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Developing Switchgrass as a Bioenergy Crop

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DISCLAIMER

Developing Switchgrass as a Bioenergy Crop

The utilization of energy crops produced on American farms as a source of renewable fuels is a concept with great relevance to current ecological and economic issues at both national and global scales. Development of a significant national capacity to utilize perennial forage crops, such as switchgrass (Panicum virgatum, L.) as biofuels could benefit our agricultural economy by providing an important new source of income for farmers. In addition energy production from perennial cropping systems, which are compatible with conventional farming practices, would help reduce degradation of agricultural soils, lower national dependence on foreign oil supplies, and reduce emissions of greenhouse gases and toxic pollutants to the atmosphere (McLaughlin 1998) .

Interestingly, on-farm energy production is a very old concept, extending back to 19 th century America when both transportation and work on the farm were powered by approximately 27 million draft animals and fueled by 34 million hectares of grasslands (Vogel 1996). Today a new form of energy production is envisioned for some of this same acreage. The method of energy production is exactly the same - solar energy captured in photosynthesis, but the subsequent modes of energy conversion are vastly different, leading to the production of electricity, transportation fuels, and chemicals from the renewable feedstocks.

While energy prices in the United States are among the cheapest in the world, the issues of high dependency on imported oil, the uncertainties of maintaining stable supplies of imported oil from finite reserves, and the environmental costs associated with mining, processing, and combusting fossil fuels have been important drivers in the search for cleaner burning fuels that can be produced and renewed from the landscape. At present biomass and bioenergy combine provide only about 4% of the total primary energy used in the U.S. (0verend 1997). By contrast, imported oil accounts for approximately 44% of the foreign trade deficit in the U.S. and about 45% of the total annual U.S. oil consumption of 34 quads (1 quad = 10^{15} Btu, Lynd et al. 1991). The 22 quads of oil consumed by transportation represents approximately 25% of all energy use in the US and exceeds total oil imports to the US by about 50%. This oil has environmental and social costs, which go well beyond the purchase price of around $15 per barrel.

Renewable energy from biomass has the potential to reduce dependency on fossil fuels, though not to totally replace them. Realizing this potential will require the simultaneous development of high yielding biomass production systems and bioconversion technologies that efficiently convert biomass energy into the forms of energy and chemicals usable by industry. The endpoint criterion for success is economic gain for both agricultural and industrial sectors at reduced environmental cost and reduced political risk. This paper reviews progress made in a program of research aimed at evaluating and developing a perennial forage crop, switchgrass as a regional bioenergy crop. We will highlight here aspects of research progress that most closely relate to the issues that will determine when and how extensively switchgrass is used in commercial bioenergy production.

THE HERBACEOUS ENERGY CROPS RESEARCH PROGRAM

The Bioenergy Feedstock Development Program (BFDP) at Oak Ridge National Laboratory has been conducting research for the Department of Energy since 1978 to identify and develop fast growing trees and herbaceous crops as well as to evaluate the potential crop residues as sources of renewable energy the nation's future energy needs (Ferrell et al., 1995). The program is comprised of both a woody crops component, which has developed short rotation forest production techniques for selected woody species such as hybrid poplar, willow, and sycamore; and an herbaceous crops program that has focused primarily on switchgrass, which we will discuss here.

After screening more than 30 herbaceous crops species during the 1980s (Wright 1994), a decision was made in 1991 to focus the future BFDP herbaceous crops research on a high yielding perennial grass species, switchgrass, which combined excellent conservation attributes and good compatibility with conventional farming practices (McLaughlin 1992). Switchgrass is a sod-forming, warm season grass, which combines good forage attributes and soil conservation benefits typical of perennial grasses (Moser and Vogel 1995). Switchgrass was an important part of the native, highly productive North American Tallgrass Prairie (Weaver 1968; Risser et al. 1981). While the original tall grass prairies have been severely reduced by cultivation of prairie soils, remnant populations of switchgrass are still widely distributed geographically within North America (Stubbendick et al. 1981). Switchgrass tolerates diverse growing conditions, ranging from arid sites in the shortgrass prairie to brackish marshes and open woods (Hitchcock 1951). Its range extends from Quebec to Central America. Two major ecotypes of switchgrass occur, a thicker stemmed lowland type better adapted to warmer, more moist habitats of its southern range, and a finer stemmed upland type, more typical of mid to northern areas (Vogel et al. 1985). The ecological diversity of switchgrass can be attributed to three principal characteristics, genetic diversity associated with its open pollinated reproductive mode, a very deep well developed rooting system, and efficient physiological metabolism.

