4)	6,158,823	14,322,112	14,322,112

8.2.3 Economic Valuation

Roadways have to be resurfaced regularly with or without the impacts of heavy trucks. The roadways in the Southeast are regularly resurfaced about once every 12 years, and roadways in the Northwest are resurfaced every 15 years. The measure of damages per mile should be adjusted to reflect the change in the resurfacing schedule for the road. The present discounted value of damage is the difference between the present discounted value of resurfacing costs given biomass truck traffic minus the present discounted value of resurfacing costs absent the biomass trucks. Finally, this difference in present discounted value should be levelized over the 40-year operation of the biomass facility.

The flexible pavement surface that characterizes the two-lane highway at the Southeast Reference site would withstand about 740,000 passages of a fully loaded biomass truck until resurfacing is required if this were the only traffic on the road. In accordance with the present twelve year resurfacing schedule, the present traffic conditions are equivalent to the passage of about 61,670 fully loaded biomass trucks annually. The proposed facility would add 5,760 truck passages to that figure. Hence, with the addition of the biomass truck traffic the roadway would need to be resurfaced according to a ten year schedule in order to maintain comparable roadway conditions during the 40-year operation of the facility. After this time we assume the resurfacing schedule reverts to a twelve year schedule.

In the Northwest, the flexible pavement two-lane highway would withstand 2,265,000 passages until resurfacing absent the biomass facility. The present 15 year resurfacing schedule is commensurate with passages of 150,947 biomass truck equivalents per year. The proposed facility would add 4,386 truck passages, requiring a 14.5-year resurfacing schedule during the life of the facility.

All lanes of a multi-lane highway are resurfaced at the same time. If roadway damage is distributed evenly on both lanes of the two-lane highway prior to the addition of biomass truck traffic, the lane bearing fully loaded trucks is the determinant for the resurfacing schedule after the addition of the biomass truck traffic. The cost of resurfacing the roadway in this example is $40,000 per lane-mile for a typical two-lane highway with flexible pavement, with a total cost per mile of $80,000. The cost of resurfacing is $100,000 per mile in the Northwest.

The present discounted value of future resurfacing needs per mile prior to the addition of biomass truck traffic is approximately $134,710. With the addition of biomass truck traffic the present discounted value of future resurfacing needs per mile is estimated to be $145,810. The difference between these numbers is $11,100 which is the net present discounted cost per mile of the new biomass truck traffic.

In the Northwest, the present discounted value of future resurfacing costs prior to the biomass facility would be $133,640 per mile. The addition of biomass truck traffic, accounting for offsetting declines in previous agricultural activities, would yield present discounted resurfacing costs of $137,130. The difference, $3,490, is the net present discounted cost per mile of biomass truck traffic.

This estimate is not an abatement cost measure of damage, but a true damage measure analogous to medical costs associated with health effects. Analogous to pain and suffering are the effects associated with more rapid deterioration of the road surface, such as the congestion and safety problems associated with a marred road surface and the resurfacing operation itself. As this set of damages is ignored, the resurfacing costs are a lower bound to the damages that result from the transport of biomass on public roads in the Southeast Reference site.

The estimate average round trip distance to be traveled from biomass sites to the generation facility in the Southeast is 88 miles. However, the one-way loader distance is only considered in estimating damages. The total annalized cost for damage that results is $28,477 per year. Expressed as a levelized cost per kilowatt-hour this estimate of road damage is equal to 0.151 mills/kWh. This is the midpoint estimate of maintenance costs, and other factors that have not been quantified.

Our estimate of a 95% confidence interval ranges from 0.109 mills/kWh as a low estimate to 1.47 mills/kWh as a high estimate. These ranges are derived based on uncertainty bounds associated with the calculation of N_j, the number of passages the roadway surface will withstand for each type of axle. These uncertainty bounds are estimated and reported in Winston and Small (1989).

8.2.4 Externalities from Road Damage

To an important degree, road taxes serve to internalize some of the damages to roadway surfaces into the private financial costs of biomass transporters. The difference between roadway damage and tax payments represents an estimate of the externality from road damage. Heavy vehicle users pay a variety of taxes. Federal taxes include a fuel tax, a tire tax, and a heavy vehicle user's tax. State taxes often include an annual registration fee, field permits, a fuel tax, and in some states, a weight/distance fee. However, these tax payments are not earmarked for resurfacing and some portion pays for other essential services such as funding new highway construction, administrative costs, short-term highway maintenance, law enforcement, etc. In this section the magnitude of tax liabilities related directly to net new truck traffic in the transport of biomass, expressed per kilowatt hour of electricity produced at the biomass power plant is calculated. The externality is calculated in two ways to bound the problem: (1) a conservative lower bound is used in which all tax collections offset resurfacing costs; and (2) an upper bound, where only the heavy vehicle use tax and the weight-distance fee apply to resurfacing costs imposed by heavy vehicles.

Transportation of fuel for the biomass plant in the Southeast Reference environment would occur within the State of Tennessee, which assesses a fuel tax of $0.18 per gallon, an annual registration fee of $1,150, and an annual operating authority tax of $8. In the Northwest Reference environment, we fuel supply and associated truck traffic is assumed to be evenly divided between the States of Oregon and Washington. The State of Oregon assesses a weight-distance tax of $.01125/mile on trucks weighing 70,000 lb.[5] Truckers in Oregon also must pay a $280 annual registration fee. The State of Washington assesses a fuel tax of $0.23 per gallon, a $1,117 annual registration fee, and a $10 annual operating authority tax. Federal taxes include a tire tax of $43.69 paid at the time the tire is sold, a fuel tax of $.201 per gallon, and a heavy vehicle use tax of $550 per vehicle.

[5]In some cases the trucks are used to transport waste ash away from the power plant, but we assume this is not the case in this example. Consequently the weight-distance tax applies in only one direction.

These taxes can be organized into two categories. One involves taxes that are variable costs assessed on a per mile basis, including the weight-distance tax and fuel taxes. The tire tax also should be interpreted as a variable cost because it is paid at the time of sale, which varies with the amount of tire usage. The total number of net new miles driven each year in hauling biomass to the power plant including the return trip, accounting for the offsetting decline in agricultural land uses, will be 506,707 in Tennessee, and 162,294 in Oregon and Washington. We assume the biomass trucks obtain 6 miles per gallon, and that each of the 18 tires on a truck lasts 100,000 miles.[6] The amount of each type of variable tax paid is presented in Table 8.2-2. The total amount of variable taxes that will be paid in biomass transportation each year, net of offsetting reductions in taxes from previous agricultural activities, will be $36,179 in the Southeast Reference environment, and $28,783 in the Northwest.

Table 8.2-2. Variable taxes paid in biomass truck transport

	State weight-distance tax	State fuel tax	Federal fuel tax	Federal tire tax
Tennessee				
Tax per mile	$0	$0.03	$0.0335	$0.0079
Annual payment	$0	$15,201	$16,975	$4,003
Oregon				
Tax per mile	$0.1125	$0	$0.0335	$0.0079
Annual payment	$9,129	$0	$5,437	$1,282
Washington				
Tax per mile	$0	$0.0383	$0.0335	$0.0079
Annual payment	$0	$6,216	$5,437	$1,282

The second type of tax includes all annual fees which do not vary with respect to the number of miles driven, and total $1,708 per truck per year in Tennessee, $830 in Oregon, and $1,677 in Washington. Eighteen trucks will be required in the

[6]A wide variety of estimates of tire durability. In the Eastern U.S. the range may be 70,000 to 110,000 miles, though the lower amount is likely to apply in Appalachia because of windy and hilly road conditions. Some estimates of durability for truck tires stretch up to 300,000 miles. Our estimate of 100,000 miles provides a potentially generous estimate of the amount of tax revenue that will be collected through tire sales.

Southeast Reference environment, and 16 in the Northwest.[7] Adjusting these numbers for offsetting truck use associated with previous agricultural activities, we estimate that $16,841 will be generated in fixed annual fees in the Southeast, and $8,370 will be generated in the Northwest.

The total annual taxes in biomass transportation is the sum of variable taxes and fixed fees. This totals $53,020 in the Southeast, and $37,153 in the Northwest. We levelize these amounts to obtain an estimate of 0.288 mills/kWh for the new taxes paid in biomass transportation in the Southeast and 0.202 mills/kWh in the Northwest, net of previous agricultural trucking activity. Of these amounts, the portion produced from the heavy vehicle use tax and the weight-distance fee in the Southeast is 0.023 mills/kWh (10.2%), and 0.070 mills/kWh (34.5%) in the Northwest.

The levelized midpoint estimate of road damage obtained above is 0.151 mills/kWh in the Southeast and 0.04 mills/kWh in the Northwest. To calculate a conservative estimate of externality, we credit all taxes paid in biomass transportation against the damage to roadways. The difference between these estimates is –0.137 mills/kWh in the Southeast, and –0.162 mills/kWh in the Northwest. The negative sign on these numbers implies that tax revenues are greater than damage to roadways, so the additional truck traffic makes a net contribution to government revenues.

A less conservative estimate of the potential externality results if only the heavy vehicle use tax and the weight-distance fee are credited against the damage to roadways. As reported in Table 8.2-3, the difference of 0.122 mills/kWh in the Southeast and –0.030 mills/kWh in the Northwest provides an upper bound of the potential externality. The upper bound estimate as the best estimate for this case study because other taxes such as vehicle registration and gasoline taxes fund the general menu of highway services provided by state and federal government.[8] The estimates are lower (or even negative) than those which have been calculated for other fuel trucks such as coal trucks, primarily because of the difference in weight.

[7]This is based on the following assumptions: truckers work a 10 hour work day for 250 delivery days per year, with an average transport speed of 30 miles per hour, and it takes 1 hour for loading and unloading. Then, allowing some slack for occasional repair, 18 trucks would be required in the Southeast and 16 in the Northwest.

[8]These payments for trucks are not significantly distinguished from that for automobiles, which may impose only 0.005% of the damage to roads as do trucks per vehicle mile.

Table 8.2-3. Midpoint estimates of externality from road damage.

(mills/kWh)	Southeast	Northwest
Damage	0.151	0.040
Tax Revenues from heavy vehicle use fees	0.030	0.070
Externality	0.122	–0.030

9. IMPACTS AND DAMAGES FROM BIOMASS COMBUSTION

Combustion of the wood at the conversion facility results in emissions to the atmosphere, as well as some water wastes and solid residuals. The impact-pathways addressed in this section are the effects of ozone on agricultural crops and on human health, the effects of NO_x on health, and the effects of primary pollutants on human health. SO_2 emissions are negligible, and much less than SO_2 emissions from coal and oil-fired plants. CO_2 emissions from a biomass-fired generation plant are essentially offset by the sequestering of CO_2 by the trees that serve as fuel for the power plant. [CO_2 emissions from truck diesel fuel is also offset by reduced truck traffic in the agricultural activities that are replaced by the biomass plantations.] Thus, SO_2 and CO_2 impacts are negligible and are not estimated in this report.

9.1 EFFECTS OF OZONE ON AGRICULTURAL CROPS

9.1.1 Precursor Emissions and Change in Ozone Concentrations

Exhaust gases from power plants that burn fossil fuels contain concentrations of sulfur dioxide (SO_2), nitric oxide (NO), particulate matter, hydrocarbon compounds and trace metals. Estimated emissions from the operation of hypothetical 30 MW biomass-fired power plant are given in Section 5.3. Ozone is considered a secondary pollutant, since it is not emitted directly into the atmosphere but is formed from other air pollutants, specifically, nitrogen oxides (NO_x) and non-methane organic compounds (NMOC) in the presence of sunlight. Additionally, ozone formation is a function of the ratio of NMOC concentrations to NO_x concentrations.

While most large power plants are considered significant sources of NO_x emissions, NMOC emissions from power plants are not considered significant and do not typically require control. Since NMOC emissions from power plants are not present in sufficient quantities to provide an optimal hydrocarbon to NO_x ratio within the plume, ozone formation from the emissions of power plants is the result of a complex series of reactions involving NO_x emissions from the plant, reacting with ambient concentrations of hydrocarbons, hydrocarbon derivatives and ozone. Ambient hydrocarbons may be from either man-made or natural sources.

The formation of ozone within a power plant plume, is controlled by a combination of conditions, including ambient ozone concentrations which provide the mechanism necessary for the initial conversion of NO to NO_2, reactive hydrocarbon concentrations of the ambient air mass, and the rate of entrainment of ambient air within the plume. These conditions, as well as sufficient photochemical activity, determine whether ozone levels in the plume will eventually exceed ambient levels to form the widely documented ozone 'bulge' (Keifer 1977; Meagher et al. 1981; Luria et al. 1983; Gillani and Wilson 1980; Davis 1974).

The biomass fuel cycle analysis requires that an estimate be made of the changes in ozone concentrations that occur as a result of NO_x emissions from a biomass-fired power plant located at the Southeast Reference site. The crop effects analysis requires an estimate of the seasonal 9 a.m. to 9 p.m. average ozone concentrations due to the plant. As discussed in ORNL/RFF (1994a, Paper 3), this modeling requirement presents a unique challenge, since all the currently available computer models that simulate ozone formations are designed to predict hourly and instantaneous ozone concentrations, over a period of several days at most. These predictions are primarily for comparison to the National Ambient Air Quality Standard (NAAQS) of 120 parts per billion (ppb) (one-hour average) not to be exceeded more than once per year (this is the standard as of 1996).

The potential impact of the power plant's NO_x and NMOC emissions on ozone concentrations was modeled for the Southeast Reference site using the U.S. Environmental Protection Agency model, Ozone Isopleth Plotting Mechanism (OZIPM-4) and a new model developed for this study, the Mapping Area-Wide Predictions of Ozone model (MAP-O_3). The OZIPM-4 model is a trajectory model that predicts ozone concentrations as a function of travel time. The MAP-O_3 model provides spatial resolution by predicting the location of the plume during each hour of the day for the ozone season. The MAP-O_3 model predicts area-wide ozone concentrations over the ozone season, by combining ozone concentrations predicted with the OZIPM-4 model with plume trajectories calculated from wind speed and direction measurements. Details of the modeling specific to the biomass- fired power plant are presented in Appendix B.

Results from the MAP-O_3 model, for the crop effects portion of the biomass fuel cycle analysis are shown on isopleth maps in Figs. 9.1-1 and 9.1-2. (Results from the MAP-O_3 model were converted to Cartesian coordinates and written to files for import to the isopleth graphing routine SURFER.) The power plant is shown in the center of each isopleth map with a triangle marker. The scale of each figure is in kilometers from the plant. Ozone concentrations are reported in ppb.

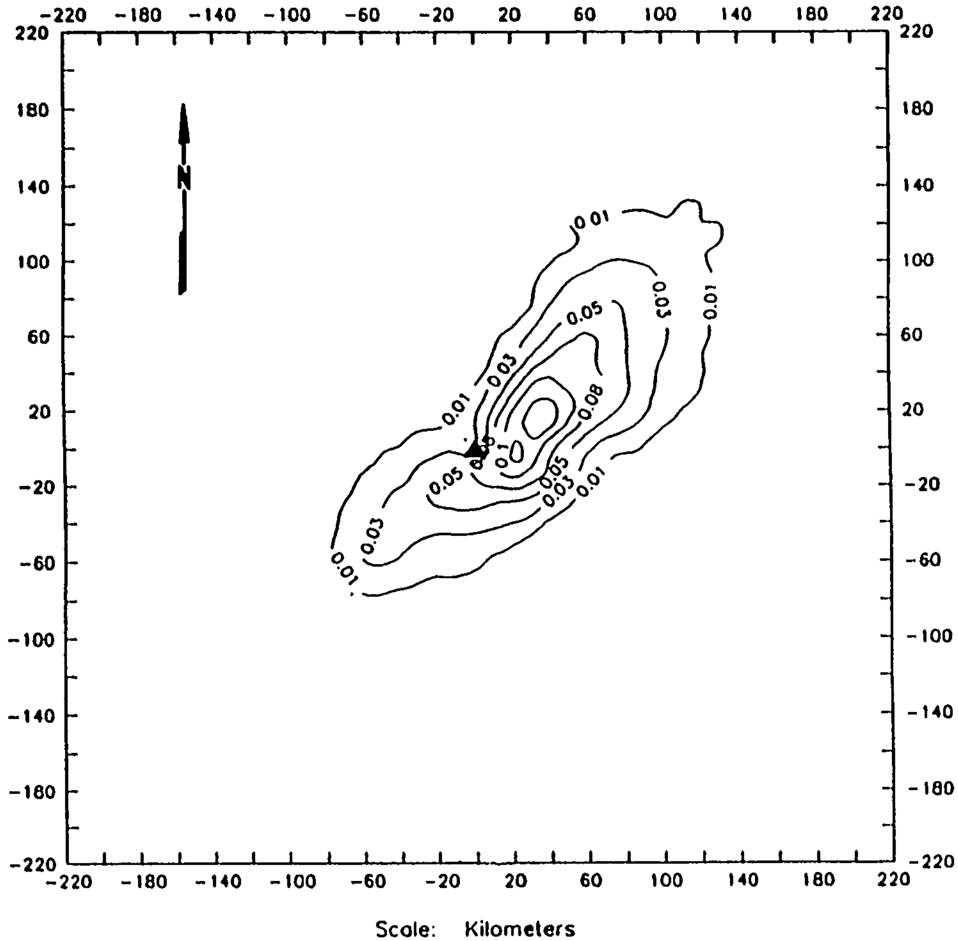

Fig. 9.1-1. Positive incremental 9 a.m. to 9 p.m. seasonal average ozone concentrations (ppb) for May to September 1990 to emissions from the biomass-fired power plant located at the Southeast reference site (positive concentrations are above ambient).

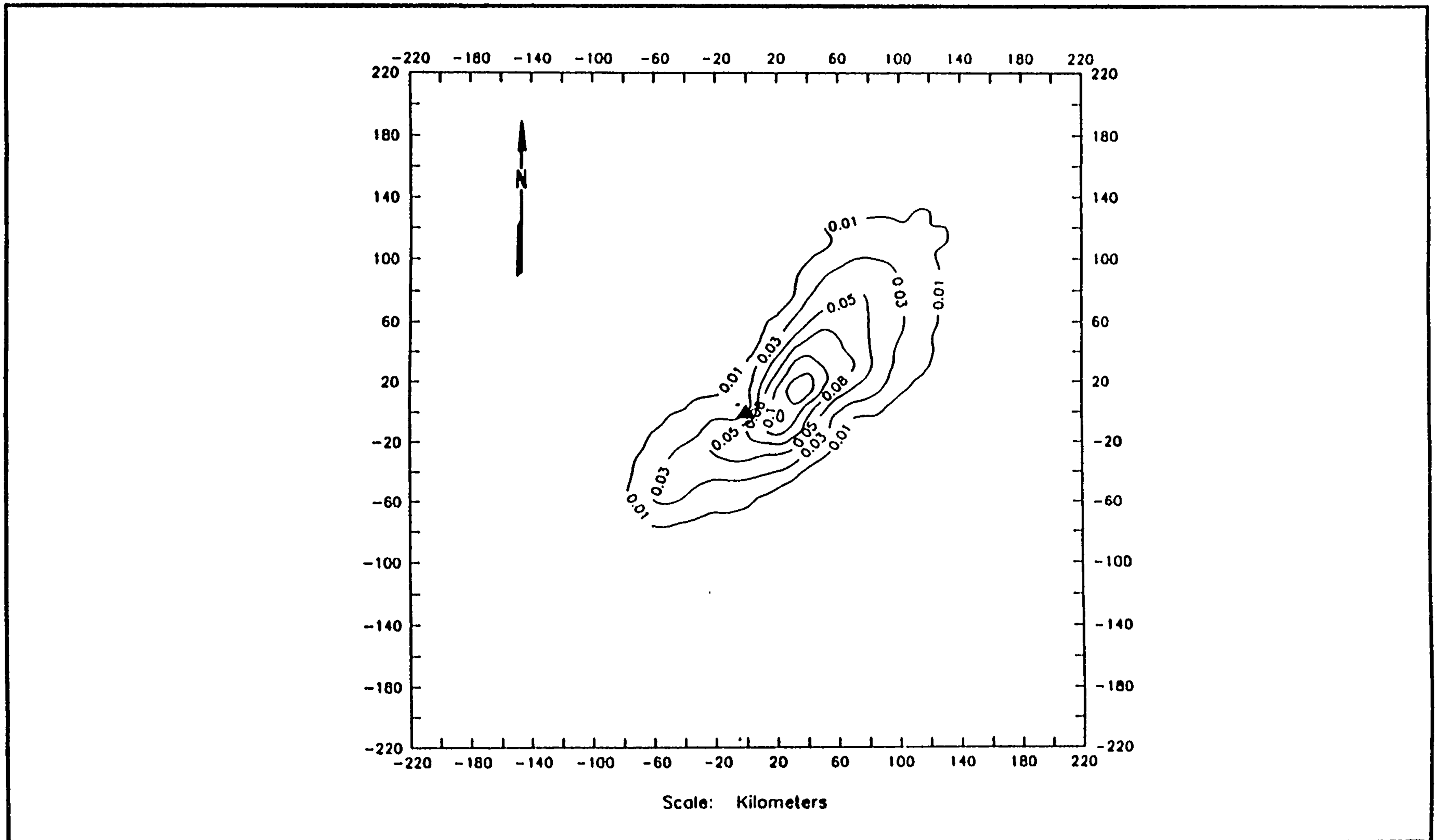

Fig. 9.1-2. Total incremental 9 a.m. to 9 p.m. seasonal average ozone concentrations (ppb) for May to September 1990 due to emissions from the biomass-fired power plant located at the Southeast reference site (total concentrations include both positive and negative incremental concentrations).

Results are presented separately for two cases; one without and one with ozone depletion (Figs. 9.1-1 and 9.1-2, respectively). (Ozone concentrations above base case are referred to as ozone bulges and ozone concentrations below base case are referred to as ozone depletions).

Figure 9.1-1 shows the predicted impact of the biomass-fired power plant emissions on the seasonal 12-hour average ozone concentrations due to ozone bulges only. These results over estimate the impact of the power plant emissions on ozone concentrations, since ozone scavenging is not accounted for. As seen in Fig. 9.1-1, the highest 12-hour seasonal average ozone concentration (based on ozone bulges only) is 0.12 ppb and occurred approximately 20 kilometers east of the plant. The lowest isopleth plotted in Fig. 9.1-1 is 0.01 ppb. This seasonal average ozone concentration occurred as far away as 180 kilometers from the plant in the northeast direction (NE) and 100 kilometers in the southwest (SW) direction.

Figure 9.1-2 shows the predicted impact of the biomass-fired power plant emissions on the seasonal 12-hour average ozone concentrations due to both ozone bulges and depletions. These results represent the lower bound estimate of the impact of the power plant emissions on ozone concentrations. The highest 12-hour seasonal average ozone concentration is 0.12 ppb (the smallest isopleth line) and occurred approximately 20 kilometers from the plant in the east direction. The lowest positive isopleth plotted in Fig. 9.1-2 is 0.01 ppb. This seasonal average ozone concentration occurred as far away as 180 kilometers from the plant in the northeast direction (NE) and 100 kilometers in the southwest (SW) direction. Ozone depletion occurred mostly in the immediate vicinity of the plant and again approximately 80 kilometers from the plant in the southeast (SE) direction. The results shown in Figs. 9.1-1 and 9.1-2 are essentially the same since emissions from the biomass plant do not cause significant ozone depletion on a seasonal average. In addition to the results seen in Fig. 9.1-1 and 9.1-2, the seasonal 12-hour average measured background ozone concentration of 53 ppb was also used in the crop effects portion of the study.

9.1.2 Impact on Ozone on Crop Production

The effects of air pollutants on crops have been reviewed and summarized by Shriner et al. (1990). Adequate data for the evaluation of crop yield reductions are available only for ozone.

The response of plants to ozone depends on many factors including concentration, species, cultivar genetics, growth stage, environmental variables (soil concentration, meteorology, temperature, humidity) and pollutant interactions (SO_2, acid deposition, and NO_2) (ORNL/RFF 1992). Because of the lack of data for many of these variables, uncertainties exist in the reliability of the available exposure-response functions for all possible scenarios. Choice of an exposure parameter many also be a critical factor. Exposure of plants to ozone is usually reported in terms of 7-h or 12-h seasonal mean concentrations. The mean values represent daily periods of highest plant sensitivity and highest ozone levels. However, there is some evidence that a seasonal mean of daily 1-h maximums may be a more appropriate measure of exposure (ORNL/REF 1992).

Ozone-induced incremental changes in crop yields resulting from the operation of a 30-MW wood-fired power plant were calculated using the same methodology described in ORNL/RFF (1994b). Adequate data were not available for analyzing this impact for the biomass gasifier gas turbine technology or for the Northwest Reference site; therefore, the following discussion refers solely to the Southeast Reference site. This analysis utilized literature-derived ozone exposure-plant growth response functions, reported ambient ozone levels for the Southeast Reference site, and estimations of the incremental increases in ozone that could be attributed to the operation of the power plant.

As discussed in ORNL/RFF (1994a), the ozone exposure-plant response functions used in this analysis were those developed by Heagle et al. (1988) from field data generated from the National Crop Loss Assessment Network (NCLAN) (see also Heck et al. 1988; Shriner et al. 1990). These studies provided crop yield losses for major cultivars for five seasonal mean ozone concentrations representative of the range of ambient ozone levels in the United States (Table 9.1-1). For a given predicted increase in ozone, crop yield loss for a particular crop can be estimated by interpolation of the data presented in Table 9.1-1. For the Southeast Reference site the existing ambient ozone level within the region was determined to be 53 ppb (12-h seasonal average, 9 a.m. to 9 p.m., May through September), and the greatest incremental increase in the 12-h seasonal ozone level associated with the power plant was calculated to be 0.12 ppb.

Losses of crop production caused by ozone increases associated with the reference power plant were calculated for each county that had about one-quarter or more of its area inside the 0.1 ppb (i.e., total concentration of 53.1 ppb) isopleth yielded by the dispersion modeling discussed above. The estimates are based on existing ambient ozone levels within the region (53 ppb 12-h average, 9 a.m. to 9 p.m., May athrough September) and on modeled increases in ozone concentrations resulting from the power plant (12-h average, 9 a.m. to 9 p.m.).

Ozone-induced crop loss in each county was approximated by a four-step calculation that yielded the following for each county: (Step 1) the new average ozone concentration representing the various levels of modeled ozone concentrations over the entire country during power plant operation; (Step 2) the percent crop losses in that county resulting from the modeled ozone concentration

Table 9.1-1. Crop yield losses estimated to result from various ozone concentrations (in percent)

Crop	Mean ozone concentration during the growing season (ppb)				
	40	50	60	70	80
Soybeans (average of 22 experiments with about 10 cultivars)	5.6	10.1	15.5	21.5	28.4
Tobacco (average of 2 experiments)	5.0	9.0	13.0	18.0	23.0
Wheat (average of 5 experiments with 3 cultivars)	9.0	15.0	20.8	26.8	33.2
Corn (average of 3 experiments with mixtures of 5 cultivars)	1.7	3.7	6.7	10.3	15.7
Hay (red clover, the main type of hay grown in the case-study area)	9	19	31	44	59

and from the existing ozone concentration (53 ppb); (Step 3) the production of each crop under the modeled and existing ozone concentrations, and (Step 4) the quantity of crop loss caused by the power plant.

In the first step, isopleths of ozone concentrations generated by air dispersion modeling were overlaid on a regional map showing county boundaries. The fractions of each county within the areas between successive isopleths (i.e., the fraction between 53 and 53.01 ppb isopleths, that between 53.01 and 53.02 isopleths, etc.) Were calculated based on map area measurements obtained with a polar planimeter. The average ozone concentration in each area between two successive isopleths was calculated as the average of the two isopleth concentrations (e.g., an average of 53.02 ppb represents the area between the 53.01 and 53.03 ppb isopleths). This yielded two or more of these averages for each county, because areas between two or more pairs of successive isopleths were present in each county. Finally, these averages for the different modeled ozone concentrations in the county were averaged to obtain the overall average ozone concentration for the county during power plant operation.

Applying the ambient and predicted ozone levels during plant operation to the exposure-response functions given in Table 9.1-1 gave the results shown in

Table 9.1-2. The crops listed in Table 9.1-2 are those for which county-level production data were available for the Southeast Reference site (Tennessee Department of Agriculture, 1990). Data for 1988 were used to estimate ozone-induced crop losses for all crops except corn, because production of these crops in 1989 [the latest year reported by the Tennessee Department of Agriculture (1990)] was poor. Corn production data for 1989 were used because this year appeared to be representative of average conditions for corn. From these calculations, crop production and estimated losses associated with the hypothetical power plant are shown in Table 9.1-3.

Table 9.1-2. Percentage crop loss due to increased ozone (1990 Southeast Reference site)

Crops	Crop loss (%)	Loss due to power plant (%)
Soybeans		
Existing ambient	12.7	
Predicted	12.81	0.11
Tobacco		
Existing ambient	11.0	
Predicted	11.08	0.08
Wheat		
Existing ambient	17.9	
Predicted	18.02	0.12
Corn		
Existing ambient	5.2	
Predicted	5.26	0.06

Since data on crop values are aggregated by county, we describe the reference environment as a group of counties surrounding the hypothetical plant site rather than as a circle surrounding that site. The total acreage occupied by the seven counties reported above is 1,672,648, compared to the larger acreage of 1,940,761 acres within 50 km of the power plant site. The numerical values of the crop losses within these seven counties must be increased proportionally to yield estimated crop losses within a 50-km radius of the power plant at the Southeast Reference site. These estimated losses are show in Table 9.1-4. Alternatively, we can consider the eight counties which roughly encircle the site. These counties contain 2,011,000 acres, making a good approximation for the reference

Table 9.1-3. Crop production and the estimated crop losses (1990 Southeast Reference site)

County	Acres	Soybeans (1,000s bu)	Wheat (1,000s bu)	Corn (1,000s bu)	Tobacco (1,000s lb)
Anderson	185,200				
Production		*a*	*a*	15	170
Loss				0.009	0.136
Blount	347,516				
Production		38	186	345	798
Loss		0.04	0.223	0.207	0.638
Campbell	253,373				
Production		*a*	*a*	32	593
Loss				0.019	0.474
Knox	228,969				
Production		6.3	16.5	89	587
Loss		0.007	0.020	0.053	0.470
Loudon	142,247				
Production		14	51	80	730
Loss		0.015	0.061	0.048	0.584
Morgan	342,810				
Production		20	13.2	84	78.3
Loss		0.02	0.016	0.050	0.063
Roane	172,533				
Production		*a*	*a*	28	297
Loss				0.017	0.237
Anderson, Roane, and Campbell[a]		3.98	7.84		
Production		0.004	0.009		
Loss					
Total loss		0.086	0.329	0.403	2.602

[a]Soybean and wheat production statistics for these counties were not reported by the Tennessee Department of Agriculture (1990) because less than 500 acres of the respective crop were planted. Total production for all non-reported counties in district #6, to which these counties belong, was: 19,900 bu of soybeans for 15 non-reported counties and 18,300 bu wheat for 7 counties—these data were used to obtain the estimates given.

Table 9.1-4. Estimated crop losses due to increased ozone (1990 Southeast Reference site)

	Soybeans (1,000s bu)	Wheat (1,000s bu)	Corn (1,000s bu)	Tobacco (1,000s lb)
Total loss in 7 counties	0.086	0.329	0.043	2.602
Loss within a 50-km radius of the powerplant	0.099	0.382	0.049	3.019

environment. The extra land in the counties (3.6%) can be factored out at the end of the calculations. This latter approach is used in the economic valuation described in the next section.

9.1.3 Economic Valuation of Crop Loss

Although many crops are grown within the reference environment, production data are available for only a few. For some crops, county data are withheld to prevent disclosure of individual farm output. Other crops are grouped under headings such as "nursery and greenhouse crops," making it impossible to apply the NCLAN dose-response functions. There are five crops for which both output data and dose-response data are available, and according to 1987 USDA data these account for 47% of the value of all crops grown in the reference environment (see Table 9.1-5).[1]

Under the baseline scenario of 53 ppb ambient ozone, crop yields are already reduced in the reference environment. The additional crop loss (in percent) due to a 0.12 ppb increase in ambient ozone can be found by linearly interpolating between the crop percentage loss at 50 ppb and 60 ppb ambient ozone.

In valuing the crop losses due to increased ambient ozone in the Southeast Reference environment, one must estimate the change in social welfare due to these losses. This change can be broken down into two parts: the change in consumer surplus and the change in producer surplus. One parameter that could potentially change both consumer and producer surplus is a price increase due to a reduction in crop output. In the crop market, however, the ozone-induced changes are so small relative to national output (on the order of 0.0001%) that the price impacts would be negligible. Because of this, we can assume that market prices are not affected by the ozone-induced crop reductions.

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[1]As a check to see if 47% was an accurate estimate of the percentage of total crop value represented by the five selected crops, the estimation was also performed 1982 data, yielding a similar result of 51%.

Table 9.1-5. Estimation of the percentage of total crop value accounted for by the five selected crops

County	Corn (1000 89$)	Wheat (1000 89$)	Soybeans (100 89$)	Tobacco (1000 89$)	Hay (1000 89$)	Total Agric. (1000 89$)	5 crops as percent of total value
Anderson	(D)	(D)	-	273	91	2,329	16
Blount	279	334	288	1,036	488	4,478	54
Campbell	48	(D)	-	999	93	1,194	95
Knox	180	24	29	971	421	4,795	34
Loudon	39	86	44	947	230	N/A	N/A
Morgan	139	(D)	94	118	188	595	90
Roane	(D)	(D)	16	550	192	1,075	71
Scott	(D)	(D)	(D)	28	108	N/A	N/A
Totals excluding Loudon and Scott Counties	$646	$358	$428	$3,947	$1,473	$14,466	47%
						Average percentage of total agricultural output represented by the five listed crops	47%

(D) = Data withheld to avoid disclosing data for individual farms—Represents zero.

We value the welfare losses in the market for a crop as the loss in yield times the market price, i.e. the market value of the lost crop. As ambient ozone increases and crop yield declines, production costs—including variable costs—remain essentially unchanged. Since small declines in crop yield do not lower the total cost of production, the decrease in social welfare equals the value of the lost crop (ORNL/RFF 1992). The loss in yield can be derived using the dose-response functions for ozone on crop yield and crop data from the reference environment. We assume that the average percentage reductions in yields for crops without data will be the same as for the five known crops.

Table 9.1-6 presents the market value of ozone-induced crop losses. This loss is the total market value of crops in each of the 8 affected counties (from Table 9.1-5) times the percent reduction in yield due to increased ozone. The resulting loss for the five crops studied ($7,958 per year) is then divided by 0.47, to account for the crops with incomplete data. The resulting figure ($16,803 per year) is

Table 9.1-6. Welfare change due to crop losses from increased ambient ozone concentrations

Crop	1987 crop value for 8 counties in ref. environ. (89$)	Loss in output due to increase in ambient ozone	Market value of crop loss (welfare loss)
Corn	$646,000	0.06%	$388
Soybeans	$428,000	0.11%	$462
Wheat	$358,000	0.12%	$415
Hay	$1,473,000	0.24%	$3,535
Tobacco	$3,947,000	0.08%	$3,158
		Welfare loss for 5 selected crops	$7,958
		÷ 0.47 to account for other crops	÷ 0.47
			$16,803
		÷ 1.036 land area adjustment	÷ 1.036
		Total social welfare loss due to ozone-induced crop reductions (89$)	$16,219
		÷ Annual output of biomass fired plant	÷ 183,960,000
		Crop loss in mills/kWh	0.088 mills

adjusted by the ratio of the eight-county land area to the 50 km reference environment land area considered in the ozone model (2,011,000:1,941,000 or 1.036). Finally, the social welfare loss from ozone induced crop losses is divided by the annual electrical output of the hypothetical biomass-fired plant to give the loss in mills per kWh of electricity produced—0.088 mills per kWh.

9.2 EFFECTS OF OZONE ON HUMAN HEALTH

9.2.1 Precursor Emissions and Change in Ozone Concentrations

Exhaust gases from power plants that burn fossil fuels contain concentrations of sulfur dioxide (SO_2), nitric oxide (NO), particulate matter, hydrocarbon compounds and trace metals. Estimated emissions from the operation of the hypothetical 30 MW biomass-fired power plant are given in Table 5.3-1. Ozone is considered a secondary pollutant, since it is not emitted directly into the atmosphere but is formed from other air pollutants, specifically nitrogen oxides (NO_x) and non-methane organic compounds (NMOC) in the presence of sunlight. (NMOC are sometimes referred to as hydrocarbons, HC, or volatile organic compounds, VOC, and they may or may not include methane). Additionally, ozone formation is a function of the ratio of NMOC concentrations to NO_x concentrations. In highly polluted urban areas characterized by relatively high concentrations of NO_x, the addition of NO_x emissions results in little or no increase in ozone concentrations due to the scavenging of ozone by NO_x emissions (see equation [1] below). Rural areas, such as the Southeast Reference site, and suburbs downwind of cities are often characterized by high NMOC/NO_x ratios. Since the only source of ozone in the troposphere is from the photolysis of NO_2 (equations [2] and [3] below), any increase in NO_x emissions in NO_x-limited areas results in higher ozone concentrations (NRC 1991).

While most large power plants are considered significant sources of NO_x emissions, NMOC emissions from power plants are not considered significant and do not typically require control. Since NMOC emissions from power plants are not present in sufficient quantities to provide an optimal hydrocarbon to NO_x ratio within the plume, ozone formation from the emissions of power plants is the result of a complex series of reactions involving NO_x emissions from the plant reacting with ambient concentrations of hydrocarbons, hydrocarbon derivatives, and ozone. Ambient hydrocarbons may be from either man-made or natural sources.

Initially, ozone that may be present in the ambient air reacts with the NO from the power plant to form nitrogen dioxide (NO_2) and oxygen (O_2), described by the reaction:

$$NO + O_3 \rightarrow NO_2 + O_2 \qquad [1]$$

This reaction causes the characteristic ozone depletion observed near the stack in power plant plumes. Ozone depletion is defined here as ozone concentrations within the power plant plume that are less than those outside the power plant plume. In the presence of sunlight, within the first few tens of kilometers of the plant, the photochemistry within power plant plumes (with low hydrocarbon concentrations) can be described by these three equations (White 1977), known as the NO_2 photolytic cycle:

$$NO + O_3 \rightarrow NO_2 + O_2 \qquad [1]$$

$$NO_2 + h\nu \rightarrow NO + O(^3P) \qquad [2]$$

$$O(^3P) + O_2 + M \rightarrow O_3 + M \qquad [3]$$

where M is any energy-accepting third body, usually nitrogen (N_2) or O_2 and $O(^3P)$ is one of two electronic states of oxygen known as the triplet-P (Seinfeld 1975). NO_2 absorbs ultraviolet energy from the sun which breaks the molecule into NO and a ground state oxygen atom $O(^3P)$. Energy from solar radiation is represented by $h\nu$, which is the product of Planck's constant (h) and the frequency of the electromagnetic wave of solar radiation (ν). The net effect of these three reactions is conversion of the NO emissions to NO_2 with no increase in ozone concentrations.

The net generation of ozone in power plant plumes can only occur in the presence of reactions which compete with the ozone depletion reaction [1]. Further downwind, as the plume disperses, ambient air containing pollutants from other sources, most importantly reactive hydrocarbons, becomes entrained into the plume. Reactive hydrocarbons in the ambient air participate in a complex series of oxidation reactions which result in the formation of highly reactive radicals.

An extremely important intermediate compound in this series of reactions is a group of hydrocarbon derivatives known as aldehydes, most importantly formaldehyde. These compounds play a key role in photochemistry since they are the major source of radicals (Gery et al. 1989) which compete with the ozone depletion reaction [1]. Formaldehyde is also emitted directly from such sources as automobiles, forest fires, manufacturing, printing, and spray painting (Graedel 1978). Formaldehyde (and other aldehydes) react in the presence of sunlight to form the highly reactive hydroperoxy radical ($HO_2\bullet$) by the reactions (Carlier et al. 1986):

$$HCHO + h\nu \rightarrow H + HCO \qquad [4]$$

$$HCO + O_2 \rightarrow HO_2 + CO \quad [5]$$

Ozone depletion is slowed by the reaction of NO with the hydroperoxy radical ($HO_2\bullet$):

$$HO_2 + NO \rightarrow OH + NO_2 \quad [6]$$

as well as, the alkylperoxy radical (RO_2, where R is any organic fragment):

$$RO_2 + NO \rightarrow RO + NO_2 \quad [7]$$

as the ozone generating reactions [2] and [3] continue in the plume. Eventually, the ozone concentration within the plume may exceed ambient levels.

The formation of ozone is controlled by a combination of conditions, including ambient ozone concentrations which provide the mechanism necessary for the initial conversion of NO to NO_2, reactive hydrocarbon concentrations of the ambient air mass, and the rate of entrainment of ambient air within the plume. These conditions, as well as sufficient photochemical activity, determine whether ozone levels in the plume will eventually exceed ambient levels to form the widely documented ozone "bulge" (Keifer 1977; Meagher et al. 1981; Luria et al. 1983; Gillani and Wilson 1980; Davis 1974).

Of the meterological parameters, atmospheric mixing shows the most direct and positive correlation with ozone formation (Gillani and Wilson 1980). Mixing dilutes the plume No_x and provides ambient NMOC by entrainment of ambient air, both of which may lead to an optimum local NMOC/NO_x ratio. Gillani and Wilson (1980) reported that "a moderate amount of sunlight exposure (~110 Langleys), ground-temperature above 2°C, and relative humidity above 50% are sufficient conditions for rapid formation of excess plume ozone" and furthermore, "ozone bulges appear in power plant plumes on warm summer afternoons quite regularly in the Midwest."

To summarize, the major factors in the formation of excess ozone in power plant plumes are:

1. NO_x emissions from the plant,
2. ambient ozone concentrations,
3. reactive hydrocarbons,
4. favorable ratio of ambient hydrocarbons to plume NO_x,
5. atmospheric mixing, and
6. sufficient photochemical activity (sunlight and temperature).

The biomass fuel cycle analysis requires that an estimate be made of ozone concentrations that occur in the vicinity of a biomass-fired power plant located at the Southeast Reference site, due to emissions of nitrogen oxides (NO_x) and non-methane organic compounds (NMOC) from the plant. Estimates of the peak daily ozone concentrations, due to the plant, for each day of the ozone season, are needed for the health effects analysis. These modeling requirements present a unique challenge, since all the currently available computer models which simulate ozone formations are designed to predict hourly and instantaneous ozone concentrations, over a period of several days at most. These predictions are primarily for comparison to the National Ambient Air Quality Standard (NAAQS) of 120 parts per billion (ppb) (one-hour average) not to be exceeded more than once per year.

The OZIPM-4 model is a trajectory model which predicts ozone concentrations as a function of travel time. ... MAP-O_3 model provides spatial resolution by predicting the location of the plume

The potential impact of the power plant NO_x and NMOC emissions on ozone concentrations was modeled for the Southeast Reference site using the U.S. Environmental Protection Agency model, Ozone Isopleth Plotting Mechanism (OZIPM-4) and a new model developed for this study, the Mapping Area-Wide Predictions of Ozone model (MAP-O_3). The OZIPM-4 model is a trajectory model which predicts ozone concentrations as a function of travel time. The MAP-O_3 model provides spatial resolution by predicting the location of the plume during each hour of the day, for the ozone season. The MAP-O_3 model predicts area-wide ozone concentrations over the ozone season, by combining ozone concentrations predicted with the OZIPM-4 model with plume trajectories calculated from wind speed and direction measurements. A detailed description of the modeling methods is presented in ORNL/RFF (1994a, Paper 3) for a coal-fired power plant. The same modeling methods are used for the biomass-fired plant. Details specific to the biomass-fired power plant are presented in Appendix B.

Results from the MAP-O_3 model for the health effects portion of the fuel cycle analysis are in tabular form. The peak daily ozone increment due to the power plant, as well as the daily peak background ozone concentrations, are reported at each location in a polar grid (for each downwind distance and sector) for each day of the ozone season (provided the combined total of the background and the increment due to the plant were greater than or equal to 80 ppb). This criterion was met (and results were reported) for fifteen days during the 1990 season. Three of the fifteen high days were in the month of June, seven were in July, four were in August and one was in September.

> *... the greatest increase in daily peak ozone concentrations due to the biomass-fired power plant's emissions during the ozone season was 2 ppb...*

As stated above, results for the health effects study are in tabular form and correspond to fifteen days of the ozone season. (If the actual results used in the health effects portions were presented here graphically it would require 15 figures, one for each day). Figure 9.1-3 illustrates the spatial distribution of daily peak ozone concentrations during the 1990 ozone season at the Southeast Reference site. (Results from the MAP-O_3 model were converted to Cartesian coordinates and written to files for import to the isopleth graphing routine SURFER). The power plant is shown in the center of each isopleth map with a triangle marker. The scale of the figure is in kilometers from the plant. Ozone concentrations are reported in parts per billion (ppb) by volume.

The ozone concentrations shown in Fig. 9.1-3 are the maximum daily peak ozone concentrations at each location in the receptor grid. As seen in Fig. 9.1-3 the greatest increase in daily peak ozone concentration due to the power plant emissions during the ozone season, was 2 ppb, occurring within twenty kilometers of the plant. An increase in peak daily ozone concentration of 1 ppb occurred over a wide area, from 130 kilometers in the northeast (NE) direction to 80 kilometers in the southwest (SW) direction. An increase in daily peak ozone concentration of 0.5 ppb was seen as far away as 150 kilometers in the northeast (NE) direction and 30 kilometers in the southwest (SW) direction.

9.2.2 Morbidity Impacts

Ozone is a highly active oxidizing agent capable of causing injury to the lung (Mustafa and Tierney 1978). Lung injury may take the form of irritant effects on the respiratory tract which impair pulmonary function and result in subjective symptoms of respiratory discomfort. These symptoms include, but are not limited to, cough and shortness of breath, and they can limit exercise performance.

The vast database on the effects of ozone on humans and animals provides abundant evidence of its adverse acute effects. Laboratory-based human and animal studies have suggested effects on pulmonary host defenses and the immune system. In addition to acute effects, a wide range of subchronic and chronic effects have been identified in laboratory-based animal studies. Because chronic exposures are

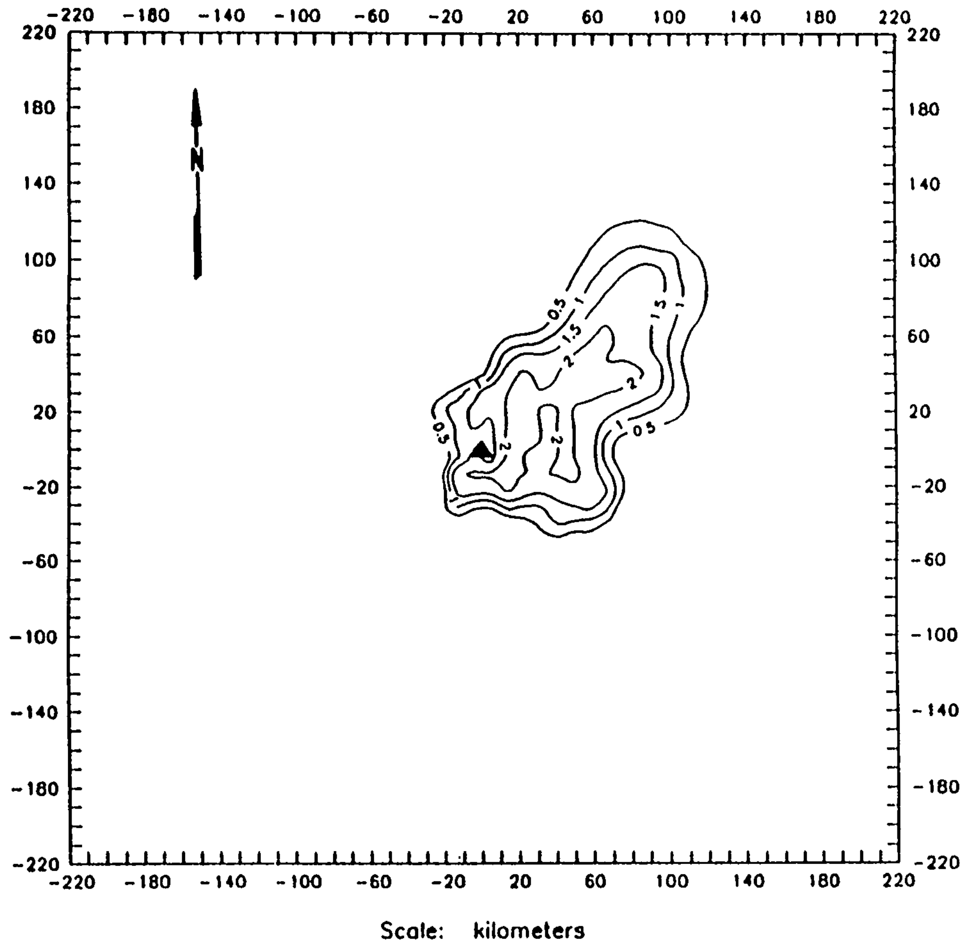

Fig. 3 Maximum daily peak incremental ozone concentrations (ppb) (one-hour average) for May to September 1990 due to emissions from the biomass-fired power plant located at the Southeast reference site.

some cumulative function of a series of acute exposures a linkage exists between acute and chronic exposures, but the mechanisms, at present, are not fully defined.

The results of studies in animals and the range of chronic effects observed suggest that there is a significant potential for chronic effects in humans. In addition, the types of morphological changes caused by ozone in animals are also observed in the lungs of cigarette smokers. These changes are generally interpreted as representing early stages of chronic lung disease in smokers. Nonetheless, several epidemiological studies tend to support a concern about the potential for chronic effects in humans (Detels et al. 1987, Knudson et al. 1983, Kilburn et al. 1985). While there are acknowledged imperfections in their studies, they suggest an increased rate of lung function decline with ozone exposure that has also been observed in animal studies. Notwithstanding, at present, there is no absolutely definitive evidence from epidemiological studies that ambient ozone exposures cause chronic effects in humans. Consequently, there will be considerable uncertainty in any estimates of externalities associated with the effects of ozone on health.

NAPAP Report 22 (USEPA 1990) identified a set of observations that are detailed in ORNL/RFF (1994a). These observations are considered to provide clear and consistent evidence from human clinical, epidemiological and field studies regarding the acute effects of ozone on human pulmonary function.

Risk estimates for a number of urban areas have been performed using existing or projected levels of ozone (e.g., Hayes et al. 1987, Whitfield 1988, Krupnick and Kopp 1988, Hayes et al. 1989 and Hayes et al. 1990). These estimates were developed for both pulmonary function and lower respiratory tract symptoms. Pulmonary function is not a useful measure for assessing damage. Pulmonary decrements have not been linked to specific symptoms of ill health by the medical community and without a symptom, there is no corresponding measure of the willingness to pay to avoid the pulmonary decrement.

The particular symptoms chosen for our analysis, based on the earlier development of Krupnick and Kopp (1988), are as follows:

Epidemiologically-Based Endpoints

1. Total Respiratory Restricted Activity Days (TRRAD), used by Portney and Mullahy (1986). This measure is based on responses by adults over a two-week recall period. The effects model was based on an average for a two-week period of daily one-hour maximum concentrations of ozone, as recorded within a 20-mile radius of the study's respondents. The authors found no effects of ozone on bed-disability days (BDDs) or work loss days

(WLDs). Hence, they recommended that these effects be designated as minor respiratory restricted activity days (RRADs).

2. Any-Symptom or Condition Day (Krupnick, Harrington, and Ostro 1987). This study resulted in a variety of response functions for a variable that took the value of one if any of nineteen symptoms or conditions were present on a given day and zero otherwise. Except for eye irritation and headache, these symptoms and conditions were all respiratory related. The response function is based on adults and daily one-hour maximum ozone concentrations. In the accounting framework, the total number of Any-Symptom Days is reduced to remove double counting other endpoints.

3. Asthma-Attack Day (Holguin et al. 1985). Based on a 12-hour period of observations on identified asthmatics, and related to total oxidants, this study was modeled by Krupnick and Kopp (1988).

4. Eye-Irritation Day (Schwartz, Hasselblad, and Pitcher 1989).

5. Days of Coughing (Schwartz, Hasselblad and Pitcher 1989). This study investigated the relationship between total oxidants, coughing, eye irritation and chest tightness. Only the first two symptoms were found to be significantly associated with oxidant exposure to members of the total population.

Clinical Study-Based

This study (McDonnell et al. 1983) found the difference in symptom scores taken before and after two-hour ozone exposures in a clinical setting. Morton and Krupnick (see Krupnick 1988) obtained the raw data from this study and performed a re-analysis, and then developed a procedure for adapting results from two-hour incidence to a symptom-day measure. Krupnick (1988) also found that the McDonnell et al. study provided the steepest dose-response function of any of the four "key" clinical studies relied upon by EPA's Clean Air Scientific Advisory Committee as evidence of the effect of low-level ozone on acute health.

6. Cough incidence (McDonnell et al. 1983).

7. Shortness of breath (McDonnell et al. 1983).

8. Pain upon deep inspiration (McDonnell et al. 1983).

The following text boxes contain more details on the dose-response functions used in this analysis.

Several steps were required to apply the Krupnick and Kopp (1988) results to estimate the effects of ozone on health at our two reference sites:

(1) The concentration-response functions from Krupnick and Kopp (1988) were coded into a simple Fortran program using the middle value coefficients plus the upper and lower 75% confidence limits based on the curve fitting procedure by Krupnick and Kopp (1988) on the source data.

(2) For the months of May, June, July, August and September, during which ozone production is significant at the Southeast Reference site, daily one-hour maxima were transcribed from the EPA's Aerometric Information Retrieval System (AIRS) data base and used as data input to which incremental ozone values were added. These increases in ozone concentrations were obtained from the modeling described in Section 9.2.1.

The baseline and its increment were used as input to the health effects algorithms.

(3) On the basis of data presented in EPA (1986), and the recent studies by Larsen et al. (1991), and McDonnell et al., (1991), both of whom found consistent lung function decrement with exposures at the lowest exposure level utilized (80 ppb), we choose to adopt a **threshold for respiratory effects of ozone at 80 ppb.**

(4) The population used for this evaluation was the population centered at the reference site and extending over the distance that ozone is dispersed. Consistent with the calculations of incremental ozone, population data was distributed according to the sixteen major sectors.

Results of the computations for the five months were summed over the appropriate population to result in the following numbers of cases per year (Table 9.2-1).

9.2.3 Economic Valuation of Ozone-Related Morbidity

To convert these predicted increases in acute effects (see Table 9.2-1) symptoms, asthma attacks, and restricted activity days into damages, estimates of individual WTP to avoid such changes are needed. An approach is also needed for aggregating these partly non-separable benefits to avoid double-counting. The full details on the WTP estimates and the aggregation approach are available in Krupnick (1987) and Krupnick and Kopp (1989). Here, the approach is only sketched out.

Dose Response Functions
OZONE

Days of coughing: Based on Schwartz, Hasselblad and Pitcher (1989),

$$\Delta c = \{[1/(1+\exp(-\gamma-\beta X_1))] - [1/(1+\exp(-\gamma-\beta X_0))]\}\ (pop)$$

where

Δc = change in number of coughing incidents for the day

X_0 = daily 1-hour maximum for total oxidants, baseline in reference environment; total oxidants are set equal to ozone concentration/0.9

X_1 = daily 1-hour maximum for total oxidants including reference plant

γ = −1.98

β = 0.40, 0.61, 0.82

pop = entire population

Days of eye irritation: Based on Schwartz, Hasselblad and Pitcher (1989),

$$\Delta e = \{[1/(1+\exp(-\gamma-\beta X_1))] - [1/(1+\exp(-\gamma-\beta X_0))]\}\ (pop)$$

where

Δe = change in days of eye irritation

X_0 = daily 1-hour maximum for total oxidants, baseline in reference environment; total oxidants are set equal to ozone concentration/0.9

X_1 = daily 1-hour maximum for total oxidants including reference plant

γ = −2.48

β = 1.72, 2.02, 2.32

pop = entire population

Dose Response Functions (continued)
OZONE

Incidences of coughing: Based on McDonnell et al. (1983),

$$\Delta C = \{[1/(1+\exp(-\gamma-\beta\omega X_1))] - [1/(1+\exp(-\gamma-\beta\omega X_0))]\} f\theta(\text{mpop})$$

where

ΔC = change in number of coughing incidences in two-hour period t

X_0 = daily maximum hourly ozone concentration, baseline in reference environment

X_1 = daily maximum hourly ozone concentration including reference plant

γ = -1.742

β = 10.961, 14.1, 17.239

mpop = entire population

θ = percent of a two-hour period the population is exercising

f = the incidence-day factor

ω = the scaling factor for two-hour period t

Dose Response Functions (continued)
OZONE

Incidences of shortness of breath: Based on McDonnell et al. (1989)

$$\Delta C = \{[1/(1+\exp(-\gamma-\beta\omega X_1))] - [1/(1+\exp(-\gamma-\beta\omega X_0))]\} f\theta(mpop)$$

where

ΔC = change in number of shortness of breath incidences for two-hour period t

X_0 = daily maximum hourly ozone concentration, baseline in reference environment

X_1 = daily maximum hourly ozone concentration including reference plant

γ = −0.076

β = 4.938, 7.265, 9.562

mpop = entire population

θ = percent of a two-hour period the population is exercising

f = the incidence-day factor

ω = the scaling factor for two-hour period t

Dose Response Functions (continued)
OZONE

Any symptom or condition (ARD): Based on Krupnick, Harrington and Ostro (1987)

$$\Delta ARD = \beta^* (X_1 - X_0) (apop)$$

where

ΔARD = change in the number of days of "any" symptoms/conditions

β^* = marginal change in the stationary probability of experiencing any symptom/condition

= $p_0(1-p_i)\beta[p_1+(1-p_0)]/(1-p_1+p_0)^2$, where p_0 is the conditional probability of illness on day t given wellness on day t-1, p_1 is the conditional probability of illness on day t given illness on day t-1, and β is the ozone coefficient from the logit model regression.

