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RECOVERY OF ABOVE-GROUND WOODY BIOMASS USING OPERATIONAL MODIFICATIONS OF CONVENTIONAL HARVESTING SYSTEMS

Final Report

By
John W. Herschelman
Douglas W. Domenech

61

June 1, 1980

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FINAL REPORT

RECOVERY OF ABOVE-GROUND WOODY BIOMASS USING OPERATIONAL MODIFICATIONS OF CONVENTIONAL HARVESTING SYSTEMS

SUBMITTED TO

U.S. DEPARTMENT OF ENERGY
DIVISION OF SOLAR ENERGY
FUEL FROM BIOMASS SYSTEMS BRANCH

FG01-78ET20045

I.B.4. ALTERNATE HARVESTING, COLLECTION, TRANSPORTATION, AND STORAGE PROGRAM INTEREST AREA

SUBMITTED BY

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DEPARTMENT OF NATURAL RESOURCES
AND ENVIRONMENTAL STUDIES

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NORMAL, ALABAMA 35762

JUNE 1, 1980

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RECOVERY OF ABOVE-GROUND WOODY BIOMASS USING OPERATIONAL MODIFICATIONS OF CONVENTIONAL HARVESTING SYSTEMS

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ABSTRACT Two harvesting systems were assembled during each of two summers to compare the operational efficiency of a whole tree harvesting system with a conventional harvesting system. Skidding of whole trees proved to be 27% more efficient than the skidding of primary stems because of operators habits of underutilizing skidder capacity. Although 5% more gals/hour were used by the whole tree system, there was a net gain of 21% more tons/gal. produced by this same system.

A whole tree chipper was analized for its potencial to process large hardwood trees for energy products. A comparison of five harvesting systems revealed that whole tree systems producing sawtimber, round pulpwood, and energy chips proved most energy efficient and economically viable. A variety of machine/system factors were measured. It was determined that with certain modifications, whole tree chippers offer the best potencial for processing logging residue for fuel.

Forty-eight equations were developed predicting green and ovendry weights in summer and winter for whole tree weight, primary product weight, and the weight of limbs and tops for hardwood trees associated with the oak-hickory forest type in the Southern Appalachian Region based on diameter at breast height and whole tree length. Eight sawlog prodiction equations were also developed based on log length, diameter small end outside bark and diameter large end outside bark.

The energy efficiency of harvesting systems was studied by analizing the equipment involved in manual and mechanized shortwood, longwood, and whole tree systems. Three basic types of information was developed:

1. fuel consumption rates for machine types on a per hour or per mile basis.

2. fuel consumption to produce one ton of wood as delivered to a utilization point.

3. net energy efficiency ratio comparing energy equivalent of wood produced (output) to amount expended (input).

AREA: Natural Resources

I. INTRODUCTION

With the renewed interest in utilizing woody biomass as an energy source, harvesting techniques must be adapted to recover energy products as well as traditional forest products. New prototypes are being designed strictly to harvest residues (U.S.D.A., 1978); however, these machines are not yet available for widespread distribution. Therefore, conventional harvesting systems will supply wood energy products until specialized equipment is developed, tested, manufactured, and accepted on a large-scale basis.

Harvesting systems are grouped according to the type of products recovered: shortwood, longwood, and tree length. Shortwood systems are primarily used to harvest pulpwood and are normally labor intensive. Longwood or random length systems are used in producing both pulpwood and sawtimber. Product separation in longwood systems may take place either at in-woods processing points (landings) or at merchandising yards at points of delivery. The tree-length or whole tree harvesting system brings whole trees to a landing where, normally, only the sawlog and pulpwood portions of the tree are used. With the introduction of the chipper, limbs and tops can now also be utilized.

Chippers, first commercially introduced in 1971, are newly developed harvesting machines that have been accepted by the forest industry (Altman, 1980); however, unrealistic cost and production estimates for whole-tree recovery systems have been very costly experiments for some companies. Even though chippers have not met full expectations, they remain the best potential for processing logging residues and other portions of forest stands for energy products.

The broad purpose for this project is to provide basic information for the harvesting and transportation of energy wood products. This project is divided into three distinct studies:

1. Operational Modifications of Conventional Longwood Harvesting Systems to include Recovery of Energywood Products.

2. Woody Biomass Weight Prediction Equations

3. Energy Efficiency of Harvesting Systems

II. OPERATIONAL MODIFICATIONS OF CONVENTIONAL LONGWOOD HARVESTING SYSTEMS TO INCLUDE RECOVERY OF ENERGYWOOD PRODUCTS

A. Problem Description

Fuel from woody biomass can be derived from several sources, including logging residues (traditionally left in the forest following timber harvesting operations), non-commercial or surplus stands of timber, thinnings, short rotation silvicultural biomass farms, and wood and bark mill residuals which accumulate at primary wood manufacturing plants (Howlett, 1977).

This study addresses the logging residues that are traditionally left in the forest, and it defines the resources needed to recover such residues for energy production. Because hardwood trees offer the largest potential supply of energywood in the Eastern United States (Howlett, 1977) this study will investigate only the recovery of logging residues from hardwood stands.

B. Statement of Research Objectives

1. Compare skidding efficiency of a conventional longwood harvesting system to that of a system designed to recover logging residues as well as traditional forest products in hardwood stands.

2. Evaluate operational efficiency, production rates, and fuel consumption for a whole-tree chipper to process hardwood trees for energy products.

3. Evaluate the additional logging costs to harvest forest residues of hardwood stands using conventional harvesting equipment.

C. Description of Observed Harvesting Operations

1. Skidding

Two harvesting systems were assembled during each of two summers, 1978 and 1979 to compare the operational efficiency of a whole tree harvesting system with a conventional harvesting system. Personnel were rotated throughout both systems to prevent operator aggressiveness from influencing results. Persons selected for the study were not professional loggers; therefore, production rates for either system cannot be assumed to be typical of actual operations. The comparative efficiency, however, can be used to evaluate the two systems.

The systems were as follows:

Conventional Longwood Harvesting System

a. Crew Organization

3 sawyers
1 skidder operator

b. Equipment

2 McCulloch model 700 chainsaws
1 McCulloch model 650 chainsaw
1 Timberjack model 230 rubber tired skidder

c. Method of Operation

Two sawyers felled, limbed, and topped trees;
Skidder operator transported bole of trees to deck;
Sawyer bucked sawlogs from bole

Wholetree Harvesting System

a. Crew Organization

3 sawyers
1 skidder operator

b. Equipment

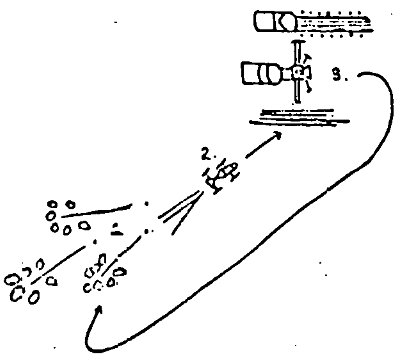
2 McCulloch model 700 chainsaws
1 McCulloch model 650 chainsaws
1 Timberjack model 230 rubber tired skidder

c. Method Operation

One sawyer felled trees
Skidder operator transported whole trees to deck
One sawyer limbed and topped whole trees while other sawyer bucked sawlogs from bole of tree.
Limbs and tops were stored to be chipped at a later date.

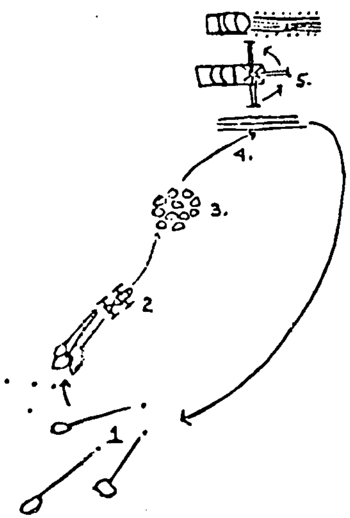
FIGURE 1: HARVESTING SYSTEMS FOR 1978 AND 1979 STUDIES

A. Conventional Longwood Harvesting System



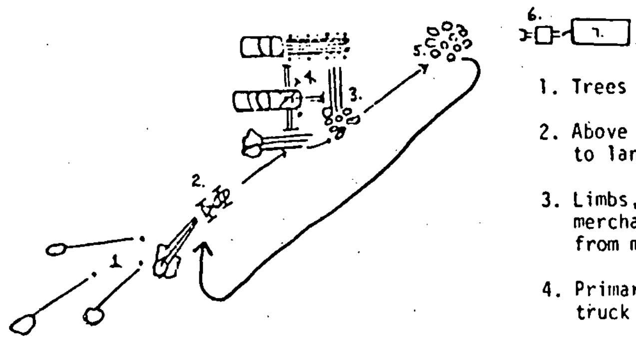
1. Trees felled and limbed and tops removed. Tops left scattered over site.
2. Merchantable stems skidded to landing.
3. Merchantable stems loaded on truck-trailer.

B. Whole Tree Harvesting System 1978 Study



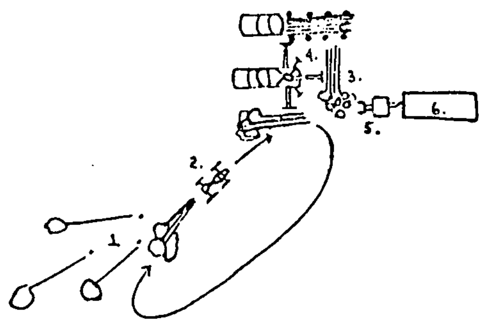
1. Trees felled
2. Above stump biomass skidded to intermediate landing.
3. Limbs, tops, and sub-merchantable stems seperated from merchantable stems.
4. Merchantable stems skidded to landing for loading
5. Merchantable stems loaded on trailers.

C. Whole Tree Harvesting System 1979 Study - Configuration 1



1. Trees felled
2. Above stump biomass skidded to landing
3. Limbs, tops, and sub-merchantable stems seperate from merchantable stems
4. Primary products loaded ont truck trailer.
5. Skidder pushes residue to chipper.
6. Residue is chipped
7. Chipvan

D. Whole Tree Harvesting System 1979 Study - Configuration 2



1. Trees felled
2. Above stump biomass skidded to landing
3. Limbs, tops, and sub-merchantable stems seperate from merchantable stems
4. Primary products loaded ont truck trailer
5. Residue is chipped. Stems out of chippers reach can be moved closer with primary product loader.
6. Chipvan

2. Chipping

A model 12 Morbark chipper was leased to study the feasibility of chipping hardwood tops. Because of the large diameters and numerous branching of the tops, it was evident that the twelve-inch diameter capacity was too small to be operationally efficient (see Table 8). Branches often jammed the chipper, and many large tops could not be used because of the diameter limitation.