As an open pollinated species, switchgrass expresses tremendous genetic diversity, with wide variations in its basic chromosome number ($2n = 18$), typically ranging from tetraploid to octoploid (Moser and Vogel 1995). Morphologically switchgrass in its southern range can grow to more than 3m in height, but what is most distinctive is the deep, vigorous root system, which may extend to depths of more than 3.5 m (Weaver 1968). It reproduces both by seeds and vegetatively and, with its perennial life form, a stand can last indefinitely once established. Standing biomass in root systems may exceed that found aboveground (Shifflet and Darby 1985), giving perennial grasses such as switchgrass, an advantage in water and nutrient aquisition even under stressful growing conditions.

Physiologically, switchgrass, like corn (maize), is a C4 species, fixing carbon by multiple metabolic pathways with a high water use efficiency (Moss et al. 1969; Koshi et al., 1982). In general C4 plants such as grasses will produce 30 % more food per unit of water than C3 species such as trees and broadleaved crops and grasses and are well adapted to the more arid production areas of the mid-western U.S. where growth is more limited by moisture supply (Samson et al. 1993).

The challenges of the herbaceous crops research program have been to combine the near-term objectives of maximizing potential current economic yields with the longer term objectives of improving and protecting yields through breeding and biotechnology (Sanderson et al. 1996). Included among the former are evaluating performance of the best currently available varieties and determining optimum management regimes for increased production efficiency and environmental benefits. Breeding, tissue culture research, physiology, and molecular biology are components of the longer term objectives of improving switchgrass genetically.

The current switchgrass research program was initiated in 1992 with 7 projects implemented through collaborative research agreements at 5 university and two government laboratories. These projects have been augmented with additional breeding research at two locations, and with additional field testing sites at 6 U.S. Department of Agriculture, National Materials Testing Centers, which are implemented through the Natural Resources Conservation Service. The current network of research sites encompassing regional field trails and testing sites, breeding activities, and basic research on tissue culture and physiology/genetics is shown in Fig. 1. In the following sections, we highlight progress towards the objectives of evaluating and improving production of switchgrass for use as a bioenergy crop.

Field Trials and Management Research

Through a network of 18 field sites established in 1992, yields of a total of 9 switchgrass cultivars have been evaluated. These tests have included two basic harvest regimes, a single cut late in the growing season versus a 2-cut system with the first cut typically at the date of formation of seed heads, around July. Comparisons of yield performance among cultivars indicate that the most promising cultivars for bioenergy production are Alamo, for the deep South, Kanlow, for mid latitudes, and Cave-in- Rock for the Central and northern states. Alamo and Kanlow are lowland ecotypes, while Cave-in-Rock is an upland ecotype. Yield data from three years of field trials (Fig. 2) emphasize the regional specificity of optimum cutting practices. In field trials, highest yields have typically occurred with the 2-cut system at VPI and Auburn study sites, while in Texas, where drought has been a frequent problem, the 1-cut system has been superior. Average yields of the best cultivar at each location were approximately 16 Mg/ha (7 dry tons/acre), while maximum yields at any plot within each of the 3 testing regions were typically $\geq$ 20 Mg/ha. We believe that the poor performance of the 2-cut system in Texas reflects the effects of cutting on persistence of deep roots, which would represent an impediment to late season water uptake under drier growing conditions.

Maintenance of a deep rooting system appears to be a key consideration in the management of switchgrass and a potential source of ultimate superiority of the 1-cut system in variable climatic regimes and over time. Our continuing research with 1 and 2 cut systems in Alabama indicates that, proper timing of the 1-cut system can be critical to yields attained as shown in Table 1. Here 1 cut and 2-cut systems yielded essentially the same biomass over a five year cutting cycle (approximately 27 Mg/ha-y), and the influence of timing of the first cut of the 2-cut system on yield attained is readily apparent. Additionally, the later harvests of switchgrass have generally lower ash contents (Sanderson and Wolf 1995). This is apparently associated with with retranslocation of mobile nutrients, such as K, P, and N, and carbohydrates and storage in crowns and root systems later in the growing season as plants approach senescence. This apparently contributes to the relatively low nutrient requirements of switchgrass. It also reduces ash content of the feedstock making it more acceptable for use for combustion endpoints where boiler slagging of high ash fuels can be a problem (Miles et al 1993 ; McLaughlin et al 1996;). The reduction in ash content, which includes parallel reductions in potassium, an important contributor to slagging, can also be attributed to increasing proportions of stem relative to leaf mass later in the growing season. Changes in tissue ash content are shown in relationship to the length of growth period (expressed as degree days) in Fig. 3.