= 0.13, 0.20, 0.27

X_0 = daily maximum ozone concentration, baseline in reference environment

X_1 = daily maximum ozone concentration including reference plant

apop = adult population

Dose Response Functions (continued)
OZONE

<u>Total respiratory-related restricted activity days (TRRADs)</u>: Based on Portney and Mullahy (1986),

$$\Delta TRRAD = TRRAD\,[\exp\,[\beta(X_1 - X_0)] - 1]\,(apop)$$

where

ΔTRRAD	=	change in number of respiratory-related restricted activity days for the 2-week period
TRRAD	=	baseline per capita TRRADs for a 2-week period
X_0	=	average daily 1-hour maximums of ozone concentrations for each 2-week period, baseline in reference environment
X_1	=	average daily 1-hour maximums of ozone concentrations for each 2-week period including reference plant
apop	=	adult population
β	=	2.63, 7.99, 13.34

Dose Response Functions (continued)
OZONE

Asthma attacks: Based on Holguin et al. (1985)

$$\Delta a = [m/(1+m) - p]\,(apop)$$

where

$$m = [p/(1-p)]\,\exp\,(\beta\omega X_1 - \beta\omega X_0)$$

and

Δa = change in number of asthma attacks for the 7AM–7PM or 7PM–7AM period

p = baseline number of attacks per asthmatic for the day

X_0 = maximum 1-hour ozone concentration for 7AM–7PM, baseline in reference environment

X_1 = maximum 1-hour ozone concentration for 7AM–7PM including reference plant

apop = asthmatic population

ω = scaling factors for half-day periods

β = 3.58, 6.20, 8.82

Dose Response Functions (continued)
OZONE

Incidences of coughing: Based on McDonnell et al. (1983),

$$\Delta C = \{[1/(1+\exp(-\gamma-\beta\omega X_1))] - [1/(1+\exp(-\gamma-\beta\omega X_0))]\} f\theta(\text{mpop})$$

where

ΔC = change in number of coughing incidences in two-hour period t

X_0 = daily maximum hourly ozone concentration, baseline in reference environment

X_1 = daily maximum hourly ozone concentration including reference plant

γ = -1.742

β = 10.961, 14.1, 17.239

mpop = entire population

θ = percent of a two-hour period the population is exercising

f = the incidence-day factor

ω = the scaling factor for two-hour period t

Table 9.2-1. Pathway: Ozone morbidity; thousands of impacts per year at the Southeast Reference site associated with the 30 MW biomass plant

Aggregation	Pathway endpoint	Low	Mid	High
Epidemiological studies	Minor respiratory restricted activity days	0	0.406	0.824
	Any symptom-day	0.379	1.016	1.468
	Asthma attack-day	0.033	0.053	0.076
	Eye irritation-day	1.145	1.350	1.564
	Cough-day	0.322	0.525	0.711
Clinical studies	Cough incidence	2.483	3.212	4.174
	Shortness of breath	1.253	1.847	2.366
	Pain upon deep inspiration	0.744	1.668	2.765

9.2.3 Economic Valuation of Ozone-Related Morbidity

To convert these predicted increases in acute effects (see Table 9.2-1) symptoms, asthma attacks, and restricted activity days into damages, estimates of individual WTP to avoid such changes are needed. An approach is also needed for aggregating these partly non-separable benefits to avoid double-counting. The full details on the WTP estimates and the aggregation approach are available in Krupnick (1987) and Krupnick and Kopp (1989). Here, the approach is only sketched out.

Three CV studies (Loehman et al., 1979; Tolley et al., 1986; and Dickie et al., 1987) have used bidding procedures to elicit estimated values for respiratory symptom days, with estimates ranging from $1 to $25 and more, on average, depending on the symptom, its severity, and whether a complex of symptoms are experienced.

All of these studies have significant drawbacks, mainly related to their age the CV studies were performed before many of the most important advances in CV methodologies. At the same time, they offer quite consistent ranges of estimates for willingness-to-pay to avoid a particular type of symptom.

Krupnick's (1987) detailed analysis of these studies' strong and weak points led to a choice of values for the acute effects that attempted to make a fine distinction between studies. In a subsequent study by Krupnick and Kopp (1989), this approach was abandoned and "ballpark" estimates of values were used instead. Here, both sets of estimates (updated to 1989 dollars) are provided (Table 9.2-2) and used; the "ballpark" any symptom-day values are used to estimate morbidity damages when relying on epidemiological dose-response functions and the more specific and finely differentiated specific symptom-day values are used to estimate damages when relying on clinical dose-response functions.

One problem in the use of these studies to estimate population benefits is that most studies simply multiply the total number of symptom-day reductions by the relevant unit values to obtain benefits. This may be incorrect if one assumes (with some empirical justification) that marginal valuations decline with additional days illness reduced. Hall et al. (1989) pooled the WTP estimates from asthmatics in the Rowe and Chestnut (1985) study with estimates for respiratory symptom reductions from the Loehman study to estimate WTP as a function of days sick. This function is $WTP = WTP_1 * N^{-0.5}$. Where the number of symptoms per person per year, (N), was obtained by dividing total estimated symptom-days reduction (16 per year for a person living in Los Angeles) by population. Overall this procedure resulted in WTP estimates only 24% of what they would have been with N assumed equal to 1.0.

Four caveats are in order, however. First, the distribution of symptom- days for each person cannot be estimated from the data but must be determined by dividing total days reduction by population. Second, the studies finding declining marginal WTP are unclear about whether these days of reductions are to be experienced continuously or spaced over a year. WTP responses would likely be quite sensitive to this spacing. Third, outside of the Los Angeles area, and for small enough changes in ambient air quality, N may be less than 1.0, which would mean that the Hall et al. procedure would raise WTP above that obtained when N is assumed to equal 1.0. Is this reasonable, since no one actually experiences half a symptom-day? Fourth, the estimated decline in marginal WTP is very sensitive to assumed functional form, but there is too little information in the literature to estimate such functions confidently. In our calculations, we assume that $N = 1.0$.

As noted in the above section, two types of health effects estimates are generated—one from clinical studies and the other from epidemiological studies. The former cannot be used directly with the above estimates of value because the values are for a day's effect, while the clinical dose-response functions estimate 2-hour incidences of health effects. Thus, use of health effect estimates from the clinical studies requires converting incidences into days, for example, the number of two-hour incidences of coughing that would be valued equally to a "day" of

Table 9.2-2. Unit values of ozone-morbidity end-points (in 1989 dollars)

Endpoint	Low	Medium	High
Any symptom day (Krupnick and Kopp 1989)	2.98	5.97	11.93
MRRAD (Krupnick and Kopp 1989)	13.13	21.48	36.40
Asthma attack (Krupnick and Kopp 1989)	10.74	29.84	48.93
Specific symptoms (Krupnick 1987)			
Cough	1.66	4.77	13.13
Short breath	0.72	9.55	21.48
Chest tightness	2.98	5.97	21.48
Throat irritation	2.90	3.58	10.31
Eye irritation	2.98	5.97	12.95
Upper respiratory	5.04	5.37	8.74
Lower respiratory	2.07	5.32	14.81

coughing. There are no studies to rely on for these estimates. Krupnick (1987) and Krupnick and Kopp (1989) used values ranging from 1.0 to 8.0 (incidences per day), with a best estimate of 2.0. We do the same here.

Estimates

Focusing on midpoint estimates of damages within the Southeast Reference site estimated using epidemiological studies (see Table 9.2-3), the largest damages are expressed as MRRADs—$10,000, followed by eye irritation-days at $9,000 and symptom-days, at $6,400. Using the clinical studies, damages from cough, shortness of breath, and pain upon deep inspiration are in the range of $6,500 to $11,000.

Aggregations

Once the benefits of ozone reductions from a scenario have been computed for the individual dose-response functions, these benefits must be aggregated to obtain the total benefits from that scenario. Because of the different approaches to estimating dose-response functions taken by the epidemiological and clinical studies, separate aggregations are used for each of these classes of studies. In

Table 9.2-3. Ozone morbidity: damages per year (in thousands of 1989 dollars) in the southeast

Aggregation	Pathway endpoint	Low	Mid	High
Epidemiological studies	Minor respiratory restricted activity days	0.13	10	23
	Any symptom-day	0.62	6.4	14
	Asthma attack-day	0.46	1.6	3.1
	Eye irritation-day	4.2	9	16
	Cough-day	0.78	2.8	6.4
	Total pathway damages	16	27	41
	Total pathway damages (mills/kWh)	0.085	0.15	0.22
Clinical studies	Cough incidence	1.2	6.5	18
	Shortness of breath	1.4	9.8	29
	Pain upon deep inspiration	23	11	25
	Total pathway damages	11	28	53
	Total pathway damages (mills/kWh)	0.062	0.15	0.29

addition, benefits for the clinical aggregation are calculated for a "low clinical" and a "high clinical" case, where the "low" case assumes that eight two-hour incidences equal a symptom-day and the effects of ozone are restricted to heavy exercise periods and the "high" case assumes that two two-hour incidences equal a symptom-day and the effects of ozone are felt at any exercise rate above rest.

For the aggregation of the results of individual epidemiological studies, one key issue is accounting for overlap between a symptom-day and a MRRAD. Note that, logically, any time a MRRAD is experienced, one or more respiratory symptoms or conditions must be experienced. At the same time, not all experiences of a symptom result in a MRRAD. One simple and reasonable procedure for accounting for the overlap is to count all of the RRADs and only those symptom-days that exceed the number of MRRADs (A possible complication to this procedure would be if the reduction in the number of MRRADs exceeded the reduction in the number of symptom-days. Fortunately, this does not occur).

In line with the above discussion, the benefits of MRRAD reductions (computed only for adults, as no effect of ozone on RADs in children is apparent) are counted and added to the benefits from "residual" reductions in "any" symptom-days (reductions in "any" symptom-days minus reductions in MRRADs) predicted using the "any symptom-day" function estimated by Krupnick, Harrington, and Ostro (1990). These are added to the benefits of asthma attack reductions estimated by Holguin et al. and applied to the entire asthmatic population. The benefits of eye irritation-day and cough-day reductions in children (taken from the Schwartz, Hasselblad, and Pitcher study) are then added.

For the clinical aggregation, the symptoms reductions predicted by the set of clinical studies are restricted to those from the dose-response functions estimated by Morton and Krupnick using the underlying data from all four of the key clinical studies and those taken from the McDonnell et al. study, as these provide the largest damages. The estimates of effects and damages from the individual symptoms are simply applied to the entire population and summed together.

As seen in Table 9.2-3, for the epidemiological studies, total damages range from $16,000 to $41,000, with a midpoint estimate of $27,000. For the clinical studies, total damages range from $11,000 to $53,000, with a midpoint estimate of $28,000. In kWh terms, the midpoint estimate using epidemiological studies is 0.15 mills/kWh, while for clinical studies the midpoint estimate is also 0.15 mills/kWh. The confidence interval on the clinical studies is greater, ranging from 0.062 to 0.29 mills/kWh. This wider range is a consequence of alternative assumptions used to convert incidences of symptoms to days of symptoms for the purpose of valuation.

9.3 EFFECTS OF NO_X ON HEALTH

9.3.1 Emissions and Changes in Concentration

When biomass is burned, nitrogen oxides (NO_x) are formed. These compounds are primarily nitrogen oxide (NO), with much smaller quantities of nitrogen dioxide (NO_2). Nitrogen oxide is formed from the oxidation of nitrogen in biomass and the thermal fixation of nitrogen in the combustion air. The ground-level pollutant concentrations of NO_x that could be expected to occur as a result of the operation of the 30 MW reference biomass-fired power plant were predicted with an atmospheric dispersion model.

Using stack information (i.e., stack diameter, exit gas velocity, and exit gas temperature), the model predicts the release height of pollutants to the atmosphere. Wind direction, wind speed and other meteorological measurements made in the vicinity of the stack are used to predict the dimensions of the plume (i.e., its vertical and horizontal width) and its travel path downwind. The model calculates pollutant concentrations at receptor locations that are defined by a system of grid points. The Environmental Protection Agency Industrial Source Complex Long-Term (ISCLT) model (EPA 1986) was used to predict the annual average ground-level concentrations of NO_x expected to occur as the result of operating the reference power plant. A summary of the computer modeling is presented in Appendix C. The highest predicted increase in ambient annual concentration[2] of NO_x from the Southeast Reference plant site was 0.157 micrograms per cubic meter ($\mu g/m^3$).

The maximum values are not used in the impacts analysis. Rather, a population weighted concentration of NO_X was evaluated according to the process described earlier in Sect. 9.4. The population weighted concentration of NO_x is 0.04 $\mu g/m^3$ for the Southeast Reference site.

9.3.2 Impacts of NO_2 on Phlegm-Days

Epidemiological studies have generally not found significant effects of nitrogen dioxide at ambient levels on morbidity endpoints. The primary concern about NO_2 lies in its role as a precursor to ambient ozone (see Sections 9.1 and 9.2). One recent study that does find a significant direct effect of NO_2 on health is Schwartz and Zeger's (1990) analysis of the daily effects of air pollution on students beginning nursing school in Los Angeles in the early 1970's. Most effects of NO_2 on health were insignificant, except for the effect of NO_2 on daily incidence of phlegm. Applying the results of this study (including the confidence intervals) [see ORNL/RFF (1994a)] to the children in the Southeast Reference environment, and using the population location weighted location 24-hour average increase in NO_X (0.04 $\mu g/m^3$), the incremental (midpoint) impact is 1,100 phlegm-days per year, with a range from 27.8 to 2,180 symptom-days. Schwartz and Zeger's (1990) data are linearized for application to this study; coefficients are presented in Table 9.3-1.

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[2]The ambient annual concentration is defined as the arithmetic mean (or average) concentration predicted to occur during a 365 day period at outdoor, ground level receptors. The highest ambient annual concentration is the highest concentration predicted among the 857 receptor locations used in the dispersion model.

In the ISCLT model the ambient annual concentration is calculated using an average annual distribution of wind speeds, wind directions and atmospheric stability classes, determined from one year (or several years) of meteorological data collected near the reference sites.

Table 9.3-1. Linearized dose-response function for effects of NO_2 on morbidity

Study	Coefficient	Units
Schwartz and Zeger (1990)	0.0395	upper change in the probability of a case of phlegm-day/person/μg/m^3 change in NO_2
	0.028	central change in the probability of a case of phlegm-day/person/μg/m^3 change in NO_2
	0.0165	lower change in the probability of a case of phlegm-day/person/μg/m^3 change in NO_2

9.3.3 Economic Valuation

No studies have ever asked for the willingness-to-pay to avoid a phlegm-day, hence, we leave this impact unmonetized.

9.4 EFFECTS OF PARTICULATES ON HEALTH

9.4.1 Effects of Particulates on Mortality

9.4.1.1 Emissions and Changes in Concentration

Particulates is a term used to describe dispersed airborne solid and liquid particles. The composition and emission levels of biomass-fired boiler particulate matter are a complex function of firing configuration, boiler operation and biomass properties (EPA 1988). Emission levels are also a function of the particulate control device employed. An electrostatic precipitator (ESP) is used to control particulate emissions for the power plant at each reference site. The primary interest in particulate matter centers around the respirable fraction, which is known as PM_{10}. PM_{10} is the fraction of particulate matter with an aerodynamic diameter less than 10 micrometers.[3]

[3]After completion of this analysis, scientific and regulatory attention has focused on fine particles, $PM_{2.5}$, and on acid aerosols formed from SO_2 and NO_x emissions. Our analysis does not account for transformation of SO_2 and No_x into acid aerosols. Future research should focus on this important area of study.

The ground-level pollutant concentrations of total suspended particulates (TSP) and PM_{10} that could be expected to occur as a result of the operation of the 30 MW reference biomass-fired power plant were predicted using atmospheric dispersion modeling. Using stack information (i.e., stack diameter, exit gas velocity, and exit gas temperature), the model predicts the release height of pollutants to the atmosphere. Wind direction, wind speed and other meteorological measurements made in the vicinity of the stack are used to predict the dimensions of the plume (i.e., its vertical and horizontal width) and its travel path downwind. The model calculates pollutant concentrations at receptor locations which are defined by a system of grid points.

The Environmental Protection Agency Industrial Source Complex Long-Term (ISCLT) model (EPA 1986) was used to predict the annual average ground-level concentrations of particulates expected to occur as a result of the operation of the power plant. The highest predicted increase in ambient annual concentration of PM_{10} from the Southeast Reference plant site was 0.014 micrograms per cubic meter ($\mu g/m^3$). Calculations of impacts utilized the PM_{10} concentrations predicted around the reference sites, weighted by the populations. As described in Section 9.3., the population weighted concentration of PM_{10} is 0.0058 $\mu g/m^3$ in the Southeast Reference site. A summary of the results of the modeling is presented in Appendix B.

9.4.1.2 Impacts of Particulates on Mortality

Over the last few decades, numerous epidemiologic studies have reported associations between daily concentrations of ambient particulate matter and mortality among the general population in various cities. These studies found effects and similar dose-response functions at very high concentrations and at ambient concentrations currently found in U.S. cities, even cities in attainment of the National Ambient Air Quality Standards (NAAQS) for particulates. Dose-response functions have been determined for various measures of particulates, although there is still no generally accepted way of disentangling the effects associated with particulate emissions from those associated with sulfur emissions. Another set of studies has found consistently significant associations between annual particulate measures and annual mortality rates over a cross section of cities for various years. The former set of studies is more convincing, however, because studying mortality in a given city over time has the effect of controlling for many of the possible intervening variables associated with comparing data from one city with data from another city.

Table 9.4-1 on the following page provides a summary of this research for nine mortality studies, converting the results of each to common units for comparability. These conversions include expressing the pollutant in terms of

24-hour average PM_{10} concentrations using well-known (if imperfect) conversion ratios and expressing the estimated coefficient for the linear dose-response function in terms of the percentage change in mortality related to a 10 $\mu g/m^3$ change in PM_{10}. None of these studies estimate by how much mortality is premature, although some studies rule out the possibility that the observed mortalities result in only few days of life shortening.

Table 9.4-1. Particulates mortality: deaths per year for the southeast site

Study	Low	Mid	High
Schwartz and Marcus (1990)	0.03	0.0338	0.0377
Plagiannakos and Parker (1988)	0.0087	0.0488	0.089
Schwartz and Dockery (1991a)-PM_{10}	0.0155	0.0319	0.0483
Schwartz and Dockery (1991a)-TSP	0.00928	0.0191	0.0289
Schwartz and Dockery (1991b)-PM_{10}	0.0404	0.0599	0.0794
Schwartz and Dockery (1991b)-TSP	0.0242	0.0359	0.0476
Fairley (1991)	0.0239	0.0558	0.0878
Schumway et al. (1988)	0.0815	0.115	0.149
Evans et al. (1984)	0.0047	0.0359	0.0672

Table 9.4-1 provides low, medium, and high estimates by study for numbers of premature deaths per year as a result of particulate emissions from the reference plant located in the Southeast Reference site assuming a threshold in health effects of 30 $\mu g/m^3$. Additional results are presented for the Schwartz and Dockery studies in the original emissions units (TSP). These studies yield mid-point estimates for the Southeast Reference environment, for instance, ranging from 0.020 to 0.12 excess deaths annually, with the lowest and highest estimates of 0.005 and 0.15 excess deaths.

The Schwartz and Dockery (1991a) study is used for valuation purposes for two reasons: (1) this study was conducted in Steubenville Ohio, which is more similar to our southeastern reference environment than are cities where other studies were conducted; and (2) this study and its companion study for Philadelphia are the most recent and highest quality studies. The original results for TSP are used to avoid reliance on the PM_{10}/TSP conversion ratio used to generate results in Table 9.4-1, for instance. Using this study we estimate that between 0.009 and

0.029 excess deaths per year will occur due to particulate exposure in the Southeast Reference environment, with a mid estimate of 0.019.

Economic Valuation

While there is much uncertainty over exactly how particulates raise risks of death, it is clear that risk factors include being old and having respiratory or cardiovascular disease. Using the most convincing evidence on the effects of particulates on premature mortality (Schwartz 1991), the effects on older people are clearly dominant, with relative risks of 1.09 for people 65 years and older and 1.02 for people younger than 65.[4] At the same time, people with chronic obstructive pulmonary disease (COPD) are by far the most at risk, with a relative risk of 1.19 versus relative risks of 1.11 for those with pneumonia and 1.09 for those with cardiovascular disease. Deaths from these diseases are overwhelmingly concentrated in elderly people. For instance, 86% of deaths from pneumonia occur in people 65 or older, and virtually all deaths from emphysema would occur in this age group.

The risk factors for premature death from exposure to particulates imply that the WTP for reduced risks of death of older people with chronic illness is an appropriate measure of damage. As a fairly large percentage of younger people will eventually have chronic respiratory or heart disease (5% or more with COPD, over 7% with heart disease) and also find themselves at risk of premature death from particulate exposure, it would also be appropriate to use a measure of WTP for future reduced risks of death taken from younger people and add this to the WTP of older people with chronic illness. There are no studies providing such measures.

Another issue concerns the degree to which lifetime is reduced by particulate exposure. If those who are dying prematurely would have died in, say, another week in any event, the benefits of reducing particulates would be low or even trivial. Schwartz rules out such trivial benefits, but the literature offers no guidance on the years "saved" by reducing particulate concentrations.

This leaves us with two approaches to measure damages associated with additional premature mortality in the population from exposure to higher concentrations of particulates: (1) multiplying estimates of the average value of a statistical life (from Fisher, Chestnut, and Violette 1989) by the change in the number of premature deaths; and (2) multiplying the value of a statistical life associated with a disease with a latency period by the change in the number of premature deaths using Mitchell and Carson (1986).

[4]Relative risks of 1.0 would imply no excess risk. Relative risks of 1.09 imply that risks are 9% higher than for people not exposed to particulates who are 65 years old or older.

Approach (1) is based on scenarios involving accidental death and taken from prime-age adults. It will almost surely overestimate WTP for the case considered in this section. Approach (2) is better because, although it also uses a study that polls prime age adults, the study incorporates a latency period, with the implication that a relatively small number of life-years will be saved (since for disease with a long latency, people are usually old when they die). However, this study examines WTP from death by cancer, not from a respiratory or heart disease. Values may differ by cause of death.

Tables 9.4-2 provides estimates of welfare loss associated with excess deaths associated with a change in TSP calculated using the Schwartz and Dockery (1991a) study. For approach (1), we use VSL estimates from $1.6–$8.5 million (with a mid-value estimate of $3.5 million) that Fisher, Chestnut and Violette (1989) offer.

Table 9.4-2. Particulates mortality: damages per year (in 1989 dollars) for the southeast site

This table assumes impacts based on Schwartz and Dockery (1991a)-TSP	VSL method		
	Low	Mid	High
Total pathway damages	25,000	78,000	160,000
Total pathway damages (mills/kWh)	0.14	0.42	0.88

For approach (2), we use Mitchell and Carson's estimate of the value of a statistical life derived from their CV study of willingness to pay for reductions of a cancer-causing substance—trihalomethane—in drinking water. Although latency was not invoked directly in the questionnaire, death by cancer was, and it can be assumed that most people realize that cancer is a disease with a long latency period. Mitchell and Carson find that for baseline cancer risks levels in the general population and relatively large reductions in risks (8/100,000) that the VSL is about $180,000 (in 1985 dollars).[5]

[5]VSL falls with greater reductions in risks, although the WTP for a given risk reduction rises with the size of the risk reduction, but at a diminishing rate, according to models posited by Mitchell and Carson.

The changes in mortality risks associated with particulates are about 2/100,000,000 suggesting a much higher VSL. Using their equation (4), the VSL is almost $22,000,000. However, because the mortality risks associated with particulates are well outside of the range of risks investigated by Mitchell and Carson, we do not consider this VSL valid for this pathway. In addition, risks are being increased not decreased, as they were in the Mitchell and Carson study.

Using valuation approach (1), our best estimate of marginal damage associated with the particulates-mortality pathway is $78,000 per year (0.42 mills/kWh) for the Southeast Reference site.

9.4.2 Morbidity Effects of Particulates

Dose-response functions for particulates have been identified for respiratory hospital admissions, emergency room visits, restricted activity days and symptoms in adults, lower respiratory illness in children, and asthma attacks. Below, we estimate impacts for each endpoint and present estimates of aggregate morbidity effects. Then, we estimate damages for each endpoint separately and aggregate taking care to avoid double-counting.

These pathways can be made clearer by referring to Fig. 9.4-1. Here, a "normal" adult with a symptom may have a restricted activity day (RAD). If he has a RAD it may be serious enough to visit the emergency room or be admitted to a hospital, and if the former, the emergency room patient may be admitted to the hospital. We assume that having a RAD is a necessary condition for an emergency room (ERV) or hospital visit (RHA). In addition, asthmatics, whether children or adults, may be admitted to the hospital or emergency room, as may non-asthmatic children.

9.4.2.1 Impacts of Particulates on Morbidity

The following shaded table (Table 9.4-3) shows the results of a wide-ranging literature search for the best studies providing dose-response functions for the particulate-morbidity pathway. From the study by Plagiannakos and Parker (1988), annual respiratory hospital admissions per 100,000 population were related to annual average SO_4 concentrations, but TSP was not significant. Pope found a similar relationship using PM_{10} as the pollution measurement. We use Plagiannakos and Parker's results converted to PM_{10} using a "standard" ratio of SO_4 to PM_{10}.

To estimate effects associated with emergency room visits/100,000 people, we rely on the Samet et al. (1981) study, which could not separate effects of SO_2 and particulates; the estimates below are based on the results for TSP. We use the

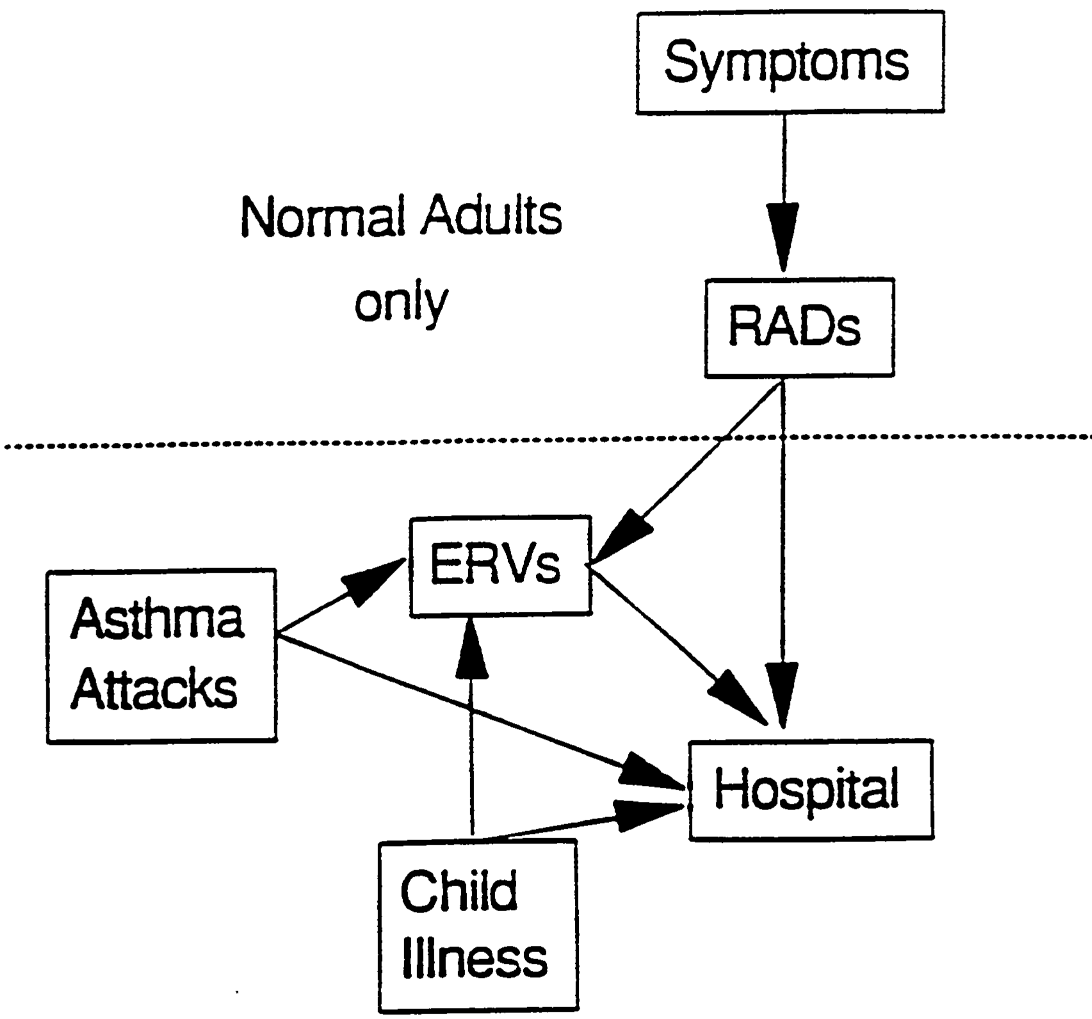

Fig. 9.4-1 Flowchart of particulate-morbidity effects.

Krupnick, Harrington, and Ostro study (1990) to estimate the annual change in "any" symptom-days/person and Ostro (1987) to estimate the annual change in RADs/person associated with change in PM_{10}.

Dockery et al. (1989) found statistically significant associations for PM_{15} (converted to PM_{10}) and both the proportion of children with bronchitis over a year and the proportion with a chronic cough over the year. Finally, the dose-response function for the probability of an asthmatic experiencing an attack related to sulfates (SO_4) is taken from Ostro et al (1991) and converted to PM_{10}.

Referring to mid-point estimates the increase in particulates in the Southeast Reference site is estimated to result, annually, in 0.053 additional respiratory hospital admissions, 1.2 emergency room visits, 210 restricted activity days for non-asthmatic adults, 7,900 additional respiratory symptoms for adults, 86 asthma attack-days, 2.1 additional children with bronchitis during the year, and 2.4 additional children with a chronic cough during the year. Table 9.4-4 provides the range of morbidity estimates for the Southeast Reference site.

9.4.2.2 Economic Valuation of Impact of Particulates on Morbidity

To convert the above estimates of acute effects into damages, estimates of individual WTP to avoid such effects are needed. An approach is also needed for aggregating these partly non-separable damages to avoid double-counting. The ideal WTP measures would capture all the medical costs, pain and suffering, time loss, and fear of an acute illness experience. This experience might also include a restriction in activity, an emergency room visit, or a hospital stay. Thus, the WTP measure would address a hierarchy of effects ranging in severity from minor symptoms to hospital stays. Unfortunately, as there are no such measures of WTP available, we must make do with proxies.

Referring back to Fig. 9.4-1, we deal with the overlap between adult RADs and adult symptom-days by valuing all RADs and adding to this the value of residual symptom-days. The Health Interview Survey data base used to estimate RADs omits hospital and emergency room days. Thus, values associated with these measures can be added to values for RADs without double-counting. On a WTP basis, avoiding double-counting of emergency room and hospital visits is problematic since estimates of the WTP of people to avoid these experiences do not exist. Instead, we have medical costs for each type of visit, plus we assume that a WLD is encountered for each day of either an emergency room or hospital visit. Since emergency room visit charges are typically added to hospital charges, we feel justified in considering their sum as involving no double-counting of medical costs.

Table 9.4-3. Results of literature search for studies on morbidity effects on particulates

Plagiannakos & Parker (1988)	14.02	Upper change in RHA/100,000 people/$\mu g/m^3$ change in annual PM_{10}
	10.15	Central change in RHA/100,000 people/$\mu g/m^3$ change in annual PM_{10}
	6.25	Lower change in RHA/100,000 people/$\mu g/m^3$ change in annual PM_{10}
		where RHA = Annual respiratory hospital admissions per 100,000 people
Samet et al. (1981)	34.25	Upper change in ERV/100,000 people/$\mu g/m^3$ change in annual PM_{10}
	23.54	Central change in ERV/100,000 people/$\mu g/m^3$ change in annual PM_{10}
	12.83	Lower change in ERV/100,000 people/$\mu g/m^3$ change in annual PM_{10}
		where ERV = Emergency room visits
Krupnick et al. (1990)	2.57	Upper change in symptom-day/ year/person/$\mu g/m^3$ change in annual PM_{10}
	2.05	Central change in symptom-day/ year/person/$\mu g/m^3$ change in annual PM_{10}
	1.63	Lower change in symptom-day/ year/person/$\mu g/m^3$ change in annual PM_{10}
Ostro (1987)	0.0903	Upper change in RAD/person/ year/$\mu g/m^3$ change in annual PM_{10}
	0.0575	Central change in RAD/person/ year/$\mu g/m^3$ change in annual PM_{10}
	0.0356	Lower change in RAD/person/ year/$\mu g/m^2$ change in annual PM_{10}
		where RAD = Restricted activity days

Table 9.4-3 (continued)

Dockery et al. (1989)	0.00238	Upper change in proportion of children with bronchitis/year/$\mu g/m^3$ change in annual PM_{10}
	0.00160	Central change in proportion of children with bronchitis/year/$\mu g/m^3$ change in annual PM_{10}
	0.0008	Lower change in proportion of children with bronchitis/year/$\mu g/m^3$ change in annual PM_{10}
Dockery et al. (1989)	0.00276	Upper change in proportion of children with chronic cough/year/ $\mu g/m^3$ change in annual PM_{10}
	0.00184	Central change in proportion of children with chronic cough/year/ $\mu g/m^3$ change in annual PM_{10}
	0.0009	Lower change in proportion of children with chronic cough/ year/$\mu g/m^3$ change in annual PM_{10}
Ostro et al. (1991)	0.0143	Upper change in asthma attacks/ day/person/$\mu g/m^3$ change in PM_{10}
	0.00962	Central change in asthma attacks/day/person/$\mu g/m^3$ change in PM_{10}
	0.00487	Lower change in asthma attacks/day/person/$\mu g/m^3$ change in PM_{10}

There is a clear potential for double-counting RADs and symptom-days since the latter are a necessary condition for the former. We address this issue by valuing all RADs plus valuing any excess of symptom-days over RADs.

Table 9.4-4. Particulate morbidity: number of impacts per year for the Southeast site

Pathway endpoint	Low	Mid	High
Restricted activity day -Ostro (1987)	45.1	212	378
Emergency room visit -Samet et al. (1981)	0.127	1.22	2.32
Asthma attack-day -Ostro et al. (1991)	11.3	86.4	157
Child chronic bronchitis -Dockery et al. (1989)	0.0354	2.1	3.84
Child chronic cough -Schwartz et al. (1991)	0.418	2.42	4.43
Respiratory hospital admission -Plagiannakos and Parker (1988)	0	0.527	1.0607
Any symptom-day -Krupnick et al. (1990)	4,950	7,940	10,900
Chronic bronchitis in adults	0.0628	0.351	0.639

A certain number of asthma attack days and child illness days will have emergency room visits and hospitalization associated with them. Estimates of the WTP to avoid an asthma attack day [taken from Krupnick (1987)]; already include these consequences (on average). We do not have estimates of the percentage of asthma attacks resulting in emergency room visits. Based on data on hospitalization of asthmatics from the Heart, Lung and Blood Institute (1982) and an estimate of 9.9 asthma attacks per year per asthmatic on average in Krupnick (1987), we estimate that 0.5% of asthma attack-days result in hospitalization. We assume that 1% of asthma attacks result in emergency room visits.

Unit values (Table 9.4-5) for "any" symptom-days (midpoint=$6) and asthma attack days (midpoint=$30) are taken from Krupnick and Kopp (1989). Values for a RAD are estimated as part of this project using a weighted average of values for the components of a RAD (bed-disability days (BDDs), work loss days (WLDs), and other RADs). BDDs and WLDs are conservatively valued at the average daily before tax wage for full-time workers (to reflect social opportunity costs) in the reference environments ($69.70 in Tennessee in 1989 dollars, and $73 in New Mexico[6]), while other restricted activity days (which are less severe) are valued as minor restricted activity days (MRADs) ($21.48; Krupnick and Kopp, 1989). Weights are taken from the 1979 Health Interview Survey, with MRADs 38% of RADs. This approach yields a value of a RAD of $51.38 in Tennessee. Respiratory related RADs (RRADs) are valued in the same way, using weights specific to respiratory conditions. In this case, minor respiratory related restricted activity days (MRRADs) are only 21% of total RRADs. Thus, the value of an RRAD is $59.58.[7]

Table 9.4-5. Unit values for particulate-morbidity endpoints (in 1989 dollars) for the Southeast Reference environment

Pathway endpoint	Low	Mid	High
Respiratory hospital admission (Krupnick and Cropper 1989)		$6306	
Emergency room visit (Hagler-Bailly 1988)		178	
Restricted activity day (Krupnick and Kopp 1989)			51
Any symptom-day (Krupnick and Kopp 1989)	3	6	12
Asthma attack-day (Krupnick and Kopp 1989)	11	30	49
Child chronic bronchitis (Krupnick and Cropper 1989)		132	

Emergency room visits were estimated by Hagler-Bailly (1988) as the value of a loss-work day plus medical cost, the latter taken from EPA (1987) as equal to $90 in 1986 dollars. We use this approach updated to 1989 dollars ($178). Hospitalization costs ($6,306 per event in Tennessee) are estimated using Krupnick and Cropper (1989) to obtain a weighted average of hospital cost per hospitalization event for admittances for chronic bronchitis and for emphysema, which is $1,801 in 1977 dollars, plus the value of days lost, equal to weighted average length of

[6]Since the average wage is so similar in the two reference environments, we use the Tennessee wage throughout.

[7]Note that valuing an RRAD higher than a RAD is a departure from the literature. However, an RRAD is more likely to result in a BDD and a WLD than an average RAD.

stay (LOS) times the average daily wage. LOS was 9.1 days for chronic bronchitis and 9.8 days for emphysema (Heart, Lung, and Blood Institute 1982).

We do not have estimates of WTP to avoid an increased annual risk of bronchitis and chronic cough as they apply to children (although we have estimates of medical costs and WTP to reduce risks of chronic bronchitis in adults). However, Krupnick and Cropper (1989) report an estimate of the average yearly medical costs associated with chronic bronchitis in children up to 10 years old. Inflating this 1977 estimate of $42 to 1989 dollars, medical costs are $132. As this estimate of costs is probably a very small percentage of total costs, which would include the value of parent time, pain and suffering, etc., we feel that double-counting is not an issue.

Table 9.4-6 provides low, mid, and high estimates of damage in the Southeast Reference environment by endpoint, aggregate estimates, and mills per kWh. Focusing on midpoint estimates for the Southeast Reference environment only, damages are largest for "any" symptom days ($51,000) and chronic bronchitis days ($15,000). Aggregate damages are about $82,500 annually, or 0.44 mills/kWh.

Table 9.4-6. Particulates morbidity: damages per year (in thousands of 1989 dollars) for the southeast site

Pathway endpoint	Low	Mid	High
Restricted activity day	2.4	11	19
Emergency room visit	0.017	0.22	0.41
Asthma attack-day	0.4	2.6	5.3
Child chronic bronchitis	0.045	0.28	0.52
Child chronic cough	0.0019	0.013	0.032
Respiratory hospital admission	0.082	3.4	7.0
Any symptom-day	22	51	94
Chronic bronchitis in adults	27	15	26
Total pathway damages	49	82	130
Total pathway damages (mills/kWh)	0.27	0.44	0.69

10. NONENVIRONMENTAL IMPACTS AND DAMAGES

10.1 EMPLOYMENT BENEFITS

10.1.1 Increased Employment

Total employment could be increased in an area, if energy crops do not displace agriculture. If agriculture is displaced then the number and type of jobs may not change significantly. For example, some row and close grown crops could be displaced by wood feedstock production. On balance such a change could result in a net loss of labor hours. By contrast, some fallow land, pasture, and hayland could be displaced. This change would result in an increase in labor hours. The growing of short-rotation woody crops is more intensive than these latter land-uses.

Estimating the net changes in employment must explicitly account for the factors that enter a farmer's decision to convert cropland to wood biomass production. This decision is affected by the price of wood feedstocks, the impacts production will have on traditional farm operations (labor and equipment complementarity), and the overall profitability of the farm enterprise. Moreover, the role of government policy (e.g., conservation reserve program, agricultural price supports, etc.) and its effect on wood feedstock operations must be assessed.

The total labor hours required for supplying a wood-fired facility are shown in Table 10.1-1. Production and harvesting labor hours, which are based on average annual equipment operating hours, are about 115,000 hours for the 1990 time period at each site and 80,000 hours for the 2010 time period. The labor hours at each site are about the same because fewer acres in production are offset by more hours required for harvesting because of greater productivity.

Transportation labor hours are also reported in Table 10.1-1. These hours are based on a 20 ton truck delivery load and an assumption of the number of hours required to deliver a load in each time period. It was assumed that a round trip would require 4 hours for the 1990 time period and 3.5 hours for 2010. Average haul distances range from 44 miles for the Southeast Reference site in 1990 to a low of 28 miles for the Northwest Reference site in 2010. Total transport labor hours range are about 42,040 hours in 1990 and 29,190 in 2010.

Table 10.1-1. Total annual labor hours for energy crop production and harvesting

Time Period	Production and harvesting labor hours		
	Hours/acre	Total acres	Total hours
Southeast Reference Site			
1990	2.87	39,930	114,590
2010	3.17	24,910	79,970
Northwest Reference Site			
1990	3.74	30,150	112,780
2010	4.52	17,200	77,760
Time Period	Transportation labor hours		
	Haul tonnage	Loads	Total hours
Southeast Reference Site			
1990	210,220	10,510	42,040
2010	166,830	8,340	29,190
Northwest Reference Site			
1990	210,220	10,510	42,040
2010	166,830	8,340	29,190

The amount labor employed at the conversion facility is derived by Tewksbury (1987), who discusses operations at the McNeil wood-fired generating plant in Burlington, Vermont. For the 1990 and 2010 conversion facilities, operations crews, a maintenance crew, and administrative and management staff will be required to operate the facility. The facility operators are assumed to consist of five 5-man crews. As discussed by Tewksbury (1987), four of the five crews would operate the facility for the normal 24-hour day. The fifth crew is needed to cover vacations, sick-time, and aperiodic maintenance. Each crew would consist of a supervisor (actual operator), a station operator, a fireman responsible for ash removal, and two yardmen responsible for feedstock handling and loading. The maintenance crew would consist of a chief mechanic, a welder, an electrician, recorder and monitor, and a janitor and keeper of stores. The management staff would include a superintendent, assistant superintendent, secretary, and a plant engineer. Total annual labor hours for the conversion facility are summarized in Table 10.1-2.

Table 10.1-2. Total annual labor hours for conversion facilities

Reference time period—Technology	Total annual hours
1990—Whole tree energy	
Operations crews	52,000
Maintenance crew	10,400
Management staff	8,320
Total annual labor hours	70,720
2010—BIG/STIG	
Operations crews	41,600
Maintenance crew	10,400
Management staff	8,320
Total annual labor hours	60,320

Notes: Annual labor hours based on a 2080 workhours per year. For the 2010 technology, operations crews were reduced by 5 personnel.

If it is assumed that wood feedstock production and harvesting displaces traditional agriculture and becomes a new crop in the total farm operation, then net changes in farm employment could be reasonably assume to be zero. Gains in employment for a biomass-to-electricity fuel cycle would come from feedstock hauling and from the conversion facility (assuming that the conversion facility does not displace some other form of power generation).

10.1.2 Net New Employment Benefits

Net new employment benefits that may result from construction of a new biomass power plant in Tennessee or Washington (the two reference environments considered in this study). It is important to note that similar employment benefits will accrue in varying degrees to each fuel cycle. For example, the majority of employment benefits that we identify result from the construction of the facility, and other types of facilities will share similar benefits. Consequently, evaluation of these employment estimates must occur through a comparison between fuel cycles, rather than a direct comparison between these estimates and other damage estimates.

Net new employment opportunities are sometimes described as "employment benefits." New employment opportunities create real (net) benefits only when there exists a situation in which labor resources would otherwise be involuntarily idle or under-utilized. When properly specified, these benefits are equivalent to the difference between society's opportunity cost (or the shadow price) of labor and the private cost of labor (the market wage).

Labor input into the production of new energy services draws labor away from other activities. Economists refer to the value of goods and services that society must forego in order to direct labor into new activity as society's opportunity cost of the labor input, or the shadow price of labor.[1]

In a perfectly competitive economy the wage rate will equal a worker's marginal contribution to the value of what is produced. Hence, the market wage will be a good measure of society's opportunity cost of labor because it will be just sufficient to draw labor away from its next most productive activity. However, when the ideal circumstances that characterize a competitive economy are not satisfied then the opportunity cost of labor will differ from the market wage. For example, persistent unemployment in a specific occupation and region of the country may cause the opportunity cost of labor to be less than the market wage, which may be rigid due to a number of institutional factors.

One assumption special to the biomass fuel cycle has to do with the previous use of the land that would be brought into production, and associated employment that would terminate. Employment associated with the production and harvesting of close crops, corn, hay, row crops and soybean production on average is assumed to be equivalent to that in biomass production and hauling. These land uses represent about 45% of acreage that would be brought into biomass production in the Southeast Reference environment. Consequently, in calculating employment impacts, only 55% of the employment in biomass production and transportation necessary to sustain the power plant is counted as the net employment impact of the power plant. Increased agricultural production in other regions to make up for the deficit in these crops is assumed to be negligible or nonexistant. The remaining acreage brought into biomass production comes from low valued uses, is assumed to be diverted from the conservation reserve program or otherwise is fallow.

In the Northwest, about 58% of the acreage to be brought into biomass production would previously have been in close crops, corn, hay, row crops and soybean production. Accordingly, only 42% of the employment in biomass production and transportation is counted as the net employment impact.

10.1.3 Data and Research Approach

Data for the unemployment rate in thirty-seven industrial categories for the nation and for regions of the country were gathered from annual publications of *Employment and Earnings* and *Geographic Profile of Employment and Unemployment* published by the U.S. Bureau of Labor Statistics.[2] Tables 10.1-3 and 10.1-4 are numerical references to the data presented in these documents. Data for the United States, for the East South Central region which includes the State of

[1]Implicit in this formulation is the idea that social welfare is an aggregation of individual welfare. The concept of opportunity cost includes the value of services flows provided from idle time and nonmarket activities, so in general the opportunity cost of an unemployed person's time is not zero.

[2]These publications actually provide data for thirty-seven industries. The mapping from the reported industries to the thirty-seven industries that are used along with an index of the numerical references are presented in Table 10.1-7.

Table 10.1-3. Matching of the input-output and unemployment table categories

Category in Input-Output Table	Category No. for reference to other tables	Category from which the data was taken in the unemployment data
Agricultural products and agricultural, forestry, and fishery services	1	Farming, forestry and fishing[a]
Forestry and fishery products	2	Farming, forestry and fishing[a]
Coal Mining	3	Mining
Crude petroleum and natural gas	4	Mining
Miscellaneous mining	5	Mining
New construction	6	Construction
Maintenance and repair construction	7	Construction
Food and kindred products and tobacco	8	Food and kindred products
Textile mill products	9	Textile mill products
Apparel	10	Apparel and other textile products
Paper and allied products	11	Paper and allied products
Printing and publishing	12	Printing and publishing
Chemicals and petroleum refining	13	Chemicals and allied products
Rubber and leather products	14	Rubber and misc. plastic products
Lumber and wood products and furniture	15	Average of Lumber and wood products and Furniture and fixtures
Stone, clay, and glass products	16	Stone, clay, and glass products
Primary metal industries	17	Primary metal industries
Fabricated metal products	18	Fabricated metal products
Machinery, except electrical	19	Machinery, except electrical
Electric and electronic equipment	20	Electrical machinery, equip., and supplies
Motor vehicles and equipment	21	Motor vehicles and equipment
Transp. equip., except motor vehicles	22	Transportation equipment (incl. motor v.)
Instruments and related products	23	Prof. and photo equip, watches, etc.
Miscellaneous manufacturing industries	24	Manufacturing Average
Transportation	25	Transportation
Communication	26	Commun. and other public utilities
Electric, gas, water, and sanitary services	27	Commun. and other public utilities
Wholesale trade	28	Wholesale trade
Retail trade	29	Retail trade
Finance	30	Finance, Insurance, and Real Estate
Insurance	31	Finance, Insurance, and Real Estate
Real estate	32	Finance, Insurance, and Real Estate
Hotels and lodging places and amusements	33	Services, excl. households
Personal services	34	Services, excl. households
Business services	35	Professional services
Eating and drinking places	36	Services, excl. households
Health services	37	Medical services, including hospitals
Miscellaneous services	38	Services, excl. households
Households	39	no corresponding entry

[a]Farming, forestry and fishing is an occupational category. All of the other unemployment categories are industrial sectors.

Table 10.1-4. United States unemployment rates by industrial sectors for the years 1981, 1983, 1988-1990[a]

Sector	1990	1989	1988	1987	1986	1985	1983	1981	Average
1	6.2	6.4	7.0	7.1	7.8	8.3	9.9		7.5
2	6.2	6.4	7.0	7.1	7.8	8.3	9.9		7.5
3	4.8	5.8	7.9	10.0	13.5	9.5	17.0	6.0	9.3
4	4.8	5.8	7.9	10.0	13.5	9.5	17.0	6.0	9.3
5	4.8	5.8	7.9	10.0	13.5	9.5	17.0	6.0	9.3
6	11.1	10.0	10.6	11.6	13.1	13.1	18.4	15.6	12.9
7	11.1	10.0	10.6	11.6	13.1	13.1	18.4	15.6	12.9
8	7.1	7.4	8.3	8.6	9.9	9.8	13.1	10.1	9.3
9	5.9	4.9	5.3	6.7	7.6	9.9	9.6	10.6	7.6
10	9.3	8.4	8.2	9.7	10.7	11.4	12.4	11.5	10.2
11	4.1	3.5	3.2	3.9	4.1	4.5	6.8	5.3	4.4
12	4.2	4.0	4.2	4.4	4.8	5.5	6.7	5.4	4.9
13	3.5	3.1	2.9	4.1	6.1	4.7	7.5	5.1	4.5
14	6.2	6.2	5.6	5.4	7.9	7.6	10.8	10.9	7.6
15	7.6	6.1	7.9	8.0	10.3	11.6	15.0	12.6	9.9
16	5.6	5.5	5.8	6.2	7.8	9.6	11.2	8.6	7.5
17	4.9	4.1	4.5	7.3	10.0	11.3	20.0	8.5	8.8
18	7.0	6.6	5.6	7.0	8.3	8.8	14.4	9.6	8.4
19	4.6	3.6	4.1	5.2	6.3	6.2	12.2	5.9	6.0
20	5.6	4.8	4.9	4.9	6.4	7.8	8.9	6.8	6.3
21	9.0	6.2	6.3	7.9	6.9	7.3	12.6	14.7	8.9
22	6.4	4.8	5.3	5.8	5.2	5.8	10.9	5.9	6.3
23	3.9	3.4	3.3	3.9	4.3	4.4	7.0	5.1	4.4
24	5.8	5.1	5.3	6.0	7.1	7.7	11.2	8.3	7.1
25	5.1	5.0	5.2	5.9	6.7	5.9	8.6		6.1
26	2.0	2.2	2.1	2.6	3.0	2.5	3.6	2.3	2.5
27	2.0	2.2	2.1	2.5	3.0	2.5	3.6	2.3	2.5
28	4.5	4.0	4.3	4.5	5.3	5.2	7.5		5.0
29	6.8	6.5	6.7	7.6	8.1	8.2	10.7		7.8
30	3.0	3.1	3.0	3.1	3.5	3.5	4.5	3.5	3.4
31	3.0	3.1	3.0	3.1	3.5	3.5	4.5	3.5	3.4
32	3.0	3.1	3.0	3.1	3.5	3.5	4.5	3.5	3.4
33	7.2	7.0	7.1	7.7	8.8	8.7	11.3	9.4	8.4
34	7.2	7.0	7.1	7.7	8.8	8.7	11.3	9.4	8.4
35	3.2	3.0	3.2	3.6	4.0	4.2	5.5	4.7	3.9
36	7.2	7.0	7.1	7.7	8.8	8.7	11.3	9.4	8.4
37	3.2	3.0	3.2	3.6	4.0	4.2	5.5	4.7	3.9
38	7.2	7.0	7.1	7.7	8.8	8.7	11.3	9.4	8.4

[a]Unemployment rates are taken from Table 5, Geographic Profile of Employment and Unemployment, published by the Bureau of Labor Statistics (BLS), for the years presented above. A blank cell indicates either that the value did not meet BLS reliability standards or that the category definition in that year was inconsistent with the rest of the years.

Tennessee, and for the Pacific region which includes the State of Washington, for selected years between 1981 and 1991, are presented in Tables 10.1-5 and 10.1-6.[3] The averages of these data for each industrial category are presented in the final column of the table. These averages are taken to represent a forecast of the persistent rates of unemployment over the 40-year life of the facility.

The year 1989 is selected as a modern estimate of a full employment period with low inflation. The year 1989 has the lowest average unemployment rate (5.3%) for the U.S. of any year in this period. Inflation for all items less food and energy was 4.5%, the midpoint between 1983 and the present when inflation ranged from 4% to 5% annually.[4] Unemployment rates observed in this year in each industry are taken to be industry-specific natural rates of unemployment.

Johnson and Layard (1986) survey recent estimates of the natural rate of unemployment ranging from 4.7% to 6.5%, and the average rate for 1989 (5.3%) falls well within this range. As an alternative and more conservative estimate, calculations are presented using the year 1987 as a base. The average unemployment rate for the U.S. was 6.2% in 1987, near the upper bound suggested by Johnson and Layard, while inflation was 4.0%, the lowest of any year in the decade.

Unemployment rates are based on rates for the East South Central and Pacific regions as a whole. Although the biomass farm and generation facility are to be located within Tennessee and Washington respectively, the appropriate labor markets include portions of each entire region.[5]

In general the East South Central region has persistently higher rates of unemployment than the national average. Consequently employment benefits are likely to occur even when the nation is "fully employed". The high unemployment rate in the region would be dampened inappropriately by using base year (1989 or 1987) levels of unemployment for the region, so base year levels for the entire U.S. are used.

The unemployment rates that we utilize pertain to the experienced civilian labor force. This will tend to exclude new entrants to the labor market. Also, unemployment numbers are reported by industry rather than by occupation. One occupation may appear in several industries; however, we were not working at a sufficient level of detail to enable us to map from occupation to industry. The existence or direction of a bias in the estimates from this limitation is unclear.

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[3]The years 1982 and 1984 were omitted in these series in order to place greater weight on recent observations.

[4]Energy is excluded because prices have been heavily influenced by international markets. Food is excluded because fluctuations are due in large part to weather.

[5]Myers (1983) investigated population and employment changes in major coal- producing counties during 1973-1979 and concluded that the rapid increase in coal production in the West during this period created job opportunities far in excess of the local labor supply. Many new jobs were filled by workers moving into the coal counties.