Shelton Industries of Horton, Alabama operates a whole tree chipping operation producing energy and metallurgical wood and sawlogs. This operation was observed for the study.

The system consisted of two John Deere model 640 cable skidders, two chainsaw operators, and a model 22 Morbark Chipper. The model 22 chipper is equipped with a knuckleboom loader which can also serve to load sawlogs on a trailer (unlike the model 12 telescoping boom which cannot be used in the loading function). Two chip vans and one truck tractor were available for transporting chips. When logs were to be hauled, a trailer was brought in from another operation owned by Shelton Industries.

D. Data Gathering Techniques

Time and motion studies were used in studying the system's operational efficiency, production rates, and fuel consumption. Sample data sheets are included in the appendix.

E. Procedure for Measuring Variables

1. Skidding

a. skidding cycle (or "turn") time: defined as the time to pick up, transport, and deliver a load of logs and return to felling site for another load. Timed with a stopwatch, operational and delay times were recorded along with delay times to the nearest 1/100th of a minute.

b. number of trees per turn: with each cycle, trees were counted and recorded.

c. size of trees per turn: ocular estimate of butt diameter of each tree per cycle was recorded.

d. fuel usage: each machine was filled each evening and the amount of fuel consumed was recorded. A hand pump with a fuel indicator was used. (An electric pump would be more efficient and should be used in the future.)

2. Chipping

a. pounds per load for chip van: chip vans were weighed full and empty at point of utilization and pounds per load was calculated.

b. trees per load: the number of trees per chip van were counted as the van was filled.

c. time per load: gross time to load chip van from positioning to completed load was recorded. Operational and delay times were recorded and were timed with a stopwatch to the nearest 1/100th of a minute.

d. fuel consumed per chip van load: chipper was filled with fuel after each chip van was loaded and amount of fuel consumed was recorded.

e. chipping time per tree: for each tree chipped, species, butt diameter, length, and time to chip were recorded. Tree diameter was measured to the nearest inch with a Biltmore stick, tree length was measured to the nearest foot with a logger's tape, and time was measured to the nearest 1/100th of a minute with a stopwatch.

f. time to cut or crush jammed limbs: large limbs tended to jam in the chipper; to free these limbs and alter them so that they could be chipped, the limbs had to be either cut with a chainsaw or crushed with the loader's grapple. Once a limb jammed, the time to correct the situation and the procedure used were recorded to the nearest 1/100th of a minute.

F. Basic Equations Used to Compute Variables

Weight calculation for whole tree and merchantable bole are listed below.

Weight equations developed at Alabama A&M University for mixed hardwoods were used to estimate the weight of trees skidded and chipped. Diameter estimates were made from butt diameter measurements. These equations are presented in Table 1.

Table 1: Prediction Equations for Mixed Hardwoods

General Form of Equation:

$$LOG_{10}Y = A + B\ (LOG_{10}D.B.H.^{2} \times WTL)$$

Where: Y = Weight In Pounds

D.B.H. = Diameter at Breast Height

WTL = Whole Tree Length

Tree Component	A	B	R^2	Season
Whole Tree	-0.381	0.926	0.88	Summer
Whole Tree	-0.660	0.964	0.95	Winter
Primary Stem	-0.519	0.911	0.81	Summer
Primary Stem	-1.083	1.042	0.96	Winter
Limbs and Tops	-1.157	0.998	0.61	Summer
Limbs and Tops	-0.522	0.727	0.43	Winter

Table 2: Hardwood Stand Models in Tons per Acre

Fully Stocked Stand

Ht Class (FT)	DBH Class (Inches)	Trees Per Acre	Total Tons Per Acre	Sawtimber Tons/Acre	Non/Saw-Timber Stem Wt. Tons/Acre	Residue Tons/Acre
10	2	42	0.294	-	-	0.294
20	4	80	3.520	-	-	3.520
30	6	56	7.504	-	4.928	2.576
40	8	38	11.324	-	7.334	3.990
50	10	78	42.432	-	27.690	14.742
60	12	98	90.160	38.158	22.994	29.008
60	14	13	15.873	8.360	2.287	5.226
70	16	15	27.060	15.305	2.575	9.180
70	18	8	17.976	10.755	1.021	6.200
70	20	3	8.187	4.666	0.656	2.865
Total		431	224.330	77.244	69.485	77.601

High Graded Stand

Ht Class (FT)	DBH Class (Inches)	Trees Per Acre	Total Tons Per Acre	Sawtimber Tons/Acre	Non/Saw-Timber Stem Wt. Tons/Acre	Residue Tons/Acre
10	2	30	0.210	-	-	0.210
20	4	60	2.640	-	-	2.640
30	6	42	5.250	-	3.696	1.554
40	8	25	7.025	-	4.825	2.200
50	10	19	9.994	-	6.745	3.249
60	12	12	11.040	4.373	3.115	3.552
60	14	11	13.431	6.668	2.341	4.422
70	16	5	9.020	4.853	1.107	3.060
70	18	2	4.494	2.547	0.857	1.090
70	20	1	2.729	1.493	0.281	0.955
Total		207	65.833	19.934	22.967	22.932

Table 3: Harvesting Systems Production Assumptions

Longwood System — Tons/Productive Machine Hour

Equipment	Avg. DBH 2	4	6	8	10	12	14	16	18	20
Chainsaw: Fell, Limb, Top	4.6	6.6	8.6	10.6	12.6	14.6	16.6	18.6	.21	.22
Fell	18	21	23	25	27	30	32	34	36	38
Limb & Top	18	20	22	24	26	28.4	31	33	35	36
Buck	10	12	14	16	18	20.6	23	25	27	28
Skidder	3.5	5.5	7.5	9.5	12.1	12.5	13.0	13.5	13.9	14.4
Loader	12	14	16	18	20	21.5	23	25	27	27.5

Whole Tree System — Tons/Productive Machine Hour

Equipment	Avg. DBH 2	4	6	8	10	12	14	16	18	20
Chainsaw: Fell, Limb, Top	4.6	6.6	8.6	10.6	12.6	14.6	16.6	18.6	.21	.22
Fell	18	21	23	25	27	29.9	32	34	36	37
Limb & Top	18	20	22	24	26	28.4	31	33	35	36
Buck	10	12	14	16	18	20.6	23	25	27	28
Skidder	4.4	6.9	9.5	12.1	15.3	15.8	16.5	16.8	17.2	17.5
Loader	12	14	16	18	20	21.1	23	25	27	28
Chipper	7.6	9.6	11.6	13.6	15.6	17.6	18.0	19.5	21.5	22

Skidder Distance Not Greater Than: 1320 Feet

Tractor Trailer Log Load: 27.5 Tons

Tractor Trailer Chip van Load: 21.5 Green Tons

	Sawtimber	Pulpwood	Energywood
Haul Distance:	40 miles	20 miles	20 miles
Revenue Per Ton:	$12.12	$10.50	$10.50

Insurance, Interest, and License is 14% of Capital

Investment: Overhead is 10% of Capital Investment

Support is Construction of Roads and Landings and Mechanical Support

G. Analysis of Data

Stepwise regression analysis was used; and, where moderate to strong correlations existed, equations are presented. Where regression correlation was low, averages were used to compare systems.

Five systems were compared to evaluate the additional logging costs to harvest forest residues of hardwood stands using conventional harvesting equipment. These systems were balanced for maximum productivity, and acreage to be cut was considered unlimited for comparison purposes. The stand models used are described in Table 2. The systems compared are shown in Table 4.

Table 4: Harvesting Systems Evaluated

Harvesting System	Diameter Cutting Limit	Portion of Tree Utilized	Products
Conventional Long-wood	7.0 inches and larger	Primary stem	Sawtimber, pulpwood[1]
Whole tree	7.0 inches and larger	Whole tree	Sawtimber, pulpwood[1], energywood[2]
Whole tree	7.0 inches and larger	Whole tree	Sawtimber, energywood[3]
Whole tree	All trees	Whole tree	Sawtimber, pulpwood[1], energywood[2]
Whole tree	All trees	Whole tree	Sawtimber, energywood[3]

1. in roundwood form
2. from limbs and tops
3. chips from non-sawtimber and limbs & tops.

H. Results and Conclusions

1. Results for Objective 1: Compare skidding efficiency of a conventional longwood system to that of a system designed to recover logging residue as well as traditional forest products in hardwood stands.

Skidding of whole trees proved to be more efficient than the skidding of primary stems; however, the difference lies in the skidder operators' on-the-job habits, rather than in the harvesting systems themselves.

Table 5: Comparison of Skidding Efficiency

	Longwood	Whole Tree	% Change
Skidder Production			
Green Tons/PMH*	6.47	8.24	+27
Trees/Turn	3.96	2.85	-28
Tons/Turn *	2.31	2.91	+26
Turns/Hour*	2.80	2.83	+01
Trees/Hour	11.09	8.07	-27
Skidding Fuel Consumption			
Gallons/Hour*	2.20	2.31	+05
Tons/Gallon	2.94	3.56	+21

*PMH = Productive Machine Hour
%Change = Whole Tree Results/Longwood Results

Skidder operators tend to underutilize the pulling capacity of the machine. When pulling whole trees they attempt to hook as many stems as they did when skidding only primary stems; therefore, the load weight per turn was increased by skidding whole trees. A method to reduce this inefficiency is to calculate machine capacity for a given machine and then calculate the average tree size for a stand that is to be cut. The proper number of chokers can then be placed on the machine to optimize load size and to encourage operators to utilize their machines more efficiently.

2. Results for objective 2: Evaluate operational efficiency, production rates, and fuel consumption for a whole-tree chipper to process large hardwood trees for energy products.

Prior to the introduction of the whole-tree chipper, hardwood tops could not be utilized because of their bulkiness for transportion. The ability to reduce woody biomass to chip form has been an important step in the utilization potential of a given stand of hardwood timber. The capital investment and operational cost is, however, still a deterrent for the wide use of chippers, since wood buyers are understandably reluctant to increase their cost for raw materials.