Attaining consistent establishment results with switchgrass is a prerequisite for rapid scale-up of switchgrass production and therefore an important research priority. As a light seeded species, it is sensitive to proper planting depth (approximately 0.6- 1.2 cm), firm seed bed establishment, and control of weeds during the first growing season, particularly if planted before warm temperatures allow it to compete well with cool season weeds (Wolf and Fiske 1995). Weed control is typically attained by a single application of herbicide during the establishment year. In addition, high levels of seed dormancy, which can be removed by stratification or allowing adequate time for afterripening, must be considered in providing adequate germinable seed at planting (Wolfe and Fiske 1995). Because switchgrass allocates so much energy to root establishment, stands typically are not harvested during the first growing season, reach 2/3 of their capacity during the second year and full yield potential by the third year. Research at VPI has identified significant advantages to early establishment success by incorporating an insecticide at planting. With this as a component of prescribed planting instructions VPI was able to achieve 100% establishment success in a 20 farm field trial.

Nitrogen management is an important component of any non-leguminous cropping system, but it is particularly important for bioenergy systems as nitrogen is an important cost energetically, economically and, potentially ecologically, as a contributor to air and stream pollution. "Standard" practices for switchgrass have called for $\leq$ 50 kg of N during the first year after switchgrass emergence, followed by 80-100 kg/ha thereafter (Wolf and Fiske 1995). Our research has included these and much higher rates in the search for an optimum balance between costs and yield. To date positive yield responses have been found up to and including 224 kg N/ha-y, however we suspect that long term yield stability and economics will be favored by lower annual or even longer interval applications of N, particularly where a single annual harvest is used. Data in Table 2, compare yields and nitrogen utilization rates of 1 and 2-cut systems from the Knoxville test location within the VPI system. An important feature of these data is that total N use was reduced by approximately 2/3 with the single cut system in all three cultivars examined. Interestingly, while single cut harvests removed only about half of the 110 Kg/ha N supplied, two cut systems removed 50% more than was supplied. Since some weakening of the integrity of the single cut stands was beginning to appear during the 1995 season, nitrogen has been withheld during each of the last two growing seasons. Data analyses are not yet complete, however, early indications are that much lower N levels can be applied once stands are fully developed. This can be attributed in part to the level of root growth and the accumulation of soil carbon under perennial grasses as noted in studies in the Soil Conservation Program (Gebhardt et al. 1994).

An additional consideration is the establishment of soil flora and fauna that are a part of nutrient cycles of perennial agricultural systems. Switchgrass is a mycorhizzal species, with dominant site-adapted mycorrhizal populations that stimulate growth, as BFDP-sponsored studies in Nebraska have indicated (Brejda 1996 and Brejda et al. 1998). How long these take to establish to their full potential is not known and how important other microbial components involved in mineralization of soil organic carbon produced by switchgrass root turnover is not known. There is evidence that switchgrass can also apparently gain some nitrogen through fixation by associative soil bacteria (Tjepkema and Burris 1975). Thus establishment of an active mycorhizzal root system and the associated microbial community may take time to develop and may also be inhibited by high nitrogen application. We consider improved understanding of the nitrogen economy of switchgrass to be an important research priority in energy crops production and are pursuing ways to improve nitrogen utilization rates with lower and optimally-timed nitrogen application rates.