Table 10.1-5. East South Central region unemployment rates by industrial sectors for the years 1981, 1983, 1985-1990[a]

Sector	1990	1989	1988	1987	1986	1985	1983	1981	Average
1	5.4	5.5	5.8	6.8	9.1	7.2	10.1	4.5	6.8
2	5.4	5.5	5.8	6.8	9.1	7.2	10.1	4.5	6.8
3	7.6	7.6	8.0	11.5	22.3	11.4	24.2	9.1	12.7
4	7.6	7.6	8.0	11.5	22.3	11.4	24.2	9.1	12.7
5	7.6	7.6	8.0	11.5	22.3	11.4	24.2	9.1	12.7
6	14.8	10.8	13.6	15.5	17.9	18.0	23.7	15.1	16.2
7	14.8	10.8	13.6	15.5	17.9	18.0	23.7	15.1	16.2
8	10.3	7.3	8.6	8.7	11.3	10.8	15.2	10.4	10.3
9	6.5	9.3	6.8	7.1	8.4	12.2	7.5	10.5	8.5
10	7.5	8.7	8.5	13.4	11.8	13.0	12.1	10.5	10.7
11	2.6	3.5	4.7	2.7	2.7	2.1	8.9	5.8	4.1
12	4.3	3.7	4.3	5.2	5.9	6.0	4.5	5.8	5.0
13	2.5	1.3	2.5	3.0	7.2	6.5	7.2	5.0	4.4
14	4.8	3.6	5.5	6.8	6.6	7.3	8.9	6.3	6.2
15	4.8	6.5	9.8	9.1	10.4	12.6	17.4	13.8	10.5
16	8.2	4.3	7.2	7.3	8.7	11.9	14.8	11.6	9.3
17	5.6	5.5	6.6	3.6	10.5	8.5	14.8	10.8	8.2
18	4.0	7.2	4.6	5.8	8.1	10.2	15.1	14.3	8.7
19	7.6	3.7	5.5	6.3	8.1	7.4	11.9	7.0	7.2
20	6.1	5.2	7.8	6.3	9.2	11.3	8.2	11.7	8.2
21	8.1	7.5	7.6	8.9	8.8	7.0	14.7	14.5	9.6
22	8.5	8.8	7.3	8.6	9.0	9.6	17.2	11.2	10.0
23	6.1	6.1	7.2	7.3	9.3	10.4	14.8	11.6	9.1
24	6.2	6.2	7.0	7.7	9.3	10.1	12.7	10.0	8.7
25	4.7	4.3	5.6	7.1	7.8	7.4	9.4	6.7	6.6
26	1.9	2.7	1.9	2.4	3.6	1.7	3.4		2.5
27	1.9	2.7	1.9	2.4	3.6	1.7	3.4		2.5
28	4.7	4.3	4.4	4.6	7.7	4.5	8.7	10.1	6.1
29	7.5	7.8	7.8	8.9	11.3	10.7	14.2	11.3	9.9
30	1.3	3.2	3.0	4.5	4.0	3.0	5.1	4.1	3.5
31	1.3	3.2	3.0	4.5	4.0	3.0	5.1	4.1	3.5
32	1.3	3.2	3.0	4.5	4.0	3.0	5.1	4.1	3.5
33	5.2	5.2	6.1	6.5	7.8	6.5	10.3	6.7	6.8
34	5.2	5.2	6.1	6.5	7.8	6.5	10.3	6.7	6.8
35	3.4	3.8	4.3	4.1	4.8	4.6	7.5	5.1	4.7
36	5.2	5.2	6.1	6.5	7.8	6.5	10.3	6.7	6.8
37	3.3	3.8	4.6	4.7	4.8	5.4	6.7	6.7	5.0
38	5.2	5.2	6.1	6.5	7.8	6.5	10.3	6.7	6.8

[a]Unemployment rates are taken from Table 5, Geographic Profile of Employment and Unemployment, published by the Bureau of Labor Statistics (BLS), for the years presented above. A blank cell indicates either that the value did not meet BLS reliability standards or that the category definition in that year was inconsistent with the rest of the years.

Table 10.1-6. Pacific Region unemployment rates by industrial sectors for the years 1981, 1983, 1988-1990[a]

Sector	1990	1989	1988	1987	1986	1985	1983	1981	Average
1	9.6	9.6	10.7	8.6	11.6	13.5	17.4	13.1	11.8
2	9.6	9.6	10.7	8.6	11.6	13.5	17.4	13.1	11.8
3	5.3	7.8		9.2	11.0	9.2			9.6
4	5.3	7.8		9.2	11.0	9.2			9.6
5	5.3	7.8		9.2	11.0	9.2			9.6
6	10.2	7.8	8.9	10.9	12.3	13.9	19.1	15.5	12.3
7	10.2	7.8	8.9	10.9	12.3	13.9	19.1	15.5	12.3
8	7.6	11.0	11.8	11.1	13.4	14.4	20.0	15.4	13.1
9		9.0	7.8	7.0	7.5	9.4	8.3	10.0	8.9
10	8.2	9.0	7.8	7.0	7.5	9.4	8.3	13.0	8.8
11	2.5	2.5	1.4	3.0	4.3	6.5		5.0	3.6
12	3.7	3.5	5.2	4.4	5.3	6.3	7.2		5.1
13	6.0	4.9	3.2	3.9	6.1	5.2	9.8	5.5	5.6
14	6.0	3.4	5.1	5.0	7.5	13.6	13.1	8.5	7.8
15	9.1	8.1	9.7	5.9	10.2	12.9	16.8	17.1	11.2
16	4.3	6.3	4.7	7.4	5.2	11.3			6.5
17	5.7	4.8	3.3	8.5	12.4	13.2	15.7	11.0	9.3
18	7.5	7.4	5.7	7.8	9.7	10.7	12.5	9.6	8.9
19	4.8	3.7	5.1	5.3	6.5	6.3	9.9	5.6	5.9
20	5.2	4.6	3.1	5.2	6.0	7.1	7.6	5.7	5.6
21	8.7	3.1			5.6	15.2			8.2
22	3.8	2.6	3.5	3.1	3.5	4.3	8.0	5.8	4.3
23	4.4	4.0	3.7	5.3	4.8	4.4	10.6	5.6	5.4
24	5.7	5.4	5.3	5.6	6.9	8.1	11.2	8.3	7.1
25	4.9	5.4	5.5	5.6	6.1	6.2	9.7	7.8	6.4
26	2.3	3.0	2.5	1.9	2.8	3.0	3.8		10.2
27	2.3	3.0	2.5	1.9	2.8	3.0	3.8		10.2
28	4.2	4.4	5.6	4.9	6.0	6.2	9.0		5.8
29	6.3	6.3	6.6	7.2	8.2	8.3	11.0	8.9	7.9
30	3.2	3.0	3.4	3.9	4.2	3.5	4.7	3.2	3.6
31	3.2	3.0	3.4	3.9	4.2	3.5	4.7	3.2	3.6
32	3.2	3.0	3.4	3.9	4.2	3.5	4.7	3.2	3.6
33	5.0	5.0	5.1	5.6	6.6	6.7	8.7	6.2	6.1
34	5.0	5.0	5.1	5.6	6.6	6.7	8.7	6.2	6.1
35	3.3	3.3	2.9	3.9	4.3	4.8	6.3	4.6	4.2
36	5.0	5.0	5.1	5.6	6.6	6.7	8.7	6.2	6.1
37	3.2	3.3	2.6	3.6	3.8	4.4	6.5		3.9
38	5.0	5.0	5.1	5.6	6.6	6.7	8.7	6.2	6.1

[a]Unemployment rates are taken from Table 5, Geographic Profile of Employment and Unemployment, published by the Bureau of Labor Statistics (BLS), for the years presented above. A blank cell indicates either that the value did not meet BLS reliability standards or that the category definition in that year was inconsistent with the rest of the years.

The construction and operation of the facilities in Tennessee and Washington/Oregon will directly stimulate employment in three industries. One is the New Construction industry (6). The construction phase is assumed to entail a \$51.5 million "overnight" construction cost for a 30 MW facility. Expenditures on the operation and maintenance of the facility have been divided according to their fuel component and all other expenditures. The fuel expense is attributed to the Forestry and Farming industry (2). Transportation related costs are subsumed into the fuel expense due to the level of aggregation of the data and analysis. Accounting for reduced employment associated with previous agricultural uses of land brought into biomass production, it is assumed that net new expenses in Forestry and Farming are \$1.79 million annually in the Southeast Reference environment, and \$1.37 million in the Northwest. All other expenses are attributed to the Electricity, Gas, Water and Sanitary Services industry (27), which are assumed to total \$2.52 million annually throughout the 40-year operation of the plant.

Expenditures in these three industries constitute direct (or primary) demand for final goods and services. In addition, secondary demand is created in industries that supply inputs to these primary industries. Finally, induced demand is created in all other industries that create goods and services that will be sought by workers in the primary and secondary industries.[6]

Earnings multipliers for the U.S. reported in Table 10.1-7 reflect the increase in the total annual primary, secondary and induced earnings (wages) that are received by workers in all 38 industries for each dollar of expenditure in the three primary industries. These multipliers are taken from input-output tables provided by the Bureau of Economic Analysis of the U.S. Department of Commerce.[7]

The possible existence of employment benefits–that is, a difference between the opportunity cost of labor and its market wage–depends on the possibility that newly employed workers are drawn from the pool of workers who were previously involuntarily unemployed. This possibility is represented as an S-shaped probability function of the unemployment rate. A precise mathematical expression for this S-function for the midpoint estimate, and for a low and high estimate, is presented in Table 10.1-8. There actually are a family of functions behind each estimate, one

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[6]A possibility for error results from the assignment of expenditures in the primary industries. Expenditures for the ongoing operation of the facility have been broken into two parts, a fuel component and an operations and maintenance component, corresponding to two different categories of expenditures. The fuel component is viewed as an expenditure in the biomass industry, while the operations and maintenance is viewed as an expenditure in an industry that includes electric, gas, water and sanitary services. Some part of an expenditure in the latter industry includes expenditures for fuel, although it will be an average of a variety of fuels from a variety of locations. This double-counting is expected to be minimal because the primary expenditure is not counted twice, but rather how parts of the primary expenditure are spent may be counted twice while other parts are under- counted. On net, it is unclear whether this error will serve to inflate or deflate the estimate of employment benefits.

[7]See *Regional Multipliers: A User Handbook for the Regional Input-Output Modeling System (RIMS II)*, May 1986. Data for unemployment in households are not relevant and they are not included. More detailed input-output tables disaggregated for 531 industries may be obtained from the Bureau of Economic Analysis.

Table 10.1-7. United States input-output coefficients (multipliers). for earnings to industrial sectors[a]

Sector No.	(2) Forestry and fishery services	(6) New construction	(27) Elect. services
1	0.0472	0.0108	0.0050
2	0.0987	0.0004	0.0001
3	0.0016	0.0032	0.0278
4	0.0061	0.0069	0.0229
5	0.0009	0.0039	0.0008
6	0.0000	0.3027	0.0000
7	0.0142	0.0164	0.0329
8	0.0123	0.0121	0.0058
9	0.0049	0.0044	0.0016
10	0.0042	0.0058	0.0027
11	0.0037	0.0062	0.0027
12	0.0064	0.0105	0.0052
13	0.0161	0.0167	0.0111
14	0.0037	0.0074	0.0033
15	0.0022	0.0167	0.0021
16	0.0018	0.0179	0.0019
17	0.0053	0.0202	0.0035
18	0.0088	0.0287	0.0054
19	0.0069	0.0148	0.0080
20	0.0050	0.0174	0.0048
21	0.0023	0.0038	0.0021
22	0.0214	0.0019	0.0013
23	0.0018	0.0029	0.0015
24	0.0012	0.0023	0.0010
25	0.0244	0.0399	0.0310
26	0.0076	0.0139	0.0065
27	0.0050	0.0088	0.1117
28	0.0333	0.0559	0.0228
29	0.0280	0.0662	0.0251
30	0.0179	0.0225	0.0155
31	0.0153	0.0172	0.0118
32	0.0025	0.0042	0.0028
33	0.0053	0.0084	0.0039
34	0.0050	0.0084	0.0048
35	0.0545	0.1044	0.0302
36	0.0109	0.0195	0.0093
37	0.0264	0.0479	0.0227
38	0.0159	0.0253	0.0116
39	0.0016	0.0030	0.0014
Total	0.5303	0.9795	0.4649

[a]These are the earnings multipliers extracted from the three columns of interest in a 39× 39 input-output table provided by the Bureau of Economic Analysis of the U.S. Department of Commerce.

Table 10.1-8. Functional forms to describe the probability that a newly employed person was drawn from the pool of previously unemployed

$$\text{Low: } P = 1 - \sin\left\{\frac{\pi}{2}\left(1 - \beta_1\right)\right\}$$

$$\text{Mid: } P = 0.5\left[\sin\left\{\pi\beta_i - \frac{\pi}{2}\right\} + 1\right]$$

$$\text{High: } P = \sin\left\{\frac{\pi}{2}\,\beta_i\right\}$$

where

P = probability

$$\beta_i = \frac{v_i - h_i}{h^* - h_i}$$

i = pertains to industry *i*.

h_i = natural rate of employment in industry *i*.

h^* = 0.25 for all industries.

v_i = unemployment rate for industry *i*.

for each industry. The S-function depends on the difference between the average unemployment rate for each industry and the base year 1989 unemployment rate (the natural rate of unemployment).[8] The value for this function for each industry in the United States and the East South Central and Pacific regions are presented in Table 10.1-9.

In each case, if some percentage of the newly employed workers will be drawn from the pool of previously idle workers, the market wage will be an overestimate of the social opportunity cost of employment. This difference is the net new

[8] When this difference is negative, it is set equal to zero.

Table 10.1-9. Percent probability that newly employed person was drawn from the pool of previously unemployed (base year 1989)[a]

Sector No.	United States			Pacific Region			East South Central Region		
	Low	Mid	High	Low	Mid	High	Low	Mid	High
1	0.5	0.9	9.5	10.1	19.1	43.8	0.1	0.1	3.4
2	0.5	0.9	9.5	10.1	19.1	43.8	0.1	0.1	3.4
3	4.1	8.0	28.3	2.4	4.8	21.9	15.6	28.7	53.6
4	4.1	8.0	28.3	2.4	4.8	21.9	15.6	28.7	53.6
5	4.1	8.0	28.3	2.4	4.8	21.9	15.6	28.7	53.6
6	4.7	9.2	30.3	2.9	5.8	24.1	20.2	36.3	60.3
7	4.7	9.2	30.3	2.9	5.8	24.1	20.2	36.3	60.3
8	1.4	2.8	16.8	12.6	23.6	48.6	3.4	6.7	25.8
9	2.2	4.3	20.7	4.7	9.3	30.4	4.0	7.9	28.0
10	1.4	2.9	17.0	0.1	0.1	3.5	2.3	4.6	21.5
11	0.2	0.5	6.8	0.0	0.0	0.7	0.1	0.2	4.6
12	0.2	0.5	6.7	0.3	0.7	8.1	0.3	0.5	7.2
13	0.5	1.0	9.8	1.6	3.1	17.7	0.4	0.9	9.3
14	0.7	1.3	11.5	0.9	1.7	13.1	0.0	0.0	0.2
15	4.9	9.6	31.0	8.9	17.1	41.3	6.7	12.9	35.9
16	1.5	2.9	17.2	0.5	1.0	9.8	4.9	9.6	31.0
17	6.2	12.1	34.8	7.6	14.6	38.3	4.8	9.4	30.6
18	1.2	2.4	15.4	1.9	3.7	19.2	1.5	3.1	17.5
19	1.6	3.1	17.6	1.4	2.8	16.8	3.4	6.8	26.0
20	0.6	1.3	11.3	0.2	0.4	5.9	3.5	6.9	26.3
21	2.5	4.9	22.1	1.3	2.6	16.2	4.1	8.0	28.3
22	0.6	1.3	11.3	0.0	0.0	0.0	8.1	15.6	39.5
23	0.3	0.5	7.4	1.0	2.0	14.1	8.5	16.2	40.3
24	1.2	2.4	15.4	1.2	2.4	15.4	3.9	7.6	27.7
25	0.3	0.7	8.3	0.6	1.2	11.0	0.0	1.0	16.7
26	0.0	0.1	2.3	0.1	0.1	3.8	0.0	0.0	2.2
27	0.0	0.1	2.3	0.1	0.1	3.8	0.0	0.0	2.2
28	0.3	0.6	7.8	0.9	1.7	13.1	1.3	2.5	15.8
29	0.6	1.2	11.0	0.7	1.3	11.4	4.2	8.3	28.8
30	0.0	0.0	2.2	0.1	0.1	3.9	0.0	0.1	3.0
31	0.0	0.0	2.2	0.1	0.1	3.9	0.0	0.1	3.0
32	0.0	0.0	2.2	0.1	0.1	3.9	0.0	0.1	3.0
33	0.7	1.5	12.2	0.0	0.0	0.0	0.0	0.0	0.0
34	0.7	1.5	12.2	0.0	0.0	0.0	0.0	0.0	0.0
35	0.2	0.4	6.6	0.4	0.7	8.4	0.7	1.5	12.1
36	0.7	1.5	12.2	0.0	0.0	0.0	0.0	0.0	0.0
37	0.2	0.4	8.6	0.2	0.4	6.5	1.0	2.0	14.2
38	0.7	1.5	12.2	0.0	0.0	0.0	0.0	0.0	0.0

[a]United States unemployment rates for 1989 were taken to represent the natural unemployment rates for these industries.

employment benefit that we seek to measure. A preliminary estimate of the employment benefits associated with each expenditure in a primary industry is obtained by multiplication of the total earnings using the earnings multipliers by the probability that workers are drawn from the pool of previously unemployed workers, and summing for all thirty-seven industries.[9] Finally, this estimate must be adjusted to reflect the opportunity cost of unemployed workers time.

An important feature that differentiates regional earnings multipliers and multipliers for the United States is referred to as the "leakage effect." Some portion of economic activity that is stimulated by the demand for goods and services in a region leaks over that region's borders and stimulates secondary and induced activity in other states. Consequently, multipliers for an individual state will necessarily be smaller than multipliers for a region, which will be smaller in turn than for the entire United States.

The preferred analysis should match earnings multipliers with unemployment rates for the relevant labor market to estimate net new employment benefits. However, earnings multipliers for each region were not available to us given available resources. Therefore, earnings multipliers for the entire United States are used.

The approach we use combines unemployment rates for a region with national multipliers. This will result in an over-estimate of true benefits if the region has higher than average unemployment, because this approach ignores the leakage of earnings to other areas where unemployment may be lower and hence, net employment benefits would be lower. Conversely, this approach will under-estimate true benefits if the region has lower than average unemployment.

The earnings multipliers presented in Table 10.1-7 are for total earnings and capture the sum of primary, secondary, and induced effects. These multipliers are an overestimate for our purposes because they reflect the induced effects for all the primary earnings that result from this investment.

To a significant degree these "respending" effects would have occurred anyway as a result of activity that would engage many workers in the primary industries in their next best employment opportunity. A proper accounting should only include the induced effects that result from net new earnings in the primary and secondary industries. To correct for this problem, we reduce all earnings that occur outside the three primary industries by the ratio of net new earnings over total new earnings that

[9]Krutilla and Haveman (1968, p. 75) cite Marglin (1962) on this point. "[The] appropriate shadow wage rate is the marginal opportunity cost of the force actually drawn from alternative employments [the market wage rate] multiplied by the percentage which this force forms of the total labor employed in this category..." (p. 51).

occur in the primary industries, which represents that portion of induced earnings that are new.[10]

The estimates that are obtained by the process described thus far are preliminary because they do not account for the social opportunity cost of workers previously unemployed. Estimates of the opportunity cost of time for unemployed workers are usually expressed as a fraction of their previous market wage. Unfortunately, existing estimates must be viewed as unreliable for our purposes. Estimates depend on a number of factors including the possibility of flexible working hours (most jobs have a fixed work schedule), whether the worker can maintain a subsistence lifestyle during periods of unemployment, costs of searching for employment, the activities of the worker during periods of unemployment, and the location of residence.[11] Since a worker typically cannot make marginal adjustments to working hours, the true opportunity cost of the worker's time may include an element of consumer surplus flowing from activities during unemployment.

Three alternative estimates of the opportunity cost of an unemployed worker's time are examined in order to illustrate the range of plausible estimates.[12] The most conservative approach is to value time for unemployed workers at after-tax wages. Conversion of before-tax to after-tax rates requires information about the average rates applied to new earnings for each household. Instead, the 1987 average tax rate on individual income (federal and state income taxes and FICA) of 20.8 percent was used.[13] This estimate provides an extreme lower bound on employment benefits, which are equivalent to net new contributions to the public treasury. This estimate is unreliable for at least one important reason. Assuming that the market wage, a worker's reservation wage, and the opportunity cost of time are equal is logically inconsistent with observed persistent unemployment and apparent labor market disequilibrium.

The second approach is to value time for unemployed workers at the estimated minimum wage after taxes. The 1990 after-tax minimum wage was calculated to be $3.42 or about 26% of average hourly earnings across all industries in our model.[14] The third approach is to value the opportunity cost of time at zero. This number is also unreliable, but it serves to provide an upper bound on net employment benefits.

Since potential benefits (negative costs) occur as a flow over time, they must be annualized. The overnight construction cost estimate of $16.4 million is based on

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[10]This approach underestimates secondary effects. Secondary industries are more closely linked to primary industries and are stimulated by the demand for new output in the primary industries, rather than by just the net new respending effects.

[11]For a recent survey of similar issues and the underlying theory, see Shaw (1992).

[12]See Harrington, et. al., 1991, p.106–108.

[13]Calculated from the U.S. Bureau of the Census, 1991, *1991 Statistical Abstract*, 111th edition, Washington, DC. The tax rates for 1990 remain virtually unchanged.

[14]Calculated from the U.S. Bureau of the Census, 1991, *1991 Statistical Abstract*, 111th edition, Washington, DC. The tax rates for 1990 remain virtually unchanged.

1990 dollars. Benefits that are calculated for the construction phase are annualized over all the kilowatt-hours of electricity that are generated by the project using constant 1990 dollars and a real interest rate of 5%. These are added to employment benefits related to fuel and operation which are incurred during each period of operation, so they are already annualized.

10.1.4 Estimates of Employment Benefits

Employment benefit estimates are summarized in Table 10.1-10 for the most persuasive set of assumptions that we identified. These assumptions include using 1989 as a base year index for the natural rate of unemployment, and using unemployment rates for the East South Central and Pacific regions. The opportunity cost of a person's time who was previously involuntarily unemployed is taken to be the after-tax minimum wage. The significance of these and other assumptions on the estimates that are obtained will be discussed further below.

Table 10.1-10. United States employment benefits (mills/kWh)[a]

Sector of output	Low	Mid	High
Southeast Facility			
Forestry and Fishery Services	0.00	0.00	0.06
New Construction	0.19	0.35	0.73
Electric Services	0.00	0.00	0.02
Total	**0.19**	**0.35**	**0.80**
Northwest Facility			
Forestry and Fishery Services	0.11	0.22	0.69
New Construction	0.03	0.05	0.27
Electric Service	0.00	0.00	0.03
Total	**0.13**	**0.27**	**0.99**

[a]1989 Base year natural rate of unemployment and regional unemployment rates.

Each entry in Table 10.1-10 represents the monetary value of net new employment benefits (primary, secondary and induced) for the entire U.S. resulting from expenditures in each primary industry. The first three rows for each reference environment pertain to the three primary industries—biomass production (Forestry and

Fishery Services), new construction and electric services—and the fourth row is the sum of all three. Benefits are presented as mills per kilowatt-hour of electricity that would be produced at the proposed facility. Within each row, three numbers are presented. These are the low estimate, mid estimate, and high estimate, which vary according to the three specifications of the S-function.

The model projects that the mid estimate benefits across all industries due to all spending associated with the project is the shaded number in the final row for each reference environment; or 0.35 mills/kWh for the Southeast Reference environment and 0.27 mills/kWh for the Northwest Reference environment. These numbers are boxed to indicate that they are our preferred midpoint estimates of net new employment benefits according to our analysis.

We have calculated estimates based on alternative assumptions in order to determine the sensitivity of results to each assumption and to provide a judgmental ninety percent confidence interval for this benefit estimate. The assumption about the opportunity cost of an unemployed person's time may be most critical. This opportunity cost is expressed as a function of the market wage, so the employment benefit is changed in direct proportion to the assumption that is made. The estimates we present are based on an opportunity cost estimate that is 26% of the market wage on average. Instead, if one assumes an opportunity cost equal to the after-tax wage, then the midpoint estimate of net new earnings is reduced to obtain a comparable point estimate of 0.10 mills/kWh in the Southeast and 0.08 mills/kWh in the Northwest Reference environments. If an opportunity cost of zero is assumed, then net new benefits equal net new earnings, or 0.48 mills/kWh in the Southeast and 0.37 mills/kWh in the Northwest Reference environments.

The next most critical assumption is the choice of base year. The choice of a base year index is important to the estimates that are obtained because the S-function is nonlinear. A small change in the definition of the natural rate of unemployment for each industry has a relatively large effect on the estimate of employment benefits. Using 1987 as the base year in the Southeast Reference environment, the midpoint estimate of total employment benefits as a result of expenditures in all three primary industries is 0.24 mills/kWh, or about two-thirds of that obtained when 1989 is used as a base year. Using 1987 as the base year in the Northwest Reference environment produces a midpoint estimate of 0.18 mills/kWh, again about two-thirds of that obtained when 1989 is used as a base year.

Another assumption that proves unimportant is the recognition of regionally specific benefits associated with persistent unemployment in a particular region. Application of unemployment numbers for the East South Central region and use of earnings multipliers for Tennessee does not change the midpoint estimate. On the other hand, application of unemployment numbers for the entire U.S. reduces the midpoint estimate to 0.09 mill/kWh. The reason is that higher than average unemployment rates in New Construction in the East South Central region and

Forestry and Fishery Services in the Pacific Region are leading to higher benefit estimates from a regional perspective.

In order to construct a reasonable confidence interval for the point estimate of employment benefits, one can not in general combine reasonable conservative or generous assumptions for each relevant parameter and feed these into the model. The actual level of confidence that is generated by combinations of assumptions depends in a complicated way on the nature of the underlying probability distributions. Absent the resources to conduct a sophisticated uncertainty analysis using Monte Carlo sampling methods, we have to exercise judgement to identify the endpoints for a 90% confidence interval.

Our basic estimate of a 90% confidence interval is represented well by the low and high estimates. In the Southeast, for the upper bound of 90% confidence interval for employment benefits 0.80 mills/kWh is selected, the high point estimate presented in Table 10.1-10 under the basic set of assumptions. For the lower bound we select 0.19 mill/kWh. The low point estimate under the basic set of assumptions in the Northwest we also select the range of estimates under the basic set of assumptions for a judgmental 90% confidence interval, is assumed to range from 0.13 mills/kWh to 0.99 mills/kWh.

Our reasoning for the selection of our preferred midpoint estimate and the 90% confidence interval is the following. The set of assumptions for this example are the most persuasive. These include the use of 1989 unemployment rates by industry as the definition of an index of the natural rate of unemployment because this rate is closer to the midpoint of the range provided in the literature. For almost two-thirds of the industries the unemployment rate in 1989 across the U.S. was the lowest observed in the decade, while 1989 was also within a period of low inflationary pressures. The inflation rate in 1989 was the midpoint observed between 1983 and the present. We note that the natural rate of unemployment is not likely to be much less than this index provides. On the other hand, the calculation of projected unemployment rates is fairly conservative. We have truncated the observations that are the basis for this projection at 1981, leaving out many years of relatively high unemployment in the 1970s. In addition, we have assigned greater weight to observations toward the end of the last decade, a period of unusually stable economic performance.

The possibility that the estimate we obtain is an underestimate is best captured by the high value for the S-function under the strongest assumptions we can make about other variables. This bound reflects, in particular, the great uncertainty in this analysis surrounding the actual search process for employment opportunities. It also stands in for the possibility that unemployment could be greater than we have projected, which we think is more likely than for it to be less than we projected.

The possibility that we have obtained an overestimate is best captured by the alternative assumption using 1987 as a base year for the natural rate of unemployment. It seems to use that the distribution of true values is somewhat skewed, and although the 1989 index is the expected value there is considerable probability mass around a greater index (the median of this distribution is greater than the mean, in our minds). This estimate also stands in for the possibility that the true opportunity cost of unemployed labor is greater than the after-tax minimum age. It is noteworthy that this estimate is close to the low point estimate provided under the basic set of assumptions in Table 10.1-10.

In the Southeast, the range of the confidence interval from 0.19 to 0.80 mills/kWh should be taken as a measure of the uncertainties that are embedded in this analysis. On the other hand, this range and our identified midpoint estimate of 0.35 mills/kWh indicate our confidence that employment benefits are significant. Similarly, in the Northwest the 90% confidence interval between 0.13 and 0.99 mills/kWh, and the midpoint estimate of 0.27 mills/kWh indicate that the true value is greater than zero. These numbers represent about 3% of total (primary, secondary, and induced) earnings generated by this project.

10.2 AESTHETIC ISSUES

The conversion of about 40,000 acres of land at the Southeast Reference site in 1990 and lesser amounts at the Northwest Reference site may have numerous effects on the local economy. For example, supplying 161,450 dry tons/year (or about 201,820 wet tons) will require that, on average, approximately 40 trucks enter and leave the facility each day (assuming 250 delivery days and a 20 wet ton load). This means that 4 truck loads will be delivered per hour on a 10 hour schedule. This level of truck traffic should not present an aesthetic or noise problem. However, Frankena (1987) cautions that there has been opposition to wood-fired facilities that threaten the quality of the rural environment.

There may also be impacts resulting from changes in land use and ownership patterns. However, at the outset it was decided that energy crops would be viewed as a secondary crop occupying only 5 of the suitable land base. This low level of penetration should avoid competition with major agricultural crops yet make energy production a significant part of the local economy. Of course, specific impacts will depend on the relative economics of energy crops as compared with traditional crops and the influence of governmental policy on energy and agriculture. The nature of any impact depends on whether energy crops displace some existing crop or whether energy crops are grown in addition to current agricultural production.

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APPENDICES

APPENDIX A
BIOMASS-TO-ELECTRICITY FUEL CYCLE: TECHNOLOGY CHARACTERIZATION AND EMISSIONS

1. INTRODUCTION

This appendix provides more details of the fuel cycle characterization, boundary assumptions, and emissions than is contained in the main text of the report. The emissions and/or assumptions that are required to estimate ecological, health, and nonenvironmental impacts and damages are summarized in Table 1. The organization of this Appendix follows the stages of the biomass fuel cycle. The next section discusses the reference sites and data. Subsequent sections discuss feedstock production, feedstock transport, and electricity generation.

Table 1. Emissions and other residual effects characterized by fuel cycle stage

Feedstock production and harvesting	Feedstock transport	Electricity generation
Air emissions from equipment operations: VOCs, CO, NO_x, SO_x, PM, CO_2, fertilizers, pesticides	Air emissions from feedstock hauling: VOCs, CO, NO_X, SO_x, PM, CO_2	Air emissions from conversion plant stack: VOCs, CO, NO_x, SO_x, PM, CO_2
Water effluents from feedstock production; fertilizers, pesticides suspended solids, biogenic VOCs, biogenic CO_2	Water effluents from feedstock hauling: none assessed	Water effluents from conversion plant: none assessed
Land effects from feedstock production: fertilizers, pesticides, soil erosion, habitat change, biodiversity	Land effects from feedstock hauling: road damage	Land effects from conversion plant: ash disposal
Other effects employment, health and safety, aesthetic issues	Other effects employment	Other effects: employment, health and safety, aesthetic issues

Notes: VOCs—volatile organic compounds; SO_x—sulfur oxides; CO—carbon monoxide; PM—particulate matter; NO_x—nitrogen oxides; CO_2—carbon dioxide.

2. DESCRIPTION OF REGIONAL REFERENCE SITES, SOCIOECONOMIC BASE, AND THE ENVIRONMENT

2.1 DESCRIPTION OF REGIONAL REFERENCE SITES

The National Resources Inventory (NRI) was used to assess the capability of land for growing woody biomass feedstocks for each reference site (SCS 1987). The NRI data base provides estimates of the extent of land and water, current land uses, conservation treatment needs, amounts of soil loss from water and wind, the potential cropland, the extent of flood-prone areas, and other conservation related data. County level data were extracted from the NRI based on criteria or filters established by Graham (1992). These filters were used to eliminate unsuitable or incompatible land uses. Land was excluded if it had any of the following characteristics:

- Land not classified by the Soil Conservation Service (SCS) as cropland or not having a high to medium conversion potential (to cropland).
- Land considered a riparian area (i.e., natural streambanks, manmade canals or ditch banks, natural or manmade ponds or lake shoreline, or a tidal area shoreline).
- Pasture, range or forest land with a woody canopy cover of more than 55%, if currently classified as pasture, range, or forest land.
- Land with a wetness limitation or described as being a "seasonally flooded basin or flat" or as "inland fresh meadow." (Excludes all swamp, marsh, bog, and open waters.)
- Cropland secondarily classified as "horticulture" (i.e., fruit, nut, vineyard, berries, etc.), "other vegetables" (i.e., truck farms), or "aquaculture".
- Land classified with a current land use of residential, commercial, industrial, institutional, wilderness, wildlife, recreation, nature, study, research and experimentation, or roads and railways.
- Land owned by the Federal Government.
- Land in capability classes V, VI, VII, and VIII.

The amount of wood that can be grown on the capable land within the surrounding area of a reference site was partly addressed by Graham (1992). Graham provides estimates of the amount of wood, measured in terms of annual productivity (dry tons/acre), that might be grown in the U.S. using best management practice (i.e., best current genotype, fertilization, weed control, and planting densities). These estimates were based on expert opinion of nineteen researchers, who provided productivity estimates for each major biomass production growing region by agricultural class and subclass. Their results showed an obvious correlation between capability class, subclass (available moisture) and biomass productivity. Higher biomass yields are associated with higher land classes and wetter sites within any given land class.

The lowest yields are on the class III and IV sites with subclass designations of erosive and shallow. Although these subclasses can be used to grow wood the potential productivity is sufficiently low that they could produce feedstocks at economically competitive costs. Imposing a minimum productivity requirement of 4 dry tons/acre would eliminate marginal or uneconomic production sites. Research has clearly demonstrated that the single most important factor in determining the economic viability of a wood energy plantation is productivity (Perlack et al. 1986). Moreover, sensitivity analyses consistently show productivity being more important than land costs or rents and factor input costs. In fact, higher productivity tends to offset any marginal increases in land rents attributable to higher agricultural capability classes.

How well this 1980s data may reflect 2010 land use for both reference sites is uncertain. A comparison between the 1982 NRI and the 1987 NRI shows that land use statistics and capability changed less than 1% (Graham, 1992).

2.1.1 Southeast Reference Site

The Southeast Reference site is the Clinch River Breeder Reactor (CRBR) in Roane County, Tennessee. This site is analyzed for the purpose of illustrating the damage function approach (DFA) methodology. While the area is technically a viable location for growing trees, the economics of growing trees at this upland area are marginal. The soils are generally poor and lack sufficient moisture and nutrients to support high biomass growth. High biomass growth is essential for production of low-cost feedstocks (Perlack and Ranney 1987). The best locations (fertile soils and ample moisture) for growing trees in the Southeast are the bottomlands, Coastal Plains, and some upland sites provided soil depth and moisture are adequate (Wright et al. 1991). Although the Southeast Reference site is an unlikely candidate for an actual biomass power plant, the *analytical methods* that apply to it are equally applicable to any site.

Although the reference area lacks good sites for high biomass growth, trees can be grown on land that is currently used for secondary agricultural crops, pasture and hayland, and fallow land. All of this land is classified by the SCS as cropland or potential cropland. Land capability data were extracted from the NRI for counties along the Tennessee River Valley within 75 miles of the conversion facility.

The extracted NRI data are summarized in Table 2. The data show that most of the land (nearly 56%) is class II erosive. That is, the land may have an erosion

Table 2. Land use for the Southeast Reference site

Agricultural class/subclass and landuse		Acres (000s)	% of total	Erosion (tons/acre)	Productivity (tons/acre)	
					1990	2010
I	closecrop	4.3	0.3	0.8	5.5	8.0
I	corn	7.8	0.5	2.5	5.5	8.0
I	fallow	9.9	0.6	0.3	5.5	8.0
I	forest	1.2	0.1	0.2	5.5	8.0
I	hayland	12.2	0.8	0.1	5.5	8.0
I	pasture	59.6	3.8	0.2	5.5	8.0
I	soybeans	13.2	0.8	3.1	5.5	8.0
IIe	closecrop	18.7	1.2	6.9	4.5	5.0
IIe	corn	71.4	4.5	10.1	4.5	5.0
IIe	fallow	26	1.7	2.8	4.5	5.0
IIe	forest	25.8	1.6	0.1	4.5	5.0
IIe	hayland	58.2	3.7	0.3	4.5	5.0
IIe	pasture	193.5	12.3	0.2	4.5	5.0
IIe	rowother	11.8	0.8	14.5	4.5	5.0
IIe	soybeans	73.5	4.7	12.0	4.5	5.0
IIs	corn	1.2	0.1	1.0	4.5	5.0
IIs	fallow	1.2	0.1	0.2	4.5	5.0
IIs	hayland	2.3	0.1	0.0	4.5	5.0
IIs	pasture	8.4	0.5	0.0	4.5	5.0
IIs	soybeans	3.6	0.2	7.6	4.5	5.0
IIw	closecrop	8.3	0.5	2.8	5.5	8.0
IIw	corn	29.4	1.9	4.3	5.5	8.0
IIw	fallow	13.1	0.8	1.9	5.5	8.0
IIw	forest	3.6	0.2	0.1	5.5	8.0
IIw	hayland	17	1.1	0.2	5.5	8.0
IIw	pasture	80.9	5.1	0.1	5.5	8.0
IIw	rowother	2.9	0.2	5.2	5.5	8.0
IIw	soybeans	22.3	1.4	3.6	5.5	8.0
IIIw	closecrop	1.7	0.1	7.1	4.0	6.0
IIIw	corn	4.3	0.3	4.1	4.0	6.0
IIIw	fallow	6.1	0.4	1.6	4.0	6.0
IIIw	forest	2.5	0.2	0.1	4.0	6.0
IIIw	hayland	10.1	0.6	0.0	4.0	6.0
IIIw	pasture	32.3	2.1	0.1	4.0	6.0
IIIw	soybeans	8.2	0.5	6.7	4.0	6.0
IVw	closecrop	1.2	0.1	5.1	4.0	6.0
IVw	corn	1.2	0.1	2.3	4.0	6.0
IVw	fallow	0.6	0.0	1.2	4.0	6.0
IVw	forest	0.9	0.1	0.1	4.0	6.0
IVw	hayland	1.7	0.1	0.2	4.0	6.0
IVw	pasture	5.5	0.3	0.3	4.0	6.0
IVw	soybeans	2.4	0.2	6.1	4.0	6.0

Notes: Subclasses e, s, and w denote erosive, shallow, and wet soils, respectively. Estimates of productivity are from Graham (1992) and English et al. (1992). Productivity estimates in 2010 reflect the use of tree species genetically improved for faster growth.

hazard or may have substantial damage from previous erosion. About 13% of the suitable land base is class I having no major restrictions for growing tree crops. Nearly 30% of the suitable land base is subclass w for classes II, III, and IV. This land has excess water that may be caused by poor drainage, wetness, high water table, and flooding. However, the availability of moisture makes this land appropriate for tree production. Class III and IV land having erosive or shallow soils are not listed in Table 2 because this land cannot support wood production in excess of 4 dry tons/acre. The dominant land uses are pasture (45%) and row crops (28%). The row crops are mostly corn and soybeans. About 12% of the current land use is classified by the SCS as hayland. Extracted NRI data show that less than 4% of the land base is forest land with a canopy cover of less than 55%.

2.1.2 Northwest Reference Site

A similar approach was used to characterize land use data for the Northwest Reference site. These data are summarized in Table 3. The Northwest Reference site is different from the Southeast Reference site in that only 15.5% of the land is class II erosive. Most of the suitable land base is class II with a wetness limitation, which is beneficial for tree production. Relative to the Southeast Reference site there is a smaller percentage of class I land but a much higher percentage of lower class land having wetness limitations. Erosive and shallow land in capability classes III and IV are not included because of low tree growth.

Current land use for the Northwest Reference site is similar to the Southeast Reference site in that there are two dominant uses. However, instead of row crops the Northwest Reference site has close grown crops (wheat, barley, etc.) and pasture. These two crops account for over 70% of current use. There is less fallow land and a higher percentage of forest land (less than 55% canopy) relative to the Southeast Reference site.

2.2 SOCIOECONOMIC AND ENVIRONMENTAL DESCRIPTORS

Socioeconomic descriptors include population, economic base (employment and income), housing, government services, transportation, land use, water sources, and historic, cultural and archaeological features. Environmental descriptors include the hydrology of both surface water and groundwater, water quality, meteorology, air quality, noise, geology and seismology, aquatic ecology, and terrestrial ecology. The information in this section describes the types and sources of data that can be used to obtain information at other sites.

Table 3. Land use for the Northwest Reference site

Agricultural class/subclass and landuse		Acres (000s)	% of total	Erosion (tons/acre)	Productivity (tons/acre)	
					1990	2010
I	closecrop	44.3	2.7	0.7	7.0	10.0
I	corn	3.1	0.2	0.9	7.0	10.0
I	fallow	0.8	0.0	1.1	7.0	10.0
I	hayland	4.8	0.3	0.1	7.0	10.0
I	pasture	15.4	1.0	0.1	7.0	10.0
I	rowother	0.9	0.1	0.9	7.0	10.0
IIe	closecrop	85.3	5.3	3.0	4.5	5.0
IIe	corn	2.7	0.2	2.0	4.5	5.0
IIe	fallow	1.8	0.1	2.3	4.5	5.0
IIe	forest	38.5	2.4	0.1	4.5	5.0
IIe	hayland	32.6	2.0	0.5	4.5	5.0
IIe	pasture	88.8	5.5	0.4	4.5	5.0
IIe	range	0.6	0.0	1.5	4.5	5.0
IIs	closecrop	10.5	0.6	0.5	4.5	5.0
IIs	corn	5.4	0.3	1.3	4.5	5.0
IIs	fallow	7.2	0.4	0.3	4.5	5.0
IIs	forest	0.9	0.1	0.0	4.5	5.0
IIs	hayland	4.4	0.3	0.1	4.5	5.0
IIs	pasture	12.0	0.7	0.0	4.5	5.0
IIs	rowother	2.1	0.1	0.3	4.5	5.0
IIw	closecrop	320.7	19.8	1.1	7.0	10.0
IIw	corn	40.4	2.5	1.5	7.0	10.0
IIw	fallow	43.6	2.7	0.6	7.0	10.0
IIw	forest	29.2	1.8	0.3	7.0	10.0
IIw	hayland	66.7	4.1	0.2	7.0	10.0
IIw	pasture	186.3	11.5	0.1	7.0	10.0
IIw	rowother	21.3	1.3	0.9	7.0	10.0
IIIw	closecrop	94.4	5.8	0.6	7.0	10.0
IIIw	corn	4.5	0.3	1.0	7.0	10.0
IIIw	fallow	7.7	0.5	0.6	7.0	10.0
IIIw	forest	30.3	1.9	0.1	7.0	10.0
IIIw	hayland	44.2	2.7	0.1	7.0	10.0
IIIw	pasture	130.7	8.1	0.1	7.0	10.0
IIIw	range	5.8	0.4	0.1	7.0	10.0
IIIw	rowother	3.7	0.2	1.8	7.0	10.0
IVw	closecrop	126.9	7.8	0.4	5.5	8.0
IVw	corn	2.2	0.1	0.9	5.5	8.0
IVw	fallow	3.4	0.2	0.4	5.5	8.0
IVw	forest	30.2	1.9	0.0	5.5	8.0
IVw	hayland	21.7	1.3	0.1	5.5	8.0
IVw	pasture	41.7	2.6	0.3	5.5	8.0
IVw	rowother	0.4	0.0	0.3	5.5	8.0

Notes: Subclasses e, s, and w denote erosive, shallow and wet soils, respectively. Estimates of productivity are from Graham (1992) and English et al. (1992). Productivity estimates in 2010 reflect the use of tree species genetically improved for faster growth.

2.2.1 Socioeconomic Descriptors

Socioeconomic descriptors of a region include population, economic base (employment and income), housing, government services, transportation, water sources, and historic, cultural, and archaeological features. These data are discussed below.

Population. U.S. Bureau of the Census population data were used to derive population densities for both site-specific areas. Population data for the area near the site are available in specified distance intervals in 16 directions. These population figures were used as a proxy for the Southeast Reference site. These are data from 1990 U.S. Bureau of the Census data. The total number of people within 50 miles of the plant was estimated to be 943,037. Tables 4 and 5 contain incremental and cumulative populations, respectively, for given distances. For the Northwest Reference site, population numbers in distance increments from the plant are not available. Therefore, the total population within a 50-mile radius was estimated with U.S. Bureau of the Census county-level data (1990). The estimated proportions of the counties lying within a 50 mile radius of Camas at the Northwest site was applied to county population figures to derive an estimated population of 1,655,333 within 50 miles of the biomass plant. There are several additional sources of population data, at differing levels of detail and aggregation. The U. S. Department of Commerce publication *Census of Population and Housing, Census Tract Reports* (1980) contains population characteristics at the census tract level. These characteristics include age cohorts, sex, marital status, and race. Census tracts are defined for Standard Metropolitan Statistical Areas (SMSAs). Although the Southeast Reference site in Roane County does not lie within the Knoxville SMSA, much of the surrounding area does. The Northwest Reference site is within the Portland, Oregon SMSA.

Economic Base, Housing, and Services. The *Characteristics of the Population, General Social and Economic Characteristics* contains county-level information on such characteristics as employment (by occupation and industry) and income. State sources of various social and economic variables, at the county-level, are the state statistical abstracts (i.e., the *Washington State Data Book* and the *Tennessee Statistical Abstracts*). These publications contain data on population, income, employment, housing, and services.

The *Washington State Data Book* contains State- and county-level employment and wage data by industry. The *Tennessee Statistical Abstract* contains county-level employment by occupation and average wages. Additionally, the Bureau of Labor Statistics publishes employment, hours, and earnings data by State and selected areas within states.

Table 4. Incremental counts of people by radial distance and sector direction, Southeast Reference site

Sector	Miles									
	0–1	1–2	2–3	3–4	4–5	5–10	10–20	20–30	30–40	40–50
N	652	358	1,314	1,105	330	667	2,092	4,808	4,935	12,749
NNE	0	973	1,759	2,039	3,047	2,196	9,703	21,050	8,411	6,988
NE	0	682	874	550	778	5,925	11,429	8,274	6,292	14,392
ENE	0	0	0	0	0	4,333	30,995	21,892	11,581	21,618
E	0	0	0	205	909	5,270	123,499	58,872	17,884	18,495
ESE	0	0	122	883	325	5,482	59,542	24,080	17,733	14,330
SE	0	0	0	93	270	9,088	9,966	50,783	2,185	555
SSE	0	0	0	282	153	3,524	5,320	9,475	1,032	1,116
S	0	0	0	120	24	1,687	11,884	6,299	8,252	4,618
SSW	0	0	0	0	0	891	8,602	11,745	14,458	27,471
SW	0	0	0	0	0	112	5,910	4,646	8,171	9,873
WSW	0	0	0	391	0	431	18,410	12,238	6,944	5,519
W	0	211	323	418	155	1,971	5,377	2,465	6,325	19,948
WNW	441	371	1,300	674	286	1,936	5,244	3,616	2,689	5,599
NW	464	755	2,837	333	1,172	965	1,401	1,795	4,760	7,918
NNW	351	477	928	1,365	505	481	312	3,008	11,095	7,806
Total	1,908	3,827	9,457	8,458	7,954	44,959	309,686	245,046	132,747	178,995

Table 5. Cumulative counts of people by radial distance and sector direction, Southeast Reference site

Sector	Miles									
	0–1	0–2	0–3	0–4	0–5	0–10	0–20	0–30	0–40	0–50
N	652	1,010	2,324	3,429	3,759	4,426	6,518	11,326	16,261	29,010
NNE	0	973	2,732	4,771	7,818	10,014	19,717	40,767	49,178	56,166
NE	0	682	1,556	2,106	2,884	8,809	20,238	28,512	34,804	49,196
ENE	0	0	0	0	0	4,333	35,328	57,220	68,801	90,419
E	0	0	0	2 05	1,114	6,384	129,883	188,755	206,639	225,134
ESE	0	0	122	1,005	1,330	6,812	66,354	90,434	108,167	122,497
SE	0	0	0	93	363	9,451	19,417	70,200	72,385	72,940
SSE	0	0	0	282	435	3,959	9,279	18,754	19,786	20,902
S	0	0	0	120	144	1,831	13,715	20,014	28,266	32,884
SSW	0	0	0	0	0	891	9,432	21,238	35,696	63,167
SW	0	0	0	0	0	112	6,022	10,668	18,839	28,712
WSW	0	0	0	391	391	822	19,232	31,470	38,414	43,933
W	0	211	534	952	1,107	3,078	8,455	10,920	17,245	37,193
WNW	441	812	2,112	2,786	3,072	5,008	10,252	13,868	16,557	22,156
NW	464	1,219	4,056	4,389	5,561	6,526	7,927	9,722	14,482	22,400
NNW	351	828	1,756	3,121	3,626	4,107	4,419	7,427	18,522	26,328
Total	1,908	5,735	15,192	23,650	31,604	76,563	386,249	631,295	764,042	943,037

Transportation. For transportation, the CRBR Environmental Impact Statement (EIS) provides a listing of major roads, railroads, and airports for the Southeast Reference environment. The same information is available for the Northwest Reference environment from the Washington Department of Transportation.

Fishing. Recreational fishing is addressed in what is known as the "Creel Survey." Most States maintain a "Creel Survey." The survey contains several variables: fishing pressure (measured in trips/acre, hours/lake, or fish/acre), catch per unit of effort (both lake wide and for intended species), total estimated harvest size and average fish size. The data are too voluminous to present in this document, but a "Creel Survey" is available from the Tennessee Wildlife Resources and the Fish Management Division of the Washington Department of Wildlife.

Water Use. Water use information pertinent to the Southeast site is in the CRBR EIS. Information on water use is also available, for both sites, in the sources listed below for water quality.

Other Sites and Structures. The EIS for the CRBR lists historic and archeological sites, as well as natural landmarks. Additionally, historical sites may be obtained from the Tennessee Historical Commission and from the Tennessee Department of Environment and Conservation. The Washington Office of Archaeology and Historic Preservation maintains an inventory of historical and archaeological sites.

A final variable of interest is the stock of buildings for an area, in terms of the materials of which the buildings are made, for the purposes of evaluating the physical damage caused by pollutants.

2.2.2 Environmental Descriptors

Hydrology. Hydrology data for the Southeast Reference site are available from the Tennessee Valley Authority (TVA). An additional source is the Division of Public Water Supply in the Tennessee Department of Health and Environment. For the Northwest Reference site, the data source is the United States Geological Survey (USGS).

The Environmental Protection Agency (EPA) maintains and updates a water quality data base, for surface and ground water, called STORET. STORET contains information on a multitude of variables, among which are geographic data about water quality, the water's physical and chemical characteristics, municipal waste sources and disposal systems, pollution-caused fish kills, and daily stream flow. If desired, hydrological data obtained from a source other than STORET can be matched with STORET data by dates and times. Additionally, the Tennessee

State Division of Public Water Supply performs regular chemical analyses on all public water supplies.

Meteorology. Meteorological data (e.g., temperature, wind direction and speed, precipitation, and incidents of hurricanes and tornadoes) are available from the National Oceanic and Atmospheric Administration (NOAA). There is a publication titled *Climates of the States* (1985) that contains NOAA data for each State for selected weather stations. According to the Southeast Reference site EIS, for a nearby weather station, mean average annual temperature is 58.5°F, annual relative humidity is 70%, and average annual precipitation is 51.52 inches. Wind speed and direction distributions (wind roses) for the Southeast plant site are used in the air dispersion modeling. The closest weather station to Camas is located in Vancouver, Washington, which is approximately 15 miles northwest of Camas. According to *Climates of the States* (1985), mean average annual temperature is 51.9°F and mean annual precipitation is 41.07 inches for the Vancouver weather station.

Other meteorological variables of interest include mixing height, the ambient ratio of VOC to NO_x, and visibility. A source for mixing height data has been identified as a book by G. C. Holzworth (1972). An EPA (1989) document contains information on using ambient monitoring data to derive the VOC/NO_x ratio. Currently, researchers at the University of Tennessee, Knoxville and the Tennessee Air Pollution Control Division of the Department of Health and Environment are working on the issue of the sensitivity of ozone to changes in VOC and NO_x. Finally, the Office of Technology Assessment (1984) published a report that contains a map of the U.S. with visibility ranges. According to this report, the visibility for the Southeast Reference site area is approximately 20 miles and for the Northwest Reference site, visibility is approximately 15 miles.

Air Quality. Air quality data are from the National Air Data Branch of EPA. The specific data base is EPA's Aerometric Information Retrieval System (AIRS). This data base contains observations for the six criteria pollutants, by monitoring station, as well as observations for a variety of toxics. EPA also has a Toxic Release Information System (TRIS) data base. This data base includes emissions to air and water from certain manufacturers.

An emissions inventory of ozone precursors for counties in middle and west Tennessee was obtained from the University of Tennessee, Department of Environmental Engineering. These emissions are used in the ozone modeling for the Southeast Reference site (University of Tennessee 1990). A description of the ozone modeling is contained in Appendix B.

Noise. Baseline noise levels for the two reference sites are unavailable.

Geology. The geology and seismology of the southeast site is found in the CRBR EIS. The geology and seismology of the northwest site would need to be investigated further if any analysis required those parameters.

Biodiversity. For the biodiversity of the area, including both aquatic and terrestrial ecology, threatened and endangered species are generally of greater concern. For the Southeast Reference site, the CRBR EIS contains a list of threatened or endangered species. The Ecological Division of the Tennessee Department of Conservation has data on species that are threatened, endangered, of special concern, or that have been deemed in need of management. The Nongame Data Systems of the Washington Department of Wildlife maintains an inventory of threatened and endangered animal species. The Washington Department of Natural Resources maintains a similar data base for plant species.

3. CHARACTERIZATION OF THE BIOMASS FUEL CYCLE

The biomass-to-electricity conversion facilities are fueled with feedstocks grown exclusively for power generation. The wood feedstocks are produced using short-rotation woody crop (SRWC) methods. SRWC methods use fast-growing hardwood trees, short cutting cycles of five to eight years, a planting density of about 700 trees/acre, intensive weed control, and fertilization. The managed tree plantations also rely on coppicing (i.e., regrowth from cut stumps) to regenerate succeeding biomass stands. After six years of growth, trees are harvested, stored, and transported to a facility for conversion to electricity. This section characterizes the fuel cycle in sequence, beginning with feedstock production operations, transport (haul distances and land requirements), and conversion technology.

3.1 FEEDSTOCK PRODUCTION

3.1.1 Species Selection and Productivity

The Lake States, the Southeast, the Pacific Northwest, the Northeast, the Central Great Plains, the Midwest, and subtropical areas of southern Florida and Hawaii are the regions where the conditions for managed tree plantations look most favorable. In these regions, trees have been screened and selected for rapid early growth, high productivity, wide site adaptability, ease of establishment, high stress tolerance, and coppice (regrowth) potential. Since 1978, over 125 species have been evaluated for these characteristics, resulting in a list of about 20 candidate species including 5 prime species—poplar, black locust, sycamore, sweetgum, and silver maple (Wright et al. 1991).

Research has been aimed at determining the extent of natural variation within these screened and selected species and the possibilities for genetic improvement. Species with a significant amount of genetic diversity can offer the greatest potential for improvements in productivity, adaptability, and tolerance. It is estimated by staff of The Department of Energy's (DOE's) Biofuels Feedstock Development Program (BFDP) that these energy crop systems offer at a minimum a 100% increase in production rates over the conventional forest management systems. Based on data taken from experimental research plots, SRWC grown of cropland having only moderate site limitations (Classes I, II, and III) currently produce average annual yields ranging of 4.5 dry tons/acre in the Northeast, 5.0 dry tons/acre in the South/Southeast and the Midwest/Lake States, and 7.5 dry tons/acre in the Pacific Northwest and Subtropics (Wright 1993, 1994).

3.1.1.1 Southeast Reference Site Feedstock

The tree species of choice in the Southeast region are sycamore (*Platanus* occidentalis) and sweetgum (*Liquidambar* styraciflua) (Wright et al. 1991). Although sycamore grows better on bottomland sites, it can be grown successfully on upland sites that have good fertility, moisture, and drainage. Sweetgum has greater tolerance to drought and weed competition and can tolerate seasonally wet soils. These tree species have been the focus of much of the genetic improvement studies focused in the Southeast. Black locust (*Robinia* pseudoacacia) is another promising species. Black locust is a nitrogen-fixing tree that can be intermixed with sycamore and sweetgum or grown alone on upland sites that are low in nutrients.