Productivity of whole-tree chippers is a function of stem diameter, stem length, season, ground conditions, limb size, limb angle, engine size and number of knives used. Regression analysis was used to estimate time to chip whole trees. The variables used were diameter of butt outside bark and length of tree or segment. Because of the low correlation as measured by R^2, averages are also presented.

Table 6: Chipping Time of Hardwood Trees
General Form of Equation:
$LOG_{10}Y = A + B_1(LOG_{10}X_1) + B_2(LOG_{10}X_2)$
Where: $Y =$ time to chip tree or tree segment
$X_1 =$ butt diameter
$X_2 =$ length of tree or tree segment
$A =$ -1.071
$B_1 =$ 0.451
$B_2 =$ 0.610
$R^2 = 0.24$ Standard Error of $B_1 = 0.049$ and of $B_2 = 0.462$

Table 7: Average Chipping Time and Chip van Load Size

	Average	Range
Total Time* to Load	88	53-125
Productive Machine Time*	73	53-99
Delay Times*		
Knife Change	14	8-20
Waiting on Wood	12	3-28
Unplug Chute	16	7-20
Tons/Chipvan	21.462	20.6-22.8
Trees/Load	43.3	33-59
*Time in Minutes		

The jamming of trees being chipped and handling delays were not excluded from productive machine time. Jam delays included limbs being at too great an angle to chip, butts too large, engine choking down, and low friction on vertical or horizontal feed roll. Handling delays included crowns caught in pile and stems lying too far from the chipper to reach with its grapple.

Only 24.5% of the stems were chipped without any delay. The average time to cut limbs with a chainsaw in order for limbs to be chipped was 0.61 minutes (range .30 to 1.25), and the average time to crush limbs with the loader was 0.06 minutes (range 0.03 to 0.11). However, limbs can be crushed only when they are less than four inches in diameter and are within the 3.8 foot opening capability of the grapple.

Table 8: Chipping Delay by Diameter Class

Diameter Class	Percent Jammed or handling delay
4	43
6	50
8	100
10	100
12	100
14	100
16	67
18	0
20	100

Application of Research

* The Morbark Model 12 (twelve inch diameter limit) chipper was too small to practically convert limbs and tops of large hardwood trees into chips.

* Hot logging (processing trees without storage) is best when chipping hardwood trees. When hardwood limbs and tops are stored in piles to be chipped at a later date, they entangle and are extremely time consuming to separate when chipping is done.

* Chipping delay by limbs and tops is a function of limb angle and limb diameter, and is not necessarily a function of the number of pieces being chipped.

* Delays in chipping caused by low friction can be reduced by adding more material to the chipper when low friction circumstances occur.

* Greater production could be realized by chipping only the "merchantable" bole instead of the whole tree.

* Greater production per hour can be realized when chipping non-sawlog portions of stems with limbs and tops attached. Separated limbs and tops tend to jam the chipper. When tops with large limbs (greater than four inches in diameter at base) are to be chipped, they should be partially severed at bole to reduce machine jamming.

* When a knuckleboom loader is used on the same landing with a chipper, it should be placed close to the chipper to help feed material not within the reach of the chipper boom.

3. Results for Objective 3: Evaluate the additional logging costs to harvest forest residues of hardwood stands using conventional harvesting equipment.

Of the five systems compared, the whole-tree system producing three separate products proved most efficient. Where small trees, (six inches d.b.h. and below) were utilized, the net profit per ton was decreased by seventy-five cents per ton (see table 9).

Table 9: Comparison of Harvesting Systems for the Recovery of Energy Wood

	Longwood System	Wholetree System	Wholetree System	Wholetree System	Wholetree System
Diameter Limit	>7 inch.	> 7 inch.	> 7 inch.	All trees	All trees
Products*	ST,PW	ST,PW,EC	ST,EC	ST,PW,EC	ST,EC
Personnel	8	23	11	19	9
Capital Investment	$266,820	$584,707	$395,900	$597,700	$407,500
Tons Produced/Year	30,222	86,359	41,084	65,621	32,166
Capital/Ton Produced	8.83	6.77	9.64	9.11	12.67
Product Cost/Ton	9.31	8.11	9.57	9.58	11.58
Income/Ton	11.38	11.12	11.08	11.09	11.10
Pretax Profit/Ton	2.07	3.00	1.51	1.51	-0.48
Net Profit/Ton	1.03	1.50	0.75	0.75	-0.48
Net Profit/Year	31,128	129,539	30,813	49,216	-15,440
Return on Investment	11.7%	22.2%	7.8%	8.2%	-3.9%
Fuel Consumed**/Ton	1.29	1.34	1.45	1.34	1.49

*Products: ST = Sawtimber
PW = Pulpwood (roundwood)
EC = Energy Chips

**Fuel consumption in gallons of all petroleum products used.

Because chipping costs are greater than loading costs, per ton, it is more profitable to load all possible products with the knuckleboom loader, then chip only the limbs and tops that cannot be efficiently transported in any form other than chips. This constraint forces the system to produce a high volume of wood per year in order to fully utilize the chipper; thus this system would be practical only where large cutting blocks are readily available. When restricted to smaller cutting blocks, because of ownership patterns or restricted cutting practices, the whole-tree system producing sawtimber and chips would be most efficient.

The information presented depicts conditions in the North Alabama region. Conclusions will vary according to supply systems used.

Logging contractors who receive no benefit from increased utilization per acre and from reduced site preparation cost will continue cutting the traditional products of roundwood pulpwood and sawtimber unless higher prices are paid for chips than for roundwood pulpwood. Where strong energywood markets develop, there will be intense competition between energywood and pulpwood.

Companies with large hardwood land bases will find it most profitable to utilize all above-ground woody biomass for multiple products. The increase in wood supply (from utilization of all above-ground biomass) and reduced site preparation cost will tend to offset the higher costs of logging, and because the system of high-grading will be eliminated with total utilization, hardwood stand quality will be improved.

III. WOODY BIOMASS WEIGHT PREDICTION EQUATIONS

A. Problem Description

Traditional inventory methods of woody biomass in the United States consists of estimating only volumes of primary products ("merchantable bole") of forest stands (Goldstein, 1979). To accurately estimate wood supply on a regional basis to include energy wood, it is necessary to calculate total tree volumes in product components by weight.

B. Statement of Research Objectives

Develop prediction equations for hardwood trees typical of stands in oak-hictory forest type of the Southern Cumberland Plateau.

C. Methods and Precedures

1. Whole trees and primary components

Hardwood trees from five stands in the Northeast Alabama region were cut, measured, and weighed to develop prediction equations for mixed hardwoods, red oak group (*Quercus sp*) white oak group (*Quescus sp*) and hickory group (*Carya sp*) both in green and oven-dried weights for whole trees, primary product (merchantable bole), and limbs and tops in summer and winter conditions. Trees were selected in diameter classes from 2 inches to 30 inches, however the larger diameter trees were not abundant and the weight estimation of trees above twenty inches is mostly by extrapolation.

Trees were randomly selected throughout each stand; four trees from each diameter class were measured. All stands were of the oak-hickory type and contained other species associated with this type. Prior to felling, trees were marked at four and one-half feet above ground level (D.B.H.) so accurate measurement could take place on logging deck. Trees were then transported by rubber tired skidders to the logging deck for measurements to be taken.

Once trees were brought to the logging deck, the following measurements were taken:

1. tree species
2. whole tree weight green
3. whole tree length
4. diameter at breast height
5. weight of primary product, green
6. length of primary product
7. diameter at small end of primary product
8. site location was recorded
9. disc was cut and placed into a self-sealing plastic bag to be later analyzed for moisture content

Data collection conforms to procedures of cooperative research efforts of woody biomass researchers in the Southeastern United States (Taras, 1979). Tree weights were measured with a dynamometer attached to a knuckleboom loader. Trees were limbed and topped and the primary product (merchantable bole to 4 inch top) was weighed. In many instances, due to the deliquescent branching characteristic of hardwoods, the top diameter of the merchantable bole was greater than four inches in diameter; where this occurred the diameter at the small end of the bole was measued.

Data were analyzed and prediction equations were developed using stepwise regression procedures. Many combinations were attempted to develop the most accurate estimates of whole-tree, primary-product, and residue (limbs and tops) weights.

2. Sawlog Weight Estimates

Hardwood sawlogs from Moss Lumber Company in Gurley, Alabama were weighed and measured to develop prediction equations for mixed hardwoods, red oak (Quercus sp.), white oak (Quercus alba), hickory (Carya sp.), yellow poplar (Liriodendron tulipifera), black walnut (Juglans nigra), blackgum (Nyssa sylvatica), and black locust (Robinia pseudoacacia).

Measurement Variables:

1. species
2. log weight
3. log length
4. diameter outside bark at small end
5. diameter outside bark at large end

Data were analyzed and prediction equations were developed using stepwise regression procedures.

D. Results

1. Whole Trees and Primary Components

Forty-eight equations were developed (see Table 10) for hardwood trees associated with the oak-hickory forest type in the Southern Applachian Region.

The general form of the equation is:

$$\mathrm{LOG}_{10}(Y) = A + B\ (\mathrm{LOG}_{10}X)$$

Where Y = predicted weight in pounds

X = $\mathrm{D.B.H.}^2$ x whole tree length

A = intercept

B = slope

Table 10-A: Hardwood Prediction Equations (2/80)
Oak-Hickory Type S. Cumberland Plateau
Ridge Top Sites

	Intercept	Slope	R^2	Signif.
A. Mixed Hardwoods				
1. Whole Tree Weight				
A. Green - summer	-0.381	0.926	0.88	.000
B. Ovendry - summer	-0.578	0.929	0.86	.000
C. Green - winter	-0.660	0.964	0.95	.000
D. Ovendry - winter	-0.771	0.943	0.94	.000
2. Primary Product				
A. Green - summer	-0.519	0.911	0.81	.000
B. Ovendry - summer	-0.717	0.914	0.81	.000
C. Green - winter	-1.083	1.042	0.96	.000
D. Ovendry - winter	-1.194	1.021	0.95	.000
3. Limbs and Tops				
A. Green - summer	-1.157	0.998	0.61	.000
B. Ovendry - summer	-1.354	1.001	0.59	.000
C. Green - winter	-0.552	0.727	0.43	.000
D. Ovendry - winter	-0.632	0.706	0.41	.000
B. White Oak Group				
1. Whole Tree Weight				
A. Green - summer	-0.445	0.946	0.87	.000
B. Ovendry - summer	-0.657	0.952	0.87	.000
C. Green - winter	-0.249	0.865	0.98	.000
D. Ovendry - winter	-0.341	0.839	0.98	.000
2. Primary Product				
A. Green - summer	-0.598	0.929	0.80	.000
B. Ovendry - summer	-0.810	0.935	0.82	.000
C. Green - winter	-1.067	1.051	0.96	.000
D. Ovendry - winter	-1.159	1.024	0.96	.000
3. Limbs and Tops				
A. Green - summer	-1.429	1.080	0.66	.000
B. Ovendry - summer	-1.641	1.086	0.65	.000
C. Green - winter	+0.121	0.557	0.34	.049
D. Ovendry - winter	+0.029	0.531	0.32	.056

Table 10-B: Hardwood Prediction Equations (2/80)
Oak-Hickory Type S. Cumberland Plateau
Ridge Top Sites

	Intercept	Slope	R^2	Signif.
C. Red Oak Group				
1. Whole Tree Weight				
A. Green - summer	-0.255	0.896	0.92	.000
B. Ovendry - summer	-0.535	0.919	0.93	.000
C. Green - winter	+0.153	0.769	0.87	.000
D. Ovendry - winter	-0.089	0.784	0.89	.000
2. Primary Product				
A. Green - summer	-0.430	0.895	0.87	.000
B. Ovendry - summer	-0.709	0.918	0.89	.000
C. Green - winter	+0.011	0.778	0.92	.000
D. Ovendry - winter	-0.233	0.793	0.92	.000
3. Limbs and Tops				
A. Green - summer	-0.645	0.858	0.63	.000
B. Ovendry - summer	-0.925	0.881	0.64	.000
C. Green - winter	-0.518	0.730	0.21	.020
D. Ovendry - winter	-0.762	0.746	0.21	.018
D. Hickory Group				
1. Whole Tree Weight				
A. Green - summer	+0.172	0.775	0.75	.000
B. Ovendry - summer	+0.076	0.756	0.69	.000
C. Green - winter	-1.000	1.046	0.97	.000
D. Ovendry - winter	-1.088	1.028	0.95	.000
2. Primary Product				
A. Green - summer	+0.108	0.741	0.68	.000
B. Ovendry - summer	+0.012	0.723	0.61	.000
C. Green - winter	-1.320	1.097	0.96	.000
D. Ovendry - winter	-1.411	1.079	0.95	.000
3. Limbs and Tops				
A. Green - summer	-0.724	0.886	0.57	.000
B. Ovendry - summer	-0.820	0.867	0.54	.000
C. Green - winter	-0.865	0.835	0.71	.000
D. Ovendry - winter	-0.956	0.817	0.68	.000

Example:

Mixed Hardwood 12 inches DBH, 60 feet tall

Predicted green weight in summer:

$LOG_{10}(Y) = -0.381 + 0.926\ (LOG_{10}8640)$

$LOG_{10}(Y) = -0.381 + 0.926\ (3.9365)$

$LOG_{10}(Y) = 3.264$

$Y = 1837$ pounds or 0.919 tons

2. Sawlog weight estimates

Eight equations were developed (see Table 11) for hardwood sawlogs of tree species associated with the oak-hickory type in the Southern Appalachian Region.

Table 11: Sawlog Weight Prediction Equations

SPECIES	Form	LBS/Cu.Ft.	A	B_1	B_2	B_3	R^2	SIG	CASES
Mixed Hardwoods	.85	62.9	.510	.491	.419	1.201	.78	.000	70
Red Oak	.87	69.4	.183	.746	.896	.835	.95	.000	10
White Oak	.75	68.0	-.381	1.060	.964	.961	.94	.000	10
Hickory	.85	58.5	.615	.354	.870	.813	.99	.000	10
Yellow Poplar	.86	63.2	.735	.745	.758	.461	.89	.000	10
Black Walnut	.90	62.9	1.902	-.632	.338	.564	.52	.050	10
Blackgum	.85	63.2	-.550	1.200	1.097	.811	.92	.000	10
Black Locust	.86	55.2	.331	.097	.796	.107	.67	.05	10

The general form of the equation is:

$$LOG_{10}(Y) = A + B_1(LOG_{10}X_1) + B_2(LOG_{10}X_2) + B_3(LOG_{10}X_3)$$

Where: Y= predicted weight in pounds
A= intercept
X_1= log length in feet
X_2= diameter small end of log outside bark (inches)
X_3= diameter large end of log outside bark (inches)

Example: Log 14.0 feet long
16.0 inches at large end
13.5 inches at small end

For Mixed Hardwood:

$$LOG_{10}(Y) = .510 + .491\ (LOG_{10} 14.0) + .419\ (LOG_{10} 13.5) + 1.201\ (LOG_{10} 16.0)$$

$$LOG_{10}(Y) = 2.993$$

$$Y = 983 \text{ lbs. or } 0.49 \text{ tons}$$

3. Total Utilization per Acre

To determine the potential amount of woody biomass available by using the modified harvesting system two hardwood stands were evaluated. The first stand was a well-managed, fully-stocked stand. Data were obtained from a simulation model at Virginia Polytechnic Institute and State University (Porter, 1979). The second stand was a 360-acre high-graded hardwood stand in Jackson County, Alabama, and data were obtained from sixty-four sample plots.

If a conventional harvesting system were modified to recover all woody biomass of trees eight inches (@D.B.H.) and larger, an increase of 58% in tons per acre could be realized in the fully stocked stand, and 59% in the high graded stand. If all trees, two inches (@D.B.H.) and larger were recovered, a net increase of 65% would be obtained from the fully stocked stand and 81% from the high graded stand (see Table 12), as compared with recovery from conventional operations.

Table 12: Percent Increase with Total Tree Utilization

Stand Condition	Diameter classes utilized	Number of trees/ acre	Woody Biomass Tonage/Acre			Percent Increase with wholetree Use
			Total tree	Primary Products	Residue	
Fully Stocked	7.0 inch larger	253	213	135	78	58%
Fully Stocked	All trees	431	224	135	83	66%
"High Graded"	7.0 inches larger	75	59	37	22	59%
"High Graded"	All trees	207	67	37	26	81%

D. Conclusions

Based on this study the following conclusions are drawn:

1. Utilization of total available woody biomass can increase wood supplies substantially. Production per acre can be increased 160% or more using whole tree harvesting systems as compared with conventional systems.
2. When using forest models for assessing harvest potential of stands or equipment feasibility, models should represent average stands, as opposed to fully-stocked ones. Fully-stocked stands are an exception rather than a typical occurance.

IV. ENERGY EFFICIENCY OF HARVESTING SYSTEMS

A. Introduction

Rapidly accelerating oil prices have caused increased awareness of energy conservation and renewed interest in wood energy utilization. Basic data to calculate fuel consumption of harvesting equipment is generally unavailable, and not until recently have equipment manufactures begun to provide the fuel consumption rate for their equipment. This report will provide interim data until extensive studies can be made.

B. Data Collection and Analysis

Harvesting managers and equipment manufacturers were asked to provide fuel consumption information for their equipment. Surprisingly some managers and manufacturers had no information available; some used only "rules of thumb" and others provided detailed information. Because of the types of materials received, strict statistical analysis could not be made; however, it was attempted to synthesize information available into meaningful information. Where possible, stepwise regression equations were calculated and presented.

C. Results and Discussion

Three basic types of information was developed:

1. fuel consumption rates for machine types on a per hour or per mile basis
2. fuel consumption to produce one ton of wood as delivered to a utilization point
3. net energy efficiency ratio comparing energy equivalent of wood produced (output) to amount of energy expended (input).

Fuel consumption includes engine fuel (diesel or gasoline), engine oil, and hydraulic fluid.

Machine types were divided into the following categories:

1. basic diesel engine
2. chainsaw
3. tractor, crawler (track under carriage)
4. tractor, rubber-tired (wheel under carriage)
5. yarder
6. "whole-tree" chipper
7. knuckleboom loader
8. truck
9. motorgrader
10. crane
11. welder

Machinery types were further divided by function performed and by horsepower. Harvesting systems were divided as follows:

1. shortwood - manual
2. shortwood - mechanized
3. longwood - manual felling
4. longwood - mechanized
5. wholetree - manual felling
6. wholetree - mechanized

Part I: <u>Fuel consumption rates for machine types on a per hour of per mile basis</u>

Figure 2 gives the fuel consumption for the basic diesel engine for static on load bench test and indicates average fuel consumption for applications in rubber-tired tractors for skidding and site preparation functions.

Figure 3 compares fuel consumption rates for a crawler tractors and rubber-tired tractors by horsepower for different functions.

Figure 4 shows the effect of age on fuel consumption of crawler tractors. As indicated, fuel efficiency becomes reduced with age, but the amount of reduction is machine specific and depends upon care and working conditions.

Figure 5, 6, and 7 lists average consumption rates for diesel fuel, engine oil, and hydraulic fluid for harvesting and support machinery. These are industry averages for actual equipment in the field and does not indicate consumption for different size engines or for individual manufacturers.

Figures 8 and 9 list average consumption rates for different classes of trucks.