Supply, management and risk considerations lead to decisions to mix tree species.[1] Risks of crop losses from pests, diseases or climate can be lessened by having a variety of species including those that can fix nitrogen. For the Southeast Reference site, it is assumed that black locust will be grown with either sycamore or sweetgum. In total, 20% of wood production is assumed from black locust.

Annual productivity (dry tons/acre) is expected to be highest in the class I and IIw sites and lowest on class IIe and IIs. Productivity on class IIIw and IVw sites should exceed class IIe and IIs. Table 2 summarizes the assumed productivity levels for each capability subclass. These estimates are based on Graham (1992) and English et al. (1992) and reflect the use of current tree production technology. As noted previously, results from current production research trials are four to seven dry tons/acre (Wright and Ehrenshaft 1990). Also, shown in Table 2 is an

[1]In some circumstances, a mix of lignocellulosic crops, production of tree crops and annual and perennial herbaceous crops, could be more desirable for several reasons. Higher overall yields can be obtained by matching trees and herbaceous crops to site characteristics. Storage losses can be minimized and labor resources more evenly utilized by producing crops with different optimal harvest windows. However, for this study we did not assume the presence of herbaceous crops.

estimate of the long-term potential of the sites. These estimates of potential reflect the use of improved species (i.e., advances in the selection and breeding of desirable traits). The potential productivity estimates are used for the 2010 reference time period.

3.1.1.2 Northwest Reference Site Feedstock

In the Pacific Northwest region, hybrid poplars have consistently produced the highest yields on high-moisture, high-fertility bottomlands (Wright et al. 1991). These hybrid poplars are crosses of native black cottonwood (*Populus* trichocarpa) and southeastern cottonwood (*Populus* deltoides). On upland sites acceptable productivity has been obtained provided there is adequate moisture and soil fertility. However, a nitrogen-fixing tree, red alder (*Alnus* rubra), has performed better on some low fertility upland sites (Wright et al. 1991). As with the Southeast Reference site, 20% of wood production in the Northwest is from a nitrogen fixing species—red alder.

Table 3 shows the assumed productivity levels for each capability subclass. Higher productivity is associated with higher capability classes and the availability of moisture. Relative to the Southeast Reference site, overall productivity is greater in the Pacific Northwest. Productivity is assumed to be 7 dry tons/acre on class I sites and wet class II and class III sites. On wet class IV sites productivity is placed at 5.5 dry tons/acre. The erosive and shallow class II sites will be the lowest producing with only 4.5 dry tons/acre. In the future, productivity is placed at 10 dry tons/acre. On the poorest sites productivity is not expected to increase much over current levels because of the absence of moisture.

3.1.2 Production and Harvesting Operations

Obtaining high tree growth and survival requires the use of improved planting material that has been selected for rapid growth and disease resistance; good site preparation; weed control to eliminate competition for light, water, and nutrients; fertilization; and occasional use of insecticides and fungicides (Ranney et al. 1987). These establishment procedures can result in survival exceeding 90%.

Although land preparation practices are rather site-specific and depend on the previous land use, a typical procedure on abandoned cropland or pasture land includes spraying of a total-kill herbicide (e.g., glyphosate), mowing, and plowing during the fall season prior to planting.[2] In the spring, the site is disked and sprayed with a pre-emergent herbicide. After planting, weeds are controlled with

[2]On land that has just previously been used for row crops, the soil may only require plowing (Wright 1993, 1994).

mechanical cultivations and herbicides. Cultivation and herbicides are sufficient to control weeds in the second year of growth. After two years of growth, canopy closure occurs and further weed control measures are not required. Fertilizers (nitrogen—$N_2H_4O_3$ and urea, phosphorous—P_2O_5, and potassium—K_2O) are applied at time of canopy closure. The use of insecticides and fungicides are applied only when necessary (perhaps once during each rotation or cutting cycle). For the coppice rotations (regrowth from cut stumps), weed control is not necessary as the rapidly sprouting trees will shade-out competing vegetation. Fertilizers are applied at time of canopy closure and insecticides are used when necessary (assumed once during each rotation).

Harvesting of SRWC is done with feller bunchers that sever or cut, accumulate, and offload bunches of trees. Skidders or forwarders are then used to move the bunched trees to a landing for chipping and blowing directly into a van for transport. In addition to direct harvesting costs, there are indirect costs. These indirect costs are in the form of biomass losses that occur in cutting, handling, and chipping operations. Biomass also decomposes during storage. It is assumed that felling, skidding, chipping, and storage operations result in losses of 12% before hauling and 4% after hauling.

For both the Southeast and Northwest sites, harvesting takes place in year six followed by two additional coppice cycles of six years each. The total life of any tree is 18 years. After 18 years the site is replanted. Based on a 6 year cutting cycle, one-sixth of the total acreage required to meet the needs of the conversion facility is planted each year. This sequenced production assures that equal feedstock amounts are available to the power plant each year. For example, if the total land requirements for feedstock production is 36,000 acres, then 6,000 acres is established in each of the first 6 years of plantation operation. At the end of year six, the first block of land is harvested. In year seven, the second block of land is harvested and, the first block is ending its first year of coppice regrowth. This sequencing continues through both coppice cycles. In year 19, the first block of land is re-established. The planting density is 1,100 trees/acre.

3.1.2.1 Southeast Reference Site Production and Harvesting

The factor input requirements for producing sycamore, sweetgum, and black locust are summarized in Tables 6 and 7. On a life-cycle basis, annual nitrogen requirements for sycamore and sweetgum average 15 pounds per acre with phosphorous and potassium averaging 13 pounds per acre. Herbicides average only 0.2 pounds per acre reflecting application in just the first two years of tree life. Insecticide and fungicide use is minimal for non-nitrogen fixing trees. Black locust does not require nitrogen but requires more insecticide use. Tables 8 and 9 show

Table 6. Factor input requirements for primary tree species (Sweetgum, Sycamore, and Hybrid Poplar)

Activity	Material	Amount
Crop Establishment (year 1)		
Herbicide spray	Broad-kill	1.0 lb/acre
	Diesel	0.4 gal/acre
Mow	Diesel	0.6 gal/acre
Subsoil	Diesel	1.4 gal/acre
Plant	Diesel	2.8 gal/acre
Herbicide spray	Preemergent	1.0 lb/acre
	Diesel	0.4 gal/acre
Mow (mid-year)	Diesel	0.6 gal/acre
Herbicide spray (mid-year)	Broad-kill	1.0 lb/acre
	Diesel	0.4 gal/acre
Crop maintenance (years 2–18)		
Fertilizer spread (one application during each rotation)	N	90 lb/acre
	P_2O_5	80 lb/acre
	K_2O	80 lb/acre
	Diesel	0.3 gal/acre
Insecticide/fungicide spray (one application during each rotation)	Pesticide	0.06 lb/acre
	Diesel	0.4 gal/acre
Mow (in year 2 only)	Diesel	0.6 gal/acre
Herbicide spray (in year 2 only)	Broad-kill	1.0 lb/acre
	Diesel	0.4 gal/acre
Harvesting operations (years 6, 12, and 18)		
Harvesting and handling	Diesel	1.9 gal/ton

Notes: N is half urea and half ammonium nitrate. Pesticides amounts are given in terms of active ingredient. Amounts are derived from Ranney and Mann (1991).

Table 7. Factor input requirements for N-fixing tree species (Black Locust and Red Alder)

Activity	Material	Amount
Crop Establishment (year 1)		
Herbicide spray	Broad-kill	1.0 lb/acre
	Diesel	0.4 gal/acre
Mow	Diesel	0.6 gal/acre
Subsoil	Diesel	1.4 gal/acre
Plant	Diesel	2.8 gal/acre
Herbicide spray	Preemergent	1.0 lb/acre
	Diesel	0.4 gal/acre
Mow (mid-year)	Diesel	0.6 gal/acre
Herbicide spray (mid-year)	Broad-kill	1.0 lb/acre
	Diesel	0.4 gal/acre
Crop maintenance (years 2–18)		
Phosphorous and potassium spread (one application during each rotation)	P_2O_5	80 lb/acre
	K_2O	80 lb/acre
	Diesel	0.3 gal/acre
Insecticide/fungicide spray (one application during each rotation)	Pesticide	2.7 lb/acre
	Diesel	0.4 gal/acre
Mow (in year 2 only)	Diesel	0.6 gal/acre
Herbicide spray (in year 2 only)	Broad-kill	1.0 lb/acre
	Diesel	0.4 gal/acre
Harvesting operations (years 6, 12, and 18)		
Harvesting and handling	Diesel	1.9 gal/ton

Notes: Pesticides amounts are given in terms of active ingredient. Amounts are derived from Ranney and Mann (1991). Harvesting operations include cutting, crushing, baling, moving/loading, and unloading. For the Southeast Reference site and surrounding area, it is assumed that black locust will be grown with either sycamore or sweetgum in proportions of one to four. In total, 20% of wood production is assumed from black locust.

Table 8. Summary of average annual chemical inputs by time period

Time	Species	N	P_2O_5	K_2O	Herbicides	Insecticides/ fungicides
		lb/acre				
1990	Sweetgum, Sycamore, Hybrid Poplar	15.0	13.3	13.3	0.22	0.03
1990	Black Locust, Red Alder	0	13.3	13.3	0.22	0.45
2010	Sweetgum, Sycamore, Hybrid Poplar	15.0	13.3	13.3	0.22	0.01
2010	Black Locust, Red Alder	0	13.3	13.3	0.22	0.45

Notes: Pesticides amounts are averages over an 18 year tree life.

Table 9. Summary of chemical inputs

Time–Site	Maximum impact amounts (lb/year)				
	N	P	K	Herbicides	Insecticides/ fungicides
1990 Southeast	479,130	532,370	532,370	19,960	3,910
1990 Northwest	361,840	402,050	402,050	15,080	2,960
2010 Southeast	298,930	332,140	332,140	12,460	2,440
2010 Northwest	206,440	229,380	229,380	8,600	2,92

Notes: Maximum per acre amounts are 90 lb for N, 80 lb for P, 80 lb for K, 3 lb for herbicides, and 2.7 lb for insecticides/fungicides. Total application amount is a function of the per acre amount and the number of acres under treatment (1990--6,655 acres at the Southeast site, 5,026 acres at the Northwest site; 2010--4,152 acres at the Southeast site, 2,867 acres at the Nortwest site.

the maximum amount of chemicals that would be applied in any given year on a per acre and annual basis respectively. This maximum amount is the basis on which impacts are calculated.

Fuel use and power requirements are calculate on the basis of average field capacities for various agricultural implements (Table 7).[3] Field capacities were derived from Dobbins et al. (1990) and Blankenhorn et al. (1985). Fuel consumption is based on a standard enclosed cab 100 bhp (brake horsepower) tractor operating at an average loading of 54%. Fuel use is based on 0.50 and 0.44 lb/bhp-hr for the 1990 and 2010 time periods, respectively. This translates into a fuel consumption rate of 3.8 gal/hr for 1990 and 3.4 gal/hr for 2010 (assuming a density of diesel fuel of 7.08 lb/gal). Fuel usage was then increased by 10% to reflect movement of equipment and materials to the field and by another 2% to account for lubricants (Liljedahl et al. 1984). Power requirements are a function of fuel use, the tractor power rating, and the average loading. Total and average annual fuel consumption is shown in Table 11.

3.1.2.2 Northwest Reference Site Production and Harvesting

Tables 8 and 9 summarize chemical use at the Northwest site and Table 10 and 11 summarize fuel use.

3.2 ACREAGE AND HAUL DISTANCE REQUIREMENTS

A planting density assumption was used to determine what fraction of the available land base (Tables 2 and 3) would be used to operate the conversion plant required. That is, of the acreage available for production it was assumed that only 5% would be converted for wood production. A 5% planting density is low enough to avoid competition with agriculture yet utilize sufficient land to make energy crop production a significant part of the farm economy.[4]

The 5% availability restriction was applied uniformly across land capability classes I, IIe, IIs, IIw, IIIw, and IVw. This means the higher the percentage of land in a capability class, the higher the relative amount of wood crops to occur in that class. A disproportionately higher percentage of class III and IV land might appear to be more economically justified because of the presumption of lower land cost.

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[3]Because all equipment operations are assumed to be powered as tractor attachments, it is not necessary to describe completely a specific operation. Dedicated self-powered equipment is not assumed. Therefore, it is only necessary to note the number of operations to arrive at fuel consumption and hence emissions.

[4]Major agricultural crops tend to use more than 5% of the land area, while minor crops use 5% or less.

Table 10. Equipment fuel use and power requirements

Implement	Field Capacity	Fuel Use		Power Requirements
		1990	2010	
Subsoiler	3.0 ac/hr	1.4 gal/ac	1.3 gal/ac	18.0 hp-hr/ac
Chisel plow	5.2 ac/hr	0.8 gal/ac	0.7 gal/ac	10.4 hp-hr/ac
Mower	6.5 ac/hr	0.7 gal/ac	0.6 gal/ac	8.3 hp-hr/ac
Sprayer	11.1 ac/hr	0.4 gal/ac	0.3 gal/ac	4.9 hp-hr/ac
Spreader	14.6 ac/hr	0.3 gal/ac	0.36 gal/ac	3.7 hp-hr/ac
Planter	1.5 ac/hr	2.8 gal/ac	2.5 gal/ac	36.0 hp-hr/ac
Harvester	2.0 tons/hr	2.1 gal/ton	1.98 gal/ton	27.0 hp-hr/ton

Notes: Field capacities derived from Dobbins et al. (1990) and Blankenhorn et al., (1985). Fuel use is 0.50 and 0.44 lb/bhp-hr for years 1990 and 2010, respectively. An enclosed cab tractor rated at 100 bhp and an average loading of 54% is assumed. Diesel fuel is assumed to have a density of 7.08 lb/gal. In addition to diesel use, 10% was added to reflect movement of equipment and materials to the field and 2% to account for lubricants (Liljedahl et al. 1984).

Table 11. Total annual diesel fuel use and power requirements

Time	Reference Site	Fuel use		Power requirements	
		Total gallons	gal/acre	Total bhp-hr	bhp-hr/acre
1990	Southeast	430,540	10.8	6,096,460	152.7
1990	Northwest	425,240	14.1	6,021,340	199.7
2010	Southeast	298,840	12.0	4,808,540	193.0
2010	Northwest	293,740	17.1	4,726,630	274.8

Notes: Fuel use is based on weighted average productivity.

However, such land produces lower yields and does not necessarily result in positive returns.[5]

3.2.1 Southeast Reference Site Acreage and Haul Distance

As shown in Table 12 about 39,930 acres would be required to fuel the 1990 conversion facility. Most of this production would come from IIw and I land. This amount of acreage could produce over 191,100 dry tons of feedstock each year. After accounting for pre- and post-haul losses (16% total losses), 161,450 dry tons could be supplied to the conversion facility (Table 11). Also shown in Table 12 are the feedstock flows and losses computed as wet or field tons. The average haul distance is computed at 44 miles (one-way).

For the 2010 facility, only 24,910 acres would be required to supply the conversion facility generating the same amount of electricity (Table 13). Total wood feedstock production would be 151,660 dry tons with 128,120 dry tons delivered to the conversion hopper after accounting for handling and decomposition losses. The 2010 actual haul tonnage would be 166,830 wet tons (Table 13). The lower feedstock requirements means a shorted average haul distance. The average haul distance for the 2010 time frame is computed at 35 miles (one-way).

3.2.2 Northwest Reference Site Acreage and Haul Distance

Fueling the conversion facility from the area surrounding the Northwest Reference site would require less acreage because of the higher assumed productivity (Table 14). The average productivity for the Northwest Reference site is about 1.5 dry tons/acre higher. Approximately 30,150 acres would be required with most of the production coming from IIw and IIw land. For the 2010 time period the amount of acreage required declines to about 17,200 acres (Table 15). The reduced acreage is because of the greater assumed conversion efficiency and the use of improved species. The haul tonnage for the Northwest Reference site is the same as the Southeast Reference site. Computed average haul distances (one-way) are 37 miles and 28 miles for the 1990 and 2010 time periods, respectively.

[5] A 5% planting density surrounding the conversion plant may not necessarily coincide with land availability based on economic considerations—prices, biomass productivity, and net returns to the landowner. In general, a farmer's decision to grow wood energy crops will depend on how tree crops impact traditional agricultural operations. Factors such as labor and equipment complementarity, crop rotation restrictions, erosion limits, and the influence of government policy (e.g., Conservation Reserve Program) will all be important in determining where, how much, and what crops will be displaced by wood.

Table 12. Land available for wood energy production by land class, feedstock tonnages and losses, and haul distance requirements 1990 Southeast Reference site

Land class/subclass	Acres	Annual productivity (tons/acre)	Annual production (tons)
I	5,023	5.5	27,629
IIe	22,234	4.5	100,054
IIs	775	4.5	3,489
IIw	8,241	5.5	45,325
IIIw	3,027	4.0	12,108
IVw	627	4.0	2,507
Total	39,928	4.8	191,113
Feedstock flows and losses	Dry tons		Wet tons
Standing yield	191,110		382,220
Pre-haul losses	22,930		
Haul tonnage	168,180		210,220
Post-haul losses	6,730		
Conversion hopper	161,450		201,82
		66 miles	
Haul Distances		44 miles	
Maximum haul distance		176,860 gallons	
Average haul distance			
Total annual fuel use			

Table 13. Land available for wood energy production by land class, feedstock tonnages and losses, and haul distance requirements 2010 Southeast Reference site

Land class/subclass	Acres	Annual productivity (tons/acre)	Annual production (tons)
I	3,134	8.0	25,073
IIe	13,872	5.0	69,359
IIs	484	5.0	2,419
IIw	5,141	8.0	41,132
IIIw	1,889	6.0	11,332
IVw	391	6.0	2,346
Total	24,911	6.1	151,660
Feedstock flows and losses	Dry tons		Wet tons
Standing yield	151,660		303,620
Pre-haul losses	18,200		
Haul tonnage	133,460		166,830
Post-haul losses	5,340		
Conversion hopper	128,120		160,150
Haul distances			
Maximum haul distance		52 miles	
Average haul distance		35 miles	
Total annual fuel use		97,550 gallons	

3.3 BIOMASS-TO-ELECTRICITY CONVERSION TECHNOLOGY

A conventional steam turbine (spreader-stoker) technology is assumed for the 1990 time period. The 2010 technology is based on the aeroderivative gas turbine. These turbines are currently fired with natural gas. Efforts are underway to use this technology with a gasifier so that solid fuels (coal and biomass) might be used.

3.3.1 1990 Reference Conversion Technology

There are a number of direct combustion technologies that are available for the conversion of biomass to electricity. These include pile burners, spreader-stoker boilers, suspension-fired boilers, circulating fluidized bed combustors, and

Table 14. Land available for wood energy production by land class, feedstock tonnages and losses, and haul distance requirements 1990 Northwest Reference site

Land class/subclass	Acres	Annual productivity (tons/acre)	Annual production (tons)
I	1,291	7.0	9,036
IIe	4,662	4.5	20,981
IIs	792	4.5	3,562
IIw	13,205	7.0	92,434
IIIw	5,985	7.0	41,895
IVw	4,219	5.5	23,205
Total	30,154	6.3	191,113
Feedstock flows and losses	Dry tons		Wet tons
Standing yield	191,110		382,220
Pre-haul losses	22,930		
Haul tonnage	168,180		210,220
Post-haul losses	6,730		
Conversion hopper	161,450		201,820
Haul distances			
Maximum haul distance		56 miles	
Average haul distance		37 miles	
Total annual fuel use		149,360 gallons	

bubbling fluidized bed combustors (Hollenbacher 1992). The efficiency of these boilers ranges between 65 and 75%, depending on the amount of moisture in the fuel (US DOE 1992). Net plant heat rates lie between 17,000 to 13,500 Btu/kWh for the most efficient plants.

The equipment used in biomass steam-turbines is very similar to that used in coal-fired boilers. Superheated steam generated in a boiler is used to drive a turbine and a generator. Steam that has been partially expanded is then extracted from the turbine and utilized to preheat water entering the steam generator (USDOE, 1992). The major differences between biomass-fired and coal-fired systems lie in the fuel feed system, operating characteristics, and the post-combustion flue gas cleanup systems (Hollenbacher 1992).

Table 15. Land available for wood energy production by land class, feedstock tonnages and losses, and haul distance requirements 2010 Northwest Reference site

Land class/subclass	Acres	Annual productivity (tons/acre)	Annual production (tons)
I	736	10.0	7,365
IIe	2,660	5.0	13,300
IIs	452	5.0	2,258
IIw	7,534	10.0	75,336
IIIw	3,415	10.0	34,145
IVw	2,407	8.0	19,256
Total	17,203	8.8	151,660
Feedstock flows and losses	Dry tons		Wet tons
Standing yield	151,660		303,320
Pre-haul losses	18,200		
Haul tonnage	133,460		166,830
Post-haul losses	5,340		
Conversion hopper	128,120		160,150
Haul distances			
Maximum haul distance		42 miles	
Average haul distance		28 miles	
Total annual fuel use		78,790 gallons	

The most commonly used equipment for larger facilities is the spreader-stoker boiler incorporating automatic fuel feeding and traveling grates.[6] In this system a fuel feeder distributes biomass over a traveling grate. The fuel is burned on the floor of the grate using air from a chamber located under the grate.

[6]An alternative concept is the whole tree burner (WTB) (Ostlie 1991). This design integrates feedstock handling, processing, and combustion operations in a single facility. The WTB was developed to maximize system efficiency and use of total tree biomass by integrating a drying facility within the power plant complex. The feedstock requires no further size reduction (e.g., chipping) or processing after it has been batch cut. Energy costs are minimized by employing an extended conditioning period and by utilizing a pile burning furnace configuration.

The 1990 conversion technology is assumed to be a conventional steam-turbine cycle (spreader-stoker). The plant is sized at 30 MW with a net heat rate of 14,920 Btu/kWh. This heat rate (net plant efficiency) is about average for plants currently being installed. The quantity of feedstock required for the facility is based on a 70% capacity factor (baseload operation) and a higher heating value of wood of 17 MMBtu/dry ton. The 1990 conversion facility would thus require approximately 161,450 dry tons of feedstock each year net of losses to handling and decomposition. These assumptions are summarized in Table 16.

Table 16. Technical assumptions for biomass conversion technology

Technical parameter	Conversion technology	
	1990 Conventional steam turbine	2010 Biomass-gasifier gas turbine
Plant size	30 MW	40 MW
Capacity factor	70%	70%
Net heat rate (Btu/kWh)	14,920	8,890
Dry tons/year	161,450	128,120
Annual generation (MWh)	183,960	245,280

Notes: The higher heating value of wood is assumed to be 17 MMBtu/dry ton.

3.3.2 2010 Reference Conversion Technology

Conventional biomass-fired steam turbines may gradually be replaced over the next couple of decades with more advanced biomass conversion technologies. Intercooled steam-injected gas turbines (ISTIG) and integrated gasification combined cycle (IGCC) technologies could be commercially available early in the next century and technologically mature by 2010 (USDOE 1992). Projected 2010 costs for both of these technologies are estimated to be about $0.047/kWh. This represents a cost reduction of about $0.015/kWh over current technology (USDOE 1992).

A biomass-gasifier ISTIG power plant is assumed for the 2010 time period. The ISTIG is expected to be tested with natural gas firing by 1997 and a gasifier should be optimized for biomass by 2010 (US DOE 1992). In contrast to conventional steam turbine cycles, gas turbines are relatively insensitive to scale and offer low capital costs. The gas turbine also offers high efficiency.

In a biomass-gasifier gas turbine, wood is converted to a gas in a pressurized air-blown reactor. The raw fuel is cleaned of particulates at elevated temperatures before being burned in the turbine (Larson et al. 1989). Hot gas cleanup to remove alkali compounds and particulates is the most important development issue associated with the technology.

For the 2010 time period a 40 MW plant operating with an annual capacity factor of 70% is assumed. Larson et al. (1989) provide a conservative estimate of conversion efficiency of 38.4%. This estimate would correspond to a net heat rate of 8,890 Btu/kWh. As summarized in Table 16, this facility would require approximately 128,120 dry tons of feedstocks each year.

4. BIOMASS-TO-ELECTRICITY EMISSIONS

4.1 FEEDSTOCK PRODUCTION

4.1.1 Equipment Operations

Diesel farm tractors give off a variety of airborne emissions—exhaust VOCs, CO, NO_x, particulates (PM), CO_2, and SO_2. These emissions were computed as the product of average annual power requirements (Table 6), acres in production (Tables 12–15) and emission factors for VOCs, CO, NO_x, PM, CO_2, and SO_2. The emission factors are based on g/bhp-hr (grams per brakehorsepower-hour) or the amount of emissions that are released for each unit of energy delivered by the tractor engine. The emission factors for the 1990 reference time period are 1.7, 3.34, 9.39, and 1.28 grams/bhp-hr for exhaust VOCs, CO, NO_x, and PM, respectively. For the 2010 reference time period, tractor emissions are assumed to reach levels of current high-speed diesel truck engines. These assumed future emission factors are: 1.1, 4.8, 4.8, and 0.5 g/bhp-hr for exhaust VOCs, CO, NO_x, and PM, respectively.

Emissions of CO_2 and SO_2 from equipment operations are assumed to be a function of the amount of fuel used (gallons). CO_2 and SO_2 emission factors are in units of g/lb of fuel (grams per pound of fuel combusted). The assumed emission factors are 1,448 and 0.45 g/lb-fuel for CO_2 and SO_2, respectively. These emission factors are assumed not to change between the 1990 and 2010 reference time periods. Emission factors are summarized in Table 17. Emission factors are from EPA Report AP-42 (1985).

Table 17. Emission factors for feedstock equipment operations

Emission factor	Units	1990	2010
Exhaust VOCs	g/bhp-hr	1.7	1.1
CO	g/bhp-hr	3.34	4.8
NO_x	g/bhp-hr	9.39	4.8
PM	g/bhp-hr	1.28	0.5
CO_2	g/lb-fuel	1448	1448
SO_2	g/lb-fuel	0.45	0.45

Source: Appendix G (Accounting of Transportation Emissions), *Fuel Cycle Evaluation of Biomass-Ethanol and Reformulated Gasoline Fuels*, Draft Report, 1992.

4.1.1.1 Southeast Reference Site Equipment Emissions

Table 18 summarizes emissions for equipment operations used to grow and harvest tree feedstocks. Emissions are presented both in terms of yearly totals and dry ton basis.

4.1.1.2 Northwest Reference Site Equipment Emissions

Emissions from tractor operations are approximately the same as those for the Southeast Reference site for both time periods. Higher productivity that translates into more fuel for harvesting operation offsets fewer areas in production in the Northwest relative to the Southeast.

4.1.2 Agricultural Chemical and Soil Erosion

Estimation of chemical emission rates were synthesized from numerous literature sources (Ahuja 1986; Alberts et al. 1978; Haith 1986; Hon et al. 1986; Isenee et al. 1990; McLaughlin et al. 1985; Ranney and Mann 1991; and Vaughan et al. 1989). Table 19 shows these emission rates (non-point) as a percentage of the applied agricultural chemical. For example, for every unit of phosphorous applied 5% is assumed to leach into groundwater, 5% leaves the site as runoff, 10% is lost to erosion, and the remainder (80%) is plant uptake. The product of these rates (Table 19) and the average annual chemical inputs (Table 9) provides an estimate of average annual emissions from the application of agricultural chemicals. The

Table 18. Annual air emissions from equipment operations

Annual emissions		Emission factor					
		VOCs	CO	NO_x	PM	CO_2	SO_2
Southeast reference site							
1990	lb/year	22,848	44,890	126,203	17,203	9,730,689	3,024
	lb/dry ton	0.142	0.278	0.782	0.107	60.27	0.019
2010	lb/year	11,661	50,884	50,884	5,300	6,754,000	2,099
	lb/dry ton	0.091	0.397	0.397	0.041	52.72	0.016
Northwest reference site							
1990	lb/year	22,567	44,327	124,648	16,991	9,610,778	2,987
	lb/dry ton	0.140	0.275	0.772	0.105	59.53	0.018
2010	lb/year	11,462	50,017	50,017	5,210	6,638,958	2,063
	lb/dry ton	0.090	0.390	0.390	0.041	51.82	0.0

Notes: Fuel consumption is 0.50 and 0.44 lb/bhp-hr for 1990 and 2010, respectively. Emissions of CO_2 are based on 0.87% C/lb fuel (22.57 lb CO_2/gal of fuel). CO_2 equivalence based on the ratio of molecular weight of CO_2 to the atomic weight of C (3.664). SO_2 emissions are based on a factor of 0.45 grams/lb fuel. Emission expressed in lb/dry ton reflect total delivered wood feedstocks at the conversion hopper (after handling and storage losses).

product of these rates and the maximum annual application amount provide an upper limit on the emissions.

As discussed previously, the establishment of short-rotation woody crops requires the use of equipment for various tillage operations. Disturbing the soil and removing existing cover crops will cause erosion. However, once the trees are planted and become established and litter layers are deposited, soil erosion from a tree plantation should be minimal. For each land class and subclass, it was assumed that erosion during the tree crop establishment year (first year only) would be the same as an agricultural row crop such as corn. Row crops tend to cause large amounts of erosion. The actual erosion from a tree crop plantation during establishment operations should be less than that for corn because of the use of strip cultivation discussed earlier. The assumption of corn erosion during the first year of a plantation would probably overstate the actual erosion. During the second year it was assumed that erosion would be one-half of the erosion rate for corn. Thereafter, erosion was assumed to be the same as pasture or forest. For example, on class I land near the Southeast Reference site annual erosion from corn is about

2.5 tons/acre and erosion from pasture is 0.2 tons/acre (Table 21). Average annual erosion from a tree plantation on this land would be equal 0.7 tons/acre [i.e., (2.5

Table 19. Agricultural chemical emission rates

Agricultural chemical	Allocation of applied chemical (%)				
	Groundwater	Runoff	Air	Plant uptake	Erosion
N-fertilizer	5	5	10	75	5
P-fertilizer	5	5	–	80	10
K-fertilizer	5	5	–	85	5
Herbicides	8	10	75	2	5
Insecticides	8	10	75	2	5

Notes: Emission rates are derived from a number of sources: Ahuja (1986), Alberts et al. (1978), Haith (1986), Hon et al. (1986), Isensee et al. (1990), McLaughlin et al. (1985), Ranney and Mann (1991), and Vaughan et al. (1989). Estimates are non-point emissions as a percent of chemicals applied to fields. These estimates do not include handling, transport, and storage of biomass, chemical spills and drift, container cleanup wastes, or fuel emissions.

Table 20. Assumed erosion rates for the Southeast and Northwest Reference sites Reference site (1990 and 2010 time periods)

Land class/cubclass	Southeast (tons/acre)	Northwest (tons/acre)
I	0.39	0.16
IIe	0.93	0.52
IIs	0.13	0.11
IIw	0.45	0.21
IIIw	0.43	0.17
IVw	0.37	0.34
Total	0.70	0.27

tons/acre + 0.5(2.5 tons/acre) + 16(0.2 tons/acre/18] assuming a tree life of 18 years. This approach was repeated for each land class and subclass using the appropriate NRI erosion rates for corn and pasture. Table 20 summarizes the calculated erosion rates for each land class and subclass for the Southeast and Northwest Reference sites. Overall, erosion is about 2.5 times lower at the Northwest Reference site.

4.1.2.1 Southeast Reference Site

Average annual emissions of fertilizers (N, P, and K) and pesticides (herbicides and insecticides and fungicides) are summarized in Table 21 for both time periods. These summary data are presented in units of lb of agricultural chemical per thousand dry tons of wood delivered to the conversion facility. The data show that chemical usage is reduced considerably between the 1990 and 2010. This reduction is due to fewer acres in production (higher efficiency of the 2010 conversion facility and higher productivity from improved species). Table 21 also summarize soil erosion at the Southeast Reference site. Soil erosion is presented in units of lb of soil per dry tone of wood delivered.

4.1.2.2 Northwest Reference Site

Similar conclusions can be made when comparing between time periods at the Northwest Reference site as at the Southeast site (Table 21). Comparisons between reference sites shows that chemical emissions are lower at the Northwest Reference site. This is due primarily to the higher assumed productivity. Because of physical differences between sites, erosion is much lower at the Northwest Reference site.

4.1.3 Feedstock Transport

High speed diesel engines used in trucks give off exhaust VOCs, CO, NO_x, particulates, CO_2, and SO_2. Emissions of VOCs, CO, NO_x, and particulates from diesel trucks are computed as the product of annual load-miles and an emission factor. Total annual load miles are a function of the haul tonnage, the average round trip distance, and an assumed 20 ton load. The haul tonnages and distances are shown in Tables 12–15.

The emission factors are based on g/bhp-hr (grams per brakehorsepower-hour) or the amount of emissions that are released for each unit of energy delivered by the truck engine. The emission factors for the 1990 reference time period are 1.1, 4.8, 4.8, and 0.5 grams/bhp-hr for exhaust VOCs, CO, NO_x, and PM, respectively. For the 2010 reference time period, truck emissions are assumed to decline and reach the following levels: 0.5, 2.0, 2.0, and 0.08 g/bhp-hr for exhaust VOCs, CO, NO_x, and PM, respectively. (These factors are converted to lb/mile by an assumption of 2.69 bhp-hr/mile and 454 grams/lb.) Table 22 summarizes the emission factors and Table 23 provides estimates of total annual emissions and emissions per unit input.

Emissions of CO_2 and SO_2 from feedstock transport are assumed to be a function of the amount of fuel used (gallons). CO_2 and SO_2 emission factors are in units of g/lb of fuel (grams per pound of fuel combusted). The assumed emission factors are 1,448 and 0.45 g/lb-fuel for CO_2 and SO_2, respectively. These emission factors are assumed not to change between the 1990 and 2010 reference time periods. Emission factors are summarized in Table 25 and total emissions per year and per dry ton are in Table 23. All emission factors are from EPA Report AP-42 (1985).

4.1.3.1 Southeast Reference Site Feedstock Transport

Table 23 summarizes emissions from feedstock transport. These emissions are much lower than those for equipment operations. This difference is due primarily to the fact that emissions from tractors are unregulated.

4.1.3.2 Northwest Reference Site Feedstock Transport

Emissions for the Northwest Reference site are somewhat lower than the those for the Southeast Reference site. This reflects shorter transport distances.

4.2 BIOGENIC FEEDSTOCK EMISSIONS

Known biogenic emissions from woody feedstocks would include the CO_2 that results from decomposition of biomass during storage and from that left on the ground after harvest. It is possible that methane could be emitted in small quantities, if some of decomposition occurs under anaerobic conditions. However, most, if not all, of the decomposition is assumed to occur under aerobic conditions. Actively growing trees also produce volatile organic compounds (VOCs) that can mix with other air pollutants to generate higher tropospheric ozone conditions (Ranney and Mann 1991). In this section, the calculation approach and the resultant CO_2 and VOC emissions are discussed.

Table 21. Chemical and soil emissions for Southeast and Northwest Reference Sites

Emission fate/chemical	Southeast		Northwest	
	1990	2010	1990	2010
	lb/1000 dry tons			
	Groundwater			
Nitrogen	148.4	92.6	112.1	63.9
Phosphorous	164.9	102.9	124.5	71.0
Potassium	164.9	102.9	124.5	71.0
Herbicides	9.9	6.2	7.5	4.3
Insecticides	1.9	1.2	1.5	1.4
	Surface water			
Nitrogen	148.4	92.6	112.1	63.9
Phosphorous	164.9	102.9	124.5	71.0
Potassium	164.9	102.9	124.5	71.0
Herbicides	12.4	7.7	9.3	5.3
Insecticides	2.4	1.5	1.8	1.8
	Air			
Nitrogen	296.8	185.2	224.1	127.9
Phosphorous	0	0	0	0
Potassium	0	0	0	0
Herbicides	92.7	57.9	70.0	40.0
Insecticides	18.2	11.3	13.6	13.6
	Soil			
Nitrogen	148.4	92.6	112.1	63.9
Phosphorous	329.7	205.7	249.0	142.1
Potassium	164.9	102.9	124.5	71.0
Herbicides	6.2	3.9	4.7	2.7
Insecticides	1.2	0.8	0.9	0.9
	lb/dry ton			
Total soil erosion	347	272	100	71

Table 22. Emission factors for feedstock transport

Emission factor	Units	1990	2010
VOCs	g/bhp-hr	1.1	0.5
CO	g/bhp-hr	4.8	2.0
NO_x	g/bhp-hr	4.8	2.0
PM	g/bhp-hr	0.5	0.08
CO_2	g/lb-fuel	1448	1448
SO_2	g/lb-fuel	0.45	0.45

Source: EPA, Report AP-42, 1985.

Table 23. Annual air emisisons from feedstock transport

Emissions factor	Southeast		Northwest	
	1990	2010	1990	2010
VOCs	0.037	0.014	0.0-32	0.011
CO	0.164	0.054	0.139	0.044
NO_x	0.164	0.054	0.139	0.044
PM	0.017	0.002	0.014	0.002
CO_2	24.76	17.21	20.91	13.90
SO_2	0.008	0.005	0.006	0.004

Notes: Emission factors for exhaust VOCs, CO, NO_x, and PM are from Table 22. Fuel consumption is 0.50 and 0.44 lb/bhp-hr for 1990 and 2010, respectively. Emissions of CO_2 are based on 0.87% C/lb fuel (22.57 lb CO_2/gal of fuel). CO_2 equivalence based on the ratio of molecular weight of CO_2 to the atomic weight of C (3.664). SO_2 emissions are based on a factor of 0.45 grams/lb fuel. Emission expressed in lb/dry ton reflect total delivered wood feedstocks at the conversion hopper (after handling and storage losses).

4.2.1 CO_2 emissions and sequestration

Carbon dioxide is taken up by plants in the growth process and emitted as they decompose or are converted to other forms of energy. Once CO_2 is absorbed by the plants, the carbon is incorporated into plant tissues and the oxygen is released through respiration. The production of wood energy feedstocks would contribute a small amount of CO_2 to the atmosphere. This small amount is from the fossil fuels that are used in equipment operations and feedstock transport. The vast majority of the CO_2 released during conversion processes is merely CO_2 that has been sequestered from plant growth. If biomass were to substitute and displace a fossil fuel in the generation of electricity (which is not being assumed here) there would be positive not requestration of CO_2 (negative CO_2 emissions).

4.2.2 Volatile Organic Compounds

The growing of energy crops will contribute VOCs to the atmosphere. These are mostly non-methane aromatic hydrocarbons (NMHCs), primarily isoprenes and terpenes. Other compounds may be present, but data on their rates of evolution are virtually nonexistent. In fact, more than one-hundred NMHCs have been identified. Ranney and Mann (1991) note that the kinds and quantities of compounds vary considerably by species with the level of emissions highly dependent on local temperature. These emissions are known to combine with fossil fuel NO_x to produce ozone and peroxyacetyl nitrate.

As summarized by Ranney and Mann (1991), the large-scale planting of trees in areas that currently do not have significant emissions of NMHCs has the potential to change atmospheric chemistry. However, the magnitude and importance of this change will be impossible to determine with current data. In areas that are forested, the growing of trees will probably have little net effect.

Given the availability of data, emissions of isoprene and terpene are the only biogenic hydrocarbons that are estimated from the growth of biomass feedstocks. Estimates are based on the foliage of woody plants. Data are essentially unavailable for emissions from bark, forest floor, and soil surfaces. Although it would seem likely that the steps involved in the operation of a biomass plantation (e.g., site preparation, growth, harvest, and storage) might lead to different rates of emissions per unit land area over time, the data are insufficient to allow this detail to be resolved.

Table 24 summarizes emission rates for isoprene and terpene. Isoprene emissions are assumed to take place only during daylight hours of the growing season. Whereas, terpene emission rates are assumed to take place as a function of temperature throughout the frost-free period, and are not subjected to the diurnal patterns of evolution that appear to function in the case of isoprene. Rates of isoprene and monoterpene emissions from plant foliage are species specific with *Populus* having the highest biogenic emissions. Greater annual levels of emission in the Southeast are primarily a function of the length of the growing season and a higher average temperature (emissions increase with temperature). Except for the high rates of isoprene emissions from *Populus* (Sharkey et al. 1991; Monson and Fall 1989), emission rates for biomass plantations should not exceed those of surrounding forested areas. For comparison, emission from pines and oaks are included in Table 24. Emissions for both reference sites are summarized in Table 25.

Table 24. Estimated annual emissions for isoprene and monoterpene for selected locations.

Species	Location	Annual rates of emissions	
		Isoprene (lb/acre)	Monoterpene (lb/acre)
Sweetgum	GA	82	13
Sycamore	GA	125	nd
Hybrid Poplar	PNW	272	nd
	NB	438	nd
	NY	438	nd
	IL	550	nd
	GA	169–1428	nd
Pine	GA	nd	10–17
Oak	NY	90	nd
	IL	112	nd
	GA	66–299	nd

Table 25. Estimated annual biogenic emissions of volatile organic compounds

Time period		Isoprene 103.5 lb/acre	Monoterpene 13 lb/acre
Southeast Reference site			
1990	lb/year	4,135,530	519,060
	lb/dry ton	25.60	3.21
2010	lb/year	2,578,270	323,840
	lb/dry ton	20.12	2.53
Northwest Reference site			
1990	lb/year	3,120,920	392,000
	lb/dry ton	19.33	2.43
2010	lb/year	1,780,540	223,640
	lb/dry ton	13.90	1.75

4.3 QUALITATIVE ENVIRONMENTAL ISSUES

4.3.1 Biodiversity and Habitat Change

Biodiversity and habitat change have three important factors. They are time, space (scale), and some definition of background genetic or species diversity. Different forces are at work at the microsite scale compared to landscape-regional-global ones. Tree plantations may have measurable influence at larger scales, if they occupy more than a few percent of land use at that given scale. If energy crops are disposed to utilize uncommon, unusually productive, or relatively undisturbed habitats, the effect on biodiversity may be disproportionately worsened since these sites would be associated with higher background biodiversity. Conversely, if energy crops are disposed to displace agricultural monocultures, improvements in biodiversity and habitats may be possible.

To determine the effects of energy crops on biodiversity and habitat, several variables need definition. The first is the characterization of energy crops themselves as to the species which occupy them and the kinds of habitats they may

Table 26. Acreage displaced by wood feedstock production

Land use	Southeast Reference site		Northwest Reference site	
	1990	2010	1990	2010
Closecrop	1,588	991	1,382	788
Corn	5,353	3,340	3,802	2,169
Fallow	2,642	1,648	2,150	1,227
Forest	1,579	985	1,044	596
Hayland	4,712	2,940	3,544	2,022
Pasture	17,652	11,013	13,695	7,813
Row other	682	426	331	189
Soybeans	5,720	3,569	4,205	2,399
Total	39,928	24,911	30,154	17,203

offer. The second is some definition of the kinds of habitat (land use or vegetative cover) that energy crops would displace and the characterization of biodiversity and habitat qualities within those displaced land uses. The third is the scale of change anticipated within the context of regional land use characterizations and patterns. The fourth and final variable is the regional condition and need with respect to biodiversity and habitat in the context of both larger and smaller scale known and reasonably anticipated biodiversity issues and principles. The questions exceed the data needed to answer them since energy crops have not yet reached field applications on a significant scale.

The specific crop displacement for the two reference sites and time periods is shown in Table 26. Pasture, row crops (corn, soybeans, and other row crops), and hayland would be the major displaced crops for both time periods for the Southeast Reference site. For the Northwest Reference site pasture, row crops, and hayland would be the major displaced crops.

4.4 ELECTRICITY GENERATION

Wood is a relatively clean fuel when burned in well-controlled processes. Wood-fired electric generation, when compared with fossil-fuel generation, has negligible emissions of SO_2 and reduced emissions of NO_x. Moreover, wood-fired generation adds little CO_2 to the atmosphere and, if used to displace fossil fuels, it has positive carbon sequestration benefits.

This section discusses air and land and water emissions from the combustion of wood in a conventional steam turbine (1990 reference technology) and in a biomass gasifier gas turbine (2010 reference technology). These emissions are discussed separately for each technology.

4.4.1 1990 Reference Conversion Technology

Air emissions

The most significant air emissions from the combustion of wood feedstocks is particulate matter (PM) and NO_x (Tilman 1987). Emissions of SO_x are very low since wood contains little sulfur by weight (less than 0.1%). This compares with 0.5 to 1% for low sulfur Western coal. Biomass combustion facilities do not require flue-gas desulfurization. Emissions of CO from wood-fired combustion would only be a concern if the furnace is operated under poor conditions.

Wood-fired combustion produces less particulate matter (PM) than coal. This is because wood has a low ash content (0.5 to 2.2%) relative to coal (up to 10%) (US DOE 1992). However, Langr (1992) reports that the lower ash loading of wood is often offset by a decreased efficiency in air quality control equipment. Electrostatic precipitators, which are typically used with stoker-fired boilers, also have reduced performance. Overall, wood-fired and coal-fired boilers may have similar particulate emissions levels (Langr 1992). This is after accounting for the decreased efficiency of collection equipment and the fact that wood may often be contaminated with and dirt from harvesting and fuel preparation.

NO_x emissions can come from two sources—the fuel itself (fuel NO_x) or from the atmosphere (thermal NO_x). Emissions of fuel NO_x from wood-fired combustors are expected to be lower than those from coal-fired equipment because wood contains less nitrogen by weight. For example, the amount of nitrogen in poplar, black locust, and red alder, three of the species used in this study, is 0.13, 0.57, and 0.47%, respectively (Kitani and Hall 1989). By contrast, coal may contain from 1.4 to 2% nitrogen by weight. To be sure, some biomass fuels, such as agricultural residues (e.g., cotton trash), may contain as much as 3% nitrogen by weight.

Thermal NO_x formation is a function of combustion temperature, residence time, and concentrations of N_2 and O_2 in the furnace (Ostlie, 1990). Because wood combustion takes place at lower temperatures than coal combustion thermal NO_x

will be lower. As noted by EPRI (1991), lower temperature combustion is a result of lower thermodynamic availability and higher fuel moisture content. However, the lower combustion temperatures mean less efficient combustion, higher boiler heat rates, and larger boilers for a given level of output relative to coal. Overall, EPRI (1991) states that wood-fired power plants emit about 45% less NO_x than coal.

The other major combustion emission is CO_2. However, emissions of CO_2 are negligible if one considers that any released carbon in the stack is merely carbon that has been recently sequestered during tree growth. The production of wood feedstocks contributes a small net amount of CO_2 to the atmosphere, but only to the extent that fossil fuels are used in their production. The vast majority of the CO_2 released from the conversion of biomass is merely CO_2 that has been recently sequestered from the atmosphere by plant growth. Biomass power could be used to offset CO_2 emissions from coal-based generation by replacing capacity or as incremental capacity additions that have no CO_2 contribution (US DOE 1992).

Air emission factors for the 1990 conversion technology are summarized in Table 27. The factors that are used in determining the fate of air releases are taken from the *AIRS Facility Subsystem Source Classification Codes* (US EPA 1990). Also shown in Table 28 are new power plant emission factors for wood-fired generation. These factors are from a Department of Energy report and from the report *America's Energy Choices* published by the Union of Concerned Scientists (UCS 1992). Both of these sets of emission factors are consistent with those from AIRS.

Land and water emissions

Wood is a relatively benign material containing only small amounts of heavy metals. Wood ash also contains calcium, potassium, phosphorous, and magnesium and would be a low-cost amendment for the acidic soils found in the Southeast. Wood-fired electric plants operating in New England spread the ash on the acidic soils. The ash makes the soils more alkaline, eliminates the need for lime, and provides some nutrients.

Table 27. Air emission factors for wood-fired power generation 1990 reference technology (lb/MMBtu)

Wood/bark-fired boilers	PM	PM10
Uncontrolled	0.800	0.720
Mechanical collectors		
With flyash reinjection	0.667	0.611
Without flyash reinjection	0.589	0.189
Wet scrubber	0.053	0.052
Electrostatic precipitator	0.004	-
Collection efficiency of 98%	**0.016**	
Ash production (actual)	**0.595**	-

Boiler type	NO_x	SO_x	CO	TOC	CO_2
Dutch-oven boiler	0.0542	0.008	0.733	0.020	233
Stoker boiler	0.167	0.008	1.511	0.024	233
FBC boiler	0.222	0.008	0.156	-	233

Notes: Emission factors converted from lb/ton (as fired wet with 50% moisture and 4500 Btus/lb) to lb/MMBtu.

Source: U.S. Environmental Protection Agency (EPA), Chief (Clearinghouse for Inventories and Emission Factors), AP-42, "Wood Waste Combustion in Boilers," Research Triangle Park, North Carolina, July 1993.

4.5 HEALTH, SAFETY AND SOCIOECONOMIC ISSUES

4.5.1 Health and Safety

In the production of energy crops long-term storage of biomass will be required, although storage can be minimized by growing a variety of crops with different harvest windows. As noted by Eganeus and Wallin (1985), a breakdown of plant material occurs during storage because many types of micro-organisms, which are present in the biomass, can use the lignocellulosic component as a substrate for growth. The resultant growth of spores and microorganisms can be a serious health hazard in handling biomass. Some of the potential health risks associated with spore and microorganism growth from biomass storage are presented in Table 28.

Table 28. Health and safety risks from microorganism and spore growth on biomass in storage

Health risk	Type of biomass	Etiologic agent
Farmer's lung	Grain, straw	Micropolyspora faeni, Thermoactinomyces vulgare, Aspergillus fumigatus and others
Chip boiler's complaint	Mouldy chips	Rhizopus spp., Mucor spp., Aspergillus fumigatus and others
Brewer's lung	Grain	Aspergillus clavatus and others
Sauna bather's disease	Mouldy wood	Pullaria pullulans, Paecilomyces spp., and others

Notes: Reproduced from Egeneus and Wallin (1985).

Standard forestry and farming operations have always been high risk occupations, and the production of energy crops is not likely to be much different from those situations. According to the National Safety Council about 4,000 deaths and 200,000 disabling injuries occur each year from work-related accidents in farming and ranching (Hunt 1983). About a quarter of these injuries are associated with tractors and farm machinery. Another 16% are associated with farm vehicles and trucks. However, nearly half of these injuries occur when the machinery is stopped or in-transit with the major cause being negligence on the part of the operator. Only 14% of farm-related injuries are from harvesting operations. Harvesting of short-rotation woody crops may not be as dangerous as standard forestry operations in that smaller equipment and smaller trees are being dealt with. Regulations or guidelines which address safety issues, particularly for harvesting practices, may be needed to reduce the risks involved. Such regulations are difficult to implement when many individual farmers are actually doing the work. When harvesting is done by specialized contract groups it would be easier to require that specific standards of safety be implemented.

Total employment could be increased in an area, if energy crops do not displace agriculture. If agriculture is displaced then the number and type of jobs may not change significantly. For example, some row and close grown crops could be displaced by wood feedstock production. On balance such a change could result in a net loss of labor hours. By contrast, some fallow land, pasture, and hayland could be displaced. This change would result in an increase in labor hours. The growing of short-rotation woody crops is more intensive than these latter land-uses.

4.5.2 Labor Requirements

Total employment could be increased in an area, if energy crops do not displace agriculture. If agriculture is displaced then the number and type of jobs may not change significantly. For example, some row and close crops could be displaced by wood feedstock production. On balance such a change could result in a net loss of labor hours. By contrast, some fallow land, pasture, and hayland could be displaced. This change would result in an increase in labor hours. The growing of short-rotation woody crops is more intensive than these latter land-uses.

The overall net effect in the nation as a whole is small, however (refer to paper 17 in ORNL/RFF 1994 for a discussion of the issues). Most of the employment are from the currently employed labor force. The job that they leave is filled by someone else, who leaves his job, and so on. Many of those on jobs are left unfilled. If a region's unemployment rate is at the "natural rate" if unemployment, then it is difficult to make a case for any employment externalities.

Estimating the net changes in employment must explicitly account for the factors that enter a farmer's decision to convert cropland to wood biomass production. This decision is affected by the price of wood feedstocks, the impacts production will have on traditional farm operations (labor and equipment complimentary), and the overall profitability of the farm enterprise. Moreover, the role of government policy (e.g., conservation reserve program, agricultural price supports, etc.) and its effect on wood feedstock operations must be assessed.

The total labor hours required for supplying a wood-fired facility are shown in Table 29. Production and harvesting labor hours, which are based on average annual equipment operating hours, are about 115,000 hours for the 1990 time period at each site and 80,000 hours for the 2010 time period. The labor hours at each site are about the same because fewer acres in production are offset by more hours required for harvesting because of greater productivity.

Transportation labor hours are also reported in Table 29. These hours are based on a 20 ton truck delivery load and an assumption of the number of hours required to deliver a load in each time period. It was assumed that a round trip would require 4 hours for the 1990 time period and 3.5 hours for 2010. Average haul distances range from 44 miles for the Southeast Reference site in 1990 to a low of 28 miles for the Northwest Reference site in 2010. Total transport labor hours range are about 42,040 hours in 1990 and 29,190 in 2010.

Table 29. Total annual labor hours for production harvesting and transportation

Time period	Hours/acre	Total acres	Total labor hours
	Production and harvesting labor hours		
	Southeast		
1990	2.87	39,928	114,593
2010	3.17	24,911	79,968
	Northwest		
1990	3.74	30,154	112,776
2010	4.52	17,203	77,758
	Transportation labor hours		
	Southeast		
1990	210,224	10,511	42,040
2010	166,826	8,341	29,190
	Northwest		
1990	210,224	10,511	42,040
2010	166,826	8,341	29,190

Notes: Production and harvesting labor hours are based on average annual equipment operating hours. Transportation hours are based on a 20 ton delivery load and an assumption of 4 hours per load for 1990 and 3.5 hours per load for 2010.

The amount of labor employed at the conversion facility is derived by Tewksbury (1987), who discusses operations at the McNeil wood-fired generating plant in Burlington, Vermont. For the 1990 and 2010 conversion facilities, operations crews, a maintenance crew, and administrative and management staff will be required to operate the facility. The facility operators are assumed to consist of five-man crews. As discussed by Tewksbury (1987), four of the five crews would operate the facility for the normal 24-hour day. The fifth crew is needed to cover vacations, sick-time, and aperiodic maintenance. Each crew would consist of a supervisor (actual operator), a station operator, a fireman responsible for ash removal, and two yardmen responsible for feedstock handling and loading. The maintenance crew would consist of a chief mechanic, a welder, an electrician, recorder and monitor, and a janitor and keeper of stores. The management staff would include a superintendent, assistant superintendent, secretary, and a plant engineer. Total annual labor hours for the conversion facility are summarized in Table 30.

Table 30. Total annual labor hours for conversion facilities

Reference time period—Technology	Total annual hours
1990—Conversion Technology	
Operations crews	52,000
Maintenance crew	10,400
Management staff	8,320
Total annual labor hours	70,720
2010—Conversion Technology	
Operations crews	41,600
Maintenance crew	10,400
Management staff	8,320
Total annual labor hours	60,320

Notes: Annual labor hours based on a 2080 workhours per year. For the 2010 technology, operations crews were reduced by 5 personnel.

If it is assumed that wood feedstock production and harvesting displaces traditional agriculture and becomes a new crop in the total farm operation, then net changes in farm employment could be reasonably assume to be zero. Gains in employment for a Technology Characterization and Emissions would come from feedstock hauling and from the conversion facility (assuming that the conversion facility does not displace some other form of power generation).

4.5.3 Aesthetic Issues

The conversion of about 40,000 acres of land at the Southeast Reference site in 1990 and lesser amounts at the Northwest Reference site may have numerous effects on the local economy. For example, supplying 161,450 dry tons/year (or about 201,820 wet tons) will require that, on average, approximately 40 trucks enter and leave the facility each day (assuming 250 delivery days and a 20 wet ton load). This means that four truck loads will be delivered per hour on a 10 hour schedule. This level of truck traffic should not present an aesthetic or noise problem. However, Frankena (1987) cautions that there has been opposition to wood-fired facilities that threaten the quality of the rural environment.

There may also be impacts resulting from changes in land use and ownership patterns. However, at the outset it was decided that energy crops would be viewed as a secondary crop occupying only five of the suitable land base. This low level of penetration should avoid competition with major agricultural crops yet make energy production a significant part of the local economy. Of course, specific impacts will depend on the relative economics of energy crops as compared with traditional crops and the influence of government policy on energy and agriculture. The nature of any impact depend on whether energy crops displace some existing crop or whether energy crops are grown in addition to current agricultural production.