FIGURE 2 : FUEL CONSUMPTION FOR DIESEL ENGINE

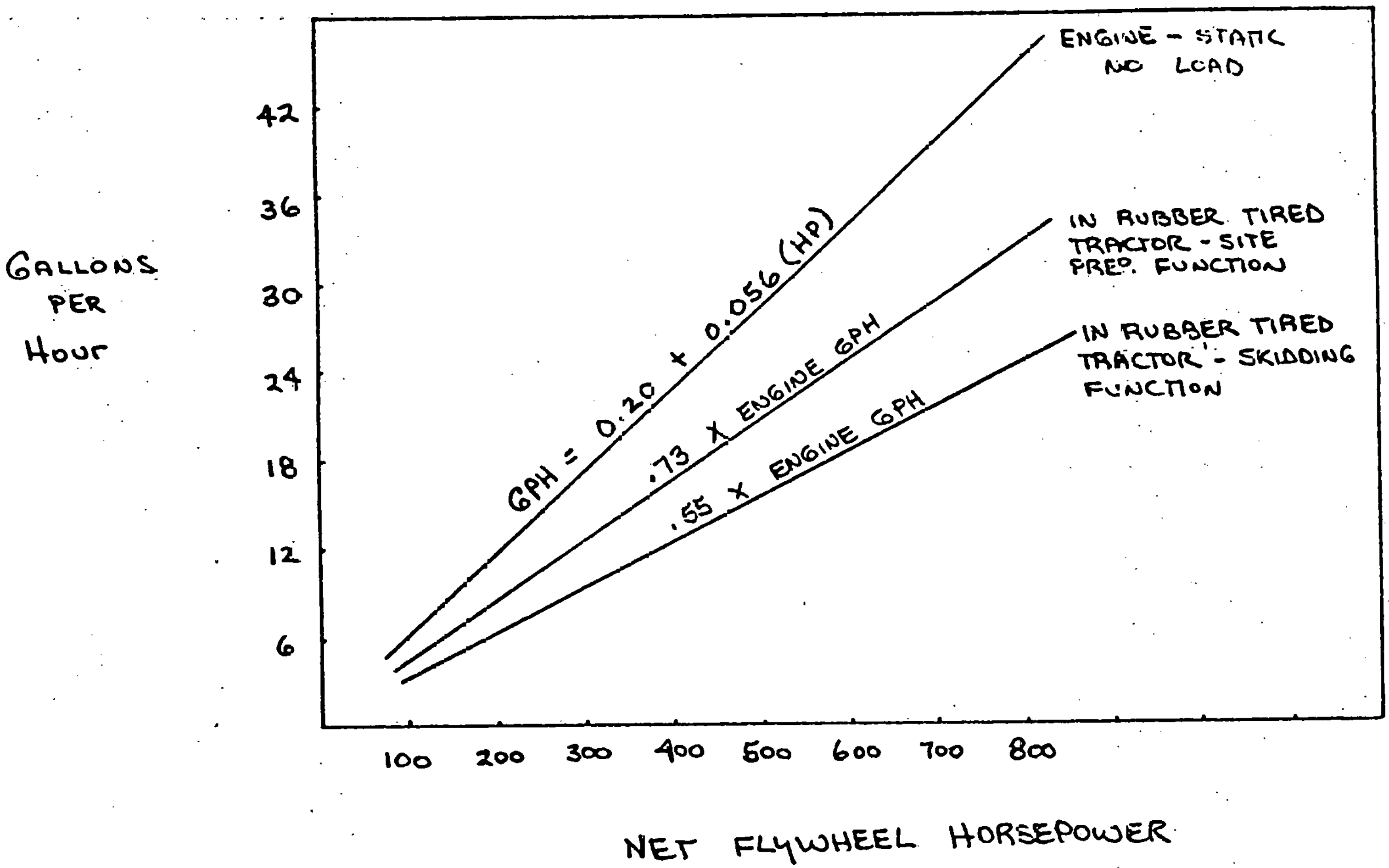


FIGURE 3 : FUEL CONSUMPTION FOR TRACTORS - TRACK AND Rubber TIRED

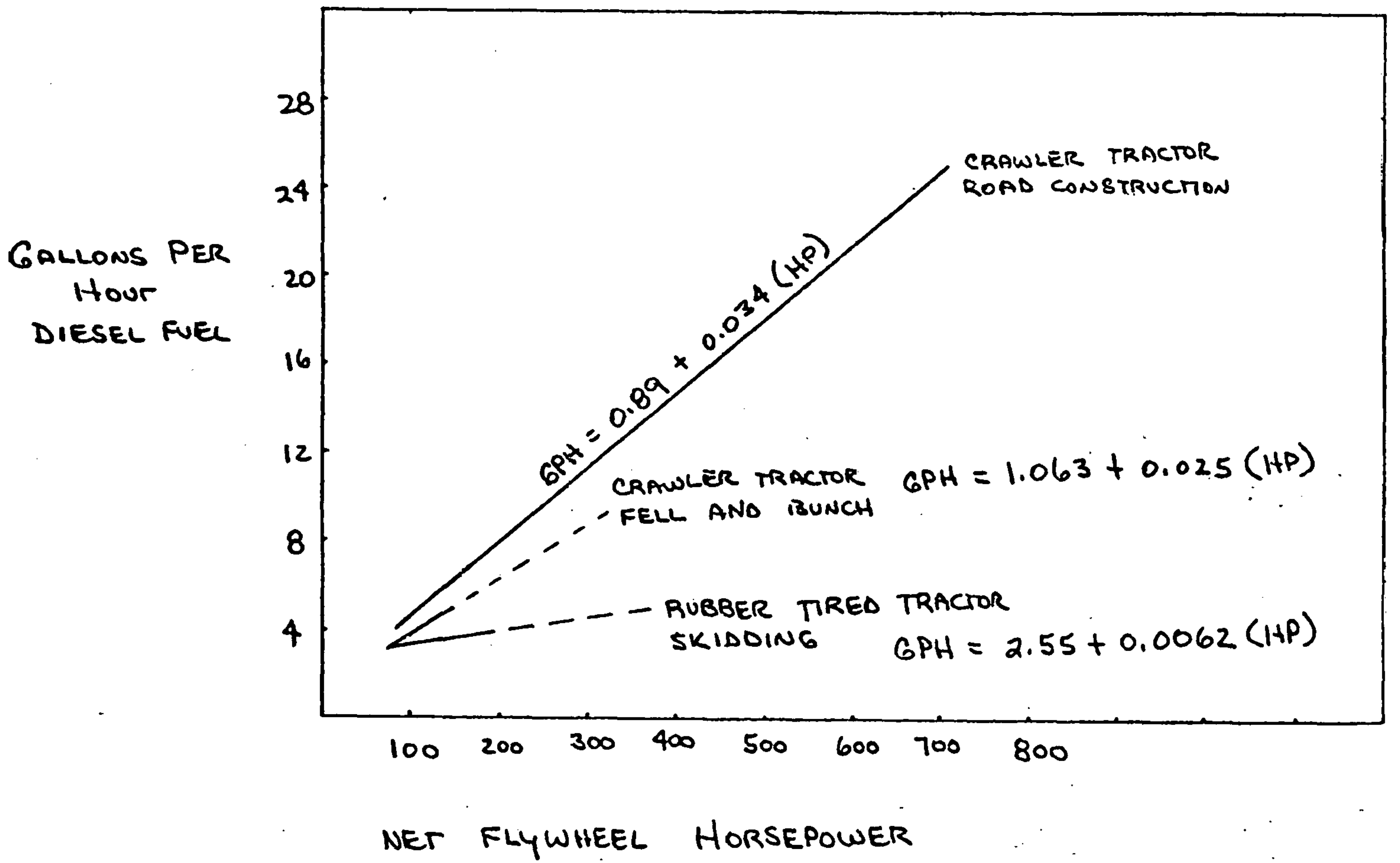


FIGURE 4 : THE EFFECT OF AGE ON FUEL CONSUMPTION OF CRAWLER TRACTORS

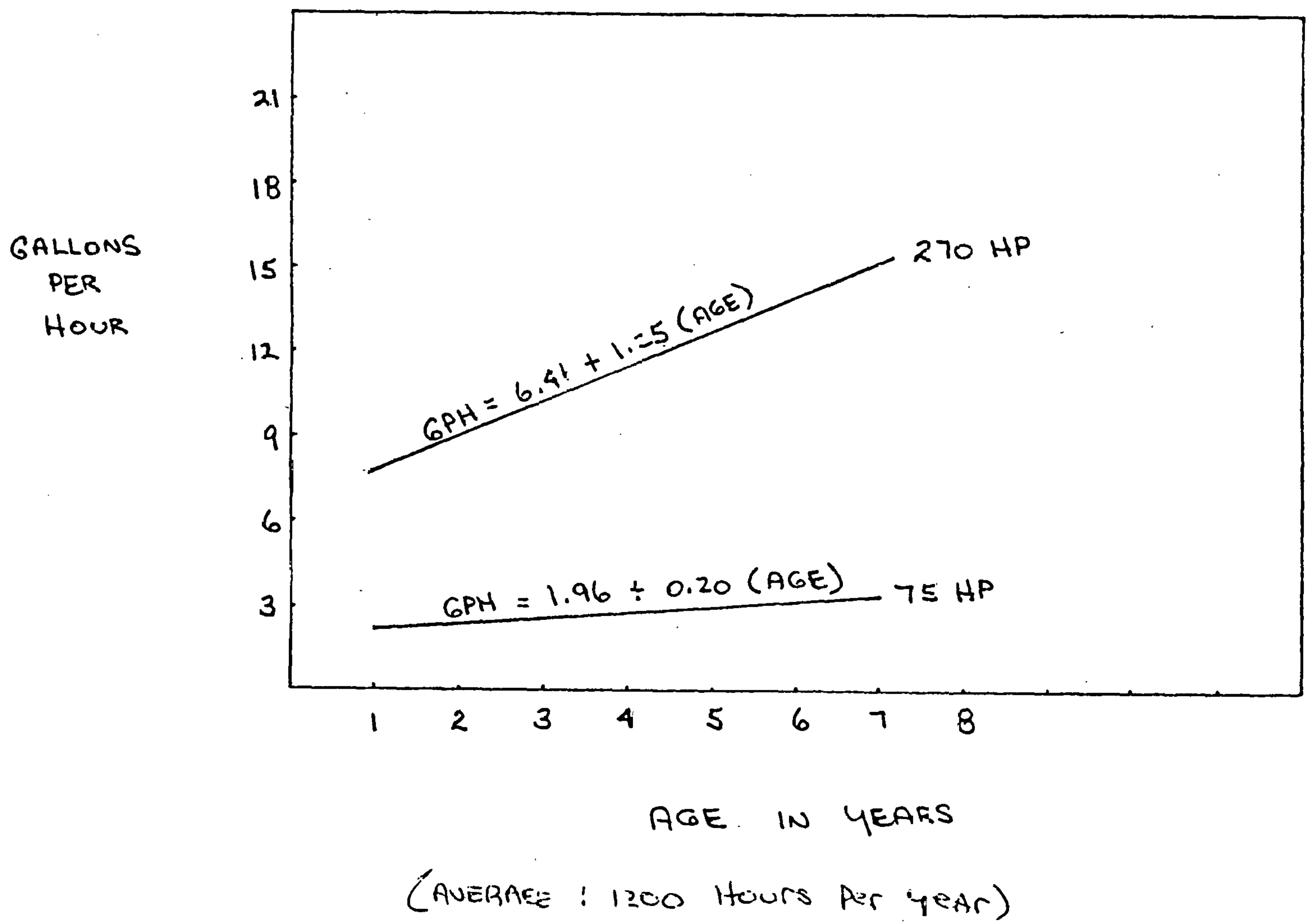


FIGURE 5 : FUEL CONSUMPTION FOR CONVENTIONAL HARVESTING AND SUPPORT MACHINERY

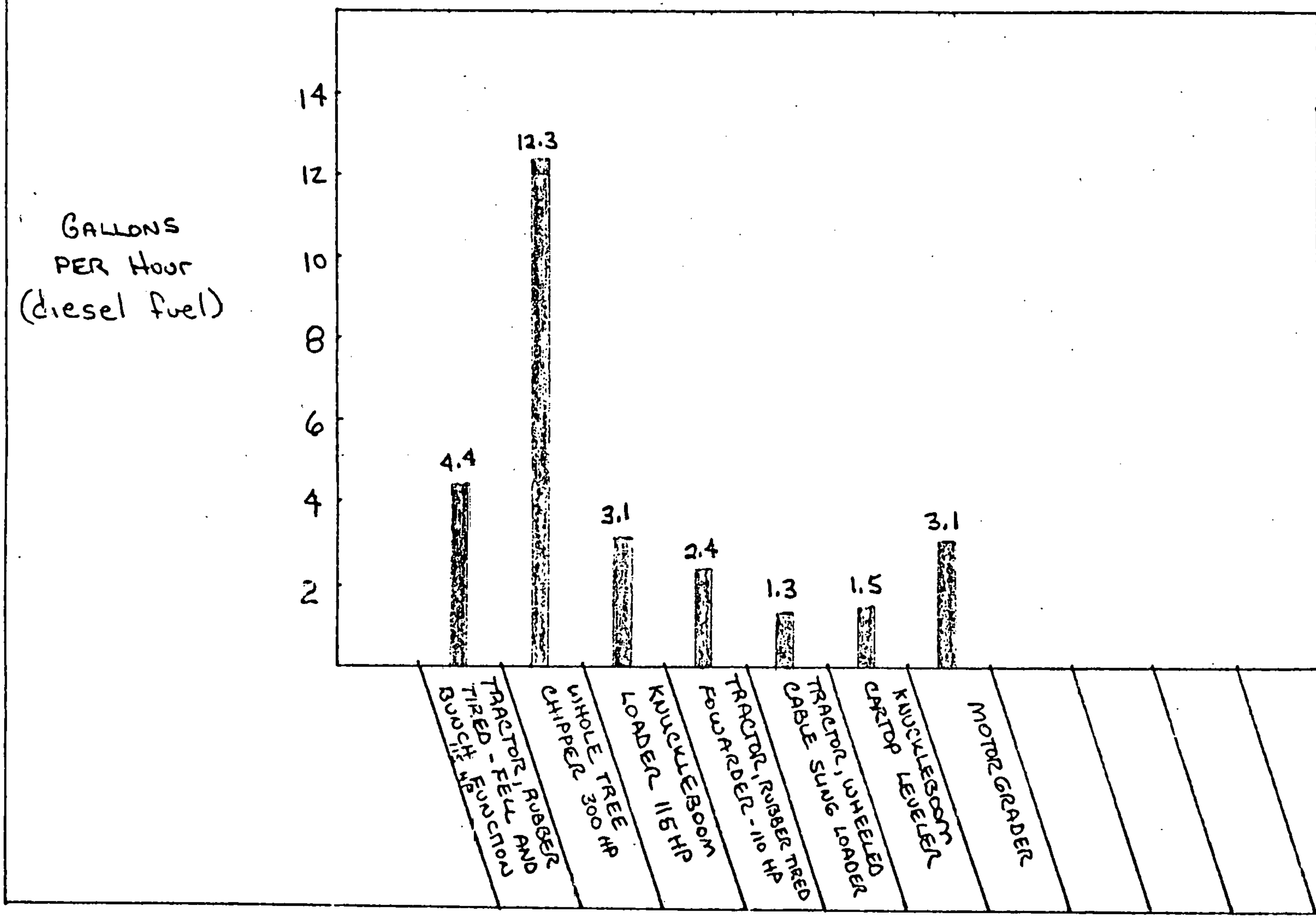


FIGURE 6 : ENGINE Oil CONSUMPTION FOR CONVENTIONAL HARVESTING AND SUPPORT MACHINERY

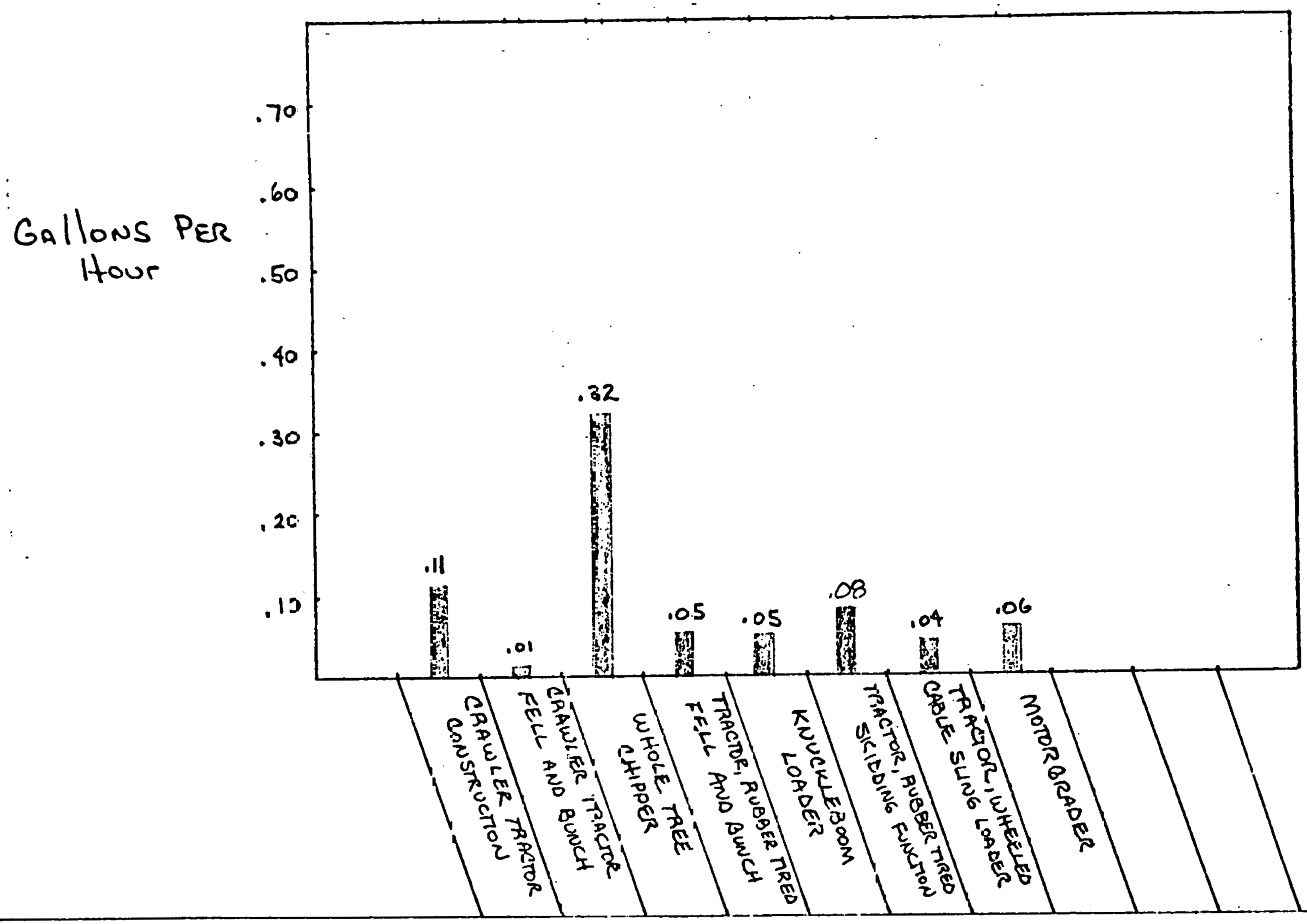