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APPENDIX B

PHOTOCHEMICAL MODELING OF POLLUTANTS FROM ELECTRIC POWER PLANTS: APPLICATION TO A BIOMASS-FIRED POWER PLANT

1. INTRODUCTION

The Environmental Protection Agency's (EPA) Ozone Isopleth Plotting Mechanism, (OZIPM-4) model (EPA, 1989a and 1989b) and the Mapping Area-wide Predictions of Ozone, (MAP-O_3) model (McIlvaine 1994) were used to predict ozone concentrations within the vicinity of the hypothetical 30 MW biomass-fired power plant. The modeling methodology is described in detail in ORNL/RFF (1994a) and McIlvaine (1994). The MAP-O_3 model predicts area-wide ozone concentrations over the ozone season, by combining ozone concentrations predicted with the OZIPM-4 model with plume trajectories calculated from wind speed and direction measurements. The MAP-O_3 model is also used to predict seasonal average ozone concentrations, as well as, daily peak ozone concentrations over the ozone season throughout the study area.

The effect of power plant NO_x emissions on ozone concentrations is a complex function of meteorological conditions, hydrocarbon concentrations (due to manmade and/or natural hydrocarbon emissions), as well as, ambient concentrations of ozone and ozone precursors. Since the various combinations of these conditions is unique for each day, the task of predicting ozone concentrations over a period of several months is complex and time-consuming. One alternative to modeling each unique day of the ozone season is to model a few days which represent the range of conditions expected to occur over the time period of interest. This approach was chosen for this analysis.

A range of parameters that are characteristic of conditions which result in low, median and high ozone concentrations were identified from a case analysis of ambient ozone monitoring data and the corresponding meteorological observations. These parameters were used in the OZIPM-4 model to predict existing ozone concentrations at the Southeast Reference site (without the power plant) for three composite base case days. These three base case scenarios were then used in the OZIPM-4 model to predict ozone concentrations expected to occur as the result of the power plant NO_x and non-methane organic compounds (NMOC) emissions on high, median and low ozone days. The difference between the base case simulations and the plant simulations is the increment of ozone due to the plant emissions under high, median and low ozone conditions.

Each day of the ozone season was identified as either a 'high', 'median' or 'low' ozone day according to the peak daily ozone concentration that was measured at a nearby monitoring station on that day. This typing scheme, together with the hourly ozone **concentrations** due to the plant emissions, predicted for each of three composite ozone days, resulted in predicted hourly ozone concentrations for each hour of each day of the ozone season. The MAP-O_3 model was used to predict the location of each ozone concentration predicted with the OZIPM-4 model and to calculate the longer-term ozone concentrations needed for this analysis. The MAP-O_3 model calculates the path of the power plant plume (trajectory) from meteorological surface observations of wind speed and direction, for each day of the ozone season. The plume trajectories are combined with the hourly ozone concentrations to provide a map of ozone concentrations occurring in the vicinity of the power plant. The MAP-O_3 model also calculates the peak one-hour ozone concentration for each day of the ozone season and the seasonal average 9 a.m. to 9 p.m. ozone concentration.

Results from the MAP-O_3 model are transferred to an isopleth plotting routine (e.g., SURFER, Deltagraph or others) which generates isopleth maps showing the distribution of ozone concentrations (both above and below ambient ozone concentrations) due to emissions of NO_x and NMOC from the power plant.

This appendix presents the pollutant emission rates (including the calculation of NO_x and NMOC emissions fluxes used as input to the OZIPM-4 model) and the results of the MAP-O_3 modeling. This appendix is intended to provide details of the ozone modeling that are specific to the biomass fuel cycle. All other details of the ozone modeling are as described ORNL/RFF (1994a) and McIlvaine (1994).

2. DATA USED IN THE COMPUTER MODELING

2.1 EMISSIONS FLUXES

Once the base case simulations for the Southeast Reference site are run, the power plant emissions are entered in the OZIPM-4 model in the form of an hourly emissions flux. Unlike Gaussian dispersion models which accept emissions from point sources as an emission rate (e.g., grams/second), the OZIPM-4 model accepts emissions of NO_x and NMOC as an emissions flux in units of kilograms per square kilometer per hour (kg/km^2-hr). Both the OZIPM-4 model and Gaussian type models predict pollutant concentrations, typically in units of grams per cubic meter, (g/m^3) or ppb. The simulated column of air in the OZIPM-4 model is assumed to extend from the earth's surface through the mixed layer and the air within the column is assumed to be uniformly mixed at all times. As the column of air passes over the power plant, the column is 'initialized' with a quantity of NO_x and NMOC emissions from the plant.

In the OZIPM-4 model, the column of air is transported at some wind speed (u) along a trajectory (Lagrangian coordinate system). Output from the model is in the form of pollutant concentrations that occur, within the column, after some period of time (travel time or downwind distance assuming some wind speed). In order to use the OZIPM-4 model to calculate ozone concentrations due to a point source, an emissions flux must be calculated and entered into the model, that will result in a concentration within the column (i.e. the plume) equal to that which would occur from the plant emissions after traveling downwind for one hour. The one-hour time period is chosen because that is the normal temporal resolution achieved with the OZIPM-4 model. That is, OZIPM-4 is typically used to calculate (instantaneous or average) ozone concentrations, hour by hour. Therefore, all input conditions such as emissions are one-hour averages.

The emissions flux, F, used as input to the OZIPM-4 model and derived in ORNL/RFF (1994a) and McIlvaine (1994) is given by:

$$F = \frac{8Q}{\pi u^2 t_t t_d} (0.2778) \tag{1}$$

where,

F = the emissions flux which has units of kg/km^2-hr,
Q = the emission rate of pollutant from the plant in units of g/s,
u = the wind speed which has units of m/s,
t_t = the travel time of the plume in hours and
t_d = the duration of emissions in hours (this value will always be one hour when the OZIPM-4 model is used to simulate a point source emission).

This is the emissions flux that will result in a NO_x concentration in the power plant plume, after one hour of travel time (i.e. one hour of dispersion) from the stack. This method of calculating flux is not appropriate for tame periods less than one hour. This calculation assumes no chemical conversion during the first hour. During this time, NO_x concentrations from the plant are expected to be predominantly NO and very high (relative to ambient). Any chemical reactions occurring would most likely be the conversion of some NO to NO_2 by ambient ozone. After this time, NO_x concentrations in the column are expected to be dominated by photochemical reactions and vertical mixing of the atmosphere, as it is subsequently simulated by the OZIPM-4 model.

The emissions flux calculated with this method is a function of the pollutant emission rate (Q in g/s), duration of the emission, (t_d), travel time of the plume, (t_t) and the wind speed, (u). The NO_x emission rate for the biomass-fired power plant at the Southeast reference site of 6.6 g/s was used to calculate the NO_x emissions flux. The non-methane hydrocarbon emission rate is 0.95 g/s. Duration of the emission (t_d) is always one hour for the OZIPM-4 simulations, since the column of air receives emissions, in units of kg/km^2-hr, from the stack as it is transported over the power plant plume.

The travel time of the plume (t_t) is the number of hours that the plume travels before mixing to the ground. Prior to 10 a.m., under typical summertime conditions, the mixing height, (which may be thought of as a lid which prevents further vertical mixing) is stall below the effective stack height. (The effective stack height is the combined height of the stack and the height that the plume has risen due to effects of momentum and buoyancy). Until the mixing height exceeds the effective stack height, the plume is essentially trapped above the mixed layer and may be transported some distance before the mixing height rises sufficiently to allow the plume to be mixed to the ground. Due to the effects of the mixing height on plume mixing, it is assumed that no plume is mixed to the ground prior to 10 am. Any plume which originates between 10 a.m. and 8 p.m. is assumed to mix to the ground within an hour of travel time. Plumes which originate prior to this time are assumed to be transported aloft until 10 a.m., after which time solar heating is sufficient to produce vertical mixing. Since sunlight and temperature are not sufficient to promote photochemical activity during early morning hours, the most likely effect from early morning emissions is to increase concentrations of NO_x aloft, until such time, as they are mixed to the ground and can react with NMOC emissions.

The flux calculation for hours prior to 10 a.m. is adjusted to account for the fact that the plume has undergone additional dispersion prior to mixing to the ground. To account for the additional dispersion which occurs in plumes which originate prior to 10 a.m., the flux for each of these hours is defined as a function of the 10 a.m. flux. Plumes which have traveled two hours (dispersed two hours) are assumed to have half the flux of a plume which has traveled one hour ($F_{9a\,m} = F_{10a\,m} / 2$) and plumes which have traveled three hours are assumed to have one third the flux of a plume which has traveled one hour ($F_{8\,a.m.} = F_{10\,a.m.} / 3$) and so on. In other words, the flux for hours prior to 10 a.m. is calculated with Equation [1] above with t_t = the travel time of the plume prior to mixing to the ground (i.e. the number of hours prior to 10 a.m. plus one hour to account for 10 - 11 a.m.)

Tables [1], [2] and [3] show the wind speed data used in calculating the NO_x and NMOC emissions flux for the biomass power plant under low, median and high ozone conditions. The 10-meter wind speeds are the 10-day average observations described in ORNL/RFF (1994a) and McIlvaine (1994) for each composite day. Since wind speed varies with height (wind speeds at the earth's surface are slower due to frictional effects of surface roughness), the stack top wind speed was calculated from the 10-meter wind speed using the stability class and the power law expression (Wark and Warner, 1981):

$$\frac{u}{u_1} = \left(\frac{z}{z_1}\right)^p \tag{2}$$

where, u is the wind speed at altitude z,
u_1 is the wind speed at altitude z_1, and
p is the positive exponent which is a function of stability class.

Default rural wind profile exponents from the Industrial Source Complex (ISC) Dispersion Model User's Guide were used (EPA, 1986). The stack height of the biomass-fired power plant is 65 meters.

In calculating the emissions flux, a 24-hour average representative wind speed was developed for each composite base case scenario. The combined 24-hour average of both the 10-meter and stack top wind speeds was computed for the flux calculation. This average wind speed was selected to dampen some of the hourly variability seen in both wind speeds and to account for the fact that the actual wind speed is, in fact, unknown and may actually be higher than the surface wind speed and lower than the calculated stack top wind speed. The average wind speeds for the high, median and low ozone conditions were 2.2, 2.9 and 3.6 m/s, respectively.

The 24-hour, average wind speeds described here were used to calculate the emissions flux for the plant under high, median and low ozone conditions during the hours from midnight to 9 p.m. Due to the uncertainty regarding the location of the mixing height, with respect to the plume, during the evening hours (9 p.m. to midnight) and to the fact that emissions from the plant during this time are not expected to have an appreciable impact on ozone concentrations during the following day, ozone concentrations were not predicted for plumes which originate between 9 p.m. and 11 p.m.

The NO_x and NMOC emissions flux for each hour are shown in Tables [1], [2] and [3]. These values were input to the OZIPM-4 model in order to predict the ozone concentrations expected to occur as the result of power plant plumes that originate at certain hours (birth hour) and travel for some period of time (plume age). Results of these OZIPM-4 model plant simulations were subtracted from the corresponding base case simulations to obtain the incremental ozone concentration due to the plant emissions as a function of birth hour and plume age under high, median and low ozone conditions.

3. RESULTS

3.1 CROP EFFECTS RESULTS

The crop effects analysis portion of the biomass fuel cycle requires an estimate of the seasonal 9 a.m. to 9 p.m. average ozone concentrations due to the plant emissions. These results are shown in Fig. [1] and [2]. The power plant is shown in the center of each isopleth map with a triangle marker. The scale of each figure is in kilometers from the plant. Ozone concentrations are reported in ppb (by volume). Results are presented separately for two cases; one with and one without ozone depletion. (Ozone concentrations above base case will be referred to as ozone bulges and ozone concentrations below base case will be referred to as ozone depletions).

Figure [1] shows the predicted impact of the biomass power plant emissions on the seasonal 12-hour average ozone concentrations due to ozone bulges only. These results do not account for ozone scavenging. As seen in Fig. [1], the highest 12-hour seasonal average ozone concentration (based on bulges only) is 0.12 ppb (the smallest isopleth line) and occurred approximately 40 kilometers from the plant in the northeast direction. The lowest isopleth plotted in Fig. [1] is 0.01 ppb. This seasonal average ozone concentration occurred as far away as 180 kilometers from the plant in the northeast direction and 100 kilometers in the southwest direction.

Figure [2] shows the predicted impact of the biomass-fired power plant emissions on the seasonal 12-hour average ozone concentrations due to both ozone bulges and depletions. The highest 12-hour seasonal average ozone concentration is 0.12 ppb (the smallest isopleth line) and occurred approximately 40 kilometers from the plant in the east northeast direction. The lowest positive isopleth plotted in Fig. [2] is 0.01 ppb. This seasonal average ozone concentration occurred as far away as 180 kilometers from the plant in the northeast direction and 100 kilometers in the southwest direction. The results shown in Fig. [1] and [2] are very similar since emissions from the biomass-fired power plant do not cause significant ozone depletion on a seasonal average.

In addition to the results seen in Fig. [1] and [2] the seasonal average baseline ozone concentration was obtained from monitoring station data. The 9 a.m. to 9 p.m. seasonal average ozone concentration for a rural monitoring station (Rutlege Pike, Knoxville) approximately 60 kilometers from the hypothetical plant site, for the period from May 1990 to September 1990, was calculated from hourly ozone concentrations in the U.S. EPA AIRS database. The five-month seasonal average background ozone concentration is 53 ppb.

3.2 HEALTH EFFECTS RESULTS

Estimates of the peak daily one-hour average ozone concentration, due to the plant, for each day of the ozone season are required for the health effects analysis. Results from the MAP-O_3 model for the health effects portion are in tabular form and are too lengthy to include here. The peak daily ozone increment due to the power plant, as well as the daily peak background ozone concentration are reported at each location in a polar grid (each downwind distance and sector) for each day of the ozone season (provided the combined total of the background and increment due to the plant was greater than or equal to 80 ppb). This criteria was met (and results reported) for fifteen days during the 1990 ozone season. Three of the fifteen days was in the month of June, seven of the days were in July, four were in August, and one was in September.

As stated above, results for the health effects analysis are in tabular form and correspond to fifteen days of the ozone season. (If the actual results used in the health effects study were presented here graphically it would require 15 figures, one for each day). Alternatively, Fig. [3] is provided here, simply to illustrate the spatial distribution of daily peak ozone concentrations during the 1990 ozone season at the Southeast Reference site. The power plant is shown in the center of each isopleth map with a triangle marker. The scale of the figure is in kilometers from the plant. Ozone concentrations are reported in ppb (by volume).

The ozone concentrations shown in Fig. [3] are the maximum daily peak ozone concentrations at each location in the receptor grid. As seen in Fig. [3], the highest daily peak ozone concentration due to the power plant emission, during the ozone season, was 2 ppb, occurring within 20 kilometers of the plant. A peak daily ozone concentration of 1 ppb occurred over a wider area, from 130 kilometers in the northeast direction of 20 kilometers in the southwest direction. A daily peak ozone concentration of 0.5 ppb was seen, as far away as 150 kilometers in the northeast direction and 30 kilometers in the southwest direction.

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Table 1. Hourly meteorological parameters for the 10-highest ozone days during 1990 at Knoxville used to calculate emissions fluxes for the biomass-fired power plant.

Begin Hour	10-meter Wind Speed* (m/s)	Stack Top Wind Speed* (m/s)	Stability, Class	NOx Flux** (kg/km^2-hr)	NMOC Flux** (kg/km^2-hr)
0	1.0	2.9	7	0.08	0.01
1	1.1	3.2	7	0.09	0.01
2	1.2	3 5	7	0.10	0.01
3	0.5	1.3	7	0.12	0.02
4	0.9	2.5	7	0.13	0.02
5	0.8	2.2	7	0.15	0.02
6	0.6	1.6	6	0.19	0.03
7	1.0	1.9	5	0.23	0.03
8	1.3	1.8	4	0.31	0.04
9	2.2	2.7	3	0.46	0.07
10	2.4	2.7	2	0.93	0.13
11	2.2	2.5	2	0.93	0.13
12	2.8	3.2	1	0.93	0.13
13	2.8	3.2	1	0.93	0.13
14	2.3	2.6	1	0.93	0.13
15	2.8	3.2	2	0.93	0.13
16	2.3	2.6	2	0.93	0.13
17	2.3	2.7	3	0.93	0.13
18	2.1	2.4	2	0.93	0.13
19	2.5	3.0	3	0.93	0.13
20	2.1	2.8	4	0.93	0.13
21	2.1	4.1	5	0.93	0.13
22	1.4	3.9	6	0.93	0.13
23	1.2	3.5	6	0.93	0.13

* 24-hr average of stack height & surface wind speed: 2.2 m/s

** Flux based on the 24-hr average stack height and surface wind speed; flux for hours 0 to 9 is adjusted for spreading of plume

Table 2. Hourly meteorological parameters for the 10-median ozone days during 1990 at Knoxville used to calculate emissions fluxes for the biomass-fired power plant.

Begin Hour	10-meter Wind Speed* (m/s)	Stack Top Wind Speed* (m/s)	Stability Class	NOx Flux** (kg/km^2-hr)	NMOC Flux** (kg/km^2-hr)
0	1.3	3.6	6	0.05	0.01
1	1.2	3.5	7	0.06	0.01
2	1.3	3.6	6	0.06	0.01
3	1.0	2.7	6	0.07	0.01
4	1.6	4.5	7	0.08	0.01
5	1.4	3.9	6	0.09	0.01
6	1.3	2.6	5	0.11	0.02
7	1.3	1.7	4	0.14	0.02
8	1.4	1.8	4	0.19	0.03
9	1.9	2.3	3	0.28	0.04
10	1.8	2.1	2	0.57	0.08
11	2.8	3.4	3	0.57	0.08
12	3.6	4.1	2	0.57	0.08
13	3.1	3.5	2	0.57	0.08
14	3.1	3.5	2	0.57	0.08
15	2.8	3.2	2	0.57	0.08
16	2.5	3.0	3	0.57	0.08
17	3.0	3.7	3	0.57	0.08
18	3.1	4.2	4	0.57	0.08
19	2.4	3.1	4	0.57	0.08
20	2.4	4.7	5	0.57	0.08
21	2.4	6.6	6	0.57	0.08
22	1.9	5.3	6	0.57	0.08
23	2.2	6.2	6	0.57	0.08

* 24-hr average of stack height & surface wind speed: 2.9 m/s
** Flux based on the 24-hr average stack height and surface wind speed:
flux for hours 0 to 9 is adjusted for spreading of plume

Table 3. Hourly meteorological parameters for the 10-low ozone days during 1990 at Knoxville used to calculate emissions fluxes for the biomass-fired power plant.

Begin Hour	10-meter Wind Speed* (m/s)	Stack Top Wind Speed* (m/s)	Stability Class	NOx Flux** (kg/km^2-hr)	NMOC Flux** (kg/km^2-hr)
0	2.8	5.4	5	0.03	0.00
1	2.6	7.4	6	0.04	0.01
2	2.3	4.4	5	0.04	0.01
3	2.1	5.9	6	0.04	0.01
4	2.0	3.8	5	0.05	0.01
5	2.0	5.6	6	0.06	0.01
6	1.8	2.4	4	0.07	0.01
7	2.3	3.1	4	0.09	0.01
8	2.4	3.2	4	0.12	0.02
9	3.1	4.1	4	0.18	0.03
10	3.5	4.6	4	0.35	0.05
11	3.5	4.6	4	0.35	0.05
12	3.5	4.6	4	0.35	0.05
13	3.7	4.9	4	0.35	0.05
14	3.9	5.2	4	0.35	0.05
15	4.1	5.4	4	0.35	0.05
16	3.8	5.0	4	0.50	0.05
17	3.4	4.5	4	0.35	0.05
18	3.4	4.5	4	0.35	0.05
19	2.7	3.6	4	0.35	0.05
20	2.3	3.0	4	0.35	0.05
21	2.4	3.1	4	0.35	0.05
22	3.1	4.2	4	0.35	0.05
23	2.1	4.0	5	0.35	0.05

*21-hr average of stack height & surface wind speed: 3.6 m/s
** Flux based on the 24-hr average stack height and surface wind speed: flux for hours 0 to 9 is adjusted for spreading of plume

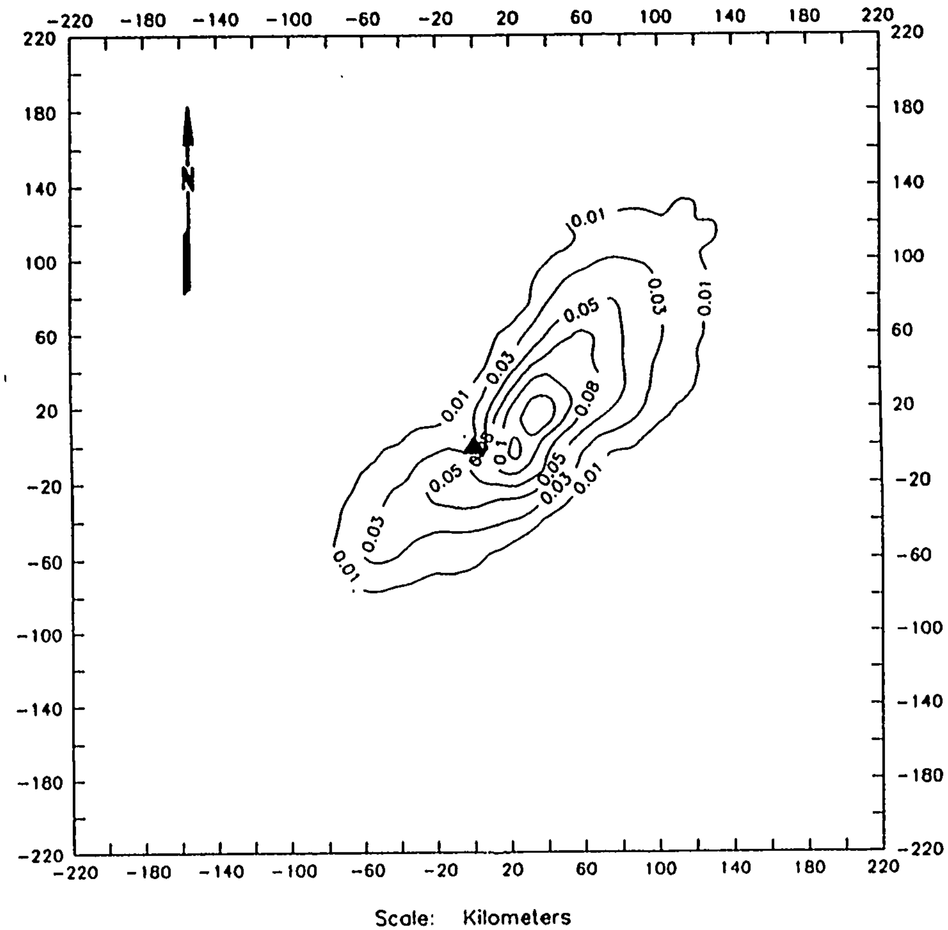

Fig. 1 Positive incremental 9 a.m. to 9 p.m. seasonal average ozone concentrations (ppb) for May to September 1990 due to emissions from the biomass-fired power plant located at the Southeast reference site (positive concentrations are above ambient).

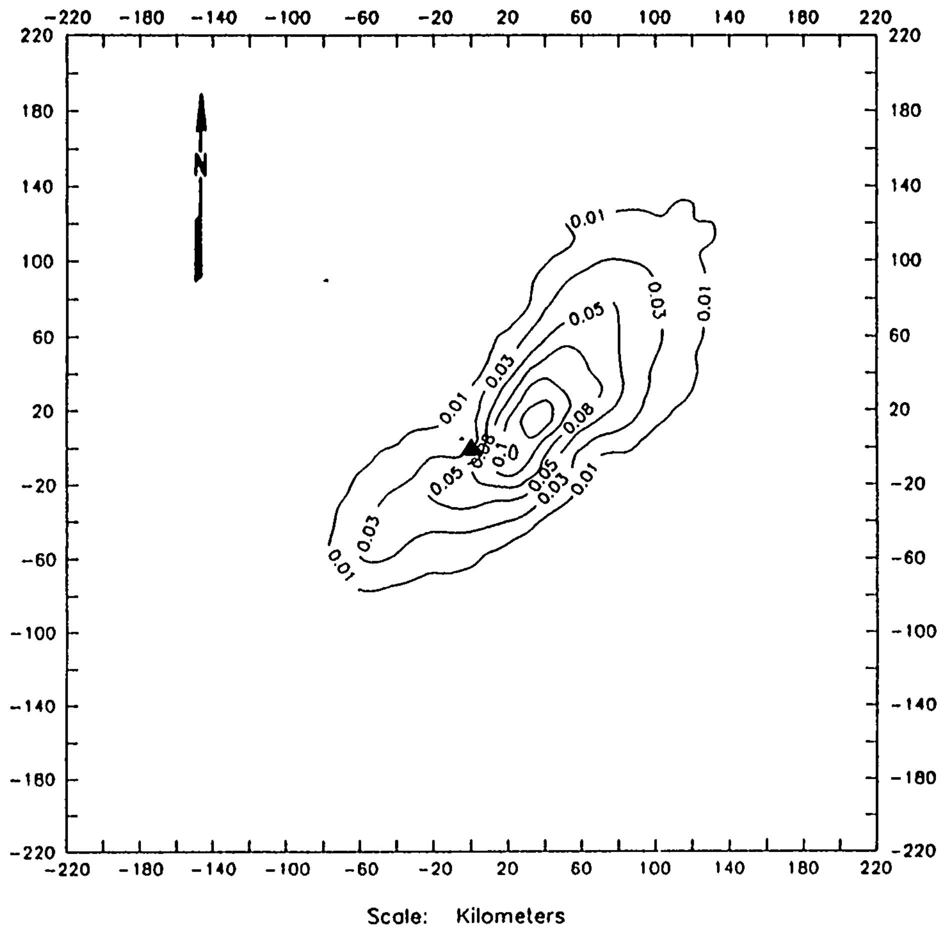

Fig. 2 Total incremental 9 a.m. to 9 p.m. seasonal average ozone concentrations (ppb) for May to September 1990 due to emissions from the biomass-fired power plant located at the Southeast reference site (total concentrations include both positive and negative incremental concentrations).

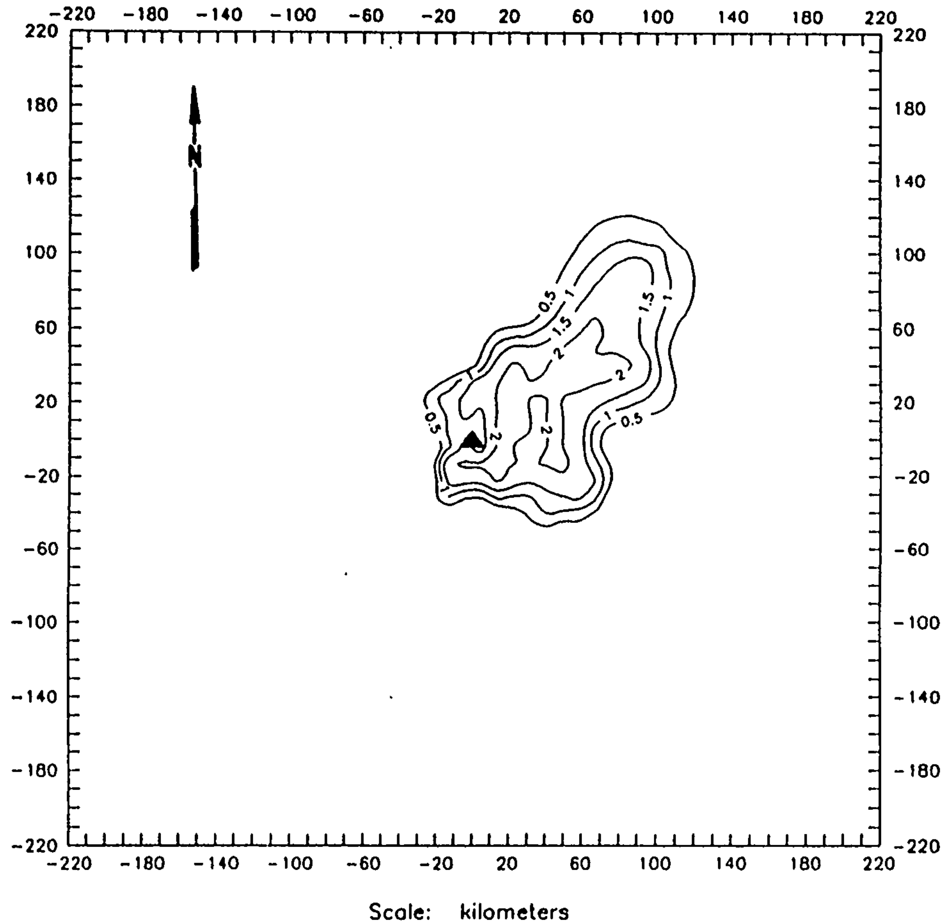

Fig. 3 Maximum daily peak incremental ozone concentrations (ppb) (one-hour average) for May to September 1990 due to emissions from the biomass-fired power plant located at the Southeast reference site.

APPENDIX C

AIR DISPERSION MODELING OF PRIMARY POLLUTANTS FROM ELECTRIC POWER PLANTS: APPLICATION TO A BIOMASS-FIRED POWER PLANT

1. INTRODUCTION

The ground-level pollutant concentrations that could be expected to occur as the result of the operation of a 30 megawatt (MW) biomass-fired power plant were predicted using atmospheric dispersion modeling. An atmospheric dispersion model is a set of mathematical equations used to characterize the dilution of pollutants by the wind. Some models also account for the chemical transformation of pollutants over time.

Using stack information, (i.e., stack diameter, exit gas velocity, and exit gas temperature) the model predicts the release height of pollutants to the atmosphere. Wind direction, wind speed and other meteorological measurements made in the vicinity of the stack are used to predict the dimensions (i.e., vertical and horizontal spread) of the plume and its travel path downwind. The model calculates pollutant concentrations at receptor locations which are defined by a system of grid points.

The air pollutants resulting from the operation of a power plant may be classified as primary (emitted directly from the plant) or secondary (formed in the atmosphere from primary pollutants). The primary pollutants of interest in this modeling study are nitrogen oxides (NO_x), sulfur dioxide (SO_2), and particulate matter. This appendix presents the source characteristics, the pollutant emission rates and the results of the primary air pollutant dispersion modeling for the hypothetical 30 MW biomass-fired power plant located at both the Southeast Reference site and the Southwest Reference site. This appendix is intended to provide details of the primary pollutant modeling that are specific to the gas fuel cycle. All other details of the modeling study are described in ORNL/RFF (1994a).

2. DATA USED IN THE COMPUTER MODELING

2.1 SOURCE CHARACTERISTICS

For the operation stage of energy production for a biomass-fired power plant, there is one source of air emissions: the exhaust gas stack. The source information needed to perform the air dispersion modeling includes the pollutant emission rate, stack height, exit gas temperature, exit gas velocity and stack tip (internal) diameter. The emissions used in the modeling are presented in the next section.

The hypothetical wood-fired boiler was modeled with a stack height of 65 meters (213 feet) according to the EPA Guideline for Determination of Good Engineering Practice Stack Height (Technical Support Documentation for the Stack Height Regulations, 1985). The boiler was modeled with an exit gas temperature of 477 Kelvin (400 degrees F) and an exit gas velocity of 15 meters per second (50 fps).

The exit gas flowrate was calculated using the F-factor from 40 CFR Part 60, App. A (7-1-90 edition). The F-factor is the ratio of the gas volume of the products of combustion to the heat content of the fuel. The average dry F-factor for wood and wood bark is 9420 dscf/MMBtu (dry standard cubic feet per million Btu). Assuming an efficiency of 22.9%, design availability of 70%; and excess air of 50% the actual flowrate for a 30 MW wood-fired boiler was calculated to be 120,000 acfm (actual cubic feet per minute) or 57 actual cubic meters per second. This flowrate was input to the model as an exit gas velocity of 15 meters per second and an inside stack diameter of 2.2 meters.

2.2 EMISSIONS

Air pollutant emissions from the operation of the biomass-fired power plant used in the modeling study are given in Table 1. A detailed description of the emissions estimates is given in Chapter 5. Emission rates of 6.59 grams per second (g/s) nitrogen oxide (NO_x), 0.32 g/s SO_2, 0.62 g/s total particulate matter and 0.57 g/s PM-10 were used in this analysis. PM-10 is particulate matter with an aerodynamic diameter less than 10 micrometers.

3. RESULTS

The Environmental Protection Agency (EPA) Industrial Source Complex Long-Term (ISCLT) model (EPA 1986) was used to predict annual average pollutant concentrations expected to occur in the vicinity of the power plant. The EPA SCREEN model (Brode, 1988) was used to predict the highest one-hour average pollutant concentrations expected to occur at 24 downwind distances from the power plant. One-hour average pollutant concentrations predicted with the SCREEN model were multiplied by a persistence factor of 0.4 (Brode, 1988) to obtain the highest 24-hour average concentration. Both models were run with an emission rate of 1 g/s. The results from these model runs represent the annual, one-hour and 24-hr average concentrations expected to occur from a unit emission rate. Finally, these concentrations were multiplied by the emission rates, in grams per second, of each of the pollutants of interest.

The ISCLT model was used to predict concentrations at 384 receptor locations (16 directions times 24 downwind distances). The highest concentration at each downwind distance is presented here for the sake of brevity. Concentrations predicted for each receptor location were used in the calculation of impacts in the fuel cycle analyses. The SCREEN model predicts the highest concentration at each receptor along a single radial.

3.1 UNIT CONCENTRATIONS

The highest annual average unit concentration for 24 downwind distances are presented in Table 2. The highest of these concentrations is 0.024 micrograms per cubic meter ($\mu g/m^3$), occurring 3 kilometers from the plant. The highest 24-hour and highest one-hour average unit concentrations for 24 downwind distances are presented in the second and third columns of Table 2. The highest 24-hour average concentration is 1.14 $\mu g/m^3$ and the highest one-hour average concentration is 2.849 $\mu g/m^3$, both occurring 1 kilometer from the plant.

3.2 POLLUTANT CONCENTRATIONS

The maximum pollutant concentrations of PM-10, SO_2 and NO_x, predicted to occur at 24 downwind distances from the power plant at the Southeast site for 1990 are presented in Table 3. These concentrations were determined by multiplying the unit concentrations in Table 2 by the emission rate (grams per second) in Table 1 for each pollutant.

The highest annual average incremental concentration of total particulate matter and PM-10 are 0.015 $\mu g/m^3$ and 0.014 $\mu g/m^3$, respectively. The highest annual average incremental concentration of SO_2 is 0.008 $\mu g/m^3$ and the corresponding value for NO_x is 0.157 $\mu g/m^3$.

The highest 24-hour average incremental concentration of total particulate matter and PM-10 are 0.707 $\mu g/m^3$ and 0.650 $\mu g/m^3$, respectively. The highest 24-

hour average incremental concentration of SO_2 is 0.365 $\mu g/m^3$ and the corresponding value for NO_x is 7.51.

The highest one-hour average incremental concentrations of total particulate matter and PM-10 are 1.766 $\mu g/m^3$ and 1.624 $\mu g/m^3$, respectively. The highest one-hour average incremental concentration of SO_2 is 0.912 $\mu g/m^3$ and for NO_x the value is 18.8 $\mu g/m^3$.

3.3 COMPARISON TO NAAQS

Under current federal law, National Ambient Air Quality Standards (NAAQS) have been established for sulfur dioxide, nitrogen dioxide, lead, carbon monoxide, ozone and inhalable particles (PM-10). Tables 4 presents a comparison of the total concentration (the sum of the incremental concentration due to the power plant plus the background concentration) and the NAAQS for PM-10 and SO_2 and NO_x at both sites, for 1990. As shown in Table 4, the total ambient concentration of these pollutants is below the NAAQS. (For regulatory purposes, the second highest receptor concentration is added to the background concentration and compared to the NAAQS.)

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Table 1. Emissions rates for wood-fired combustion

Pollutant	EPA Emission Factor lbs/wet ton burned	Uncontrolled Emission Rate			NSPS lb/MMBtu	Controlled Emission Rate		
		tons/year	grams/ second	lb/MMBtu		tons/year	grams/ second	lbMMBtu
PM	7.2	1098	31.60	0.80	0.03	22	0.62	0.016
PM-10	6.5	988	28.43	0.72	NA	20	0.65	0.014
SO_2	0.075	11	0.32	0.008	1.2	11	0.32	0.008
NO_x	1.5	229	6.59	0.167	0.6	229	6.59	0.167
TOC	0.22	33	0.95	0.024	NA	33	0.95	0.024
CO	13.6	2074	59.69	1.51	NA	2074	59.7	1.51

Controlled emission rates for particulates is based on an assumed collection efficiency of 98%.

U.S. Environmental Protection Agency (EPA), *Chief (Clearinghouse for Inventories and Emission Factors)*, AP-42, "Wood Waste Combustion in Boilers," Research Triangle Park, North Carolina, July 1993.

Table 2. Maximum unit concentrations at downwind distances from the biomass-fired power plant stack at the Southeast Reference site (micrograms/cubic meter).

Downwind Distance From Stack (km)	Maximum Unit Concentration		
	24-hr Avg. SCREEN	1-hr Avg. SCREEN	Annual Avg. ISCLT
1	0.140	2.849	0.023
2	0.702	1.754	0.021
3	0.594	1.485	0.024
4	0.517	1.292	0.023
5	0.432	1.081	0.022
6	0.439	1.098	0.021
7	0.424	1.060	0.019
8	0.396	0.990	0.018
9	0.366	0.914	0.017
10	0.337	0.842	0.016
15	0.299	0.746	0.012
20	0.275	0.687	0.010
25	0.243	0.608	0.008
30	0.216	0.541	0.007
35	0.194	0485	0.006
40	0.176	0.439	0.005
45	0.160	0.399	0.004
50	0.146	0.366	0.004
55	0.077	0.192	0.004
60	0.073	0.182	0.003
65	0.069	0.173	0.003
70	0.066	0.165	0.003
75	0.063	0.158	0.003
80	0.060	0.151	0.002

Table 3. Maximum pollutant concentration (micrograms/cubic meter) at downwind distances from the biomass power plant stack at the Southeast Reference site for 1990.

Downwind Distance From Stack (km)	Maximum Particulate Concentration			Maximum PM-10 Concentration		
	24-hr Avg. SCREEN	1-fur Avg. SCREEN	Annual Avg. ISCLT	24-hr Avg. SCREEN	1-fur Avg. SCREEN	Annual Avg. ISCLT
1	0.707	1.766	0.014	0.650	1.624	0.013
2	0.435	1.087	0.113	0.400	1.000	0.012
3	0.368	0.921	0.015	0.339	0.846	0.014
4	0.320	0.801	0.014	0.295	0.736	0.013
5	0.268	0.670	0.014	0.246	0.616	0.013
6	0.272	0.681	0.013	0.250	0.626	0.012
7	0.263	0.657	0.012	0.242	0.604	0.011
8	0.246	0.614	0.011	0.226	0.564	0.010
9	0.227	0.567	0.011	0.208	0.521	0.010
10	0.209	0.522	0.010	0.192	0.480	0.009
15	0.185	0.463	0.008	0.170	0.425	0.007
20	0.170	0.426	0.006	0.157	0.392	0.006
25	0.151	0.377	0.005	0.139	0.346	0.005
30	0.134	0.335	0.004	0.123	0.308	0.004
35	0.120	0.301	0.004	0.111	0.277	0.003
40	0.109	0.272	0.003	0.100	0.250	0.003
45	0.099	0.247	0.003	0.091	0.227	0.003
50	0.091	0.227	0.002	0.083	0.209	0.002
55	0.048	0.119	0.002	0.044	0.109	0.002
60	0.045	0.113	0.002	0.042	0.104	0.002
65	0.043	0.107	0.002	0.039	0.099	0.002
70	0.041	0.102	0.002	0.038	0.094	0.002
75	0.039	0.098	0.002	0.036	0.090	0.001
80	0.037	0.093	0.002	0.034	0.086	0.001

Table 3 (cont.). Maximum pollutant concentration (micrograms/cubic meter) at downwind distances from the biomass plant stack.

Downwind Distance From Stack (km)	Maximum SO_2 Concentration			Maximum NO_x Concentration		
	24-hr Avg. SCREEN	1-hr Avg. SCREEN	Annual Avg. ISCLT	24-hr Avg. SCREEN	1-hr Avg. SCREEN	Annual Avg. ISCLT
1	0.365	0.912	0.007	7.51	18.8	0.150
2	0.225	0.561	0.007	4.61	11.6	0.139
3	0.190	0.475	0.008	3.91	9.8	0.157
4	0.165	0.413	0.007	3.41	8.5	0.154
5	0.138	0.346	0.007	2.85	7.1	0.145
6	0.414	0.351	0.007	2.89	7.2	0.136
7	0.136	0.339	0.006	2.79	7.0	0.127
8	0.127	0.317	0.006	2.61	6.5	0.119
9	0.117	0.292	0.005	2.41	6.0	0.112
10	0.108	0.269	0.005	2.22	5.5	0.106
15	0.096	0.239	0.004	1.97	4.92	0.080
20	0.088	0.220	0.003	1.81	4.53	0.064
25	0.078	0.194	0.003	1.60	4.00	0.052
30	0.069	0.173	0.002	1.43	3.56	0.044
35	0.062	0.155	0.002	1.28	3.20	0.038
40	0.056	0.140	0.002	1.16	2.89	0.033
45	0.051	0.128	0.001	1.05	2.63	0.029
50	0.047	0.117	0.001	0.964	2.41	0.026
55	0.025	0.061	0.001	0.505	1.26	0.024
60	0.023	0.058	0.001	0.481	1.20	0.022
65	0.022	0.055	0.001	0.457	1.14	0.020
70	0.021	0.053	0.001	0.435	1.09	0.019
75	0.020	0.050	0.001	0.415	1.04	0.017
80	0.019	0.048	0.001	0.397	0.99	0.016

Table 4. Summary of modeling results and monitoring data for the biomass-fired plant located at the Southeast Reference site (micrograms per cubic meter).

	Particulate		PM-10		NO_x	SO_2	
	24-hour	Annual	24-hour	Annual	Annual	24-hour	Annual
Maximum Incremental Impact of the Facility	0.71	0.015	0.65	0.014	0.16	0.36	0.008
Background Concentration	108	47	71	37	23	76	25
Total Concentration	109	47	72	37	23	76	25
NAAQS**	None	None	150	50	100	365	80

* From 1990 EPA AIRS database McMinn Co. TN monitoring station (Site I.D. 47-107-0101); 2[nd] highest 24-hour average and annual mean.

** For regulatory purposes the second highest receptor concentration is added to the baseline concentration and compared to the National Ambient Air Quality Standard (NAAQS).

APPENDIX D
HEALTH IMPLICATIONS ASSOCIATED WITH THE BIOMASS-TO-ELECTRICITY FUEL CYCLE

1. INTRODUCTION

Biomass describes a range of renewable organic material resulting from the process of photosynthesis. With an energy content of nearly 9000 Btu/lb (if no moisture is present), biomass has a heating value/lb of 50 to 65% that of coal (Cheremisinoff, Cheremisinoff and Ellerbusch 1980; Hall 1981). Various solid, liquid and gaseous fuels may be produced from biomass feedstocks utilizing biochemical and thermochemical conversion processes (Watson and Etnier 1981; Turhollow 1991). Combustion of solid biomass for heating purposes is a technique of ancient origins which continues in use to the present in both developing and developed countries. In the United States, primary categories of usage include residential space heating, process heat and steam generation by the forest products industry, and the generation of electricity (Turhollow 1991). However, the focus of this review is exclusively on the utilization of biomass for generation of electricity, in order to identify potential health effects which may be associated.

2. EFFLUENTS

2.1 COMBUSTION PRODUCTS

Of environmental significance, most biomass, other than manure and kelp, is relatively free of sulfur (Braunstein et al. 1981, Williams 1990). Additionally, biomass contains little nitrogen, trace metals or ash (Smith 1987). Given the lack of potential pollutants identified directly with biofuels, the combustion process itself becomes key to understanding emissions. The burning of woody biomass involves four stages of temperature-dependent combustion which do not necessarily occur sequentially. These include: moisture evaporation, distillation of volatiles by pyrolysis, combustion of volatiles, and fixed carbon (char) burning (Braunstein et al. 1981). For complete combustion, several conditions are required. These are: an adequately high combustion temperature, oxygen and sufficient residence time of fuel in the presence of optimal temperature and oxygen (Smith 1987). As Smith

(1987) has stated: "Complete combustion of carbonaceous fuels...releases only carbon dioxide and water, substances not categorized as health damaging pollutants except in rare circumstances." However, there are always realistic factors which present this perfect combustion.

Although carbon dioxide (CO_2) is generated by biomass combustion, the net effect is neutral because replanting energy crops removes atmospheric CO_2 (Williams 1990; Wright and Ehrenshaft 1990; Weinberg and Williams 1990). Thus, CO_2 is fixed and recycled by biofuels technology. While coal, oil and natural gas energy sources emit CO_2, biomass is believed to contribute to the net reduction of CO_2. Elliott (1989) has estimated that at least a 4.5% reduction in present levels of CO_2 annually may be attributed to biofuels. This estimate assumes that 80% of the wood biofuels are waste products which otherwise would release CO_2 from the natural process of decay. Consequently, there is less contribution to greenhouse gases in the atmosphere and to potential global climate changes.

In contrast, incomplete combustion of carbonaceous fuel associated with forest fires, small scale combustion units, fireplaces, inefficient wood-burning stoves, and inefficient incinerators has contributed a negative image to biomass combustion. A combination of moist wood and an insufficient supply of air will result in a complex wood smoke mixture of solid particles, condensed liquid particulates and volatiles. Hundreds of separate chemical agents have been identified in biofuel smoke with the pollutants similar to those found in tobacco smoke (Smith 1987). However, drying the fuel as will be done for both 1990 and 2010 scenarios and increasing the available oxygen will accelerate the rate of burning and will diminish the smoke level.

2.2 AIRBORNE EMISSIONS

Several of the emissions from incomplete combustion of wood require discussion. Three of the six categories of criteria pollutants are involved, including particulate matter (PM), carbon monoxide (CO), and hydrocarbons (HC). Because particulates and hydrocarbons are broad categories of material, their chemical and physical characteristics will vary rather widely. High emissions of PM and CO are produced generally by a lowered combustion temperature (often due to the moisture content in the fuel). Ostlie (1989) has noted that post-combustion devices such as multicyclones, dry scrubbers and electrostatic precipitators are effective in reducing particulate emissions, which he has identified as the major pollutant from high performance wood burning furnaces.

High hydrocarbon emissions result if secondary air is not available to burn volatiles (Braunstein, Kornegay, Roop and Sharples 1981). Volatile compounds constitute a large proportion of the combustible material in biomass, which may be emitted during pyrolysis, the second stage of combustion (Smith 1987). When conditions necessary for complete combustion are deficient, formation of polycyclic aromatic hydrocarbons (PAH), including benzo(a)pyrene which is a carcinogen, will result. Emissions of organic compounds in the flue gas, due to incomplete combustion, may be reduced by sustaining efficiency of combustion and by particulate control devices (Turhollow 1991). These emission control practices are anticipated on the 1990 and 2010 scenarios.

Tillman (1987) identifies nitrous oxides (NO_x), in addition to particulates, as a primary air pollution problem associated with biomass conversion. NO_x, which also are combustion by-products, may be released from nitrogen in the atmosphere (termed thermal NO_x) or in biomass (termed fuel NO_x), but to a lesser extent than PM. Wood contains less than 0.1% nitrogen by weight (Ostlie 1987) and staged combustion techniques for control or minimization of NO_x are known. Compared to that produced by coal, biomass emits approximately 45% less NO_x (EPRI 1991). Oxides of nitrogen may present more problems with fuels such as rice hulls, grape pomace and cotton processing wastes or if low excess air biomass combustors are utilized (Tillman 1987). Smith (1987), in contrast to Tillman, contends that NO_x emissions problems are not expected with woody feedstock conversion. In any event, most researchers support the view that environmental standards can be achieved by technical control of the biomass conversion process (Turhollow 1991).

Due to the negligible sulfur (<0.1%) in wood, sulfur oxides (SO_x), and especially sulfur dioxide (SO_2), are not a problem, which results in less impact to acid rain. Unlike CO and particulates, the moisture content of woody biomass used in combustion has no influential role with this pollutant.

Compared to coal, emissions for wood-fired power plants are substantially less. Based on the possible range of emission values, CO is an exception to this comparison. EPRI (1991) reported comparative emissions as shown in Table 1.

Biomass contains 3 to 5% ash (Weinberg and Williams 1990). Wood ash, although alkaline, contains lower concentrations of heavy metals compared to coal ash and does not require hazardous waste treatment (Ostlie 1989; EPRI 1991). However, safe disposal as a fertilizer or in landfills must be managed to avoid potential for increasing the alkalinity of water which may leach through storage piles of ash (Ostlie 1989).

3. POTENTIAL HEALTH IMPACTS OF EMISSIONS

The literature on wood smoke has identified three pollutants most likely to be major factors stimulating health impacts (Smith 1987). These are: particulates,

Table 1. Comparative emissions for uncontrolled industrial boilers (lb/MBtu)

Pollutants	Fuel source	
	Wood	Coal
PM	0.88–4.7	4.7
CO	0.04–4.7	0.18
NO_x	0.28	0.51
SO_x	0.02–0.04	2.12

Source: EPRI 1991

carbon monoxide and polycyclic aromatic hydrocarbons. Other emissions will consist of NO_x, CO_2, and very small amounts of SO_x.

Particulates, identified as the major biomass-combustion pollutant serve as an irritant to the respiratory system. Small particles and tiny aerosols ("fine particulates") can penetrate deeply into the lungs and act as deposition sites for organic materials. The suggested health effects from particulate emissions are acute respiratory infections, aggravation of asthma, increased chest discomfort and chronic obstructive lung disease (e.g., chronic bronchitis). Most epidemiologic studies have not distinguished between PM and SO_x due to their usually mutual occurrence in a polluted atmosphere. Another limitation to interpretation is that dose-response findings related to PM have varied among the studies conducted (Clayton 1978).

Carbon monoxide when inhaled, binds to hemoglobin in the blood displacing oxygen. Depending on the CO dose, a range of impacts from impairment of perceptions to decreased concentration ability to aggravation of cardiovascular disease to death may result. Levels of 4% and above of the CO biomarker, carboxyhemoglobin (COHb), are considered undesirable for humans, but smokers generally exceed this level regardless of atmospheric pollution (Clayton 1978). Controlled studies conducted during the 1980s involving subjects with coronary artery disease have revealed that cardiac effects may result at low levels of CO exposure. Exacerbation of myocardial ischemia and ventricular arrhythmias were demonstrated in the range of 2.0% to 6.0% COHb, especially during periods of exercise (Allred et al. 1989; Kleinman et al. 1989; Adams et al. 1988; Sheps et al. 1987; and Sheps et al. 1990).

Benzo(a)pyrene, a hydrocarbon, may be inhaled, deposited in the lungs and serve as a precursor to cancer. Its mechanism of health effect may include metabolic activation also. The national ambient air quality standards for this pollutant are based more on the role of HC as precursors of other compounds of photochemical smog, rather than on the scant evidence of direct health effects of HC (Clayton 1978).

NO_x and HC are recognized as precursor pollutants which react chemically in the presence of sunlight to form a secondary air pollutant, ozone. Ozone produces adverse acute health effects of irritation to the human respiratory tract and may produce chronic lung damage due to its highly active oxidizing properties. Because ozone is less water soluble than other toxicants (e.g., SO_2), the mucus layer which is composed 95% of water does not serve as an effective protective barrier during ozone passage through the upper respiratory tract (Bus and Gibson 1985).

However, health effects are dependent upon the amount of material actually deposited in the human body, termed the dose. Other factors also may be influential, such as cigarette smoking, existing disease, age, and sex. To obtain a sufficient dose, the individual must be exposed to a high concentration of airborne pollutants. The extent of this exposure will be modified by atmospheric conditions, time of exposure, nature of the space, ventilation, and rate of breathing.

With the exception of CO, estimating the individual dose or measuring the body burdens of air pollutants are not well developed techniques. Carboxyhemoglobin (HbCO) as a percent of total hemoglobin in blood serves as a close surrogate for the level of CO in the body. Thus, determining dosage received and health impacts from emissions are not exacting calculations.

In any event, by utilizing an efficient combustion technology and post-combustion controls on flue gases, emissions should not exceed ambient air quality standards. Health impacts from the emissions of biomass combustion are thereby small.

4. OCCUPATIONAL HAZARDS

4.1 INJURY POTENTIAL

Short rotation woody crops (the feedstock considered in this study) utilize systematic plantings, thus permitting more mechanization, in the harvesting of woody biomass. By contrast primary timber cutting and logging workers who are placed at considerable risk of unintentional injuries by their occupation include tree fellers, choker-setters (who attach cables to logs), and mobile equipment operators. In that industry the terrain, weather conditions, the wide geographical dispersion of the trees, and the close working proximity to heavy equipment and to cutting equipment are major factors increasing the risks of injury. Also, cutting injuries are likely to occur due to worker fatigue. Factors contributing to worker fatigue during chain saw usage in commercial logging include increased physical exertion, noise, heat stress and vibration exposure (NIOSH 1990b; Paulozzi 1987).

Watson and Etnier (1981) emphasized the significant potential for occupational injuries and fatalities in this industry. They noted that the high incidence of lost workdays among workers was principally due to injuries associated with shifting logs, falling trees, chain saw kick backs and falls during entry or exit from equipment (Watson and Etnier 1981). The substantial risk of physical harm associated with logging has influenced the conclusion by the Occupational Safety and Health Administration (OSHA) and the National Institute for Occupational Safety and Health that logging is "inherently dangerous" (NIOSH 1989).

The potential severity of injury may be illustrated by a study of injury to 51 loggers in the Northwest who required treatment at a level-I trauma center (Holman, Olszewski and Maier 1987). Falling or rolling trees or logs produced the injuries for 67% of the cohort. Two loggers (4%) died of massive head injuries and 25 workers received permanent disabilities sustained from head injuries, orthopedic injuries or spinal injuries (Holman, Olszewski and Maier 1987).

A study of fatal logging injuries in Washington State revealed an annual injury mortality rate of approximately 2/1000 workers, assuming the average worker worked 2000 hours/year (Paulozzi 1987). Falling trees were cited for 34% of the fatalities and equipment for an additional 24% of the fatalities. Those at greatest risk were tree fellers and choker-setters. Company size was noted as a significant variable for risk of injury. For companies employing five or fewer loggers, mortality ratios were nearly ten times higher than those of the largest companies (Paulozzi 1987). Equipment rollovers in the logging industry are calculated to produce a fatality rate of 15 deaths per 100,000 workers per year (NIOSH 1989). The occupational hazards of the logging industry may **not** be pertinent, however, to the production and harvesting of short rotation woody crops. The latter set of activities are more like farming. Due to the development of biomass energy plantations, data on fatal farming injuries involving tractors may be more relevant. The National Safety Council (1991) reported an annual rate of 9.9 deaths per 100,000 tractors for 1990. Tractor overturns were cited for 52% of all on-the-farm tractor fatalities reported, with an additional 33% due to run over. On the basis of a tractor harvesting at a rate of 2 tons/h, it is estimated that approximately 50 tractors will be needed to harvest the approximately 191,000 tons of dry matter per year. Further, about 50 more tractors will be required for agricultural related activities. Thus, using the recent death rate for tractor accidents, the production of woody biomass would be expected to result in 0.01 tractor related deaths per year. The basis for this estimate is experience with farm tractor use, but handling 6–8 in. diameter trees may not fit the farm use definition. General farm accidents would increase this figure to 0.04.

Approximately 1×10^{-7} accidental deaths per GJ wood has been estimated for whole tree removal (IAEA 1982). Collecting widely dispersed wood residues involves more injuries per unit energy collected due to the additional person hours of exposure. For the 40 MWe 1990 technology, this rate would result in about 0.3 deaths per year. It is anticipated that the adapted agricultural procedures will result in mortality rates somewhere between the rate based on the general farm rate of 0.01 and the IAEA figure of 0.3 for the 40 MWe case. For this study we use a mean between these two of 0.17 (National Safety Council 1991).

Data by the Bureau of Labor Statistics, presented in Table 2, reveal the dramatically higher incidence rates of occupational injuries per 100 full time workers in the agriculture, forestry and logging industries for 1988 compared with all private sector workers (BLS 1990). The lost workday cases cited in Table 2 are those which resulted in days away from work or days of restricted work activity, or both. Total lost workdays for the logging industry are approximately three times higher compared to the other two industries and five times higher than that experienced in the private sector. Assuming 100 people are required to support a 40 MWe biomass plant, and assuming a mean value between agriculture and logging of 225 work days lost per 100 employees, it is estimated that the 40 MWe biomass plant will contribute to 225 work days lost per year.

Table 2. U.S. Occupational injury incidence rates for agriculture forestry and logging industries, 1988

Workdays	Incidence rates per 100 full-time workers		
	Total cases	Lost workday cases	Total lost workdays[a]
Agricultural production	11.7	6.1	107.8
Forestry	11.9	6.3	136.0
Logging camps and logging contractors	19.6	12.7	345.4
Private	8.3	3.8	72.5

Source: BLS 1990.
[a]Lost work days or restricted days.

An estimated 16,500 compensable injuries occur to logging workers per year (NIOSH 1990a). Based on this estimate, approximately one in every five loggers will experience a compensable injury each year, with over half of the injuries involving cuts, fractures, or contusions (NIOSH 1990a).

Overall, relevant data for the 1990 and 2010 alternatives is unavailable because there are no biomass plants operating yet using the types of harvesting techniques proposed. Consequently, occupational health effects are subject to much uncertainty.

4.2 MICROORGANISMS

Storage of biomass in preparation for biochemical or thermochemical conversion processes presents some problems. These include odors, fugitive dusts, loss of volatiles, spontaneous combustion and leachates. Of importance as a hazard to health is the growth of microorganisms and fungi utilizing lignocellulosic plant material as a substrate. Egneus and Wallin (1984) consider the spore and microorganism production to be a serious problem associated with handling biomass. They did not provide details regarding the length of storage time as a factor or suggest precautionary techniques.

Several health complaints were identified which have been associated with etiologic agents growing on grain, straw and wood (Egneus and Wallin 1984). The primary route of entry is by inhalation of the spores. Regarding mouldy wood chips, *Rhizopus sp.*, *Mucor sp.*, and *Aspergillus fumigatus* are specified as agents giving rise to "chip boiler's complaint." *Aspergillus* is a group of fungi of low pathogenicity for the human unless other factors impact natural resistance. Aspergillosis may become localized to the lungs, ear or parinasal sinuses or be disseminated to other parts of the body (brain, heart, kidney, and spleen) by the blood stream where abscesses or granulomas may form (NIOSH 1977). For mouldy wood, *Pullaria pullulans* and *Peacilomyces sp.* are cited in relation to "sauna bather's disease" (Egneus and Wallin 1984). Because of lack of information it was not possible to relate the presence of microorganisms to numbers of persons affected or the degree of effect.

4.3 LIMITATIONS OF BIOMASS HEALTH AND SAFETY EFFECTS REVIEW

A lack of information specific to biomass-generated electricity introduced substantial limitations to this review of associated health implications. The majority of available data on the end use of biomass is directed to alcohol fuels used in transportation. Data related to harvesting, transporting and storing of woody biofuels generally are aggregated for the total logging and forest products industries, thus making it difficult to quantify the issues of interest. Although suggestive of implications for biomass combustion technologies, these data do not permit the development of an adequate health and safety profile of biomass converted thermochemically for the production of electricity.

As Smith (1987) has noted, few studies of ill health produced by biofuel smoke exposures have been reported in the literature. Anecdotal accounts of exposures in industrial countries which are described are more often related to wood-fired heating stoves and combustion products of gas-fired cook stoves (Smith 1987).

More systematic data collection efforts will be needed to characterize the various occupationally health related factors associated with the biomass fuel cycle. Discrete data on occupational injuries associated with harvesting and transporting that biomass intended specifically for use in generating electricity are needed to improve understanding of this cost. Additional quantification of emissions from biomass-fueled power plants is needed.

5. SUMMARY

The lack of information regarding the use of biomass specifically for generating electricity hindered the conduct of this review and led to a less than complete report. Most data available in the literature are focused on residential indoor air quality exposures and on biofuels used in transportation.

The emissions which may be cited for biomass combustion are related to the incomplete combustion of wood fuel rather than to constituents of the feedstock itself. If the combustion process is technologically efficient and particulate control devices are utilized, emissions are small with respect to coal combustion. Of special note, biomass as a substitute for coal will lessen atmospheric CO_2.

However, more research attention is needed to quantify hydrocarbon emissions from the biomass combustion process. Also, the limited research and development which has been directed to biomass-fired gas turbines to date (Williams 1990) should be expanded.

The major related health impact of the biomass fuel cycle is occupational injury associated with the production and harvest industries. Again, the data are not collected at a level which enables injuries to be defined specifically for the harvesting and transporting of biomass subsequently used for power generation.

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APPENDIX E
DAMAGES FROM OFF-SITE EROSION ASSOCIATED WITH THE BIOMASS CYCLE

1. INTRODUCTION

The major distinguishing feature of the biomass fuel cycle, from an environmental point of view, is the possibility of environmental damage related to the production of the fuelwood. As this production process is more like farming than forestry, the traditional concerns about damages from agricultural pollution are germane here, including effects from soil erosion (both those related to the soil itself and the nutrients, herbicides, and pesticides that it carries), from groundwater infiltration, and from blowing soil. Of these, the most research, and probably the largest effects, are those associated with soil erosion. Accordingly, this appendix will present a brief review of the issues and a survey of the literature associated with estimating the damages associated with soil erosion from a biomass farm.

2. VALUATION MEASURES

The basic measure of the damage from off-farm soil erosion is the willingness-to-pay (WTP) of individuals to avoid these effects. Measures of defensive expenditures, changes in production costs (producer surplus losses), and changes in consumer surplus can be used to estimate WTP. For instance, if sediment clogs waterways and endangers shipping, dredging expenditures would be a perfect measure of the damage caused to navigation only if the dredging activity is a perfect substitute for the damage to shipping. More likely, dredging expenditures would underestimate damages to shipping if the sediment was permitted to build up in waterways. Other examples of defensive expenditures for soil erosion are removal of sediment from highway ditches and irrigation canals, and from drinking water treated by municipal authorities.

If water is an input to an industrial production process and sediment in the water raises production costs, then the difference in profit (assuming prices are unchanged) with and without the sediment is a measure of damage. Under certain assumptions, the change in production costs is an equivalent measure of damage. If water quality is an input into demand for goods and services, such as recreation, changes in quality will affect demand and change consumer surplus. The probability of a person participating in water-based recreation, the frequency of participation, and the enjoyment obtained in participation all may be affected. The presence of substitute sites that are affected or unaffected by the quality change complicates the procedures for measuring consumer surplus changes.

Some measures of damage are better than others. For example, water storage problems arise when sediment builds up behind a dam. Some have suggested (Ribaudo 1989) that a measure of damage might be the replacement cost of new storage capacity. However, the true measure is the WTP to avoid water shortages that might result if no additional capacity is provided in response to the loss of storage capacity. If substantial unutilized capacity exists, these damages would be zero. Similarly, most studies use average damage values derived from state level data. The lack of geographical specificity and the use of marginal rather than average values can seriously mislead. For instance, while a state may have flood control problems that are worsened by sediment build-up, particular watersheds within the state may not have flooding problems. But the application of an state average damage estimate to the reference environment would ignore this distinction. Similarly, use of the average flood damage estimate, even if geographically applicable, might be a poor estimate of the added damage related to an increment in sedimentation, particularly where there are thresholds in damages, say because of local geography, flood waters need to rise very far before a new tier of housing is affected.

One should also be wary of the difference between damages and benefits here. Numerous studies estimate the benefits of erosion control programs. Treating these estimates as negatMwe damages can seriously underestimate true damages unless one incorporates a model of sediments and stream flow in the estimation process. As Clark et al. make clear, reductions in erosion will be offset, in part, by greater streambed and bank erosion as a physical equilibrium is regained in terms of stream slope, sediment load, and water volume (p. 139). Thus, various authors say that the benefits of reducing erosion by one ton will be generally less than the damages from increasing erosion by one ton.

At least two types of damages may be only partly externalities, depending on whether hydroelectric facilities are in the utility's generation mix: water storage and flood control. Both of these problems are created by the construction of dams for water storage and flood control. Often such dams serve the additional purpose (or the main purpose) of generating electricity. In this case, at least some of the additional costs of sediment buildup behind the dam would be internalized in the cost of electricity produced from the hydroelectric facility, assuming the company running the biomass plant is also running the hydroelectric facility, or seeks to internalize these effects in its contracts with private operators. In contrast, if the dam is creating a reservoir only for water supply, sediment from the biomass plant might affect water prices, and would be external to electric utility decisions. For the particular case of

Table 1. Estimates of soil erosion damages [Clark et al (1985)]

Type of impact	Cropland's share (millions of 1980 $'s)	
In Stream		
Biological	NA	
Recreation	830	
Water storage	220	
Sediment pools		110
Replacement capacity		100
Navigation	180	
Dredging		170
Dredge spoil disposal		NA
Other	320	
Commercial fishing		140
Preservation values		180
Off-stream		
Flooding	250	
Water conveyance	100	
Water treatment	30	
Other	280[a]	
Municipal and industrial users		300
Total	**2,200**	

[a]There are some offsetting benefits not shown here. Thus, the sub-total is greater than the total.

the TVA system in the Southeast Reference environment, TVA provides both water and electric supplies and would therefore internalize all the water storage effects in one way or another if it owned the biomass farms. This would probably be a unique situation, however. In the TVA case, flood control is also part of their integrated management system; hence, this type of damage from a TVA biomass plant would also be internalized under the assumptions set forth here.

One type of damage is clearly not an externality—the loss in soil productivity associated with erosion. While such losses have very real impacts on farm productivity on certain types of soils, farmers have incentive to take this effect into account when they make land purchases, cropping decisions, etc. To the extent that they take steps to limit erosion or even decide to do nothing, but do so after considering the productivity losses that might result, the damages are internalized. Of course, if farmers are unaware of the erosion or its effect on productivity, a market failure in information might be indicated and used to justifying such losses as externalities. We do not take this approach here. Rather, we do as other analysts have done (Crosson, 1983) and treat on-farm erosion effects as internalized.

Turning specifically to damages associated with biomass farms, a major complication arises in estimating damages because the net effect of such a farm depends on the land use it replaces. According to Appendix B, erosion from a tree farm would be less than that from land being cropped, other things equal. In addition, nutrients, herbicides, and pesticides in the runoff would also be lower for tree farms than cropland. Under these conditions, one would be justified in treating the erosion effect of the biomass fuel cycle as a benefit, not a damage. At the same time, if the biomass farm replaces pasture, forested, or fallow land, sediment, nutrients, and herbicide runoff would all rise, creating damage. Clearly, then, assumptions or analyses about the mix of land uses replaced by biomass farming are critical steps in what we now term damage/benefit assessment.

Based on conclusions reached in Appendix B, it is apparent that erosion could just as easily increase as decrease in the reference environments of interest for this study. Therefore, the literature review below will address studies of both damages and benefits. In addition, an economic analysis of biomass farming (CITE) concludes that such farms will be owned and operated by traditional cropland farmers who will respond to price offers by utilities interested in contracting for long term biomass supplies. Under these conditions, it is unlikely that flood control and water storage effects will be internalized. Therefore, we examine valuation issues associated with these, and other effects associated with soil erosion, that are potential externalities.

3. DAMAGE/BENEFIT LITERATURE

3.1 CLARK ET AL. (1985)

The seminal article on estimating offsite damages from soil erosion is Clark, Haverkamp, and Chapman (1985). This source divides impacts into instream and off-stream. The instream impacts include biological damage, diminished water recreation, problems with water storage (lost capacity, changes in evaporation and transpiration rates, retention of necessary water quality characteristics in such lakes and reservoirs), navigation effects (accidents, dredging, reduced harbor capacity), commercial fishing, and aesthetics (which along with some of the above effects might affect property values). Off-stream effects would include flood damage, impaired water conveyance (increasing pumping costs for off-stream uses and clogging ditches and irrigation canals), greater expense for meeting drinking water and process water standards, and damage to water using equipment (from hardness and TSS), and irrigated crop productivity losses. Non-use values could be added to this list.

Clark et al. used existing literature and, as the literature was thin, fairly crude analysis to estimate *national* damages from *all* soil erosion. Of necessity, all of the estimates were based on average, not marginal, costs. The following estimates of damages were provided:

These estimates are only for cropland's share in damages (derived by using a series of arbitrary assumptions), and generally make no distinction between nutrients and TDS or TSS. Because of the methodology, results are presented only in total terms ($millions). No data are presented on the per acre, per ton erosion, or per ton sediment damage. The biggest damage is to recreation, followed by what they term "other in-stream" which consists of commercial fishing and "preservation" value. The latter cannot be supported and are not included in the discussion below. Municipal and industrial users are also heavily damaged. Drinking water treatment is a minor damage category.

(i) **Problems with water storage**. Clark et al estimate discounted replacement costs for lost capacity and costs of dredging reservoirs, account for reduced evaporation and increased evapotranspiration, and estimate costs to improve water quality within the reservoirs.

(ii) **Flood control.** A WRC study of the effect of flooding on damage was used, along with regional data on the effect of sediment on floodwater volume and sediment concentrations to estimate flood damages, as well as arbitrary weights for the apportionment of all flood damages to sedimentation. Added to the resulting estimates were a portion of the values for lives lost in flooding, using $1 million per statistical life, and productivity losses to agriculture from flooding. The possible benefits from creation of wetlands by flooding is mentioned but not monetized.

(iii) **Biological effects.** There are no studies to estimate such effects, although fishery and recreation damages pick up some of these affects.

(iv) **Recreation.** Clark et al start with Freeman's (1982) estimate of national recreation benefits from reducing pollution and apportion this estimate to sedimentation by using a Vaughan and Russell (1982) estimate that from 13-17 percent of the cleanup benefits would be obtained by eliminating all sediment discharges from nonirrigated cropland.

(v) **Navigation.** Clark et al estimate the national cost of groundings and dredging related to cropland erosion. Their estimate is obtained from estimates of the per cubic foot removal and disposal cost of dredge spoil: $2.39/cu.yd. and $5.29/cu.yd. (1979$).

(vi) **Water Conveyance.** Sediment removal from ditches is the major problem. Road maintenance departments spend millions removing sediments from drainage ditches. Clark et al. estimate these costs nationally, ignoring pumping costs because of a lack of information.

(vii) **Other.** Estimates are obtained for commercial fishing and preservation values. The former are estimated from an estimate of the national damages to commercial fishing from all pollution and an estimate of the proportion of this total due to erosion. The latter used an estimate of the nonuser benefits from controlling all water pollution and a weight to apportion the total to erosion. These are obviously very crude estimates.

(ix) **Water Treatment.** *For Drinking:* Clark uses an estimate of 0.5 to 5 cents per 1,000 gallons water treated for removing sediment. To use this figure, current drinking water plants would have not had sediment removal equipment in place, but would be assumed to add it as a result of the added sediment loads from the biomass plant.

For Industry: Demineralization of boiler-feed water costs about $3.50/1,000 gallons (1980$). Sedimentation can actually generate savings in cooling because water with sediments is at a lower temperature than without sediments.

(x) **Irrigation.** The only available estimates of productivity effects are related to saline water, not silt. Clark et al also estimate the benefits to irrigated agriculture from fertilizer runoff that ends up in irrigation water, using the cost savings for fertilizer as a benefit measure.

3.2 RIBAUDO (1986, 1989)

Ribaudo has been one of the more active researchers in this area. He regionalized the Clark et al national damage estimates into ten Farm Production Regions developing weights from regional data related to damages. For instance, for recreation, Ribaudo obtained weights from data on regional visitor-days affected by poor water quality and the percentage of stream miles affected by erosion. This procedure had the unexpected result that no recreation damages were apportioned to the southeast FPR because levels for nutrients and sediments did not exceed critical levels or point sources were implicated in the poor quality. As another example, for the water storage category, weights were derived from annual amounts of sediments deposited in reservoirs.

Ribaudo (1989) applied the regional estimates to obtain the benefits of the Conservation Reserve Program, a program authorized in 1985 to reduce erosion and cleanup waterways by offering subsidies to farmers for taking highly erodible lands out of production and into trees or grasslands. This is, in one sense, an improvement over Clark et al. because the unit of study is a program making fairly marginal changes in erosion rates, rather than an estimate of total damages from sediment. However, the Ribaudo analysis is a benefits study, and does not provide estimates of marginal damages. In estimating biomass damages, the implied underestimate of actual damages in using these CRP benefit estimates is counterbalanced to an unknown degree by the fact that CRP projects generally involved adding BMPs to agricultural practices, and a biomass farm will presumably have BMPs already applied.

Thus, any use of CRP benefits per ton or per acre to obtain estimates of residual damages from biomass farms will be likely to lead to an overestimate of damage, ceteris paribus.

This study also improved upon Ribaudo's earlier efforts at estimating regional damages, particularly in the estimation of recreation benefits. New approaches are as follows.

Roadside ditches. Ribaudo estimated a damage function relating erosion to maintenance expenditures. The database is not stated but I think it is each farm production region. The relevant coefficient is $79/1,000 t erosion, with confidence intervals from $40 to $119/t.

Navigation. Ribaudo estimates an elasticity (not reported) of percentage change in navigation cost per one percent change in sediment load to waterway.

Water treatment. For the sediment discharge to concentration step, Ribaudo uses regression results of NASQUAN data relating concentration (in mg/l) to discharge (t/yr), stream flow (mean vol/day) and water storage (total vol). Concentrations are converted to turbidity (NGUs) using an unspecified equation (Helvey et al. 1985) and a per unit treatment cost estimate derived from an unspecified equation (Holmes 1988) with cost as a function of production, turbidity, distribution costs, and other input prices.

Recreational fishing. First, Ribaudo estimated the change in individual participation (using a logit model) as a function of region, water quality in home and adjacent region, and other variables using the Hunting and Fishing Survey and NASQUAN data. Water quality was represented by a dummy variable for concentrations of any of three pollutants exceeding their threshold leading to impaired use. The thresholds are 200 mg/l TSS, 0.2 mg/l TP, 1.8 mg/l TKN. Second, he estimated a visitation equation in which water quality was insignificant, indicating that changes in quality effect participation but not visits, given that one participates. Using a daily value of $25, the increased number of fisherman fishing the average number of days yields the recreation benefits.

Ribaudo's average damage from soil erosion estimates for Appalachia are $1.41/ton of erosion ($0.78 to $2.25 is the confidence interval) and for Pacific $2.48/t of erosion ($1.53 to $4.77 is the confidence interval), probably in 1986$. These estimates were subsequently updated to 1989 dollars by WRI: $1.63 and $2.87/t. He also provides damage/ton estimates by category. Finally, Ribaudo gives estimates of the benefits of the CRP program in the Appalachia and Pacific regions: $180/acre PDV for 10 years at 4% discount rate and $126/acre PDV, respectively. The problem with using the last type of estimate is that the resulting damage estimates would depend on CRP effectiveness, rather than reductions in soil erosion *per se*. In Appalachia, for instance, recreation benefits were estimated to be zero because no thresholds were reached in water quality as a result of the program.

3.3 OTHER CRP BENEFIT AND EROSION DAMAGE ESTIMATES

3.3.1 Piper, Magleby, and Young (1989)

Concern over the effectiveness of the CRP resulted in a flurry of research activity to estimate the off-site benefits of soil erosion control. In addition to the Ribaudo work, is a study (Piper, Magleby, and Young, 1989) where 21 RCWP projects, including one in Tennessee and one in Oregon, are evaluated for their benefits, including at least one of the benefits from the following set: recreational fishing, commercial fishing, water storage, water supplies, water treatment, dredging, and health (in the form of providing alternative, non-polluted supply from bottled water). The Tennessee project is in the western part of the state, at Reelfoot Lake, a 13,000 acre recreational lake polluted by cropland containing sediment and nutrients, with recreation and water storage being the most impaired uses. The Oregon project at Tillamook Bay is the closest to our Camus Washington site, but is an estuarine area, with animal wastes being the major problem.

The approach is to estimate the benefits with and without the project in question. Benefits are artificially divided into those from avoiding deterioration of water quality and those from improvements caused by the project. Estimates of the former are computed as if water use would have fallen to zero (a maximum potential benefit), but for Tennessee, likely benefits are zero because the baseline did not involve deterioration.

3.3.2 Park and Dyer (1986)

This study is referenced for Tennessee by Piper, Magleby, and Young (1989). This study provides estimates of off-site damage from soil erosion in W. Tennessee, specific to a RCWP effort on Reelfoot Lake Watershed and an ACP effort on North Fork of the Forked Deer Watershed. They present a table of estimates of damages:

The authors offer a variety of useful caveats: double-counting (some costs help to reduce damages in other categories), the use of an arbitrary criterion of 5 tons/acre/year used, the highly questionable use of their results for benefits transfer, and the possibility that damages and benefits may not be the same.

3.3.3 Moore and McCarl (1985)

This case study of the marginal off-site costs of soil erosion in Willamette County, Oregon provides a much more careful set of estimates than others reviewed in this appendix, although for a limited set of damage categories. The welfare measure assumes the demand for services affected by erosion has zero elasticity. Municipal treatment, road drainage system maintenance, navigation channel maintenance, water storage, and hydroelectric generation costs are examined. Municipal treatment costs are estimated from an equation with turbidity as an explanatory variable. However, the paper lacks units for the variables. Nevertheless, Table 2 provides marginal cost estimates for various percent changes in turbidity. For instance, increasing daily turbidity by 10% throughout Willamette County results in $55,000 of water treatment costs. Adding an additional 15% turbidity increases costs $84,000. Inference from the one plant analysis to the region was done using USGS water withdrawal data, assuming sediment loads are the same everywhere in the region. Oregon sediment rates are 2-4 tons per acre per year for agricultural lands and less than an acre per year for forested lands. Average costs for road ditch maintenance were $1,140/mile ditch cleaned and $2.92 per culvert cleaned. Dredging costs may be available directly from the Corps, as it was (no cite) for Willamette County. Average costs are $.85/ton removed. Total average costs were $.71/acre assuming uniform erosion, or $2.63 per agricultural acre.

3.3.4 Alexander and English (1991)

Alexander and English (1991) provide estimates of the benefits of CRP projects and the costs of soil erosion using regionalized estimates of damages based on Clark et al and Ribaudo. This study is an improvement upon them, however, because it presents estimates based on sediments delivered to streams—the startpoint directly

Table 2. Estimate of soil erosion damages [Park and Dyer (1985)]

Type of impact	Location	Per acre cost	Current $ year	Confidence
		(>5t/yr)		
Recreation	R	$7	1984	Low
Flood control	R	8–12	1985	High
Swamping Ag	N	2–3	1981	High
Land				
Channel	N	8	1978	Medium

related to the damage—rather than soil erosion. A interregional sediment model, MOSS II (Micro-oriented Sediment Simulator II) is used to estimate these CRP benefits and erosion costs by providing a link between estimates of erosion and estimates of sediment delivery and sediment transport ratios. Their estimates of the benefits per acre of the CRP program are $65 for Appalachia and $97.12 for the Pacific States (1983$). Their dollar/ton costs of erosion in terms of suspended sediments and sediments deposited in streams are:

Table 3. Estimate of soil erosion damages [Alexander and English (1991)]

Measure	Region	
	Appalachia	Pacific
Suspended costs ($/t)		
Low	1.10	7.18
Best	2.11	13.80
High	4.49	29.40
Deposited costs ($/t)		
Low	2.22	15.30
Best	4.27	29.42
High	9.10	62.67
Acres (000)	791	1541

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ECOLOGICAL EFFECTS OF THE BIOMASS FUEL CYCLE*

1. INTRODUCTION

The purpose of this appendix is to summarize the approach used to characterize the ecological effects of the biomass fuel cycle. The general approach for the overall project is an accounting framework designed as a series of matrices that map each phase of the fuel cycle to a suite of possible emissions, each emission to a suite of impacts on resource categories, and each impact to an external cost or benefit. This appendix defines the resource categories, summarizes the impacts for all phases of the biomass fuel cycle, and identifies which of those are considered key impacts.

2. DEFINITIONS OF RESOURCE CATEGORIES

This section defines the categories to be used in the accounting framework (i.e., the column headings in the matrices that map emissions and impacts). The categories are determined by resources or conditions valued by society, rather than by the medium or path. A particular resource such as agriculture can be affected by multiple emissions and by multiple environmental pathways (e.g., both through direct effects of air pollutants on plants and on indirect effects of degraded soil quality). Resource categories affected by the procurement, processing, transport, and use of fuels for electric power generation can be characterized according to whether they relate to (1) natural biological systems, (2) man-made systems, and (3) nonbiological environmental conditions. Depending on the preexisting conditions and on the fuel cycle and energy technology utilized, the impacts discussed under each category (Table F-1) may be adverse or beneficial.

2.1 NATURAL BIOLOGICAL SYSTEMS

Natural biological systems can be affected by energy technology in three ways: (1) by changes in biodiversity, (2) by impacts on commercially important resources; and (3) by impacts on recreationally important resources.

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*Some of the data in this chapter pertain to a slightly different biomass plant from the one used for the analysis in the rest of this report.

Table F-1. Summary of Resource Categories and Potential Impacts

Resource Categories	Impact Pathways	Definition
	Natural Biological Systems:	
Biodiversity	Impaired air, water, soil quality; habitat destruction or disturbance; physical destruction	Impacts on plants and animals; loss of species; altered community structure and function
Commercial fishing	Impaired water quality; habitat loss; physical destruction	Diminished production or contamination above regulatory standards
Recreational fishing	Impaired water quality; flow reduction; habitat loss; physical destruction	Diminished opportunity due to reduced production or contamination
Hunting	Habitat/landscape destruction or disturbance; physical destruction	Diminished opportunities to hunt
Timber harvesting	Altered land use; soil contamination; plant contamination or uptake	Diminished yield due to reduced tree growth or reduced acreage
Recreational land and water use	Habitat/landscape destruction or disturbance; impaired air/water quality; reduced visibility	Diminished opportunities for touring, hiking, swimming, etc.
	Man-made Systems:	
Crops and suburban landscape	Altered land use or quality; contaminant deposition on plants; uptake by plants; soil contamination, irrigation water contamination	Diminished crop yield
Livestock	Altered land use; contaminant deposition on plants; soil contamination	Diminished productivity due to impaired production or availability of pasture
Buildings and materials	Deposition of particles, aerosols or contaminated rainwater	Enhanced weathering of exposed metal or stone
	Nonbiological Environmental Conditions:	
Land	Altered land use; disturbance; impoundment; contamination	Depression of land values; loss of archeological and historic sites
Water	Runoff; spills; atmospheric deposition	Changes in availablity, clarity, taste, potability; diminished aesthetics
Air	Dust or haze; odors; noise	Reduced visibility; diminished aesthetics

2.1.1 Biodiversity

Biodiversity refers to (1) the genetic diversity of species and populations, (2) the species diversity of biological communities (i.e., number of species of plants and animals); and (3) habitat diversity at a local, regional, or global scale. The genetic diversity of species and populations can be altered by changes in environmental parameters; by environmental contamination with xenobiotic substances (e.g., development of pesticide-resistant species); or by the intentional or inadvertent introduction of new gene pools (i.e., hybrid plants or introduced species of animals). Changes in species diversity can result from habitat alterations, extinction of native species, or the introduction of non-native species. Habitat diversity is largely affected by altered land use/land cover patterns. Habitat diversity is especially important for species of animals that require different types of habitats for different life stages or activities (i.e., feeding, shelter, nesting) and for plants that may be dependent on insect pollinators that rely on other habitats (Ranney et al. 1991). Habitat patch size and spatial location is also important, not only in determining animal population size and reproductive success, but in defining microhabitats, as is the case for animal species which survive only in the interior of large forests.

In general, the greater the biodiversity of desired species the greater the ecological richness and stability of an area. However, changes in biodiversity at a local level are not necessarily followed by identical changes at the regional or global level. Extinction of native species of plants and animals and their replacement by a greater number of non-native species might be viewed as a local increase in biodiversity but on a regional or global scale this would represent a decline in biodiversity (Ranney et al. 1991). Threats to biodiversity were recently discussed in the proceedings of the National Forum on Biodiversity (Wilson 1988).

In the context of this report, ecological impacts of fuel technologies on habitats, species, and/or populations, which are not directly related to commercial exploitation or recreational use of natural resources, are considered impacts on biodiversity. Habitat alterations often cause the greatest impacts on biodiversity because numerous species can be affected. In addition, small unique habitats, which may be of limited scenic or recreational value, but which may be considered valuable for commercial development, may contain rare or endangered species of small population size and limited geographic distribution. Specific impacts which are of concern include those on threatened or endangered species, legally protected areas (e.g., Wild and Scenic Rivers), and other ecologically valued natural systems (e.g., wetlands, pinebarrens, riparian areas, bogs). These impacts may come about as a result of (1) altered land use; (2) local or regional changes in environmental parameters; or (3) the introduction of toxic substances which may adversely affect the growth or survival of populations.

Although heavily modified by man's activities, the southeastern United States supports a number of endangered and threatened species as well as relict examples of a number of previously common ecosystem types.

2.1.2 Commercially valuable natural resources

Commercially valuable natural resources such as fisheries and timber can be affected at various stages of a fuel cycle. Fisheries resources can be affected by physical habitat destruction or alteration (e.g., dewatering of streams) or changes in water quality which can result in the loss of commercially valuable fish and shellfish populations due to direct kills, reductions in productivity (growth, population size or reproductive success), or by the accumulation of contaminants at levels above regulatory standards. Water quality parameters of importance in fisheries are temperature, pH, dissolved oxygen, suspended sediments, plant nutrients (phosphates and nitrates), and toxic substances. Water quality can be affected by spills, surface runoff, and atmospheric deposition. The latter pathwayway has recently been identified as the principal source of PCBs, dioxin, and heavy metals in many water bodies; however, no quantitative estimates of biological impacts from this source are available at this time.

Commercial fishing is not an important industry near the southeastern reference site, although there is a small mussel industry (primarily for pearl production), and aquaculture for trout and catfish is common.

The timber industry may be affected by the development of a specific energy technology as a result of the elimination of land for forest use, or the deposition of air contaminants on foliage causing direct phytotoxicity or reduced growth, or by soil contamination leading to leaching of soil nutrients. Extensive stands of pines are grown in the southeast for pulp production, and national forests in the area are utilized for hardwood production.

2.1.3 Recreationally valuable natural resources

Forests, parks, streams, lakes, rivers, and other public or private outdoor areas that may be used for fishing, hunting, camping, nature studies, birdwatching, swimming, boating, hiking, and other recreational activities may be affected by environmental changes associated with a given stage of a fuel cycle or energy technology. Changes in forest composition, wildlife abundance, water quality, and air quality may alter the use of such resources. All rivers and reservoirs in the southeast support intensive recreational use. Recreational fishing for sport or consumption is common throughout the area and is often associated with electric generating facilities such as in the tailwaters below hydroelectric dams and in the cooling water effluents from fossil fuel and nuclear power plants. The most important recreational fisheries in warmwater reservoirs, rivers, and ponds involve the families Centrarchidae (largemouth and smallmouth bass, bluegills, and crappie), Ictaluridae (catfishes), Perchidae (perches, walleye, and sauger) and Serranidae (white bass and striped bass). Coldwater streams in the southern Appalachians and on the Cumberland Plateau support fisheries for rainbow, brown, and brook trout.

Hunting refers to the noncommercial harvesting of game birds and mammals. These animals can be affected by air and water pollution and by physical disturbances (habitat destruction and noise) related to energy production. Hunting is common on private and public lands throughout the southeast. In recent years areas adjacent to the southeastern site have been used for deer hunting.

National forests and the Great Smokey Mountains National Park near the southeastern site are important recreational resources. The number of visitors to the latter was about 8.6 million in 1991 (National Park Service).

2.2 MAN-MADE SYSTEMS

2.2.1 Agricultural, silvicultural and horticultural industries

Fuel cycles and energy technologies may affect the agricultural, silvicultural, and horticultural industries by reducing the amount of land available for such use, or by reducing crop yields as a result of direct deposition of phytotoxic air contaminants or soil contamination following deposition or irrigation with contaminated water.

Common crops in the southeastern United States include corn, soybeans, and tobacco. Within a 75-mile radius of the southeastern reference site, about 115,300 acres are utilized for corn and about 123,200 acres for soybeans, 14,700 acres for other row crops (tobacco etc.), and 34,200 acres for closecrops such as wheat.

2.2.2 Livestock industry

Elimination of land for pasture, deposition of contaminants on plant surfaces followed by grazing, as well as soil contamination through the direct use of pesticides or through runoff followed by uptake in grazed plants, and contamination of surface water used as the animals' drinking water may have impacts on livestock productivity or commercial value. Livestock includes animals and poultry raised for meat or dairy products as well as animals raised for other commercial purposes such as show horses. Ambient air pollution levels in rural areas are usually far below levels that could cause significant effects on animals, and no data demonstrating such direct impacts are available. Cattle and poultry are the principal livestock raised in the southeast. Approximately 76,570 acres within a 75-mile radius of the southeastern site is used as pasture and about 19,480 acres for hay production.

2.2.3 Archeological and historical sites

Various aspects of the alternative energy technologies, including utilization of land for tree plantations, construction of roads and power plants, and impoundment of streams and rivers may result in the loss of valuable archeological and historically important sites.

2.2.4 Buildings, roads, and materials

Air emissions generated at different points in a fuel cycle can have potential impacts in terms of enhanced weathering of exposed metal, wood, and stone. Acidic depositions can erode limestone and tarnish metals. Vehicles transporting the fuel feedstock to intermediate processing or refinery sites or to the power plant may increase rates of deterioration of road surfaces. Salt spray from cooling systems utilizing seawater may enhance corrosion of some materials.

2.3 NONBIOLOGICAL ENVIRONMENTAL CONDITIONS

Included in this category are general aesthetic considerations such as physical alterations to the landscape and natural bodies of water, changes in visibility due to increases in moisture content, hydrocarbons, or particulate concentrations in the air, the release of noxious odors from stacks or motor vehicles, changes in water clarity, taste and potability due to surface runoff or the addition of process or wastewater effluents, and increases in noise due to machinery and vehicles. Water availability can also be affected by power generating facilities, and can be a major issue in areas where water resources are limited.

3. ENVIRONMENTAL IMPACTS OF THE BIOMASS FUEL CYCLE

The use of biomass as a fuel for an electric generating station requires an extensive supply of feedstock, the harvesting of this material, transport to power plant, drying to improve combustion efficiency, combustion, and control and disposal of combustion byproducts. Current technology allows for many options in these operations each of which can affect the overall environmental and economic impact at a given geographic site. These options involve: (1) the choice of single or multiple fuel sources (i.e., forest, farm, urban or industrial wastes, or mono- or polycultures of herbaceous or woody crops grown specifically for fuel use; (2) the selection of land used for energy crop production (i.e., non-agricultural or agricultural land); (3) the method of harvesting, transporting, processing (i.e., cutting or chipping) and drying the fuel stock: (4) the possible augmentation of the biomass fuel with small amounts of fossil fuel; and (5) the method used to control emissions from the power plant stack. For this report, the fuel source chosen is specifically limited to three species of cultivated hardwood trees (sycamore, *Platanus occidentalis*, sweetgum, *Liquidambar styraciflua*, and black locust, *Robinia pseudoacacia*) at the southeastern reference site and two species (hydbrid poplar, *Populus* sp. and red alder, *Alnus rubra*) at the western site. The land utilized for the tree plantations is equivalent to 1-5% of all available cropland or land suitable for cropland (excludes natural forests and environmentally sensitive areas). The individual tree plantations are of a size (20-80 acres) for maximum efficiency of production and harvesting (Ranney, per. comm.). The wood is harvested after six years of growth during winter dormancy, and also after two 6-yr periods of coppice regrowth (total cycle takes 18 yr before replanting is necessary).

Therefore, one-sixth of the total required acreage is planted in tree seedlings each year and one-sixth is harvested (Appendix A, Table 7). Twenty-ton capacity trucks transport the feedstock to the power plant where it is dried using waste heat from the flue gas and then fed into a whole tree burner (WTB, 1990 technology) or into a biomass gasifier steam-injected gas turbine (BGISTIG, 2010 technology). Supplemental fuels are not used. The proposed wood-fired power plant has a capacity of 30 MW, and stack emissions are controlled with an electrostatic precipitator and bag collector (see Appendix A). The discussion of the environmental impacts associated with biomass technology will therefore be specific for this set of conditions.

Environmental impacts of biomass energy utilization can occur at each stage of the fuel cycle; at the tree farm sites, during transport of the feedstock to the power plant, and at the power plant during drying and combustion of the wood.

3.1 STAGE 1 - TREE PLANTATIONS

3.1.1 Potential impacts

Potential impacts of tree plantations involve changes in land use and associated changes in biodiversity; soil erosion; ground and surface water contamination due to the use of herbicides, insecticides, and fertilizers; air emissions from diesel-powered farm equipment; and volatilization of hydrocarbons from the trees.

3.1.1.1. Land use

It is projected that about 39,928 acres of land would be required to provide the 161,452 dry tons of wood needed annually to operate a 30-MW power plant at the southeastern reference site in 1990. Only 24,911 acres would be needed in 2010 due to improvements in tree productivity and increased efficiency of the BGISTIG. At the western site 30,154 acres of land would be utilized in 1990 and 17,203 acres in 2010. For all sites and time periods the scenario created assumes that suitable land will be available within a 75-mile radius of the power plant (Appendix A), and that this land would be apportioned equally (1-5% depending on site and time period) among land use classifications currently designated as cropland or land available for conversion to cropland. It specifically excludes forests with a canopy cover of more than 55%, riparian areas, and other environmentally sensitive areas. The apportionment of land by crop use in each region in 1990 is shown in Figure 3 in Appendix A. It is assumed that the same crop use pattern will exist in 2010. Changes in land use are discussed further in Section 5.1.

3.1.1.2 Biodiversity

Issues of biodiversity must be examined on both a local and regional level. As a managed environment a tree plantation represents a level of biodiversity substantially below that of a natural forest. Not only are the number of species of trees reduced, development and cultivation of specific hybrids will tend to reduce genetic diversity within the population. In addition, species diversity of other groups of plants and animals may also be affected. Even the best maintained woody crop plantations are less structurally developed than natural forests and will generally not contain rarer species (Ranney et al. 1991). In a Wisconsin study it was found that the number of nesting bird species on a hardwood tree plantation stabilized at about 16 after four years (Verch 1986). Similarly, Brooks (1990) reported only 15 nesting species of birds on an 8-yr-old, 10.7 ha Christmas tree farm in upstate New York. In comparison, natural temperate woodlands in North America may contain 20 to 25 nesting species (Ranney et al. 1991).

The fact that trees on a tree plantation do not reach full maturity can also affect the types of animals occurring there. Older trees often provide nesting cavities for birds and other animals as well as microniches for insects, which in turn can be a food source for other animals. In studies of Michigan tree stands, Gysel (1961) found that cavities were generally most common in trees of the 12 to 24 in diameter class, but > 24 in an olF-growth beech-maple stand. Animals that utilized these cavities included red squirrels, fox squirrels, racoons, bats, bees and wasps, and various species of birds such as starlings, white-breasted nuthatch, and tufted titmouse. In a study of several forest habitats in the Ouachita Mountains, Arkansas, Melchiors and Cicero (1987) found that the frequency of hardwood trees with cavities ≥2.5 cm in diameter increased with increasing tree diameter; i.e., 3.4% of trees 15 to 24.9 cm, 7.5% of trees 25-34.9 cm, 11.0% of trees 35 to 44.9 cm, and 25% of trees ≥45 cm. Cavities occurred more frequently in certain species, such as American sweetgum, black tupelo, and white oak. Short-rotation harvesting on tree plantations is likely to limit the development of many cavities.

If the trees selected for use on the tree plantations do not produce an adequate amount of nuts of required nutritional value, animals such as squirrels which are dependent on mast as a food supply may be affected. Warren and Hurst (1980) reported that squirrel populations in Mississippi flatwoods were highest in streamside hardwood management zones compared to pine-hardwood forests. They suggested that this may have been due to higher mast production and more den trees in the management zones. Oaks, hickories, and walnuts are the most common nut producing hardwood species in the southeast (Melchiors and Cicero 1987). Since none of these will be used on the hypothetical tree plantations, squirrel populations are likely to be low.

Conversion of pasture or grasslands to tree plantations will adversely plants and animals that are directly and indirectly dependent upon open fielF-grassland habitats for survival. In a study conducted in Scotland, a decline in the population of one species of hawk was observed following extensive planting of trees on lands formerly used as grassland. This population decline was presumably due to habitat modification and the decrease in the availablity of the hawk's prey such as rabbits and grouse which are primarily open-field species (Ranney et al. 1991).

On a regional scale, the impact of tree plantations on biodiversity is dependent on the extent that the land is dominated by farmland, grassland, or forest. In an region where woodlands are very limited in size and distribution, conversion to tree plantations would have a far greater impact then in an area where natural forests comprise a significant portion of the landscape. For the southeastern reference site, approximately 1,579 acres of open woodland would be utilized for tree plantations in 1990 scenario; however, this represents only a small fraction of the total open woodland in a 75-mi radius of the site (about 34,000 acres) and an even smaller fraction of the total forested land in the region (about 3.4 million acres in East Tennessee, TVA 1984).

3.1.1.3 Erosion

Soil erosion on tree plantations is likely to occur during the establishment phase when the land is prepared for planting of the seedlings and also possibly after harvesting if the surface of the ground is damaged by the movement of the harvesting machinery and trucks. According to Ranney et al. (1991), erosion rates during the initial establishment period may be as high as those for corn and soybeans [e.g., 21.8 tonnes/ha-yr (9.7 tons/acre-yr) and 40.9 tonnes/ha-yr (18.2 tons/acre-yr), respectively (Pimental and Krummel 1987)]. Such high rates of erosion may be reduced by the use of a groundcover or weed strips (the hypothetical scenario used in this study) between tree rows, or by the use of crop residues and mulches before and during the planting of the seedlings. When averaged over the entire life span of the rootstock (18 or more years), erosion is not expected to be more than 2 tonnes/ha-yr (0.89 tons/acre-yr) (Ranney et al. 1991). In comparison, average annual rates of erosion are 18.1 tonnes/ha-yr for managed agricultural lands, 0.2 tonnes/ha-yr for hayland, 0.1-0.2 tonnes/ha-yr for undisturbed forest and 2-4 tonnes/ha-yr for logged forests (2-17 tonnes/ha-yr initially) (Pimental and Krummel 1987). Therefore, tree plantations can be expected to have a long term net positive impact by reducing erosion on lands previously used for row crops, but a net negative effect on lands previously used for hay, pasture, or undisturbed forest. A quantatitative evaluation of erosion rates at the two reference sites is given in Section 5.3

Water-induced soil erosion and runoff into streams can result in increased water turbidity, stream scouring and siltation and increased concentrations of nutrients or pesticides. In studies conducted on experimental forests, harvesting of timber resulted in increased runoff and increased stream flows, elevated water temperatures, and increased concentrations of nitrate and herbicides, but no significant changes in turbidity (Hall et al. 1976). For small clear water streams, such changes may have adverse impacts on aquatic fauna depending on stream size and background environmental parameters. Site-specific information would be needed before a detailed analysis can be made of the ecological impacts of erosion from tree plantations.

3.1.1.4 Herbicides

Herbicides are used on tree plantations for weed control during the first two years of establishment of the seedlings. This use can be minimized by treating only areas within, but not between tree rows, and also by planting a desirable (i.e., nitrogen fixing) groundcover between rows (Ranney et al. 1991). However, such measures will not entirely eliminate potential contamination of air, surface water, or ground water. Aerial application of herbicides under windy conditions may result in damage to nearby sensitive native plants or crops. Surface waters may become contaminated as a result of atmospheric drift, surface runoff, or direct spills. Ground water may become contaminated as a result of downward migration after soil application or spills (Ranney et al. 1991).

Estimated rates of herbicide use on tree plantations for both the 1990 and 2010 scenarios are 3 lb/acre during the first year of establishment of the seedlings and 1 lb/acre during the second year, but none thereafter until the lands are replanted after 18 years (Appendix A, Table 4). A broad kill herbicide (1 lb/acre) is used before planting and a pre-emergent (1 lb/acre) after planting. The third application occurs six months later and the fourth in the second year. These initial rates of application are similar to the average annual useage for rowcrops such as corn and soybeans (3.06 and 1.83 lb/acre/year; respectively (USDA 1987; Ranney et al. 1991); however, for tree plantations, herbicides would not be used again until the seedlings are replanted after 18 years. Therefore on tree plantations the greatest potential for air, and surface or ground water contamination will occur within the first 12-18 months of planting. A 1 lb/acre application rate is equivalent to 112 mg/m^2 of soil surface. Losses to ground water and surface water are expected to average 8 and 10% of application rates, respectively (Appendix B, Table 17). Based on these estimates, each 1 lb/acre application will result in about 0.08 lb/acre entering ground water and 0.1 lb/acre into surface water. For an average size tree farm of about 50 acres, the amount lost would be 4 lb/application into ground water and 5 lb/application into surface water.

Evaluation of the potential environmental effects of herbicides requires knowledge of the specific compound, its concentration in soil, water, and air, water solubility, volatility, soil adsorption coefficient, degradability, and other physical and chemical parameters, as well as information on the toxicity of the compound to environmental species. Although physical and chemical data are available for most compounds, information on ambient concentrations and toxicity to species is often quite limited. Application rates (i.e., 1 lb/acre or about 112 mg/m^2 of soil) provide a general measure of environmental contamination, but do not easily translate into exposure levels for mutiple environmental media. In addition, exposure levels can be considerably altered by environmental partitioning, degradation, and dispersion. Because a portion of the herbicide may be lost to the atmosphere, terrestrial animals may be affected through inhalation as well as through eating contaminated foliage or surface water. Aquatic organisms may be impacted by herbicides lost in surface runoff. Preliminary estimates based on simple dilution modeling suggest that a 1 lb/acre application rate may cause adverse effects on some aquatic organisms (see Section 5.4). Further modeling is needed to take into account soil type, erosion rates, and rainfall, as well as volume, flow rates, and chemical characteristics of the water bodies impacted.

Ground water can become contaminated with herbicides as a result of leaching of the compound through the soil. Leaching rates depend on many chemical- and site-specific factors. Chemical parameters such as volalitily, solubility, and soil adsorptivity, determine how a compound partitions between the solid, water, and air phases in the soil, and chemical and biological degradability determine the half-life of the compound in the soil. Site-specific factors such as soil structure, texture, and organic matter determine rates of leaching (Leonard and Knisel 1988). Assuming that the herbicides used on tree plantations are the same as those used on agricultural farms in the area, then it would be likely that leaching rates and potential groundwater contamination would be similar. However, for the scenario created for this study, a no-tillage method of planting would be used, and one recent study suggests that tillage may actually decrease pesticide leaching rates for some soils. In a study of leaching rates in conventional and no-tillage corn fields, a slightly higher degree of migration of cyanazine, alachlor, atrazine, and carbofuran to ground water occurred under non-tilled plots (Isensee et al. 1990). Further investigation is needed to substantiate these results and to determine if they would also apply to the types of herbicides which would be used on tree plantations.

Nearly every pesticide in use in the U.S. has been detected in one or more ground waters (Williams et al. 1988). Groundwater contamination may also impact surface waters. Immediately adjacent to the southeastern 1990 site is the Clinch River which acts as a sink for the ground water in the immediate area (Project Management Corporation 1975-1977). It is likely that other river systems within the 75-mile radius of the site (i.e., Tennessee, Telico, Emory) would also serve as sinks for ground water from tree plantation sites.

Herbicides that are likely to be used on tree plantations and their average annual application rates (for the first two years only) are as follows (Ranney et al. 1991):

Herbicide	lb/acre
Casoron	11.2
Dicamba	0.56
Fluazifop	0.21
Glyphosate	1.2-2.2
Glyphosate/balin	1.12
Glyphosate/Linuron	1.68
Goal/Surflan	-
Linuron	1.18-1.68
Oryzalin	3.0-4.5
Paraquat	2.24
Proronamide	4.0
Princip	3.5
Ronstar	3.4
Simazine	4.5
Sulfometuron methyl	0.14
Surflan/Princip	3.5

An evaluation of the ecological effects of all the herbicides listed above is beyond the scope of this study; however, a brief discussion will be given of two of these, simazine and glyphosate, which are the most likely to be used on tree plantations (Ranney, per. comm.). Simazine, a preemergent herbicide, has been identified in some ground waters and surface waters (Williams et al. 1988; Frank et al., 1982), and glyphosate, a broad spectrum herbicide, has wide commercial and residential applications.

Simazine, a triazine herbicide, is commonly used in orchards and is likely to be used on tree plantations. It has a relativly low water solubility (3.5 ppm at 20°C) and a high soil particle absorption (soil retention about 5-7 months at 4 kg/ha; Farm Chemicals Handbook 1989); therefore, much will remain in the upper strata of the soil where microbial degradation is likely to occur. Although some exposure of terrestrial animals is possible, potential adverse effects are low. The compound is considered to be practically non-toxic to birds and bees (Worthing et al. 1987). Median lethal dietary levels are quite high; 8,800 ppm for bobwhite quail, 51,200 ppm for mallard ducks (Beste 1983), >5,000 ppm for pheasant, and >3,720 ppm for Japanese quail (Heath et al. 1972). The acute oral LD_{50} in chickens and pigeons is 5,000 mg/kg (Royal Society of Chemistry 1991). The oral LD_{50} values for rats, mice and rabbits are >5,000 mg/kg, and a 4-hr inhalation LC_{50} value of >2 mg/m^3 has been reported for rats (Royal Society of Chemistry 1991). In order to quantify the impacts of simazine on terrestrial animals additional information would be needed on concentrations in environmental media and exposure levels for individual species.

Although terrestrial impacts of simazine are likely to be small, aquatic effects may be significant. Simazine is considered to be a potential surface water contaminant due to current agricultural practices (Frank et al. 1982). Median lethal concentrations, for 48- or 96-hr exposures, range from 1 mg/L for *Daphnia magna*, 13 mg/L for an amphipod crustacean, 95 mg/L for rainbow trout, and 130 mg/L for bluegill (Verschueren 1983). Concentrations producing non-lethal adverse effects would be much lower than those listed. The average half-life in ponds is estimated to be 30 days (Beste 1983). Although water quality criteria have not been established for simazine, the proposed national primary drinking water standard (MCL) is 0.001 mg/L (EPA 1992).

Glyphosate is a non-selective, phosphate-based, systemic herbicide. It is water soluble (1% at 25°C) and readily taken up through the leaves of plants (Agricultural Canada 1979). It is strongly absorbed to soil and becomes practically immobile and subject to degradation by soil microorganisms (Royal Society of Chemistry 1991). Half-life in soil is usually less than 60 days. Toxicity to terrestrial organisms is relatively low. Lethal toxicity to bees is >0.1 mg/bee by contact or orally. The acute oral LD_{50} for bobwhite quail is >3,850 mg/kg; 8-day median lethal dietary levels are >4640 ppm for both quail and ducks. In studies on rats and dogs, dietary levels of 300 mg/kg were not toxic even after 2 years.

Although high soil adsorption will limit groundwater contamination with glyphosate, losses through erosion and surface runoff as well redeposition of atmospheric releases that might occur during application could cause some contamination of surface waters. However, toxicity to aquatic animals is relatively low; the 96-hr LC_{50} values for trout and bluegill sunfish were reported to be 86 and 120 mg/L, respectively. Toxicity of the isopropylamine salt of glyphosate is about tenfold higher than that of the pure compound; i.e., 96-hr LC_{50} values 11.0 mg/L for trout, 14.0 mg/L for bluegill sunfish, and 2.3-4.3 mg/L for trout and catfish fry (Beste 1983; Johnson and Finley 1980). For invertebrates, 48-hr LC_{50}s of 5.3 mg/L and 55 mg/L have been reported for *Daphnia magna* and fourth instar *Chironomus* larvae, respectively (Beste 1983; Johnson 1980), and 96 hr LC_{50}s of 43 mg/L and 3 mg/L have been reported for *Gammarus pseudolimnaeus* and first instar *D. magna* larvae, respectively (Johnson 1980). Water quality criteria are not available for glyphosate. The proposed drinking water standard is 0.7 mg/L (EPA 1992).

3.1.1.5 Insecticides

As in the case of herbicides, the use of insecticides on the tree plantations could result in emissions to air, surface water, and ground water. Nontarget organisms in nearby areas may be exposed if aerial application occur under windy conditions. Aquatic organisms may be exposed if surface waters are contaminated as a result of atmospheric drift, surface runoff, or direct spills (Ranney et al. 1991).

In research plots of short-rotation woody crops, the insecticides Dipel, Malathion, Dimethoate, Acephate, Orthene, or Lorsban have been applied to control chewing and sucking insects (Ranney et al. 1991). It has been estimated that such use might be required just once in 5 years at perhaps 20% of the sites (Ranney et al. 1991). For the scenarios created for this evaluation, it was assumed that biennial applications would be needed at the 1990 sites, but only one application per 6-yr rotation at the 2010 sites.

The projected rate of insecticide use on tree plantations at the 1990 southeastern reference site is 0.06 lbs/acre, biennially, for sweetgum, sycamore, and hybrid poplar (Appendix A, Table 4). Losses to ground water and surface water during the year after application would be 0.0048 and 0.006 lb/acre, respectively [(based on losses of 8% to ground water and 10% to surface water (Appendix A, Table 17)]. For black locust and red alder, the projected rate of insecticide use is 2.7 lb/acre, biennially, (Appendix A, Table 5). Losses to ground water and surface water during the year after application would be 0.216 and 0.27 lb/acre, respectively. An evaluation of the ecological impacts of these chemicals would require that modeling studies be done to estimate resulting concentrations in environmental media; however the general consensus of expert opinion is that insecticide use on tree plantations would be too low to have any significant ecological impacts (Ranney et al. 1991).

3.1.1.6 Fertilizers

As with agricultural land, tree plantations require the addition of nitrogen, phosphorus, and potassium to the soil to insure adequate levels of productivity. Of these macronutrients, the one that is considered to pose the greatest potential for environmental problems is nitrogen because of its occurrence in water soluble forms which can contaminate surface and ground water.

The amount of fertilizers used on tree plantations will be governed by the background levels of nutrients in the soil, the pattern of nutrient cycling, the types of trees grown (i.e., whether or not nitrogen fixing species are included), the rate of plant uptake (dependent on root mass), and the rate of loss due to surface runoff or leaching into ground water. Typical rates of application of nitrogen, phosphorus, and potassium for a tree plantation are 60, 30, and 80 kilograms per hectare-year, respectively (Ranney et al. 1991).

At the 1990 southeastern reference site, fertilizer requirements for sweetgum, scyamore, and hybrid poplar would be 80 lb/acre each of phosphorus and potassium applied during the first year, and also once during each 6-year rotation, and 90 lb/acre of nitrogen applied biennially starting in the second year (Appendix A, Table 4). Less nitrogen would be required if nitrogen-fixing cover crops are used between the tree rows. For nitrogen-fixing species such as black locust and red alder, only phosphorus and potassium fertilizers would be needed (at the same application rates cited above for the other two species).

Surface Runoff. The amount of fertilizer lost to surrounding surface waters is dependent on surface runoff and rates of erosion. Erosion is likely to be highest during initial energy crop establishment and may be comparable to that occurring on land used for row crops. On cleared land erosion rates are affected by topography, rainfall, soil porosity, and depth of water table. These are all site-specific factors. Erosion rates can be substantially reduced by using a groundcover during the first year. Once the trees become established erosion rates are expected to be quite low. Therefore, over an extended period of time nutrient loss to surface waters can be expected to be much less than that from agricultural lands. For the 1990 southeastern reference site, average losses of nitrogen, phosphorus, and potassium to surface water were estimated to be 71,870, 26,619, and 26,619 lb/yr (Appendix A, Table 19). This equates to 2, 0.7, and 0.7 kg/ha, respectively. In comparison, a study of erosion in corn fields revealed nitrogen losses of 40-110 kg/ha (Larson 1979). Annual losses of phosphorus from forested watersheds reportedly range from 0.02 to 0.2 kg/ha; whereas losses from poorly managed agricultural lands may be as high as 20 kg/ha depending on the extent of soil erosion (see Frink 1971). Therefore, tree plantations would represent a positive impact on soil nutrient losses relative to agricultural land, but a net negative impact when compared to natural forests.

Nutrients that are lost in surface runoff will enter surrounding water bodies. In studies conducted in experimental forests, harvesting of timber resulted in increased runoff and in some cases in increased concentrations of nitrate in nearby streams (Hall et al. 1976). Losses of nitrate were dependent on the amount of vegetation (groundcover) remaining undisturbed and capable of taking up soil nitrogen. In one study, where all regrowth of trees or groundcover was prevented by the use of herbicides, the averaged weighted concentration of nitrate in a nearby stream increased to 53 mg/L from a background level of 0.9 mg/L.