FIGURE 7 : Hydraulic Fluid Consumption for Conventional Harvesting Machinery

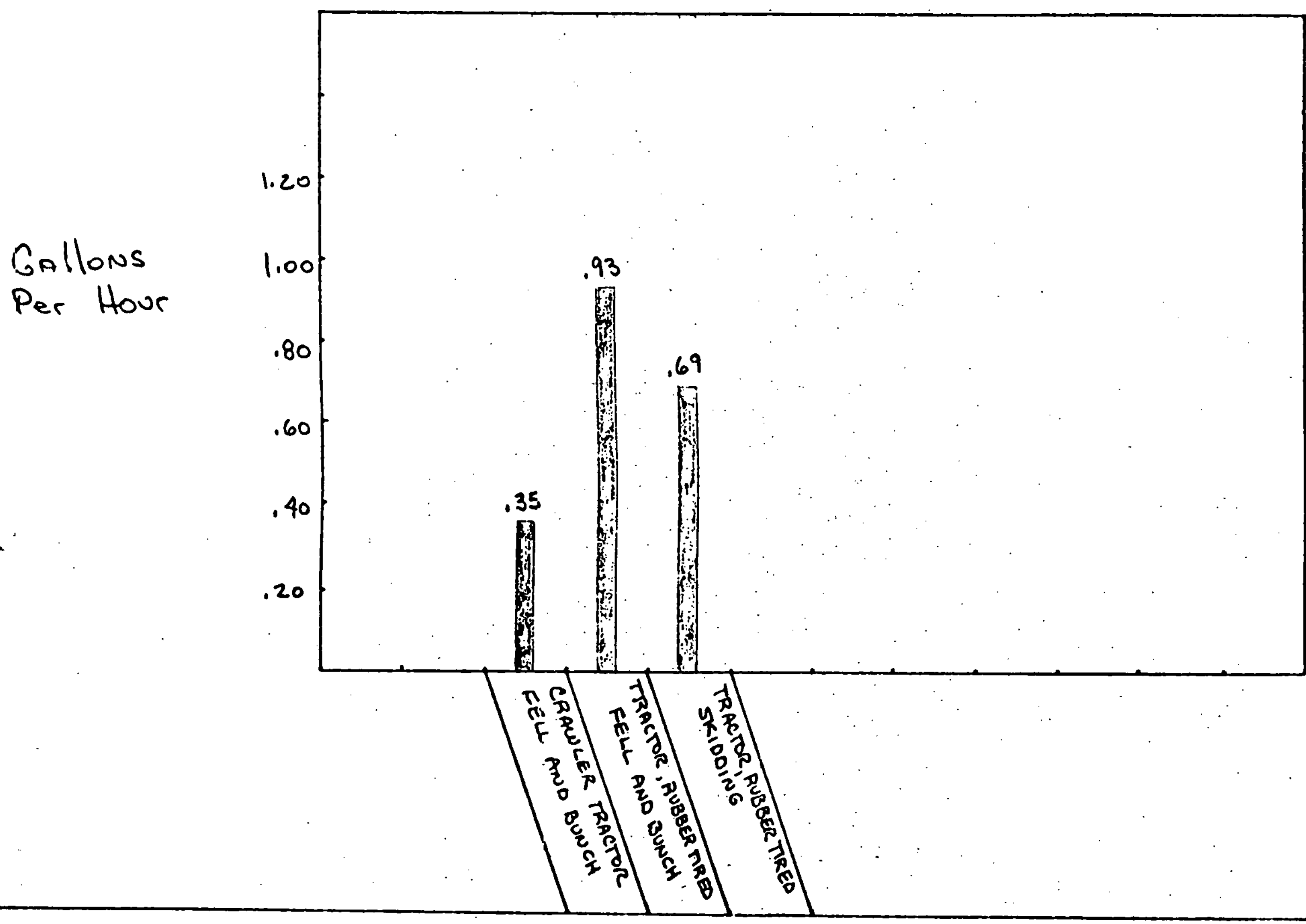


FIGURE 8 : AVERAGE FUEL CONSUMPTION FOR HAUL AND SUPPORT TRUCKS

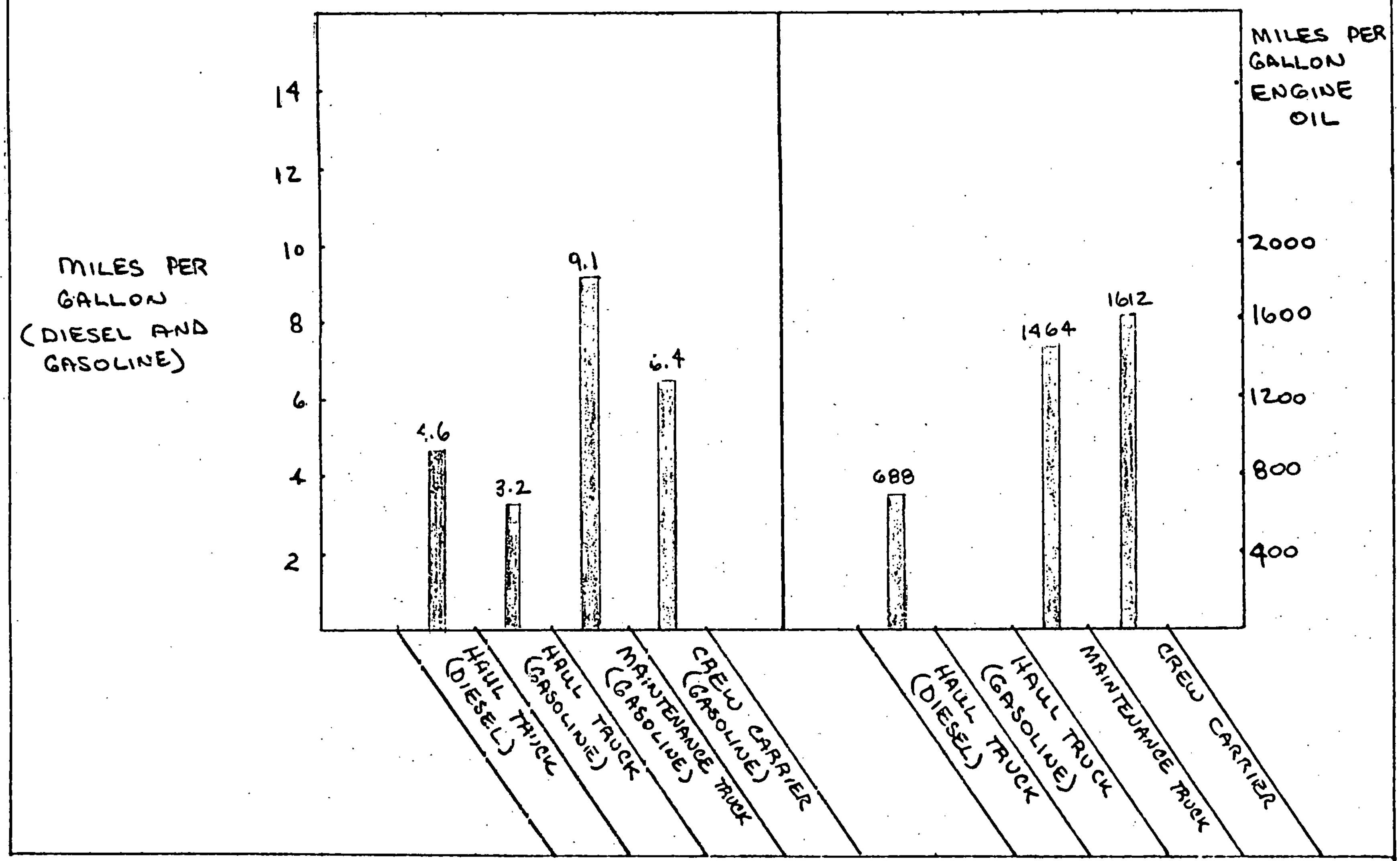
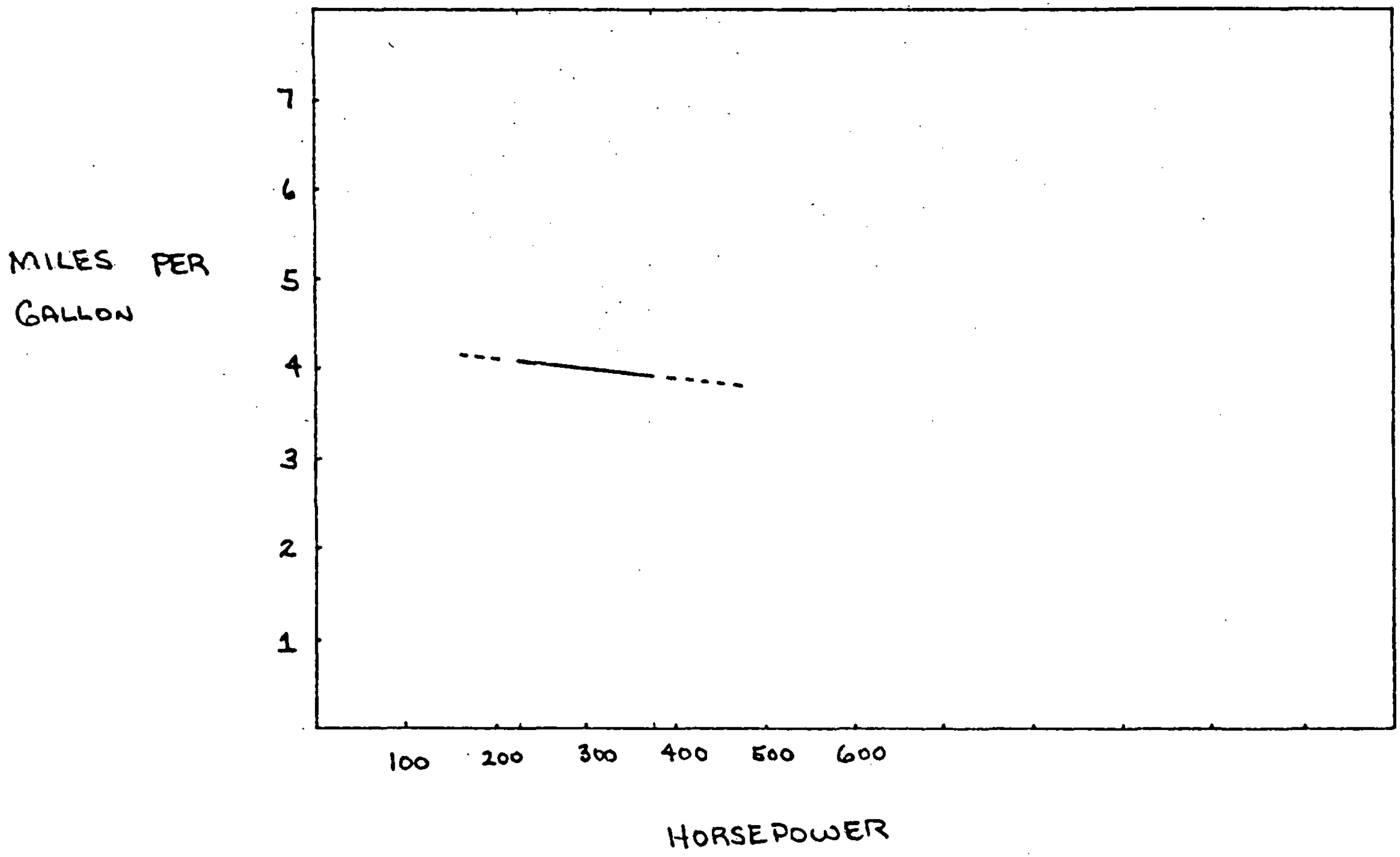