The maintenance of a natural vegetation cover (weed rows) between tree rows, would considerably lessen the impact of nitrate losses into nearby streams and rivers. Mean concentration of nitrate in the Clinch River near the southeastern reference site was 0.43 mg/L for 1974-77 (ORNL/RFF 1992). Mean concentrations of phosphate and potassium for the same period were 0.018 mg/L and 1.3 mg/L. The concentration of nitrate in the Clinch River exceeds the recommended state water quality criteria of 0.02 mg/L (Tennessee Department of Health and Environment, 1990). Therefore, any additional input of nitrates would be undesirable. The state criteria for phosphate is 0.2 mg/L.

Leaching into Ground Water. When land is cleared of vegetation, the loss of rootmass alters the normal nutrient cycling in the soil and results in increased leaching of nutrients. This occurs regardless of whether the land is used for agriculture or for tree plantations. Rates of leaching would depend on initial nutrient levels, amount of rainfall, and type of soil; porous sandy soils allowing a greater potential for groundwater contamination. The use of fertilizers following planting of tree seedlings would increase rates of leaching, with a possible loss of up to 50% of the fertilizer applied (Ranney et al. 1991). Under such conditions EPA standards for ground water (10 ppm, designated for use as drinking water) may be exceeded during the year when the seedlings are planted (Ranney et al. 1991), particularly in areas where nutrient levels in ground water are already high. In groundwater samples taken in the vicinity of the southeastern reference site nitrate concentrations were 0.7 to 9.1 ppm (Project Management Corporation 1975-77), indicating some potential for EPA standards to be exceeded. Leaching can be minimized by maintaining a groundcover which would enhance nutrient uptake, or by using smaller but more frequent fertilizer applications (Ranney et al. 1991). Once the tree seedlings develope an adequate root mass, nutrient recycling in the tree stand would reduce the need for additional annual inputs of fertilizer to the soil. When averaged over the entire 18-year period of the plantation, inputs of nutrients to the soil and the potential for groundwater contamination would be expected to be less than that for land planted in row crops.

Estimates of average losses of nitrogen, phosphorus, and potassium to ground water at the southeastern reference site in 1990 are 71,870, 26,619, and 26,619 lb/yr (Appendix A, Table 19). These values would be equivalent to 0.2, 0.07 and 0.07 g/m^2 of surface area. Field data for a short-rotation sycamore test site in East Tennessee indicate that groundwater contamination is not likely to be a problem at normal fertilizer application rates (Van Miegroet and Norby 1991).

3.1.1.7 Volatile organic compounds (VOCs)

As a result of gas exchange, plants emit non-methane volatile organic compounds (VOCs) into the atmosphere. Tingey (1981) estimated that 0.06-2% of the primary productivity (carbon dioxide fixation) is reemitted through volatilization. The loss of VOCs is significantly increased when trees are cut or damaged during logging operations (Strömvall and Petersson 1991). It is generally thought that woody plants (both conifers and deciduous trees) emit more of these compounds than herbaceous species (Ranney et al. 1991). For American scyamore, emissions of VOCs amount to 1.1% of primary productivity (Tingey 1981).

Only about 30% of the VOCs have been identified and quantified (Rasmussen 1981); two of the most common of these are isoprene (2-methyl-1,3-butadiene) and monoterpenes (high molecular weight (C_{10}) cyclic compunds with 1-3 double bonds) (Arnts et al. 1981). American scyamore emits isoprene and sweet gum emits both isoprene and terpenes (Rasmussen 1981; Appendix A, Table 29). It was estimated that total emissions of isoprene from tree plantations at the southeastern reference site would be 4,135,529 lb/year in 1990 and 2,578,268 lb/year in 2010 (Appendix A, Table 30). Emissions of monoterpenes would amount to 519,062 in 1990 and 323,840 lb/year in 2010.

Isoprene and monterpenes are moderately to extremely reactive, and like anthropogenically derived hydrocarbons, they have the potential for reacting with NO_x in the presence of sunlight to generate ozone and peroxyacetyl nitrate (PAN). When atmospheric NO_x concentrations are low, they can also react directly with ozone to form radicals, acids, alcohols, aldehydes, peroxides and other photo-oxidants (Hooker et al. 1985; Gäb et al. 1985). In addition, oxidative cleavage of the double bonds can result in the formation of dioxygenated species with lower vapor pressures and a strong tendency to form aerosols. These aerosols, which are responsible for the blue haze seen in forested areas, can also react with ozone (Rasmussen 1981). Thus, the interactions of these various competing reactions plus the initial levels of ozone and NO_x, determine the overall impact that these biogenic hydrocarbons have on atmospheric levels of ozone.

In photochemical modeling studies using a propylene/n-butane mixture as a surrogate biogenic hydrocarbon, Arnts et al. (1981) found that ozone formation was very dependent on NO_x concentration and relatively insensitive to the concentration of the olefin. Furthermore, in laboratory studies, Arnts et al. (1981) demonstrated that isoprene and monoterpenes were very inefficient ozone precursors relative to propylene. The inefficiency increased with increasing $C:NO_x$ ratio. Maximum ozone formation occurred at a $C:NO_x$ ratio of 15:1 and maximum efficiency of conversion was 0.2-0.5 ppb O_3:ppb C consummed. At high $C:NO_x$ ratios, ozone formation was favored by those monoterpenes that reacted slowly with ozone (i.e., those having low ozonolysis rate constants).

In rural and remote areas olefinic biogenic hydrocarbons generally account for less than 10% of the 40 ppbC to 100 ppbC total nonmethane hydrocarbons (TNMHC) present in the atmosphere (60% is paraffinic and 30% aromatic) (Arnts and Meeks 1980). Thus, these biogenic hydrocarbons constitute only a small fraction of the hydrocarbons present and, considering their low potential for ozone formation, they are unlikely to contribute significantly to atmospheric levels of ozone. However, on tree plantations where releases of biogenic hydrocarbon are likely to be increased during logging and cutting and where NO_x levels are elevated due to the operation of diesel-fueled vehicles and machinery, there may be localized elevations in ozone and other photo-oxidants. Similar increases in biogenic VOC releases are expected at sites where the trees are dried prior to combustion. In addition, the nearby presence of other NO_x sources, such as fossil fuel power plants, would have a major impact on rates of ozone formation.

Because only a small fraction of the biogenic hydrocarbons released from trees have been identified and characterized according to chemical reactivity and ozone forming potential, additional information is needed before a more precise evaluation can be made of the impacts of biogenic emissions from tree plantations on air quality. In areas where extensive forests already exist additional inputs of biogenic hydrocarbons from tree plantations are likely to have minimal impacts, and in the absence of high NO_x levels may contribute to lowering ozone levels.

3.1.1.8 Air emissions from soil

As a result of microbiological processes in the soil, there is a potential for chemicals such as nitrous oxide (N_2O) and methane (CH_4) to be released into the atmosphere at tree plantation sites (Ranney et al. 1991). These processes, which occur under anaerobic conditions in soils saturated with moisture, have been documented primarily for tropical forest soils and wetlands. Fertilization with nitrogen enhances emissions of N_2O. Generally, emissions of N_2O from unfertilized temperate forest soils are small compared to fertilized agricultural lands (Bowden et al. 1990; Liu et al. 1977). Although monitoring data are not available, it is generally thought that emissions of N_2O from tree plantations would be less than those for agricultural row crops (McLaughlin 1991). Emissions of methane at tree plantation sites are likely to be similar to emissions from natural forests; however, quantitative data are not available to document this assumption (Ranney et al. 1991).

3.1.1.9 Air emissions from mechanical equipment

Diesel-fueled mechanical equipment that would be used on tree plantations emit varying amounts of combustion products such as SO_2, NO_x, CO, hydrocarbons, and particulates. Air emissions from such machinery, as well as from off-road vehicles, are not subject to government regulations. It is not expected that these emissions would be significantly greater than those from diesel-powered tractors and other equipment typically used on the agricultural farms. Emission rates from such equipment operated at the southeastern reference site are listed in Appendix A. Because of the small amounts released (10% or less of the amounts emitted from the power plant stack), these emissions are not expected to have direct ecological impacts, but they would contribute to overall changes in air quality; therefore, they must be considered in relation to similar emissions from trucks transporting feedstock to the power plant, as well as stack emissions at the power plant (Table F-2). Potential ecological effects of these emissions are discussed in Section 3.3.

3.1.1.10. Other ecological effects

The assumption is made that continued research will lead to improved varieties of trees to be used on tree plantations in the future. These new varieties may be selected for enhanced productivity, or for specific morphological or physiological characteristics (i.e,, stress tolerance, pest resistance, nutrient utilization). These new varieties represent genetic modifications unnatural to wild

Table F-2. Combustion emissions associated with the biomass fuel cycle ($lb/10^6 Btu$)

	HC	CO	NO_x	PM	CO_2	SO_2
1990 SE Site:						
Plantation equipment	0.0060	0.0264	0.0264	0.0027	3.50	0.0011
Feedstock trucks	0.0010	0.0038	0.0038	0.0002	1.21	0.0004
Power plant	0.09	0.27	0.19	0.03		0.01

populations, thus they may have subtle and unpredictable ecological impacts if introduced into natural gene pools (Ranney et al. 1991).

As in the case of agriculture, the silviculture of a limited number of species of trees of identical age in a confined area increases the potential for the rapid establishment and spread of diseases or insect pests throughout the population. In contrast, natural multi-aged populations of trees scattered throughout a more heterogenous environment tend to more resistant to the impact of diseases and insect pests.

3.1.2. Potential benefits

3.1.2.1. Improved soil quality

Nutrient losses to surface waters on tree plantations are expected to be much less than those from agricultural lands they replace (see Section 3.1.1.6). Phosphorus and nitrogen losses into surface water at the southestern reference site were estimated to be about 0.7 kg/ha each. In contrast, phosphorus and nitrogen losses from agricultural land can be as high as 20 kg/ha and 40-110 kg/ha, respectively (Larson 1979; Frink 1971). In addition, storage and recyling of nutrients in tree biomass and soil will minimize losses, improve soil productivity and reduce the need for fertilizers. Over the long term, nutrient losses from harvesting and leaching on tree plantations may exceed nutrient accumulation due to soil weathering and atmospheric inputs by only 10-20%; therefore, fertilizer rates may be reduced to only once per rotation without adversely affecting soil nutrient levels (Ranney et al. 1991). Thus, potential nutrient inputs to streams and ground water would be reduced even further.

3.1.2.2. Carbon recycling and sequestering

In comparison to the effects of fossil fuel combustion on atmospheric CO_2 levels, a major environmental advantage of biomass technology is the recycling of carbon through the photosynthetic process and sequestering of carbon in above ground biomass, rootstock, leaf litter and soil. When all aspects of the biomass fuel cycle are considered (i.e., feedstock production, transportation, and combustion), net carbon emissions per unit of energy generated are considerably lower than those for fossil fuels. Turhollow and Perlack (1991) calculated that for a biomass cycle based on short-rotation hybrid poplar crop, the ratio of carbon emissions to gigajoules of energy produced was only slightly above 1, whereas the ratios for natural gas, petroleum, and coal were about 14, 22, and 25, respectively.

Because of the larger standing crop biomass, carbon sequestering on tree plantations would be relatively higher than that for replaced agricultural lands. When replacing cropland, short-rotation tree plantations may increase carbon inventories, on average, by 30 to 40 tonnes/ha over a period of 20 to 50 years (Ranney et al. 1991). Under sustainable conditions, equilibrium levels might be reached in about 75 to 100 years; however, maximum inventories would be only about half the amount occurring in natural forests (Ranney et al. 1991). Hypothetical average carbon levels, at equilibrium, for cropland, short-rotation tree plantations, and managed forests were estimated to be 32, 69.5, and 144.5 Mg/ha (Ranney et al. in press).

Conversion of agricultural lands to tree plantations is likely to result in increases in soil organic carbon levels. A potential positive benefit of this might be reductions in nutrient leaching into ground water and reduced emissions of NO_x into the atmosphere (Ranney et al. 1991).

3.1.2.3. Biodiversity

The impact of tree plantations on biodiversity in a given area is dependent on preexisting land uses as measured on both a local and regional scale. Because of their inherent spatial and temporal complexity (i.e., canopy, open areas, leaf litter, etc., which can change from year to year), tree plantations, particularly if maintained with a groundcover and located near natural woodlands containing dead trees, mast producing plants, and winter cover, would theoretically provide for a greater number of microniches and, consequently, a greater local biodiversity than land previously utilized for agriculture, hayland, or pasture (Ranney et al. 1991). On small monocultural tree plantations the number of species of birds, small mammals, and insects and soil macrofauna is likely to increase slowly from year to year to eventually become similar to woodland populations. In a Wisconsin study of a short-rotation Populus plantation, Verch (1986) found that during the first two years of tree growth only a small number of bird species were present and these were confined to the edges of the tree stand. However, as the trees grew larger and overall habitat diversity increased due to limited tree mortality and subsequent formation of open areas, the number of nesting bird species reached 16. This occurred about four years after the seedlings were planted. In contrast, adjacent open fields had only 3-6 nesting bird species and adjacent forests 20 to 25. In a study conducted in Ireland, the bird fauna on a short-rotation hardwood plantation exceeded that of a natural coniferous woodland and was similar to that of an oak woodland (Kavanagh 1991).

Soil fauna may also change as arable land is converted to tree plantations. In a German study evaluating the soil fauna in poplar and willow stands, it was found that there was a significant increase in earthworm abundance which eventually exceeded that of soils on pine plantations (Makeschin 1991). In addition, carabid beetle populations declined relative to those found in open fields, but centipede and millipede populations increased. Overall, Makeschin (1991) concluded that tree plantations posed no significant ecological risks to soil fauna.

On a regional scale, the impact of tree plantations on biodiversity is dependent on the extent that the land is dominated by farmland, grassland, or forest. For example, significant beneficial changes might be expected in regions dominated by tall grass prairies because tree plantations are likely to provide unique habitats for unusual species (Perlack et al. 1992).

At the 1990 southeastern reference site about 96% of the 39,928 acres would be derived from agricultural land, hayland and pasture, less than 4% from open woodland (less than 55% canopy coverage) and none from natural forests. Open woodlands currently account for about 34,000 acres within a 75-mi radius of the site. Therefore, the development of tree plantations would more than double this type of habitat. In addition, if the tree plantations each averaged about 50 acres, the edge habitat bordering these plots could amount, in distance, to as much 800 miles. However, in a wider regional analysis, the impact of the tree plantations associated with this one facility would be very small considering that the East Tennessee region contains nearly 3.4 million acres of forest (TVA 1984).

3.2 STAGE 2. - TRANSPORT OF FEEDSTOCK TO POWER PLANT

3.2.1 Potential impacts

3.2.1.1 Air emissions

Exhaust emissions from trucks hauling the feedstock to the power plant and returning to the tree plantations consist of hydrocarbons, NO_x, CO, particulates, SO_2, and CO_2. These emissions are not expected to have direct ecological impacts, but they would contribute to overall changes in air quality; therefore, they must be considered in relation to similar emissions from equipment operated at the tree plantations, as well as stack emissions at the power plant itself (Table F-2). Potential ecological effects of these emissions are discussed in Section 3.3.

Environmental impacts of truck haulage of feedstock must consider not only direct exhaust emissions, but also indirect emissions such as fugitive dust released into the air when the trucks travel unpaved roads in and around the tree plantations. Such emissions would be highly site-specific; however, for one tree plantation scenario, Mitre Corp. estimated that fugitive truck dust emissions would equal 200.65 tons per year (assuming 308,700 vehicle miles traveled, 6.5 lb dust/vehicle mile, 60% controlled, and 50% unpaved roads).

3.2.1.2 Road deterioration

The proposed 30-MW power plant would require 210,224 wet tons of feedstock per year in 1990 and 166,826 wet tons per year in 2010 (Appendix A). This feedstock will be hauled to the power plant in trucks each having the capacity of 20 wet tons; thus 10,511 delivery trips per year would be required in 1990 and 8,341 in 2010 (Appendix A). For the southeastern reference site, it is assumed that the average haul distance would be 44 miles in 1990 and 35 miles in 2010; similarly, at the western site average haul distance would decrease from 37 miles in 1990 to 28 miles in 2010. Total roundtrip distance for the southeastern and western sites would be 924,986 and 777,829 miles in 1990 and 583,891 and 467,113 miles in 2010. This traffic will contribute to increased road wear mostly near the power plant site since the tree plantations are expected to be widely dispersed throughout the 75-mile radius of the plant.

3.2.1.3 Traffic noise

As noted above, 10,511 truck deliveries would be required per year to furnish the feedstock to the power plant for the 1990 technology and 8,340 for the

2010 technology. On average 4.2 loads would be delivered each hour in the first case and 3.3 loads per hour in the second. Therefore, there is likely to be a small increase in local traffic noise.

3.3 STAGE 3. - POWER GENERATION

A description of the 1990 WBT technology and associated emissions is given in Appendix A. Information on emission rates and incremental increases in atmospheric concentrations of primary pollutants for the 2010 BGISTIG technology and for the western reference site were not available for evaluation of potential ecological impacts.

3.3.1 Potential Impacts

3.3.1.1 Air emissions

Emissions of air pollutants from a wood-fired power plant are determined by the characteristics and moisture-content of the feedstock, the combustion technology utilized, and the emission control devices in place. Prior to combustion, the wood must be stored and dried to improve combustion efficiency. During this time, water vapor and volatile hydrocarbons are released to the atmosphere. Combustion of the wood contributes additional water vapor and hydrocarbons to the air, as well as particulate matter, SO_2, NO_x, CO and CO_2.

3.3.1.1.1 Water Vapor

Wood has a moisture content averaging about 50% (Gates 1985). Considering that 161,452 and 128,123 dry tons of wood will be utilized each year for the WTB and the BGISTIG technologies, respectively, a nearly equivalent amount of water vapor will be lost to the atmosphere during drying of the feedstock and combustion of the wood fuel. Additional water vapor will be lost from the mechanical draft cooling tower. Releases of such large amounts of water vapor, in addition to particulates and secondary aerosols emitted from the power plant stack, may at times cause decreases in visibility. Quantitative data on local changes in visibility due to the operation of the hypothetical power plant were not available for evaluation.

3.3.1.1.2 Hydrocarbons

Hydrocarbons are emitted from the power plant stack during the combustion process. Relative to the amount of energy produced, wood combustion releases about 0.25 lb hydrocarbons (CH_4 equivalents) per 10^6 Btu (Gikis et al. 1978). For a wood-fired power plant generating 2.7 x 10^{12} Btu/yr, this would amount to 6.75 x 10^5 lb/yr (337 tons/yr) or 9.7 g/sec at the stack. For five industrial wood-fired stoker boilers, Shih and Takata (1981) reported an average emission factor of 100 ng/J for total hydrocarbons (46 for volatiles and 54 ng/J for nonvolatiles) which would be equivalent to an emission rate of 8.6 g/sec. For this study a hydrocarbon emission factor of 1.4 lb per dry ton of fuel (0.09 lb/10^6 Btu or 3.25 g/sec) was used for the 1990 WTB technology (Appendix C).

Hydrocarbons released during the combustion process differ from those volatilized from the feedstock in that they can be more complex polycyclic compounds as well as highly oxidized compounds. In the studies of Shih and Takata (1981), the emission factor for polycyclic organic matter was reported to be 0.18 ng/J (1.5 g/sec). Phenanthrene was identified in samples from one of the boilers, and benzo(a)pyrene was tentatively identified from several others. In general, such large complex hydrocarbons have a relatively low acute toxicity to animals; however, some, such as benzo(a)pyrene are known or suspect carcinogens. Additional information is needed on the types and amounts of polycyclic aromatic hydrocarbons released in stack emissions of wood-fired power plants before a reliable assessment can be made of potential ecological impacts.

Hydrocarbons released in the stack emissions also have the potential for reacting with NO_x in the presence of sunlight to generate ozone and peroxyacetyl nitrate (PAN). Ozone formation is discussed in Section 3.1.1.1.7. and PAN in Section 3.3.1.1.3.

3.3.1.1.3 NO_x and Other Nitrogen Compounds

Assuming a 0.1% nitrogen content in wood, up to 161 tons/year of nitrogen could theoretically be emitted from the stack of a wood-fired power plant burning 161,452 dry tons of feedstock (as would be the case for the 1990 WTB technology). As in fossil fuel power plants, this nitrogen can be converted during the combustion process to various nitrogen compounds including nitrogen oxides (NO_x). Total conversion to NO_x with equal amounts of NO and NO_2 formed, would result in a yield of about 437 tons/year of NO_x or 0.32 lb/10^6 Btu for a 30-MW facility generating 2.7 x 10^{12} Btu. NO_x emissions from a 50-MW wood-fired power plant were reported to be 0.157 lb/10^6 Btu (Tewksbury, 1987). The NO_x emission factor used in this study for the 1990 WTB technology was 0.19 lb/10^6 Btu (Appendix C). At this emission rate the maximum 1-hr average concentration of NO_x downwind of the power plant was calculated to be 44.0 $\mu g/m^3$ (about 30 ppb, assuming equal amounts of NO and NO_2 formed), the maximum 24-hr average 11.01 $\mu g/m^3$ (7.1 ppb), and the maximum annual average 0.540 $\mu g/m^3$ (0.36 ppb) (Appendix C). In comparison, the average annual ambient concentration of NO_x at the southeastern site was reported to be 23 $\mu g/m^3$ (about 15 ppb). NO_x emissions from the proposed 30-MW wood-fired WTB power plant in 1990 represent about a 2% maximum increase in the annual average.

Information on the effects of NO_x on animals is limited to laboratory studies (Table F-3). Nitrogen dioxide is a deep lung irritant capable of producing pulmonary edema if inhaled in sufficient concentrations (Amdur 1986). It can also cause significant alterations in pulmonary function and can increase susceptibility to respiratory infection by bacterial pneumonia or influenza virus. The lowest concentrations causing adverse effects (primarily biochemical and structural changes in the respiratory system) generally range from 250 to 1000 ppb. Therefore, no significant ecological impacts would be expected from the operation of a 30-MW wood-fired power plant.

There is no evidence that concentrations of NO_x below 50 ppb have direct toxic effects on plants. Concentrations above 50 ppb may produce signs of reduced growth in some species (ORNL/RFF, 1992, Appendix D), and levels of 500 ppb and above may cause foliar injury (Taylor and Eaton 1966). However, any incremental increase in NO_x must also be considered in terms of increased acid deposition and increased formation of ozone. In the atmosphere NO_x can react with strong oxidizing agents such as O_3, OH, and H_2O_2 to form HNO_3. Together with H_2SO_4 (formed from SO_2), HNO_3 can be transported over long distances before being removed from the atmosphere by dry and wet deposition. This acid deposition occurs over a wide area and may impact both aquatic and terrestrial systems. Impacts of acid deposition on aquatic resources are discussed in Section 3.3.1.1.5. Terrestrial studies of acid deposition have focused on impacts on vegetation.

As discussed in ORNL/RFF (1992), acid precipitation does not appear to have significant impacts on crop yield (Shriner et al. 1990). No consistent reduction in yield was found in crops, in the eastern U.S., that were exposed to levels of acid rain representing average ambient levels (pH 4.1-5.1) or rain events with relatively high acidity (pH 3.0-4.0). The levels of acid deposition required to impact crop yield are for the most part between 10- and 100-fold greater than average ambient levels. Therefore, it is unlikely that a single 30-MW power plant would contribute significantly to reductions in crop yield through acid deposition; however, it should be noted that each incremental addition of atmospheric pollutants increases the probability of cumulative effects.

Table F-3. Effects of Nitogen Dioxide on Laboratory Animals[a]

Species	Exposure	Effects	Reference
Rat	1 ppm for 4 hours	Lipid peroxidation in lung	Thomas et al. 1968
Rat	166 ppm for 1 hour	LC_{50}	Amdur 1986
Rat	88 ppm for 4 hours	LC_{50}	Amdur 1986
Rat	0.5 ppm for 4 hours or 1 ppm for 1 hour	Damage to mast cells (repaired within 24 hours)	Mueller and Hitchcock 1969
Rat	10 or 25 ppm for 16 weeks	Emphysema-like lung damage	Freeman et al. 1972
Rat	0.8 or 2 ppm for life	Concentration-related cellular alterations in bronchiolar epithelium; 2 ppm induced moderate tachypnea, bloating, increased air retention, and 20% weight increase in lungs	Freeman et al. 1972
Mouse	1.5 ppm for 18 hours; 14.5 ppm 2 hours	25% and 65% increase in mortality (1.5 and 14.5 ppm, respectively) following exposure to *Streptococcus pyrogenes*	Coffin et al. 1976
Mouse	0.5 ppm, 6 or 18 hours/day for 6 months; 0.5 ppm continuously for 3 mo	Increased mortality following exposure to *Klebsiella pneumoniae*	Ehrlich and Henry 1968
Guinea pig	5-13 ppm for 2-4 hours	Changes in pulmonary function	Murphy et al. 1964
Rabbit	0.25 ppm, 4 hours/day for 6 days	Alterations in lung collagen	Mueller and Hitchcock 1969
Dog	25 ppm for 6 months	Emphysema-like lesions	Riddick et al. 1968
Squirrel monkey	10-50 ppm for 2 hours	Concentration-related lesions in alveoli and changes in pulmonary function; frank edema at 50 ppm (function recovered 24-48 hours post exposure	Henry et al. 1969
Squirrel monkey	5 or 10 ppm for 1-2 mo; 50 ppm for 2 hours	Increased mortality following exposure to *K. pneumoniae*	Henry et al. 1970

a. Data and references from Amdur 1986

Deposition of HNO_3 in forests may have an indirect effect on forest health by modifying soil chemistry and thereby affecting plant nutrient status, symbiotic relationships, functions associated with the root system, and susceptiblity to disease and damage due to other environmental pollutants such as ozone. Recent studies have indicated that high nitrogen deposition rates in high-elevation forests in the eastern U.S. exceeded nitrogen requirements for growth and may cause nitrate leaching, soil acidification, and loss of essential soil cations such as calcium and magnesium (Van Miegroet and Cole 1984; Ulrich et al. 1980). Occurring over the long life cyle of the forest, this alteration in soil chemistry would outweigh any short-term benefits of nitrogen fertilization of such soils (Brandt 1987; Abrahamsen 1980).

NO_x emissions from a wood-fired plant can also contribute to the formation of ozone and peroxyacetyl nitrate (PAN). Both chemicals are strong reactants and can adversely affect vegetation. Ozone is discussed in Section 3.3.1.1.4. PAN can be toxic to plants and animals. It causes silvering or bronzing of the underside of the leaves of broadleaf plants, yellow to tan bleached bands in the blades of grasses, and needle blight with chlorosis or bleaching in conifers (Heck and Anderson 1980). Concentrations which cause foliar injury depend on the species, exposure time, and other environmental variables. In one study, foliar damage occurred in bean plants exposed for 1 hr to 140 ppb or for 8 hr to 20 ppb (Jacobson 1977). Animals appear to be less sensitive to PAN. In mice, a 13-wk exposure to 1,000 ppb caused only a slight irritation to the mucous membranes of the nasal cavity, 200 ppb produced no signs of adverse effects (Kruysse and Feron 1977).

Information on ambient and incremental increases in PAN at the southeastern reference site was not available for evaluation.

3.3.1.1.4 Ozone

Ozone is a secondarily derived air pollutant formed by the reaction of hydrocarbons and NO_x in the presence of sunlight. Maximum ozone formation occurs at a C:NO_x ratio of 15:1 (Arnts 1981). Because background levels of hydrocarbons in the atmosphere range from 40 to 100 ppb in rural areas and are even even higher in urban and industrial areas (Arnts and Meek 1980), ozone formation is largely controlled by the incremental increase in NO_x. The estimated emission of NO_x from a wood-fired power plant at the southeastern site using 1990 WBT technology are 226 tons per year. The resulting peak 1-hr average increase in ozone within a 50-km radius of the power plant was calculated to be 3.3 ppb, and the monthly 12-hr average was estimated to be 0.2 ppb (Appendix C).

Ozone damages plants and affects growth and yield. Broadleaf plants exhibit reF-brown spots, bleached tan to white flecks, irregular necrotic areas and chlorosis; grasses exhibit necrotic flecks or streaks and interveinal chlorosis; and conifers exhibit brown-tan necrotic needle tips and chlorotic mottling (Heck and Anderson 1980). The effects of ozone on plants depends on many factors including concentration, exposure time, species, cultivar genetics, growth stage, environmental variables (soil conditions, meteorology, temperature, humidity) and pollutant interactions (SO_2, acid deposition, and NO_2) (ORNL/RFF 1992). Concentration and exposure time are the two most critical factors. For relatively short-term exposures, damage to plants can be seen at ozone concentrations of 50 to 100 ppb. For example, a concentration of 80 ppb, 7 hr/day, five days/wk (intermittent, for a total of 420 hr) caused foliar damage and reduced growth of seedlings of four species of hardwood trees (black cherry, red maple, northern red oak, and yellow poplar) (Davis and Skelly 1992); a concentration of 100 ppb, 4 hr/day, 5 days/wk for six weeks suppressed growth of seedling white and green ash (Chappelka et al. 1988); concentrations of 40-80 ppb, 5 hr/day, 16 days, reduced seed yield in soybeans (Reich et al. 1982); and concentrations exceeding 53 ppb damaged tobacco plants (Heggestad and Menser 1962).

In the presence of other pollutants such as SO_2, NO_x, and PAN, effects on plants can be additive, synergistic, or antagonistic. Available information on the combined effects of ozone and other primary air pollutants on plants is summarized in ORNL/RFF (1992, Appendix D).

Reduction in crop yields due to incremental increases in atmospheric ozone concentrations is considered a potential key impact of a wood-fired power plant. Dose-response functions are available to quantify this impact (Section 5.1). However, data are generally not available for estimating the response of whole trees or tree stands to air pollutant stresses such as ozone. Consequently, empirical models and conclusive quantitative estimates of such responses do not exist. Existing process models relate to responses of tree seedlings and branches to air pollutants. These models are currently being modified to provide preliminary estimates of whole tree responses, which could then be used to extrapolate to responses for entire stands of trees.

Ozone can also adversely affect animals (Table F-4). Chronic bronchitis, bronchiolitis, fibrosis, and emphysematous changes have been observed in several species of laboratory animals exposed to ozone concentrations slightly above 1 ppm, and extrapulmonary effects (i.e., reduced activity, chromosomal aberrations, increased neonatal mortality, and jaw abnormalities in offspring of exposed mice) have been observed at concentrations as low as 0.2 ppm (Amdur, 1986). These

Table F-4. Effects of Ozone on Laboratory Animals[a]

Species	Exposure	Effects	Reference
Rat	0.2 ppm for 3 hours	Degenerative changes in type I alveolar cells	
Rat	0.25-0.5 ppm for 6 hours	Threshold for edema formation	Alpert et al. 1971
Rat	0.2, 0.5, or 0.8 ppm 8 hours/day on 7 consecutive days	Mild, but significant morphologic lesions at lowest concentrations. With continuous exposure, lesions reached a peak in 3-5 days and diminished. After 90 days at 0.8 ppm there was obvious damage, but less severe than at 7 days.	Dungworth 1976
Rat	0.5 to 0.9 ppm for up to 3 weeks	Morphologic lesions in respiratory bronchioles, in distal portions of the terminal bronchiolar epithelium, and in the alveolar duct and alveoli	Stephens et al. 1974
Rat	0.3 ppm for 1 hour	Tolerance - protection against subsequent exposure to otherwise lethal concentrations. Tolerance lasted 4-6 weeks and protected against pulmonary edema but not against alterations in pulmonary function.	Stokinger 1965
Rat	0.2, 0.5, or 0.8 ppm continuously for 7 days	Increased metabolic (enzyme) activity in lung tissue. Levels returned to normal when exposure ceased	Mustafa et al. 1983
Mouse	20 ppm for 3 hours	LC_{50}	Stokinger 1965
Mouse	0.3 ppm for 1 hour	Tolerance - protection against subsequent exposure to otherwise lethal concentrations. Tolerance lasted up to 14 weeks and protected against pulmonary edema but not against alterations in pulmonary function.	Stokinger 1965
Mouse	0.08 ppm for 3 hours	Enhanced mortality from subsequent exposure to a bacterial aerosol of streptococcus (Group C)	Coffin and Blommer 1967
Guinea pig	50 ppm for 3 hours	LC_{50}	Stokinger 1965
Guinea pig	0.34-1.8 ppm for 2 hours	Decreased tidal volume, increased flow resistance (both reversible); concentration-related reductions in compliance	Murphy et al.. 1964; Amdur et al. 1978
Cat	0.25, 0.5, or 1.0 ppm for 4-6 hours	Dose-related desquamation of the ciliated epithelium of all airways; alveolar damage, including swelling and denudation of the cytoplasm of type I cells	Boatman et al. 1974
Dog	1-3 ppm, 8, 16, or 24 hours/day for up to 18 months	Concentration-dependent thickening of the terminal and respiratory bronchioles (accompanied at highest conc. by infiltration of cells that reduced the caliber of the small airways)	Stephens et al. 1973

Table F-4. Effects of Ozone on Laboratory Animals[a]

Species	Exposure	Effects	Reference
Monkey	0.2, 0.5, or 0.8 ppm 8 hours a day on 7 consecutive days	Mild, but significant morphologic lesions at the lowest concentrations.	Dungworth 1976

a. Data and references derived from Amdur 1986.

concentrations are above the ambient levels predicted for the hypothetical 30-MW wood-fired power plant (55.2 ppb).

3.3.1.1.5 Sulfur Dioxide

Wood contains only small amounts of sulfur; consequently, emissions of SO_2 at the power plant stack are expected to quite small. The SO_2 emission factor used in this study is 0.01 lb/10^6 Btu (Appendix A). This value results in a total annual emission of about 12 tons of SO_2 from the wood-fired power plant at the southeastern site using the 1990 WBT technology. At an emission rate of 0.01 lb/10^6 Btu (0.35 g/sec), the maximum 1-hr average increase in SO_2 concentration downwind of the power plant was calculated to be 2.37 $\mu g/m^3$, the maximum 24-hr average increase 0.59 $\mu g/m^3$, and the maximum annual average increase 0.029 $\mu g/m^3$ (Appendix B). The reported annual average ambient concentration of SO_2 near the southeastern reference site is 25 $\mu g/m^3$ (9.54 ppb) (Appendix B). The addition of SO_2 from a single 30-MW wood-fired power plant would represent about a 0.1% increase in the annual average (to about 9.55 ppb).

Information on the toxicity of SO_2 to laboratory animals is shown in Table F-5. The reported toxicity thresholds are all above the predicted maximum ambient concentrations resulting from the operation of the 30-MW wood-fired power plant.

The lowest concentration of SO_2 reported to be deleterious to plants (lichens) is >50 $\mu g/m^3$ (Gilbert 1965, 1970; Barkman 1969; both as reported in Bradshaw 1973). For most other species thresholds occur at much higher concentrations. Bell and Clough (1973) reported a 50% reduction in growth of rye grass at about 200 $\mu g/m^3$ (76 ppb). Gupta et al. (1991) reported that soybeans were stressed by 50 ppb (130 $\mu g/m^3$). A concentration of 100 ppb (261 $\mu g/m^3$, 4 hr/day for 5 days) caused a 13% reduction in photosynthesis, a 28% reduction in specific root nodule nitrogenase activity, and a 23% reduction in foliar nitrogen (Sandhu et al. 1992). Concommittent exposure to 450 ppm CO_2 compensated for the negative effect of the SO_2. SO_2 may act synergistically with ozone to damage

TABLE F-5. Effects of SO_2 on Laboratory Animals[a]

Species	Exposure	Effects	Reference
Rat	10 ppm, 18-67 days, inhalation	Thickening of mucous layer of trachea	Dalhamn 1956
Rat	12 ppm, 4-6 minutes, direct exposure to trachea	Cessation of ciliary beat; recovery a few minutes after exposure ceased	Dalhamn 1956
Rat	25, 50, 100, 200, and 300 ppm, ten periods of 6 hours each	Dose-related effects on trachea. At 300 ppm, notable epithelial damage and complete destruction of goblet cells. At 25 ppm, increased goblet cells and increased acid phosphatase activity in alveolar macrophages	Mawdesley-Thomas et al. 1971
Rat	0.1, 1.0, or 20 ppm for 70 to 170 hours	Interference with clearance of inert particles. "The most marked effects were seen with lower doses administered over a longer period of time"	Ferin and Leach 1973
Guinea pig	0.1 to 5.0 ppm for up to one year or more	No pulmonary pathology	Alarie et al. 1972; 1975
Guinea pig	0.13, 1.01, or 5.72 ppm continuously for a year	No evidence of adverse effects on mechanical properties of the lung (t. vol., resp. rate, num. vol., flow resist., and work of breathing)	Alarie et al. 1970
Dog	1 ppm for 1 year	Slowing of tracheal mucous transport	Hirsch et al 1975
Dog	5 ppm, 21 hours/day for 225 days	50% increase in resistance; 16% decrease in compliance	Lewis et al. 1969
Dog	0.5 ppm sulfur dioxide and 0.1 mg/m^3 sulfuric acid 16 hours/day for 18 months	No impairment in pulmonary function	Vaughan et al. 1969
Monkey	0.1 to 5.0 ppm for up to one year or more	No pulmonary pathology	Alarie et al. 1972; 1975
Monkey	0.14, 0.64, or 1.28 ppm continuously for 78 weeks; one group accidentally exposed for one hour to approximately 200 to 1000 ppm	No detrimental alterations in pulmonary function detected in low conc. groups; accidental exposure resulted in deterioration in pulmonary function	Alarie et al. 1972

a. Data and references from Amdur 1986.

plants at low concentrations. In laboratory studies, a concentration of 240 ppb SO_2 and 30 ppb O_3 damaged tobacco plants, but either substance alone did not (Menser and Heggestad 1966). Dochinger et al. (1970) reported that a synergistic interaction of SO_2 and ozone might cause the breakdown of chlorophyll *a* in the needles of the white pine (*Pinus strobus*).

Atmospheric emissions of SO_2 can affect regional air quality due to reactions with oxidizing agents (e.g., O_3, OH, and H_2O_2) and the resulting formation of H_2SO_4. H_2SO_4 (and HNO_3 formed from NO_x) can be transported over long distances before being removed from the atmosphere by dry and wet deposition (acid rain). Because of this wide dispersion, regional scale modeling is required for the evaluation of incremental impacts of single point sources. Regional modeling for the evaluation of acid precipitation on aquatic resources was undertaken as part of the 10-yr National Acid Precipitation Assessment Program (NAPAP 1991; see also Baker, et al. 1990; Turner et al. 1990; Thornton et al. 1990). The models that were developed consisted of watershed chemistry models relating acid deposition to longterm changes in surface water quality, and biotic response models relating fish population status to aciF-base chemistry. The output of the combined models was an estimate, on a regional basis, of the fraction of streams or lakes with long-term aciF-base chemistry suitable for fish survival under different scenarios of future sulfur deposition. Responses differed by regions because of differences in watershed chemistry and fish sensitivity. In general, changes in fish densities were not modeled in these studies.

As discussed in ORNL/RFF (1992), the NAPAP models are useful for making general regional comparisons for different projected acid deposition rates, but they are not considered useful in quantifying specific impacts because of uncertainties associated with the watershed chemistry and dose-response models and in the estimates of acid deposition on a local as well as regional scale.

Most of the streams and reservoirs within a 50-km radius of the proposed 30-MW wood-fired power plant at the southeastern reference site are well-buffered by carbonate rock and would not be affected by acidic deposition (ORNL/RFF 1992). However, many small streams draining the ridges in the area originate in highly weathered soil with little buffering capacity and, during storms, these streams show pulses of acid runoff (Elwood and Turner 1989; Mulholland et al. 1990). In addition, a small number of streams on the Cumberland Plateau to the west and within 50 km of the site have a low acid neutralizing capacity (ANC) and are also potentially at risk from acid deposition. No streams within the study area were identified as being currently affected by acid deposition to the extent that significant ecological changes were occurring. Therefore, the small incremental increase in acid deposition due to a single wood-fired power plant is not expected to have a major ecological impact.

3.3.1.1.6 Particulates

Particulate emissions from wood combustion can be quite high. Uncontrolled particulate emissions for the proposed 1990 WTB power plant were projected to be 581 ton/yr (Appendix A). However, with mechanical collectors (80% efficiency) and electrostatic precipitators (90% efficiency) these emissions can be reduced considerably (36 tons/yr). The resulting atmospheric concentrations at the southeastern site were calculated to be 6.91 $\mu g/m^3$ for a peak 1-hr average, 1.73 $\mu g/m^3$ for a maximum 24-hr average, and 0.085 $\mu g/m^3$ for a maximum annual average (Appendix B). The maximum annual particulate deposition rate was calculated to be 0.002 $\mu g/m^2$-sec. Ambient particulate concentration in the study area has been reported to be 108 $\mu g/m^3$ for a 24-hr average (2nd highest) and 47 $\mu g/m^3$ for an annual average (Appendix B). Operation of the power plant would result in an increase of about 0.2% in the average annual concentration.

There is very little experimental data on the ecological effects of high particulate concentrations. However, in one study it was found that deposition of particulate matter on the leaves of oak trees caused an indirect loss of leaf chlorophyll (Williams et al. 1971). The particles clogged leaf stomatal pores which allowed a greater uptake and retention of SO_2. The SO_2 decreased pH levels within the leaf and resulted in hydrolysis of chlorophyll *a* to phaeophytin. Deposits of particulate matter on the leaf surface causing these effects ranged from 4 to 175 $\mu g/cm^2$. Information on deposition rates for ambient particulate matter and estimates of the fraction of ambient and incremental deposition resulting in contamination of foliar surfaces are neeeded to assess impacts from a single point source.

In the vicinity of the power plant site, emissions of particulates and secondary aerosols may cause atmospheric haze, particularly during unfavorable meteorological conditions. Quantatitive estimates of localized impacts are, however, not available. On a regional scale, visual range reduction caused by haze is a major form of visibility impairment throughout the United States. Visually important recreational areas located near the southeastern reference site include the Great Smokey Mountains National Park, Cherokee National Forest, and Nantahala National Forest. According to monitoring studies conducted by the National Park Service at Look Rock, TN, the average annual visual range in the Great Smokey National Park was 55 kilometers during 1980-1983 (Reisinger and Valente 1985).

Haze is generally considered to be caused by multiple emission sources (EPA 1988). A single 30-MW wood-fired power plant is unlikely to have direct visibility impacts on distant recreational areas.

3.3.1.1.7 Other Inorganics

Wood has trace amounts of metals and other inorganic compounds, some of which can be released as stack emissions. In a study of wood-fired industrial boilers, Shih and Takata (1981) reported emission factors of 14,280, 18,750, 1,190, 876, 750, and 577 ng/J for calcium, potassium, phosphorus, iron, strontium, and aluminum, respectively. Emission factors for other elements were all substantially lower. Ambient concentrations of these substances at the hypothetical 30-MW wood-fired power plant were not calculated.

3.3.1.2 Water Emissions

Water quality in receiving streams could be affected by the operation of condenser cooling system and by discharges of utility wastewater.

3.3.1.2.1 Cooling systems

The condenser cooling water system designed for both the WTB and BGISTIG power plants is a mechanical draft cooling tower. Impacts on the aquatic environment are expected to be minimal, and would only occur when the system was cleaned and replenished. Corrosion inhibitors, biocides, and other chemicals would then be released into the receiving water body. At the southeastern site the receiving water body is the Clinch River which has an average flow of 4,561 cfs or about 1.1×10^{12} gal/yr (Project Management Corporation 1975-77). River flow velocity is controlled by turbine operation at Melton Hill dam. Discharges during low or no-flow periods could have very localized environmental impacts; however, site-specific information on potential contaminants and concentrations is needed before a detailed evaluation can be made.

3.3.1.2.2 Wastewater

For an industrial boiler, the principal components of the wastewater discharge are boiler blowdown and water from the solid waste handling system. Chemicals contained in this wastewater consist of those added to the boiler makeup water to avoid problems with deposits, corrosion and carryover, as well as chemicals leached out of the ash (DOE 1983). The extent of pretreatment of makeup water depends on the chemical characteristics of the intake water.

Suspended solids are usually removed by coagulation and filtration and, if necessary, water hardness is reduced by an ion exchange process which replaces calcium and magnesium with sodium (from sodium chloride). Additional chemicals which may be added to the boiler water or condensate include sulfites or hydrazine for oxygen scavenging, volatile and/or filming amines for condensate corrosion control, phosphates and caustic soda for boiler corrosion control and chelates for limiting boiler fouling (DOE 1983).

For an industrial wood-fired boiler producing approximately 0.5 x 10^{12} Btu/yr, the wastewater treatment facilicity discharges approximately 1.22 x 10^6 gal/yr of wastewater of which 7.9 x 10^5 gals will be blowdown (DOE 1983). Wastewater discharges from a 50-MW wood-fired power plant were reported to be 220 gpm (1.2 x 10^8 gal/yr) (Tewksbury, 1987). A similar level of discharge is expected from the hypothetical 30-MW plant utilizing the 1990 WTB technology. At the southeastern reference site, the receiving water body is the Clinch River which has an average flow of 4,561 cfs or about 1.1 x 10^{12} gal/yr (Project Management Corporation. 1975-77); therefore, the effluent would represent only 0.01% of the river flow. Minimal impacts on the aquatic ecosystem are expected; however, site-specific information on potential contaminants and concentrations is needed before a detailed evaluation can be made.

3.3.2 Potential benefits

3.3.2.1 NO_x and SO_2 as soil nutrients

NO_x and SO_2 emissions from a wood-fired power plant can react in the atmosphere with strong oxidizing agents such as O_3, OH, and H_2O_2 to form the acids H_2SO_4 and HNO_3. Depending on atmospheric conditions, these acids may be transported over long distances before being removed from the atmosphere by dry and wet deposition. Although acid deposition can have adverse ecological effects (see Section 3.3.1.1.5), when deposited on soils, these compounds can also represent sources of sulfur and nitrogen which may be utilized as nutrients by some plants. Several field studies have documented that sulfur additions to the soil, either directly or through acid rain may be beneficial for plant growth. Jones and Suarez (1980) reported that corn showed a positive response to sulfur additions to soil (9 kg/ha), and Irving (1986) reported a similar positive response when timothy hay and red clover were treated with simulated acid rain. Furthermore, Noggle (1980) reported that soybeans growing near a point source of atmospheric sulfur obtained 10 to 50% of their sulfur requirement from the atmosphere.

As discussed in ORNL/RFF (1992), natural forests are not likely to benefit from atmospheric deposition of sulfur because deposition rates (>10 kg/ha/yr in polluted regions) are substantially higher then forest requirements for growth (1-2 kg/ha/yr). However, atmospheric deposition rates for nitrogen (5-25 kg/ha/yr) are within the range of forest requirements (1-5 kg/ha/yr), and therefore, may be beneficial to forests especially in areas where soils are deficient in nitrogen (Shriner et al. 1990).

Exposure-response functions are not available to quantity the impact of emissions of NO_x and SO_2 from a single power plant on agricultural crops or forests.

3.3.2.2 Waste heat utilization

In the hypothetical 30-MW wood-fired power plants, waste heat from the flue gas is to be used to dry the wood feedstock. Residual heat might also be provided to greenhouses where seedlings for the tree plantations are propagated.

3.3.2.3 Recycling of wood ash to soil

Wood contains about 1% ash. The ash is alkaline (pH 9-14) and relatively rich in Ca, K, Mg, Si, Fe, Al, and P (DOE 1983; Etiégni and Campbell 1991). Phosphorus and potassium content of the ash is 1-2% and 3-4%, respectively (Erich 1991). In some states wood ash is used as an agricultural soil amendment and in Maine 100,000 to 150,000 dry tons are used for this purpose annually (Erich 1991). The hypothetical 30-MW wood-burning power plants would generate about 1,614 tons of ash per year in 1990 (based on an annual feedstock consumption of 161,452 dry tons of wood/year) and 1,281 tons/yr in 2010 (128,123 dry tons of feedstock at the conversion hopper). This ash could be used as a soil conditioner on both the tree plantations as well on agricultural lands (particularly those with low soil pH levels). This would be a low-cost, environmentally beneficial alternative to disposing of the material in landfills. Depending on soil type and pH, the minerals in wood ash, particularly phosphorus and potassium, would, to some degree, be available as nutrients to the plants grown on the soil (Erich 1991), thereby reducing the amount of fertilizer required.

3.3.2.4 Supplemental fuels

A power plant designed for the utilization of wood fuel would be easily adaptible for use with other biomass feedstocks, including agricultural and yard wastes, paper products, and food wastes. Although the energy value of these materials is lower than that of wood (i.e., 7,000-8,000 Btu/lb dry vs 8,000-9,000 Btu/lb for wood, Hollander 1976), their use as supplemental biofuels could provide environmental and economic benefits in terms of reducing landfill costs and providing supplemental income to the surrounding communities. In addition, if air emission control devices are of suitable design, multi-fuel biomass units might also be designed for specialized high-energy waste products which are currently difficult to dispose One example would be rubber products which contain the energy equivalent of 10,000-16,000 Btu/lb (Hollander 1976).

3.4 SUMMARY AND SELECTION OF KEY IMPACTS

Although quantitative information on many of the potential environmental impacts of the biomass fuel cycle is limited, some general qualitative conclusions can be made based on the available data. Impacts from tree plantations involve: (1) altered land uses; (2) erosion of top soil (during the 1-2 yr tree plantation establishment period); (3) potential surface water contamination with inorganic nutrients and pesticides; (4) changes in biodiversity; and (5) changes in soil quality. Impacts from feedstock transportation involve: (1) road deterioration; (2) traffic noise; and (3) air emissions of combustion products. Impacts identified at the power plant include: (1) potential reduced visibility due to inputs of hydrocarbons, particulates, and water vapor into the atmosphere; (2) air emissions of combustion products; and (3) ozone formation from emissions of hydrocarbons and NO_x and resulting changes in crop yield. Impacts which extend across all stages of the fuel cycle include: (1) changes in air quality due to combustion of fossil fuels and wood feedstock and (2) CO_2 cycling and carbon sequestering.

Of the impacts listed above, the one that represents the greatest overall environmental change is the impact on land use, and as an extension, the resulting changes in biodiversity. Other key impacts to be considered are increased erosion and herbicide runoff to nearby streams, and increases in atmospheric ozone due to power plant emissions of NO_x. These impacts are discussed further in Section 5.

4. QUANTIFICATION METHODS

Methods for deriving quantitative relationships between levels of environmental stress and ecological impacts are reviewed in ORNL/RFF (1992, Appendix D). These methods can be divided into three general categories, (1) empirical modeling using statistical analysis of measured data, (2) mechanistic (or process) modeling which predicts steady-state conditions or dynamic fluxes from known physical, chemical, or biological relationships, and (3) expert judgement based on field and laboratory data. All three approaches are required to assess the ecological impacts of alternative fuel technologies. Reasonably well understood impacts such as the effects of ozone on crops, can be partially quantified using both types of models as well as expert judgement. Other impacts, such as herbicide contamination of surface waters due to erosion and runoff, are very site-specific, and mechanistic models could not be used because of the generic nature of the biomass plantation locations (i.e., we know number of acres, but not location of individual plantations). Empirical modeling is also needed to predict the number of streams and rivers in an area that might be affected, the size of the streams, and their overall resource potential. [More details will be added on quantification of pollutants in surface runoff once the calculations are performed]. Herbicide or nutrient impacts on ground water require models to predict partitioning of the chemical in environmental media, rates of degradation, changes in aquifer concentration, and the number of area wells in which water quality standards may be exceeded. Again, without site-specific information, some impacts, such as changes in biodiversity cannot be adequately quantified except in terms of relative changes of habitat density and distribution in a given area. Information on changes in species composition and potential increased resource use resulting from such changes is not yet available.

5. EVALUATION OF KEY IMPACTS

5.1 ALTERED LAND USE

The short-rotation woody crop scenario created for the 1990 WBT technology requires that 39,928 acres of land be utilized for tree plantations at the southeastern site and 30,154 acres at the western site. In 2010, acreage requirements decrease to 24,911 acres at the southeastern site and 17,203 acres at the western site. Most of this acreage would be established on parcels of land (20-80 acres each) previously utilized for agriculture, hayland, grazing, etc. (Appendix A, Fig. 3). The only forested land utilized would be open woodland having less than a 55% canopy cover. The projected changes in land use are indicated in Table F-6.

Table F-6. Land utilized for tree plantations (acres)

	Southeastern Site			Northwestern Site		
Previous Land Use	1990	2010	%	1990	2010	%
Closecrop	1,588	991	4.0	12,706	7,249	42.1
Corn	5,353	3,340	13.4	1,086	620	3.6
Fallow	2,642	1,648	6.6	1,201	685	4.0
Open woodland	1,579	985	4.0	2,418	1,379	8.0
Hayland	4,712	2,940	11.8	3,249	1,853	10.8
Pasture	17,652	11,013	44.2	8,846	5,047	29.3
Row crop, other	682	426	1.7	529	302	1.8
Soybeans	5,720	3,569	14.3	0	0	0
Range	0	0	0	119	68	0.4
TOTAL	39,928	24,911		30,154	17,203	

At the southeastern reference site more than half of the land for the plantations would come from pasture and hayland and about one-fourth from row crops. At the northwestern site about 40% of the land would be displaced from pasture and hayland, about the same amount from closecrops, but only about 5% from row crops. The major impact on resource categories would be the lost productivity from lands previously used for agriculture. At the southeastern site this would amount to about a 4.6% decrease in acreage in 1990 and 2.9% in 2010; at the northwestern site about 1.9% in 1990 and 1.2% in 2010.

The increase in wooded habitat represented by the tree plantations may have positive impacts on recreational resources of an area if populations of woodland game birds and animals increase and are made accessible to hunters. There is little field data to determine to what extent this might actually occur; however, extrapolation from other studies suggest that impacts may be minimal. Initial establishment of the tree plantations with the maintenance of weed strips or groundcover between the rows of tree seedlings may be provide grazing areas for local deer populations (if the deer are not intentionally excluded to avoid damage to the tree seedlings). However, as studies on pine plantations have shown, although deer populations may initially benefit after plantation establishment or after a controlled burn and thinning (on pine plantations), canopy closure and subsequent reductions in deer forage (loss of shade intolerant grasses and forbs) can lead to a decrease in the carrying capacity of the ecosystem and adverse impacts on the physical health of the deer (Johnson 1987). Populations of other potentially valuable game animals such as squirrels and turkeys may be limited by the age, size and types of trees grown on the plantations. The absence of mast-producing trees will limit food supplies and the relatively small size of the trees may limit the number of nesting cavities. Although preliminary data from tree plantations in Canada suggest that bird diversity can be relatively high on hardwood plantations (Ranney, per. com.), information is not yet available to indicate whether populations of game birds would be significant.

5.2 BIODIVERSITY

The impacts of tree plantation on biodiversity are difficult to quantify, but can be evaluated qualitatively in terms of altered land use and changes in habitat. Such changes can have impacts on both the local and regional scale depending on the types of habitats affected and the amount of land utilized.

The greatest negative impacts would arise if tree plantations displaced forests or other environmentally sensitive habitats (e.g., riparian areas); however, in the scenario created for this study, such lands are specifically excluded from use for tree plantations. Wooded lands containing less than 55% canopy coverage were included, and such open woodland, with a greater variety of trees of mixed age would very likely support a higher level of biodiversity than tree plantations; therefore, a negative impact would accrue if such land were converted to tree plantations. Assuming that lands used for tree plantations would be apportioned according to current land usage, then 985 to 2,418 acres of open woodland would be displaced at the two sites evaluated in this study. At the southeastern site about 1,579 acres of open woodland would be converted to tree plantations for the 1990 technology and 985 acres for the 2010 technology, but 32,000 acres of such land would not be affected. Even at a higher rate of usage, the overall regional impact would still be small considering that approximately 3.4 million acres of forests are present in the East Tennessee area (TVA 1984). At the northwestern site, of the 129,000 acres of open woodland available, only 2,418 acres would be used for the 1990 technology and 1,379 acres for the 2010 technology.

Most of the land used for the tree plantations will come from acreage previously used for closecrops, row crops, pasture and hayland. It was estimated that about 96% of the required plantation acreage would be derived from such lands at the southeastern site and 88% at the northwestern site. Displacement of these lands might generally be viewed as a net positive impact on biodiversity because the greater structural diversity of a wooded habitat is likely to support a greater variety of species. For example, preliminary studies indicate that hardwood tree plantations may support a rich insect fauna which, in turn, would allow for a greater diversity of bird life. However, at same time, the establishment of the plantations would result in negative impacts on species that are directly or indirectly dependent on open field and grasslands for survival. One study revealed a decline in a hawk population following extensive conversion of open areas to trees and this was thought to be due to the decrease in populations of the bird's prey, such as rabbits and grouse which are primarily open field species.

On a regional scale the establishment of tree plantations would have a far greater impact on biodiversity in areas where forests are limited in size and distribution than in areas where they comprise a significant portion of the landscape. For the southeastern site evaluated in this study, the plantations needed to support one 30 MW power plant would represent about a 50% increase in open woodland type habitat in a 75-mi radius of the site. In addition, the edge habitat defined by the estimated 500 to 800 or more individual plantations (average size of parcels 50-80 acres) may also be of ecological value depending on the state of the adjoining lands. However, in a wider regional analysis, changes in habitat diversity at the southeastern site, by the conversion of 38,000 acres of agricultural lands to wooded habitat, would represent only a small change (about 1%) in total acreage of wooded land in the East Tennessee area.

5.3 EROSION

As discussed in Section 3.1.1.2, soil erosion on tree plantations may be as high as that for corn during the establishment phase when the land is prepared for planting of the seedlings and for 1 to 2 years afterward. Maximum rates of erosion will therefore occur on those parcels of land planted each year (i.e., 6,655 acres/yr for each of the first six years at the 1990 southeastern site, 4,152 acres/yr at the 2010 southeastern site; 5,026 acres/yr at the 1990 northwestern site and 2,867 acres/yr at the 2010 northwestern site). Total soil loss for the first year is shown in Tables F-7 to F-10, as well as soil loss that would have occurred on the displaced lands. Soil loss on the tree plantations is about twice as high as that on the displaced lands.

For the following years, total soil loss for the plantations was calculated by assuming that erosion rates would be one-half that of corn in the second year and one-tenth that of corn in the 3rd through 17th year. As more acreage is added to

Table. F-7. Erosion in Year 1 on Tree Plantations and Displaced Lands (1990 Southeastern site)

Land Class	Acres[a]	Erosion Rate[b] (tons/acre)	Total Annual Erosion (tons): Tree Plant.	Prev. Use	Net Change
I	837	2.5	2,093	620	+1,473
IIe	3,706	10.1	37,427	15,745	+21,682
IIs	129	1.0	129	222	-93
IIw	1,374	4.3	5,906	2,180	+3,726
IIIw	504	4.1	2,068	768	+1,300
IVw	105	2.3	240	272	-32
TOTAL:			47,863	19,808	+28,055

a. Acreage is based on one-sixth of the total required.
b. Erosion rates based on those for corn.

Table. F-8. Erosion in Year 1 on Tree Plantations and Displaced Lands (2010 Southeastern site)

Land Class	Acres[a]	Erosion Rate[b] (tons/acre)	Total Annual Erosion (tons): Tree Plant.	Prev. Use	Net Change
I	522	2.5	1,306	393	+913
IIe	2,312	10.1	23,351	9,845	+13,506
IIs	81	1.0	81	137	-56
IIw	857	4.3	3,684	1,359	+2,325
IIIw	315	4.1	1,291	487	+804
IVw	65	2.3	150	164	-14
TOTAL:			29,863	12,385	+17,478

a. Acreage is based on one-sixth of the total required.
b. Erosion rates based on those for corn.

Table. F-9. Erosion in Year 1 on Tree Plantations and Displaced Land (1990 Northwestern site)

Land Class	Acres[a]	Erosion Rate[b] (tons/acre)	Total Annual Erosion (tons) Tree Plant.	Previous Use	Net Change
I	216	0.9	194	116	+78
IIe	777	2.0	1,554	999	+555
IIs	132	1.3	172	48	+124
IIw	2,201	1.5	3,301	1,550	+1,751
IIIw	998	1.0	998	290	+708
IVw	703	0.9	634	214	+421
TOTAL:			6,853	3,217	3,636

ixth of the total required.

[a] Acreage is based on one-s
[b] Erosion rates are based on those for corn.

Table. F-10. Erosion in Year 1 on Tree Plantations and Displaced Land (2010 Northwestern site)

Land Class	Acres[a]	Erosion Rate[b] (tons/acre)	Total Annual Erosion (tons) Tree Plant.	Previous Use	Net Change
I	123	0.9	110	66	+44
IIe	443	2.0	887	570	+317
IIs	75	1.3	98	27	+71
IIw	1,256	1.5	1,883	888	+995
IIIw	569	1.0	569	165	+404
IVw	401	0.9	361	122	+239
TOTAL:			3,908	1,839	+2,069

ixth of the total required.

[a] Acreage is based on one-s
[b] Erosion rates are based on those for corn.

the tree plantations, soil loss increases, but net changes relative to that for the displaced lands decrease. Consequently, there is a decreasing net loss in the first four years at the southeastern site and in the first three years at the northwestern site followed by a net gain in each succeeding year at both sites (Tables F-11 and F-12).

While a comparison of long-term average erosion rates between different land uses and biomass plantations provides for an overall perspective to impacts, they do not provide direct data for the assessment of impacts to aquatic organisms. Impacts to aquatic organisms occur from episodic events, thus we focus on an average mass emission rate per day of sediments (assumed erosion occurs at an equal rate each day of the year).

Biomass plantations generate non-point source pollution in the form of sediments and pesticides. If the actual location of the plantations were known, more accurate quantitative modeling of the impacts to surface waters could be done. In the absence of site-specific information, a screening level approach to modeling (EPA 1982) impacts to surface water was performed using average stream characteristics (Table F-13). For this study pollutants were considered to be conservative (not reactive and remain in solution or suspension). All of the pollutant is assumed to enter the stream at one point and undergo complete mixing in the water column. It is also assumed that no concentration of the pollutant occurs in the stream over the mixing zone (this is probably true for pesticides, but not for sediments). and that the surface water flow carrying the pollutants to the stream doubles the average flow of the stream (this is more likely to happen for small streams than for large streams). The concentration of the pollutant in the stream following mixing is then a function of the pollutant mass emission rate divided by the sum of the discharge rate of the overland flow carrying the pollutant and the flow rate of the stream above the point of entry (EPA 1982).

A suspended sediment concentration greater than 100 mg/L is likely to have adverse effects on aquatic organisms (EPA 1982). Suspended sediments adversely affect fish and their food populations by:

acting directly on the fish swimming in the water by killing them, reducing their growth, resistance to disease, etc.

preventing the successful development of fish eggs and larvae

modifying natural movements and migrations of fish

Table F-11. Total Annual Erosion at the Southeastern Site (tons)

	Years after Establishment											
	1	2	3	4	5	6	7	8-18	19	20-24	25	26-36
1990 Southeastern Site												
Plantations	47,863	71,795	76,581	81,368	86,153	90,940	47,863	28,718	71,795	90,940	47,863	28,718
Prev. use	19,808	39,616	59,424	79,232	99,040	118,848	118,848	118,848	118,848	118,848	118,848	118,848
Net loss	28,055	32,179	17,157	2,136								
Net gain					12,887	27,908	70,985	90,130	47,053	27,908	70,985	90,130
2010 Southeastern Site												
Plantations	29,863	44,794	47,781	50,767	53,753	56,739	29,863	17,918	44,794	56,739	29,863	17,918
Prev. use	12,385	24,770	37,155	49,540	61,925	74,310	74,310	74,310	74,310	74,310	74,310	74,310
Net loss	17,478	20,024	10,626	1,227								
Net gain					8,172	17,571	44,447	56,392	29,516	17,571	44,447	56,392

For tree plantations, erosion rates estimated to be equal to that of corn in the first year after establishment, one-half that of corn in the second year, and one-tenth that of corn in the third through 18th year. One-sixth total acreage planted in each of the first six years. For years 8-18, 20-24, and 26-36 values given are for each year; in year 37 the cycle begins again with the values for year 19.

Table F-12. Total Annual Erosion at the Northwestern Site (tons)

	Years after establishment											
	1	2	3	4	5	6	7	8-18	19	20-24	25	26-36
1990 Northwestern Site												
Plantations	6,853	10,279	10,965	11,650	12,335	13,021	6,853	4,112	10,279	13,020	6,853	4,112
Prev. use	3,217	6,434	9,651	12,868	16,085	19,302	19,302	19,302	19,302	19,302	19,302	19,302
Net loss	3,636	3,8454	1,314									
Net gain				1,218	3,750	6,281	12,449	15,190	9,023	6,282	12,449	15,190
2010 Northwestern Site												
Plantations	3,908	5,862	6,253	6,644	7,034	7,425	3,908	2,345	5,852	7,425	3,908	2,345
Prev. use	1,839	3,678	5,517	7,356	9,195	11,034	11,034	11,034	11,034	11,034	11,034	11,034
Net loss	2,069	2,184	736									
Net gain				712	2,161	3,609	7,126	8,689	5,182	3,609	7,126	8,689

For tree plantations, erosion rates estimated to be equal to that of corn in the first year after establishment, one-half that of corn in the second year, and one-tenth that of corn in the third through 18th year. One-sixth total acreage planted in each of the first six years. For years 8-18, 20-24, and 26-36 values given are for each year; in year 37 the cycle begins again with the values for year 19.

Table F-13. Average Stream Characteristics for the United States by Stream Order

Stream Order	Drainage area (acres)	Mean Flow (ft^3/sec)
1	640	0.65
2	3,008	3.1
3	14,720	15.0
4	69,760	71.0
5	331,520	340.0
6	1,600,000	1,600
7	7,680,000	7,600

reducing the abundance of food available to the fish (EPA 1976)

Estimated sediment concentrations are listed in Table F-14 by stream order for the southeastern and northwestern sites in 1990 (6,655 acres planted). Using 100 mg/L as a guide to impacts, adverse effects can be expected to occur to aquatic organisms in 4th order and smaller streams in the southeast and 3rd order and smaller streams in the northwest. Erosion rates throughout the life of the biomass plantation would stress aquatic organisms in streams of these sizes.

At the southeastern site most of the large rivers are impounded. These impoundments act as sediment traps so that the suspended sediment concentrations are low. Data for the Clinch River at Melton Hill dam and the Holston River near Knoxville illustrate this point (Table F-15). These are 6th order streams and could easily contain all of the 40,000 acres of biomass plantations in their drainage areas. The estimated erosion rate (249 tons/day) for year six of the plantings (full implementation) could range from an additional contribution of 44% of the 1990 suspended sediment discharge at Melton Hill during high flow periods to almost the total load during low flow periods. However, on the average, the estimated erosion rates would not significantly increase the concentration of suspended sediments to levels of concern for aquatic organisms in streams of the size of the Clinch River unless they already had high concentrations.

Table F-14. Evaluation of Suspended Sediment Loads

Erosion[a] (tons/day)	Erosion (lb/day)	Stream Order	Estimated Sediment Conc. (mg/L)
	Southeastern Site (1990, Year 1)		
131	262,263	1[b]	375
		2[c]	3,391
		3	1,625
		4	343
		5	72
	Northwestern Site (1990, Year 1)		
19	38,000	1[b]	543
		2[c]	570
		3	235
		4	50

a. Mass per year divided by 365 days.
b. Assumes 1/10th of erosion rate would enter stream of this size based on drainage area (Table F-13).
c. Assumes 1/2 of the erosion rate would enter stream of this size based on drainage area (Table F-13).

5.4 HERBICIDES IN SURFACE WATERS

Herbicides are used on tree plantations for weed control during the first two years of establishment of the seedlings. Surface waters may become contaminated as a result of atmospheric drift, surface runoff, erosion, and/or direct spills. Estimated rates of herbicide use on tree plantations for both the 1990 and 2010 scenarios are 3 lb/acre during the first year of establishment of the seedlings and 1 lb/acre during the second year, but none thereafter until the lands are replanted after 18 years (Appendix A). A broad-kill herbicide (1 lb/acre) is used before planting and a pre-emergent (1 lb/acre) after planting. The third application occurs six months later and the fourth in the second year. Therefore, the greatest potential

Table F-15. Water Chemistry Data for Southeast Rivers. (Flohr et al. 1990)

Parameter[a]	Clinch River[b]	Holston River[c]
Suspended sediment discharge (T/day)	≤1-564	88-724
Suspended sediment (mg/l)	3-10	7-17
Total phosphorus (mg/L)	0.01-0.03	0.02-0.04
Nitrogen (NO_2 + NO_3) dissolved (mg/L)	0.32-0.7	0.2-0.9

a. Water year October 1989 to September 1990. Minimum and maximum values reported for six samples during period.
b. Tailwater at Melton Hill dam, USGS 03535912.
c. At Knoxville City limits, USGS 03495500.

for surface water contamination will occur within the first 1-1.5 yr of establishment of the tree plantations.

It has been estimated that about 10% of each 1 lb/acre application of herbicide would enter surface waters (Appendix A). Using a simple dilution model, and assuming rapid runoff due to heavy rains immediately after application of the herbicide to the entire drainage area, the concentration in a first-order (640 acre drainage) or second-order stream (1,008 acre drainage) was calculated to be about 9 mg/L in the mixing zone. This concentration is sufficiently high to cause adverse effects on fish fry and the larval stages of aquatic invertebrates (See Section 3.1.1.4). More refined modeling, taking into account soil types, rainfall patterns, stream sizes, and flow rates, is needed to develop a more site-specific assessment of this impact.

5.5 EFFECTS OF OZONE ON AGRICULTURAL CROPS

The effects of air pollutants on crops has been reviewed and summarized by Shriner et al. (1990). Adequate data for the evaluation of crop yield reductions are available only for ozone. Reductions up to 56% have been reported depending on crop species, location, and ozone level.

The response of plants to ozone depends on many factors including concentration, species, cultivar genetics, growth stage, environmental variables (soil conditions, meteorology, temperature, humidity) and pollutant interactions (SO_2, acid deposition, and NO_2) (ORNL/RFF 1992). Because of the lack of data for many of these variables, uncertainties exist in the reliability of the available exposure-response functions for all possible scenarios. Choice of an exposure parameter may also be critical factor. Exposure of plants to ozone is usually reported in terms of 7-hr or 12-hr seasonal mean concentrations. The mean values represent daily periods during the growing season (9 a.m. to 4 p.m. and 9 a.m. to 4 p.m. standard time) which are thought to correspond to the periods of highest plant sensitivity and highest ozone levels. However, there is some evidence that a seasonal mean of daily 1-hr maximums may be a more appropriate measure of exposure (ORNL/RFF 1992).

The analysis of ozone-induced incremental changes in crop yields due to the operation of the proposed 30-MW power plant was accomplished by using literature-derived ozone exposure-plant growth response functions, reported ambient ozone levels, and estimations of incremental ozone increases attributed to the operation of the 1990 WTB power plant. Adequate data were not available for analyzing this impact at the northwestern reference site or for the 2010 BGISTIG technology.

As discussed in ORNL/RFF (1992), the ozone exposure-plant response functions used in this analysis were those developed by Heagle et al. (1988) from field data generated from the National Crop Loss Assessment Network (NCLAN) (see also Heck et al. 1988; Shriner et al. 1990). These studies provided crop yield losses for major cultivars for five seasonal mean ozone concentrations representative of the range of ambient ozone levels in the United States (Table F-16).

For a given predicted increase in ozone, crop yield loss for a particular crop can be estimated by interpolation of the data presented in Table F-16. For the southeastern reference site the existing ambient ozone level within the region was

Table F-16. Crop yield losses estimated to result from various ozone concentration (in percent)

	Mean ozone concentration during the growing season (ppb)				
Crop	40	50	60	70	80
Soybeans (Average of 22 experiments with about 10 cultivars)	5.6	10.1	15.5	21.5	28.4
Tobacco (Average of 2 experiments)	5.0	9.0	13.0	18.0	23.0
Wheat (Average of 5 experiments with 3 cultivars)	9.0	15.0	20.8	26.8	33.2
Corn (Average of 3 experiments with mixtures of 5 cultivars	1.7	3.7	6.7	10.3	15.7
Hay (Red clover, the main type of hay grown in study area)	9	19	31	44	59

determined to be 55 ppb (12-hr seasonal average, 9 a.m. to 9 p.m., May through September), and the incremental increase in the 12-hr seasonal ozone level associated with the power plant was calculated to be 0.2 ppb (see Appendix C).

The approach used to estimate crop losses was the same as that developed in ORNL/RFF (1992). Losses in crop production were calculated for the counties surrounding the plant. Data for entire counties and an infinite number of sites within each county was assumed. This procedure allowed for the use of a single increased ozone level averaged over the entire area, rather than for site-specific increases; it avoided the need to deal only with portions of counties falling within the 50-km perimeter of the study area; it provided results which are more generally representative of the reference site; and it allowed for the easy computation of the hypothetical crop losses in any county within the region (ORNL/RFF 1992). Counties lying about half or more than half within 50 km of the site were selected. Crop loss for each county was estimated, and then total losses for all counties was determined. The total county area (acres) was used to determine the proportional crop losses on acreage within 50 km of the power plant. The percent crop loss associated with existing ambient ozone levels levels (55 ppb) was subtracted from that associated with the estimated increased ozone level (0.2 ppb) occurring during power plant operation.

Applying the ambient and predicted ozone levels during plant operation to the exposure-response functions given in Table F-16 gave the results shown in Table F-17. Crop production and losses are shown in Table F-18.

Table F-17. Percentage crop loss due to increased ozone (1990 southeastern reference site)

Crops	Crop loss (%)	Loss due to power plant (%)
Soybeans		
existing ambient	12.8	
predicted	12.91	0.11
Tobacco		
existing ambient	11.0	
predicted	11.08	0.08
Wheat		
existing ambient	17.9	
predicted	18.02	0.12
Corn		
existing ambient	5.2	
predicted	5.26	0.06

The crops listed in Table F-18 are those for which county data were available (Tennessee Department of Agriculture 1990). Data for 1988 was used to estimate ozone-induced crop losses for all crops except corn, because production of these crops in 1989 [the latest year reported by the Tennessee Department of Agriculture (1990)] was poor. Corn production data for 1989 were used because this year appeared to be representative of average conditions for corn.

The total acreage occupied by the seven counties reported above is 1,672,648, compared to the larger acreage of 1,940,761 acres within 50 km of the power plant site. The numerical values of the crop losses within these seven counties must be increased proportionally to yield estimated crop losses within a 50-km radius of the power plant at the southeastern site. These estimated losses are shown in Table F-19.

Table F-18. Crop production and the estimated crop losses (1990 southeastern reference site)

County	Acres	Soybeans (1,000s bu)	Wheat (1,000s bu)	Corn (1,000s bu)	Tobaccco (1,000s lb)
Anderson	185,200				
production		*a*	*a*	15	170
loss				0.009	0.136
Blount	347,516				
production		38	186	345	798
loss		0.04	0.223	0.207	0.638
Campbell	253,373				
production		*a*	*a*	32	593
loss				0.019	0.474
Knox	228,969				
production		6.3	16.5	89	587
loss		0.007	0.020	0.053	0.470
Loudon	142,247				
production		14	51	80	730
loss		0.015	0.061	0.048	0.584
Morgan	342,810				
production		20	13.2	84	78.3
loss		0.02	0.016	0.050	0.063
Roane	172,533				
production		*a*	*a*	28	297
loss				0.017	0.237
Anderson, Roane, and Campbell[a]					
production		3.98	7.84		
loss		0.004	0.009		
Total loss		0.086	0.329	0.403	2.602

[a] Soybean and wheat production statistics for these counties were not reported by the Tennessee Department of Agriculture (1990) because less than 500 acres of the respective crop were planted. Total production for all non-reported counties in district #6, to which these counties belong, was: 19,900 bu of soybeans for 15 non-reported counties and 18,300 bu wheat for 7 counties - these data were used to obtain the rough estimates given.

Table F-19. Estimated crop losses due to increased ozone (1990 southeastern reference site)

	Soybeans (1,000s bu)	Wheat (1,000s bu)	Corn (1,000s bu)	Tobacco (1,000s lb)
Total loss in 7 counties	0.086	0.329	0.043	2.602
Loss within a 50-km radius of the power plant	0.099	0.382	0.049	3.019

6. CONCLUSIONS

Under the scenario created for this study, the part of the biomass fuel cycle that is likely to have the greatest potential for ecological impacts is the feedstock production phase. The utilization of large amounts of acreage for the production of fuel wood results in significant changes in land use. Establishment of short-rotation hardwood tree plantations removes land primarily from agricultural use (row crops, closecrops, hayland and pasture) and creates wooded habitat. Net changes in land use were estimated by apportioning acreage across all appropriate land use categories according to current usage. Consequently, acreage previously in agriculture at the southeastern site would be reduced by 4.6% in 1990 and by 2.9% in 2010. At the northwestern site the reductions would be 1.9% in 1990 and 1.2% in 2010. Reductions in crop production would be proportional to the acreage displaced in each agricultural land class and the estimated productivity of that land.

The increase in wooded habitat represented by the tree plantations may have positive impacts on recreational resources of an area if populations of woodland game birds and animals are increased and available to hunters. There is little field data to determine to what extent this might actually occur; however, extrapolation from other studies suggests that impacts may be minimal and limited by the size, age, and types of trees planted.

Impacts on biodiversity were not directly quantifiable at this time due to the lack of consensus among ecologists on operational definitions suitable for assessment purposes; however, a very general evaluation of biodiversity was made based on changes in land use and the relative changes in open woodland type habitat at local and regional scales. Natural forests and environmentally sensitive areas were specifically excluded from use; consequently, potential impacts on endangered species and critical habitats were assumed to be minimal. Most of the land utilized for the tree plantations would be acreage previously used for closecrops, row crops, pasture and hayland. For the 1990 southeastern reference site about 96% of the 39,928 acres would be derived from such lands and would represent about a 50% increase in wooded habitat in a 75-mi radius of the site. The edge habitat defined by the estimated 800 or more individual plantations (average size of parcels about 50 acres) may also be of ecological value depending on the status of the adjoining lands. However, in a wider regional analysis, the increase in wooded habitat would represent only a small change (about 1%) in total acreage of wooded land in the east Tennessee area.

Changes in land use can also have significant impacts on erosion. Specific information on erosion rates for tree plantations was not available, therefore, net changes were estimated by assuming erosion rates equivalent to that of corn for the first year when the tree seedlings are planted, one-half that of corn for the second year, and one-tenth that of corn for the following years. The resulting calculation revealed that total annual soil loss would be higher than that for the displaced lands during the first three to four years, but lower in all following years.

Herbicide and fertilizer (K and P) use and erosion on the plantations is expected to be high during the first year when the tree seedlings are planted, and runoff into local streams may cause ecological impacts. Because of the site-specific and non-point source nature of these releases, estimates of concentrations in receiving streams are difficult to quantify. Very preliminary estimates, based on simple dilution models and runoff into first-order streams, suggest that herbicide concentrations may be near or above critical thresholds for aquatic organisms. However, additional work in modeling these releases, and in defining dose-response relationships, is required before quantitative impacts can be assessed. Similarly, site-specific data and modeling studies would be needed to determine the ecological impact of nitrogen fertilizers which are applied biennially beginning in the second year. In contrast, impacts of insecticides are not expected to be significant because of their infrequent use. Overall soil quality is likely to improve due to leaf fall and the buildup of soil organic matter.

At the power generation stage of the fuel cycle, emissions of NO_x, SO_2, and hydrocarbons from the stack are not expected to result in ambient atmospheric concentrations that exceed currently identified toxicity thresholds. However, NO_x and SO_2 can be dispersed over wide areas, and can contribute to regional impacts such as acid deposition. At present, regional assessments of acid deposition on aquatic resources are possible for only a few well-characterized regions.

Systematic national environmental monitoring programs that could facilitate future regional assessment studies include the Environmental Protection Agency's Environmental Monitoring and Assessment Program, the National Oceanic and Atmospheric Administration's National Status and Trends Program, and the Geological Survey's National Water Quality Assessment Program. For the biomass fuel cycle, impacts of acid deposition are expected to be relatively low because of the low concentration of sulfur in the wood feedstock.

Releases of NO_x and hydrocarbons from the power plant stack can contribute to the formation of atmospheric ozone, which, in turn, can have adverse effects on plants and crop production. Quantitative estimates of the impact of ozone on crop yield indicate that the incremental effect of the power plant would represent about a 0.1% decrease in soybean and wheat production, 0.06% for corn, and 0.08% for tobacco.

Emissions of carbon dioxide and carbon monoxide from the power plant stack are not considered ecologically significant since equivalent amounts will be reincorporated into tree biomass; however, for the entire fuel cycle there would be a slight negative impact due to the use of fossil fuels in plantation equipment and trucks hauling the wood feedstock.

Emissions of particulates, NO_x, and water vapor, together with the secondarily formed acid aerosols and ozone, may cause reductions in atmospheric visibility. Changes in visibility are not associated with specific ecological impacts, but can have impacts in terms of diminished asthetics. In addition, localized reductions in visibility may create traffic hazards in the area. Atmospheric modeling is required to estimate visual range reductions caused by the operation of the power plant.

Releases of wastewater and cooling system water from the power plant are not expected to have major ecological impacts because of the use of a closed recyling cooling system, and high dilution of effluents in the receiving water body.

No other potential impacts on air or water quality were identified in this study.

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APPENDIX G.1
SIGNALING UNCERTAINTY AND QUALITY IN INFORMATION

1. INTRODUCTION

Data estimates and information require a system for signaling the uncertainty and quality of the entries for users. Few of the entries will be known with certainty, or even generally agreed upon as the prevalent quantity or relation. For example, the ecological or health responses of resources exposed to energy-related pollutants cannot be known with certainty given current knowledge of the relationships. The monetary valuations associated with the imperfectly known impacts are also uncertain and sometimes controversial. To leave entries standing alone without signaling their uncertainty and quality would overstate the precision with which the entries are known. In addition, signaling the uncertainty and quality for entries will indicate areas where further study is needed most.

Uncertainty and quality are signaled through a notational system named NUSAP as an acronym for its categories. NUSAP was developed by Funtowicz and Ravetz to provide a "quality control" of quantitative information.[1] We have adapted the NUSAP system for signali..g the uncertainty and quality of quantitative information to be used in estimating the emissions, impacts, and external costs of fuel cycles. Uncertainty refers to the spread of plausible values for a cell entry and the level of confidence placed in a quantitative statement. Quality refers to both an entry's worth as a piece of information and the credibility of the theory, data, and methods used to generate the entry.

The NUSAP system signals uncertainty by stating the spread of values associated with a numerical entry. A number standing alone does not convey the uncertainty about its true value. In fact, it falsely suggests that it is known with certainty. Thus, the uncertainty must be signaled. One may get a better feel of the need to signal uncertainty with numeric entries by contrasting our case of uncertainty to cases where probability measures are used. Probabilities quantify the likelihood or frequency of an occurrence, or quantify the degree to which an hypothesis is believed to be true. Likelihood, frequency, and degree of belief

[1] Funtowicz, S. and Ravetz, J. 1990. *Uncertainty and Quality in Science for Policy*. Kluwer Academic Publishers, Dordrecht, The Netherlands.

calibrate the lack of certainty of an element (where the element is the set of all possible occurrences or hypotheses). The lack of certainty surrounding the element has already been signaled by the mere existence of more than one possible occurrence or hypothesis. However, a number standing alone does not convey a lack of certainty. Where the element itself is a piece of quantitative information, as with a numerical entry, the uncertainty of the element must be signaled explicitly, in its own numerical terms. This is done by designating an interval of values. The interval of all possible values may be immense, and determining where "possible" begins and "impossible" ends would be perplexing. (After all, isn't *anything* possible?) This makes such an interval of possible values unworkable. Thus, the bounds of the interval are demarcated by designating a level of confidence; this "confidence interval" is called a spread.

The spread of NUSAP is not necessarily generated by statistical analysis. If there does not exist a statistical distribution, then the NUSAP spread will be generated by the subjective judgment of experts. Also, a statistical distribution may not fully capture the uncertainty about a value. Probability distributions are generated from all sorts of activities that are unrelated (or related only by analogy) to the ideals out of which probability theory developed (i.e., the logical structure of games of chance, random variation in repeated controlled experiments, and long-run frequencies of outcomes). Many times distributions are simply assumed. Probability distributions were designed around the ideals, and therefore they may not fully represent the uncertainty in less-than-ideal cases. Thus, a statistical confidence interval may not capture all of the uncertainty involved. If a statistical interval fails to fully represent all significant uncertainty about a value, a spread should be supplied from expert judgement. (A statistical confidence interval's adequacy is dealt with further under the section "Spread of value" on p. G-5.)

In addition to signaling uncertainty, NUSAP also signals quality of entries. Quality is the second facet of indeterminacy that is not captured by uncertainty. Quality pertains to the state of knowledge about an element. In evaluating the qualitative aspects of an entry, we address the questions "What do we know?" and "How ignorant are we?" The term "qualitative" here means both "non-numerical" and "goodness." Signaling uncertainty alone does not assess the goodness of an entry. The quality of entries is signaled in the Assessment and Pedigree categories of NUSAP. The Assessment category evaluates an entry's worth as a piece of information, and the Pedigree category evaluates the source or production process of the piece of information. The NUSAP scheme is presented in the box on p. G-3.

The NUSAP Scheme

Numerical information

Numeral
Notation
Variable Name
Note on Practice

Unit:

U_1: Units of measurement
U_2: Statistic used for value; for example, mean (ME), mode (MD), median (MN), lower bound (LB), upper bound (UB), expected value (EV), or no distribution (ND)

Spread of value

S_1: Level of confidence
S_2: Spread lower and upper bound (S[LB, UB])

Assessment of value:

I_1: Informative value based on spread
I_2: Informative value based on application
G: Generalizability to other applications
R: Robustness of value over time

Pedigree:

T: Theoretical basis (and application of theory)
D: Data inputs
E: Estimation methods
M: Estimation metric

Notation:

(N, U_1, U_2): $(S_1, S_2[LB, UB], A[I_1, I_2, G, R])$: $(P[T,D,E,M])$

2. NUMERICAL INFORMATION

The N of NUSAP may represent numerical entries to a data base. These entries may be constants, coefficients, or dependent variables of functions or models. Numerical entries may be, for example, rates of emission of a pollutant, incremental effects of a pollutant on an ecological asset, or a willingness to pay to avoid a health effect.

The N space of NUSAP may also be filled with the notation [LB, UB] for upper bound, lower bound. This notation would be used when an expert feels that the trifling state of knowledge does not warrant designating a specific numerical entry. A spread will exist even though an exact numerical estimate within the spread is uninformative. Thus, the N place of NUSAP will be filled with the label [LB, UB], and S_2 will contain the numbers denoting the upper and lower bound of the spread.[2]

The N space of NUSAP may also be filled with a variable name. A variable name would be used if the entry were an equation or table. An equation would be entered to represent a general-use function or model, that is, one that may be used with the independent variables for many different cases to obtain a number for the dependent variable in each case. N would hold the dependent variable name of the function or model. If the entry were a table, N would hold the name of the output column of the table. The equation denoting the general-purpose function or model or the table which supplies the output column would be included in the data record but not as the N of NUSAP. There will be a separate entry point to collect the equation when data is entered into the data base. The equation or table will be displayed along with the estimation methods part of NUSAP when the data record is retrieved.

A note on practice would fill the N space of NUSAP if the entry were a method for quantifying an accounting framework parameter. For example, a quasi-experimental design for determining an ecological impact would constitute a quantification practice. Also, quantification practices will be very useful entries if we know how an accounting framework parameter should be produced, but data or knowledge is lacking to complete the quantification process. The note on practice is a brief description of the output of the quantification practice which fills the N space of NUSAP. There will be a separate entry point for the quantification

[2] In the case of complete ignorance, the spread would be the upper and lower bound of all of the possible values (in the extreme case, positive and negative infinity), and the level of confidence would be 100%.

practice, and it will be displayed along with the estimation methods part of NUSAP, as with an equation or table entry.

3. UNIT

U_1 denotes the units of measurement of the numerical entry. For example, U_1 might be kilograms of a pollutant per hour, hectares of crops, or 1990 dollars. U_2 is the statistic used for the numerical entry–for example, any summary statistic of a distribution, no distribution if a statistic is not used, or an expected value of a model.

Because of the variety of entries possible for the N place of NUSAP, some explanation of what will fill the U places is necessary. For coefficients, the units are those of the dependent variable. This makes sense because it is the dependent variable for which a coefficient denotes a rate of change. For those cases where ignorance warrants the "[LB, UB]" label, U would be the units of the undesignated specific numeral. For general-purpose model entries, U would be the units of the dependent variable. For table entries, U would be the units of the output column. For quantification practice entries, U would be the units of the output of the practice.

4. SPREAD OF VALUE

The spread category of NUSAP contains a generalized confidence interval of the entry. The purpose of the spread is to signal uncertainty. S_1 denotes the level of confidence with which the expert believes the true value lies within the interval. The interval is denoted by its lower and upper bound [LB, UB]. The confidence interval used for the spread category of NUSAP is more general in scope than statistical confidence intervals, but statistical confidence intervals may still be spreads. A NUSAP spread is the same as a statistical confidence interval if (rule 1) there exists a statistical distribution of the value for N, and (rule 2) the expert believes the distribution fully captures all of the uncertainty about the value for N. Thus, NUSAP spreads differ from statistical confidence intervals because they can be produced by subjective judgments of experts. If there is not a probability distribution (failure of rule 1), then the uncertainty must be signaled by the subjective judgement of the expert. Thus, a NUSAP spread may be a confidence interval generated strictly by subjective judgment.

If a statistical confidence interval does not adequately signal the uncertainty of a numeric entry (failure of rule 2), then the expert designates a NUSAP spread based on both the statistical confidence interval and his expert judgement. An example of a statistical interval diverging from a NUSAP spread due to a failure of rule 2 is a practice in the health impacts field. Experts in this field take the upper bound estimate produced by health impact models. In their expert judgment, the upper bound is a better estimate than a central estimate because of a regard for a "margin of safety." Thus, a statistical confidence interval centered on a mean would be attributed a lower subjective confidence than statistical confidence. Thus, the spread at the same degree of confidence as the statistical interval would be centered around the upper bound in order to reflect the "tradecraft" practices of experts in the field. In general, the spread should reflect tradecraft expertise gained through experience in various fields. Thus, experts should apply subjective judgement to statistical confidence intervals.

To standardize the spread of entries, where possible, intervals should be designated for a 90% degree of confidence. That is, the expert has 90% confidence that the true value lies within the range denoted by [LB, UB]. However, separating spread into the S_1 and S_2 components allows the flexibility to designate an interval with lower or higher confidence. This is warranted if a piece of literature states a confidence interval other than the 90% interval (provided it adequately captures the uncertainty). There are also cases where convention or disciplinary practice warrants a confidence level different from 90% confidence.

For general-purpose models or functions, S_2 would be entered as a +,- range (or a x,÷ range) of the model or function's potential output. The +,- range may be +,- some percentage of the as-of-yet uncalculated dependent variable, for example, [+,- X%]. Or, if a distribution is implied, the range could be +,- some number of standard deviations from the dependent variable, for example, [+,- X sd]. This +,- range can be gained from the literature that presented the general-purpose model. Many authors will expectedly indicate a projected range of accuracy of a model they present.

For tables, as with models or functions, S_2 is entered as a +,- range. S_2 would be entered as a +,- range of the table's potential output for which the expert has S_1 confidence that the true value would lie within the range. In other words, S_2 indicates the plausible range surrounding potential table outputs.

However, with general-purpose models or tables, it seems objectionable to designate S_2 until the application is known and the dependent variable or output has been calculated. After all, the spread of the dependent variable or output will depend on the case at hand. Thus, we plan to design the data base to prompt users to update S_2 when the model, table, or practice is applied. In the meantime, the only information on spread that the user can access is what the expert judges as a +,- range. Given this, even a very rough judgement of S_2 is helpful. One can gain an estimate of the +,- range by imputing typical or plausible values for independent variables or table inputs and noting how the uncertainty about the parameters influences the +,- range of the dependent variable's or output's confidence interval. Where this rough estimate of S_2 would not be helpful, spread should be left blank to be filled in when the model or table is applied.

A spread for a practice would be highly subjective because in many cases where a practice entry is needed, the extent of the uncertainty is itself very uncertain. A useful spread may be designated based on experience with the practice. For example, one may ask how well the practice has worked in the past. The goal is to provide users with a conception of how uncertain the output of the practice is expected to be. Qualifiers such as "the practice's output would be highly speculative at best" or "the practice would provide an order of magnitude estimate" may be more informative than numbers. Experts could also provide notes about the uncertainty issues involved. (See "Comments," p. G-11.)

5. ASSESSMENT OF VALUE

The entries will be assessed in regard to their merit as pieces of information. In other words, an assessment is made of each entry based on its worth for providing information on the emissions, impacts, and external costs of fuel cycles. Entries will be assessed on four aspects: (1) informative value based on spread, (2) informative value based on application, (3) generalizability to other applications or sample spaces, and (4) robustness over time. Each of these aspects will be assessed by rating them low, medium, or high, as indicated in the box "Assessment Indicators" on p. G-9. Within the indicators, however, each field will have particular aspects that influence the rating. For example, in the valuation of externalities field, the characteristics of the population and the characteristics of the time period are the main features that influence the generalizability of entries.

5.1 Informative Value Based on Spread (I_1)

Informative Value Based on Spread provides an assessment of the ignorance that is overcome by the studies, methods, or works that generated the entry. To assess this, one compares the uncertainty about the entry's value now (posterior) to the uncertainty about the entry before the study that produced the entry was conducted (prior). More specifically, the posterior range of plausible values for the entry is compared to the prior range of plausible values for the entry. The extent to which the posterior range is narrower than the prior range indicates the informative value of the entry.[3]

This technique of measuring informative value based on spread is analogous to the traditional method of measuring information content in a probability context. In the probability context, the information provided by an observation is measured by comparing probabilities before and after an observation. The extent to which the posterior probability is different from the prior probability is regarded as the increase in information provided by the observation.[4]

5.2 Informative Value Based on Application (I_2)

Informative Value Based on Application provides an assessment of how much the uncertainty about the entry affects the quality of the result of analysis using the entry. I_2 is determined from a rough sensitivity analysis of the result for the different plausible values residing in the spread. Thus, I_2 is dependent on the application for which the entry is used. Due to this dependency on application, I_2 will be based on a first guess at the application for the entry. This may consist of merely contemplating the effect of the entry's uncertainty on the accuracy of the entry's likely uses. However, there will be cases where the eventual application is known better than in other cases. Thus, as with spread for general-purpose models, I_2 will be a rough estimate until the application is known, at which time

[3] The informative value may also be reflected as an increased level of confidence in the spread. However, to standardize the assessment of informative value, we propose that the level of confidence not change. Thus, the plausible range of values before and after is compared, where the same minimum level of confidence required to be "plausible" is used for the prior and posterior range of values.

[4] One advantage of measuring informative value of a spread over that of a probability measure is that it overcomes the problem of increased information without a change in probability. In the probability context, the posterior probability may not be different from the prior, while the observation still provides information. The observation may increase the credibility of the probability without changing its value. In the context of spread, however, the increase in credibility would not be overlooked. It would be reflected as a narrowing of the range of posterior plausible values at the same level of confidence.

it will be revised. Experts are encouraged to assess a tentative I_2 as long as they feel it might be useful to the users of the data base.

5.3 Generalizability to Other Applications (G)

Generalizability to Other Applications provides an assessment of the usefulness of the entry for other potential applications other than the application for which the value was originally generated. If an entry was produced for a particular purpose or for general purposes, the expert is to assess the validity of the entry for other potential purposes. (A general purpose model will, by definition, score high on this assessment aspect.) If an expert is updating the NUSAP for a general-purpose model upon applying the model to a specific case, the generalizability assessment will convey the aptness of the general-purpose model for the case at hand. (This is actually the opposite of generalizability; it is "specificizability.")

Assessment Indicators

I_1:
- L: Many prior plausible values exist in spread.
- M: Spread is a fair amount narrower than range of prior plausible values.
- H: Spread is much narrower than range of prior plausible values.

I_2: (I_2 here is a first guess; it is to be refined when the particular application is considered.)
- L: The existence of other posterior plausible values (i.e., values in spread) matters for application.
- M: The existence of other posterior plausible values matters marginally.
- H: The existence of other posterior plausible values does not matter.

G: (based on application for which it was originally generated)
- L: does not generalize to other applications
- M: can be generalized with limitations
- H: easily generalized

R:
- L: highly perishable
- M: moderately perishable
- H: time independent

5.4 Robustness of Value over Time (R)

Robustness of Value over Time provides an assessment of how valid the value is expected to remain in the future. In other words, how dependent is the value of an entry on temporal changes?

6. PEDIGREE

Pedigree signals the quality of entries by evaluating their sources. In other words, the pedigree exhibits an evaluation of the production mode of the quantitative information. Pedigree contains four categories: theoretical basis, data inputs, estimation methods, and estimation metric. An entry's quality is assessed on these categories by indicating a value between 1 and 5, as is described in the box "Pedigree Indicators" above. The ratings are given based on the expert's subjective judgement of the quality of the production mode on each aspect. For all aspects but theoretical basis, simply indicate a rating from unacceptable to excellent. Different fields will judge the aspects with different considerations because different points will be relevant for different fields. The experience of experts should guide their judgments. A special character will be used to indicate that a category is inapplicable, for example, if this was not an aspect of the entry's production.

The estimation metric pedigree category requires some explanation. Estimation metric refers to the thing that is measured in the production of the estimate. Is it the object itself, or a proxy for something immeasurable? If it is a proxy, how good is the proxy?

Pedigree Indicators

T: theoretical basis
- 1: no theory or concepts
- 2: weak theory or concepts, controversial empirical support
- 3: weak theory, good empirical support
- 4: good theory, but one of competing theories
- 5: well-understood and accepted theory

D: data inputs
- 1: unacceptable
- 2: poor
- 3: fair
- 4: good
- 5: excellent

E: estimation methods
- 1: unacceptable
- 2: poor
- 3: fair
- 4: good
- 5: excellent

M: estimation metric (proxy or indicator for what we want to measure)
- 1: unacceptable
- 2: poor
- 3: fair
- 4: good
- 5: excellent

7. COMMENTS

One of the strengths of the NUSAP system is that uncertainty and quality can be signaled in a brief cryptic and systematic format. However, this will also be a disadvantage when a user wants to know why an entry received a rating. Thus, there will be comment fields for each assessment and pedigree aspect. The comments to be input in these fields serve a purpose similar to those provided under the "explanation" subsection of the examples provided below. However, these comments may be brief since a user may refer back to the literature for more information. The comments will appraise the user of why a particular rating was received. N, U, and S may also need some further explanation.

8. EXAMPLES

Example 1. Signal uncertainty and quality of the predicted competitive price of oil in 1983. It was generated from historical data and expert judgement through computer simulation (Funtowicz and Ravetz, p. 147). For illustrative purposes, it is rather detailed.

(N, U_1, U_2): (S_1, S_2[LB, UB], A[I_1,I_2,G,R]): (P[T,D,E,M])

(6, 1983$/bl, mean): (90%, [3, 11], [M, H, M, M]): ([1,2,3,3])

Explanation:

N: The number for predicted competitive price is 6.
U: U_1 It is stated as 1983 US dollars per barrel and
U_2 is the mean of the generated distribution.

S: S_1 90% confidence interval
S_2 is from $3 per barrel to $11 per barrel based on statistical analysis.

A: I_1 The spread is a fair amount narrower than the range of prior plausible values. This is so because the actual 1983 price was $30/barrel, yet this study was needed to determine if this price was significantly lower than the competitive price that would have existed without the OPEC cartel's monopoly power. This means that, prior to the study, the spread of plausible values must have been a fair amount wider. Narrowing the spread to an upper bound of $11 makes it a fair amount narrower.

I_2 If the application is to determine if the cartel has significant market power or not, the number is highly informative. We can tell with a high degree of confidence that the $30/barrel price is not competitive.

G This estimate can be generalized as long as the same "relevant" conditions exist (Funtowicz and Ravetz, p.4).

R The estimate is moderately perishable over time. (It is good for the whole year of 1983.) As the oil market undergoes changes and more recent historical data becomes available, the simulation would have to be redone.

P: T There is no encompassing theory driving this; the simulation operates on historical data and expert judgement.

D The data are poor. The price of oil under certain conditions is measured imprecisely because of the uncertainty surrounding the definition of the conditions and the judgement that the condition exists or doesn't exist. The expert judgments required are of even lower quality because the Bayesian probability distributions of data input are subjective opinions (although based on a review of the literature).

E The estimation methods are average to fair. The estimation of the subjective probability distributions is of poor quality. The literature on subjective probability elicitation indicates that these estimates are not valid or consistent in many cases, as well as being subject to human judgment error and bias. The estimation done by the computer simulation is good provided that one key assumption is true. By putting credence in the simulation, historical data (tempered by expert judgment) can assumedly be used to predict what would have happened in the future. This assumption can not be validated. We do not know the actual 1983 competitive oil price to compare because it never existed. Logically, however, it is under the same influences as the oil price in the past. Thus, the assumption that historical data is valid for predicting what would have happened in the future is plausible. Also, there is peer acceptance of this assumption. However, the subjective judgments are more important than the computer simulation in determining the end result, that is, the prediction of price. This is evident because a less rigorous simulation, say, with a relatively small number of calculations from a hand-held calculator along with some interpolation, would still provide useful results as long as the data are of good quality. However, if the data are worthless, then no matter how sophisticated the computer simulation, the output will be useless. Thus, the method is given a fair rating.

M They want to know what the competitive oil price would have been in 1983. They measured the competitive oil price in the past and subjected the historical data to informed judgement. However, they are not actually measuring the 1983 competitive price. They are measuring means of distributions generated in many simulations of the competitive price fluctuation to predict the price. The assumption that future price depends on the same influences as past price is necessary for this to serve as a proxy. This lowers the quality of the estimate on this aspect. Thus, the metric gets a fair rating.

Example 2. Signal the uncertainty and quality of the general-purpose mathematical model used to predict future competitive prices of commodities. (It is the mathematical model used in the computer simulation in the above example for competitive oil prices.)

(N, U_1, U_2): (S_1, S_2[LB, UB], A[I_1,I_2,G,R]): (P[T,D,E,M])

(P, money, mean): (90%, [x,÷ 2], [-, -, H, H]): ([2,2,4,3])

Explanation:

N: It is a price (P).

U: U_1 The price will be stated in monetary terms.

U_2 It generates a distribution, and the general practice in this field of economics is to take the mean.

S: S_1 The subjective level of confidence is 90% that the true value is within 2 x,÷ the value generated by the model.

S_2 Ideally, this interval should be given in terms of the distribution, that is, standard deviations. However, since the statistics of the distribution were not supplied by Funtowicz and Ravetz, a x,÷ factor is used. The interval is given based on the spread in the original study and subjective judgment about the accuracy of the model's output.

A: I_1 Because the application is not known, I_1 cannot be assessed. For different applications, there is too much variation in the prior knowledge of plausible prices for a useful assessment of I_1 to be supplied.

I_2 The application is unknown, so we do not know how varying the value by as much as a factor of 2 will effect the result at this point.

G The model is easily generalized to predict competitive prices for different commodities.

R The model is time independent.

P: T The model is based on economic theory. There is a long history of expertise in the field of predicting future commodity prices. The model is a standard form for translating experts' guesses into mathematical form. However, there must be many assumptions made in applying the model, and the predicted prices often differ greatly from the actual prices realized. Thus, the theoretical basis gets a poor rating.

D The model requires historical data and subjective judgments as input. The historical data is likely to be of good or even excellent quality. However, the subjective judgments are essential inputs to the model. Because the subjective probability distributions are of questionable validity and there is a high potential for bias with this data input, a rating of poor is assigned to the data inputs.

E The estimation done by the mathematical model is excellent provided that the assumptions made are true. We assume, by putting credence in the model, that historical data (tempered by expert judgment) can be used to predict what will happen in the future. This assumption has not been completely validated. It makes sense, however, that the future price is under the same influences as the past price. Thus, the assumption that this mathematical model is valid for predicting what will happen in the future is plausible. Also, there is peer acceptance of this assumption. Thus, it is given a good rating on this aspect.

M The model predicts a future competitive price of a commodity. The mathematical model parameterizes the factors believed to influence the competitive price. However, they are not actually measuring the future competitive price. Many assumptions are necessary for this to serve as a proxy. Thus, the metric is assigned a fair rating.

APPENDIX G.2
NUSAP DATA ENTRY FORM EXPLANATION

NUSAP Data Entry Form Explanation

N: Enter the number, notation, variable name, or note about practice.

U: 1. Enter the measure for the number, upper and lower bound, or variable (e.g., pounds). Also enter the time period for the entry (e.g., per hour).
2. Enter the statistic which the number or variable is (e.g., mean, median, no distribution).

S: 1. Enter the degree of confidence of the spread. Use 90% whenever possible for standardization.
2. Enter the upper and lower bound or ± % range, ± standard deviations range, x÷ range, or factor of variation of the spread.

A: Enter the assessment ratings for each applicable category (i.e., H, M, or L). Enter N/A for not applicable.

I_1: Assess the informative value based on spread. That is, assess the extent to which the entry narrows the spread of plausible values over what was known before the study that produced the entry was conducted (prior).

L: Many prior plausible values exist in spread.
M: Spread is a fair amount narrower than range of prior plausible values.
H: Spread is much narrower than range of prior plausible values.

I_2: Assess the informative value based on the foreseen application for the entry. That is, how informative are the results of calculations with this entry expected to be given the current persisting (posterior) uncertainty about the entry. (I_2 here is a first guess, to be refined when the particular application is considered.)

L: The existence of other posterior plausible values (i.e., values in spread) matters for application.
M: The existence of other posterior plausible values matters marginally.
H: The existence of other posterior plausible values does not matter.

G: Assess the generalizability of the entry to other applications, locations, or sample spaces different from the application for which it was originally generated.
- L: does not generalize to other applications
- M: can be generalized with limitations
- H: easily generalized

R: Assess the entry's robustness over time.
- L: highly perishable
- M: moderately perishable
- H: time independent

P: Enter the pedigree ratings for the applicable categories (i.e., 1 to 5). Enter N/A for any inapplicable pedigree category.

T: Assess the theoretical basis of the entry and the tenability of the theory's application to produce the entry.
- 1: no theory or concepts
- 2: weak theory or concepts, controversial empirical support
- 3: weak theory, good empirical support
- 4: good theory, but one of competing theories
- 5: well-understood and accepted theory

D: Assess the quality of the data inputs used to generate the entry.
- 1: unacceptable
- 2: poor
- 3: fair
- 4: good
- 5: excellent

E: Assess the estimation methods used to generate the entry.
- 1: unacceptable
- 2: poor
- 3: fair
- 4: good
- 5: excellent

M: Assess the estimation metric (i.e., proxy or indicator for what we want to measure.)
- 1: unacceptable
- 2: poor
- 3: fair
- 4: good
- 5: excellent

Comments: Enter any comments about the NUSAP categories. For example, measures may require explanation such as "WLM stands for working level month." Statistics may need explanation, such as "mean from meta analysis." The level of spread may require explanation such as "confidence level corresponds to +/- 2 standard errors corresponding to multiplication or division by a factor of 1.7 for the upper and lower bound." The reasons why assessment ratings and pedigree rating were received can be explained here (and probably should be).

APPENDIX G.3
NUSAPs FOR THE ESTIMATES OF EMISSIONS FROM THE BIOMASS FUEL CYCLE

[It is suggested that the reader first read Appendix G.1 and have a separate photocopy of the NUSAP Data Entry Form Explanation (Appendix G.2) while reviewing the NUSAPs in this appendix.]

NUSAP: Bureau of Census Population
(Section 4.2: Reference Sites)

Numerical Information: Population

Units

Measurement Units: annual number of people at the county level

Statistical Units: no distribution

Spread

Level of Confidence: No spread reported or estimated

Lower Bound:
Upper Bound:

Assessment

Informative Value Based on Spread: HIGH

Even though there is no spread, the census population is highly informative over what would be known if a census were not conducted.

Informative Value Based on Application: not assessed

Generalizability to Other Applications: LOW

The site-specific data would not be applicable to any other location.

Robustness of Value Over Time: HIGH

Pedigree (credibility of the entry's origin)

Theoretical Basis: EXCELLENT

Bureau of Census is considered "the" source for population data.

Data Inputs: GOOD

Some error in Census data is recognized.

Estimation Methods: not assessed

Estimation Metric: EXCELLENT

NUSAP: Annual Chemical Inputs
(Section 4.3: Wood Feedstock Production)

Numerical Information: Quantity of herbicides applied

Quantity of insecticides and fungicides applied

Units

Measurement Units: lbs/yr

Statistical Unit: average over 18-year planting

Spread

Confidence Level: 80% to 90%

Upper Bound: (i) herbicides +25%
(ii) fungicides and insecticides +100%

Lower Bound: (i) herbicides -50%
(ii) fungicides and insecticides -100%

Assessment

Informative Value Based on Spread: MEDIUM

Informative Value Based on Application: not assessed

Generalizability to Other Applications: MEDIUM

Generalizable only for whole regional (landscape) scale.

Robustness of Value over Time: MEDIUM

Herbicide use may decrease due to development of improved species.

Pedigree (credibility of the entry's origin)

Theoretical Basis: GOOD

Data Inputs: GOOD

Estimation Methods: FAIR

Estimation Metric: not applicable

NUSAP: Emissions Factors
(Section 5.1: Emissions--Feedstock Production, Harvesting, and Transport)

Numerical Information: VOCs, CO, NO_X, PM, CO_2, and SO_2 emission factors for diesel tractors and trucks

Units

Measurement Units: grams/bhp-hr (VOCs, CO, NO_X, and PM)
grams/lb of fuel (CO_2, and SO_2)

Statistical Unit: no distribution

Spread

Confidence Level: There is miniscule uncertainty about these factors given that the vehicle type, and its average loading, are known.

Upper Bound: not applicable
Lower Bound:

Assessment

Informative Value Based on Spread: HIGH

Informative Value Based on Application: HIGH

Generalizability to Other Applications: MEDIUM

The actual vehicle types and loadings will vary across sites.

Robustness of Value over Time: MEDIUM

Vehicle emissions may decrease in the future.

Pedigree (credibility of the entry's origin)

Theoretical Basis: not applicable

Estimates generated from field test observations.

Data Inputs: GOOD

Estimation Methods: GOOD

Estimation Metric: FAIR

Field test vehicles and loadings are a proxy for actual vehicles and their use.

NUSAP: Agricultural Chemical Emissions
(Section 5.1: Emissions, Table 5.1-2)

Numerical Information: Allocation of applied chemical

Units

Measurement Units: % of total quantity applied

Statistical Unit: no distribution

Spread

Confidence Level: 80%

Upper Bound: x 4
Lower Bound: ÷ 4

Assessment

Informative Value Based on Spread: MEDIUM to HIGH

Informative Value Based on Application: not assessed

Generalizability to Other Applications: MEDIUM

Site and species specific differences are expected.

Robustness of Value over Time: MEDIUM

Pedigree (credibility of the entry's origin)

Theoretical Basis: FAIR

Volatization rates from chemicals are poorly understood.

Data Inputs: FAIR

Estimation Methods: POOR to FAIR

Estimation Metric: FAIR

NUSAP: Biogenic Emissions of Volatile Organics
(Section 5.2: Biogenic Feedstock Emissions)

Numerical Information: emissions of non-methane aromatic hydrocarbons (NMHCs) from feedstock production

Units

Measurement Units: annual lbs/acre

Statistical Unit: no distribution

Spread

Confidence Level: 80%

Upper Bound: x 10
Lower Bound: ÷ 10

Assessment

Informative Value Based on Spread: LOW

Informative Value Based on Application: MEDIUM

May not make a big difference on impacts depending on existing land uses.

Generalizability to Other Applications: LOW

Based on small plot data which does not generalize well to large plots (as would be used for tree plantations).

Robustness of Value over Time: LOW

Our state of knowledge is likely to improve considerably in the near future.

Pedigree (credibility of the entry's origin)

Theoretical Basis: POOR

Data Inputs: UNACCEPTABLE

Estimation Methods: POOR

Estimation Metric: UNACCEPTABLE to POOR

Isoprene and monoterpene are the only NMHCs which have been investigated. They are a poor proxy for all NMHCs.

NUSAP: Emission Factors for Generating Facility
(Section 5.4: Emissions, Table 5.4-1)

Numerical Information: Air emission factors for wood-fired power generation (Particulates, PM_{10}, TSP, SO_x, NO_x, VOCs, and CO)

Units

Measurement Units: lbs/ton combusted

Statistical Unit: no distribution

Spread

Confidence Level: 80%

Upper Bound: +25%
Lower Bound: -50%

Assessment

Informative Value Based on Spread: HIGH

Informative Value Based on Application: HIGH

The range of values are expected to have little effect on impacts.

Generalizability to Other Applications: MEDIUM

Dependent on feedstock composition.

Robustness of Value over Time: MEDIUM

Pedigree (credibility of the entry's origin)

Theoretical Basis: not applicable

Data Inputs: GOOD

Estimation Methods: GOOD

Estimation Metric: GOOD

REFERENCES

Funtowicz, S. and J. Ravetz, *Uncertainty and Quality in Science for Policy*, Kluwer Academic Publishers, Dordrecht, The Netherlands, 1990