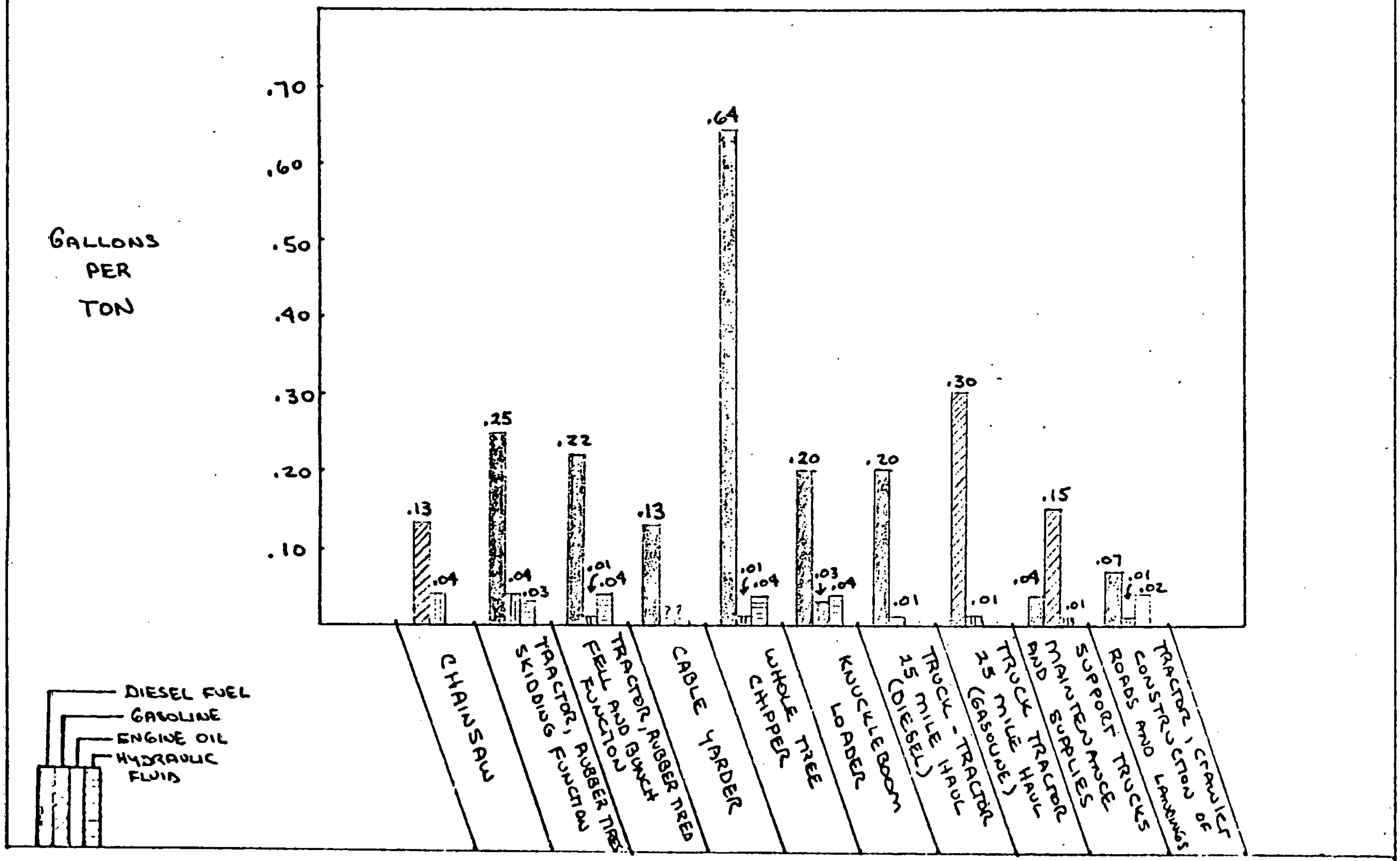
FIGURE 9 : FUEL CONSUMPTION FOR DIESEL TRUCKS IN HAULING FUNCTION



Part 2: Fuel consumption required to produce one ton of wood

Figure 10 lists average consumption of diesel fuel, gasoline, engine oil, and hydraulic fluid to produce one ton of wood. These are average figures and judgement must be used when applying these figures to actual situations. For example, support equipment would be less for manual shortwood systems then for fully mechanized wholetree systems; therefore, fuel consumption shown would be reduced when applying figures to a shortwood system. Wholetree chipping of hardwoods in winter would require approximately twenty-five percent more fuel than that indicated on the chart because of frozen wood and wetter conditions attributing to increased soil on logs. These figures represent an overall average for the industry.

FIGURE 10: FUEL CONSUMPTION REQUIRED TO PRODUCE ONE TON OF WOOD (50% MC)



Part 3: Net energy efficiency for conventional harvesting systems

Figure 11 shows the energy equivalent of wood produced as compared to the energy expended in petroleum products. This assumes a moisture content of fifty percent. Based on this assumption one pound of wood is equivalent to 4300 BTU's. The chart makes no allowance for further processing once the wood is delivered to a point of utilization. Detail equipment spread information is given in Table 13. Also, contained in Figure 11 is a comparison of actual efficiency rates for companies operating harvesting systems. To apply this to your particular system use Figure 10 to determine energy requirements for particular equipment spreads and Table 14 for BTU's equivalents.

Figure 11 compares the equivalent amount of BTU's of produced (output) to the amount of BTU's of petroleum used to produce a ton of wood (input). It does not take into consideration man hours or production rate to produce a ton of wood. It further does not consider the utilization efficiency of wood on a per acre basis.

FIGURE 11 : NET ENERGY EFFICIENCY FOR CONVENTIONAL HARVESTING SYSTEMS

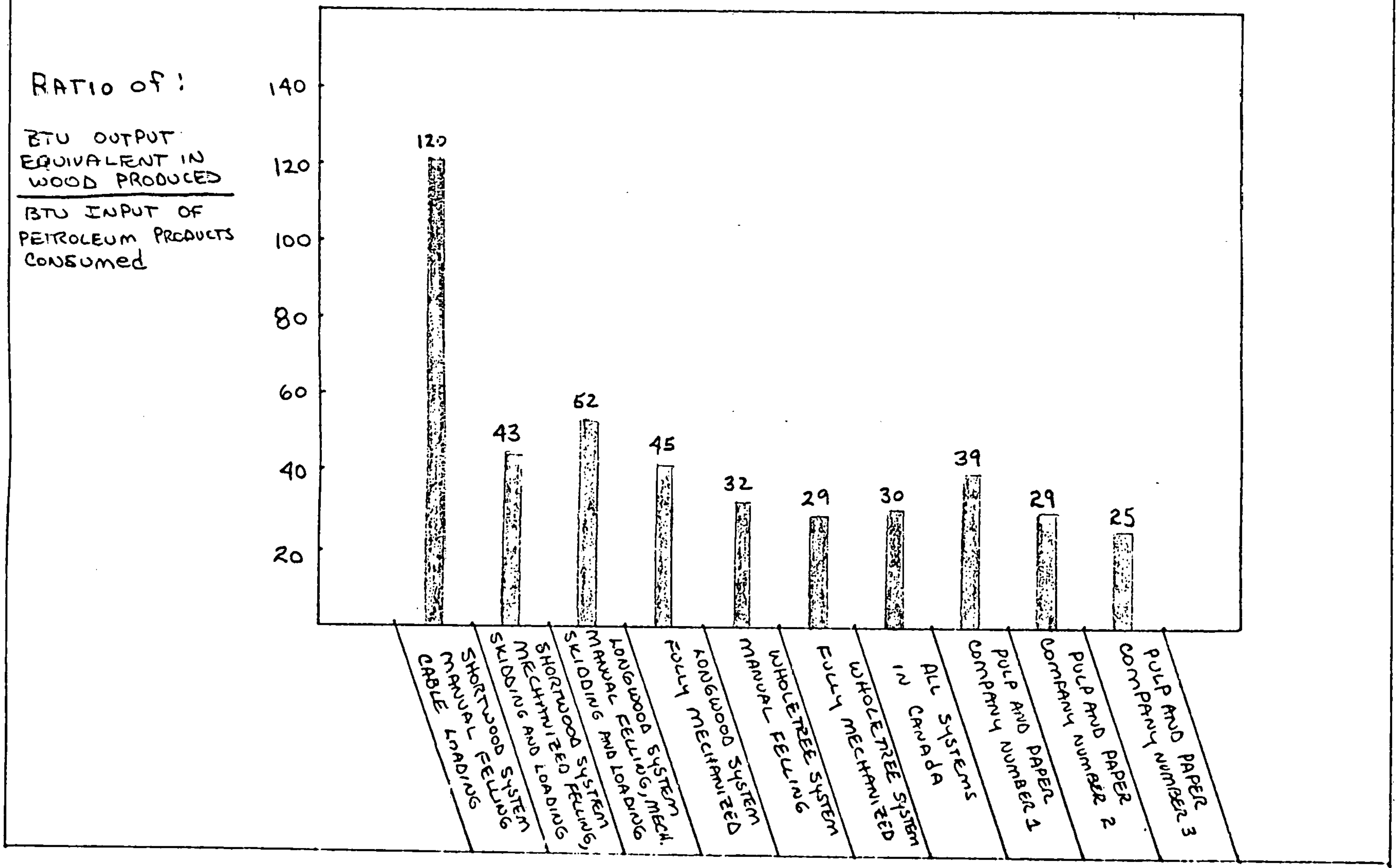


TABLE 13: Equipment Spread for Example Harvesting Systems

<u>Shortwood System</u>	
1. Manual:	Chainsaws Bob-tail truck Big stick loader
2. Mechanized:	Feller-buncher Rubber-tired skidder (tractor) Kunckleboom loader Support vehicles Truck-tractor (gasoline)
<u>Longwood System</u>	
1. Manual:	Chainsaws Rubber-tired skidder (tractor) Knuckleboom loader Support vehicles Truck-tractor (gasoline)
2. Mechanized:	Feller-buncher Rubber-tired skidder (tractor) Knuckleboom loader Support vehicles Truck tractor (diesel)
<u>Wholetree System</u>	
1. Manual:	Chainsaws Rubber-tired skidder (tractor) Wholetree chipper Knuckleboom loader Support vehicles Truck tractor (diesel)
2. Mechanized:	Feller buncher Rubber-tired skidder Wholetree chipper Chainsaws Knuckleboom loader Support vehicles Truck-tractor (diesel)

TABLE 14: Fuel Value Equivalents (Tenwolde and Stone, 1978)

	BTU's Per Gallon
Diesel Fuel	140,000
Gasoline	125,000
Engine Oil	140,000
Hydraulic Fluid	140,000

D. Summary

Information is presented to be used by harvesting managers to calculate approximate fuel consumption for harvesting equipment in the Southeastern United States. Judgement must be used in applying this information to specific circumstances; but charts presented can provide valuable information for management decisions both for budget planning and for equipment selection.

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