Breeding for Improved Yield

To date switchgrass has been bred primarily to enhance its nutritional value as a forage crop for livestock (Vogel et al. 1989). Thus, it has been managed primarily as a hay crop for which high leaf to stem ratio and high nutrient content are important. These targets are quite different from the criteria for biofuels crops for which high cellulose and low ash content are important for high energy conversion and low contamination of combustion systems, respectively. Earlier efforts to optimize both productivity and forage quality for livestock, and hence versatility of switchgrass led to the release of a new variety "Shawnee" (Vogel et al. 1996). More recently, switchgrass breeding in the BFDP has included basic research on the phenology, genetics, and breeding characteristics , combined with multiple breeding approaches designed to improve switchgrass productivity as rapidly as practical. A nursery containing 110 switchgrass accessions from both existing genetic reservoirs as well as wild collections around the country has been assembled and characterized at Oklahoma State University (OSU). Genetic characterization has revealed that lowland switchgrass varieties are predominantly tetraploid (2n = 4x = 36 chromosomes) while upland varieties are predominantly octoploid (2n = 8x = 72 chromosomes) (Hopkins et al. 1996). In addition two cytoplasmic types occur and are differentiated between upland and lowland ecotypes (Elmore et al. 1993 and Hultquist et al. 1997, 1998). Our studies have documented that self fertilization in switchgrass is very low (around 1-2% seed set), that hybridization potential between plants of different ploidy levels is very low (<0.5%), but that plants of the same ploidy level can usually easily be intercrossed regardless of ecotype (Taliaferro and Hopkins 1996; Taliaferro et al. 1996). Switchgrass varieties tested to date have been found to have a high tolerance of acid soil conditions with a low heritability of this trait (Hopkins and Taliaferro 1997), thus breeding for acid tolerance has not been pursued. Asexual seed production in switchgrass has not been detected to date in our collection of over 100 accessions.

Switchgrass breeding research over the past few years has provided new information to help identify the approaches most likely to provide the greatest genetic gains. In an effort to maximize and systematically evaluate the rate of genetic gains, initial breeding research at OSU focused on completing annual cycles of Recurrent Restricted Phenotypic Selection (RRPS) within four breeding populations. RRPS is a breeding system that has been highly effective in improving forage yields of other warm-season grasses (Vogel and Pederson 1993) . It provides a means of increasing the representation of genes associated with phenotypic expression of desirable trait , for example, high yield. Populations selected for RRPS were comprised of the best available cultivars of upland and lowland ecotypes selected primarily from the central and southern Great Plains. Earliest efforts to speed the breeding process used detached flowering shoots to intercross 30-50 plants (5 % selection index) visually judged to have the highest biomass production. The plants were selected and intercrossed near the end of the establishment growing season. Field stratification was used to minimize the effects of soil variation. Half sib seed from 25% of the visually selected plants was discarded after biomass yields of the plants that had been visually selected and crossed were subsequently verified at harvest. Three RRPS cyclic generations plus a narrow-genetic base synthetic cultivars were evaluated for performance for 2 years at Perkins, Oklahoma (Table 3). Genetic gains were indicated in all Northern Lowland (NL) RRPS cyclic populations and in the NL and southern upland (SU) synthetics.

However deficiencies in the RRPS procedure, as a tool for yield improvement in switchgrass, were identified early in the program. A major constraint was inconsistency in attaining adequate seed set on detached flowering stems of selected plants. A second constraint was relatively low correlation between biomass yields of plants in the establishment year vs subsequent years. Though correlations were positive and often statistically significant, strong environmental influences on plant development were evident, particularly during the year of establishment. The importance and costs of developing a strong root system to growth and survival of young switchgrass plants apparently results in variations in aboveground growth during the establishment year that reduce its effectiveness as an indicator of longer term yield potential. In addition, studies indicated that the performance of half-sib progeny lines is a stronger indicator of the breeding value of individual plants than is the yield performance of the plants themselves. This realization has led the OSU program to place a greater emphasis on evaluation of genotype performance relative to the phenotype performance upon which RRPS is based.

Current breeding approaches include both genotypic and phenotypic recurrent selection in broad-genetic base populations combined with the development of narrow-genetic based synthetic cultivars. The synthetic cultivars are produced by intercrossing two or more elite parental plants. The parental plants are usually extracted from the broader base breeding populations. Genotypic recurrent selection under low- and high-yield environments is being evaluated at OSU to determine the effects of selection environment on the performance stability of cultivars developed from those breeding populations. This is an important issue in providing switchgrass varieties that can be planted on the marginal lands where conventional crops provide only marginal economic returns. Research is underway in Oklahoma and Nebraska to determine if heterosis occurs for biomass yield in first generation single- and double-cross progeny populations. The development of the laboratory culture techniques later described, plus the strong self-incompatibility of switchgrass, make possible the development of hybrid varieties. The economic feasibility of doing so depends on the added performance of the cultivars relative to standard cultivars. High performing hybrid cultivars capitalize on heterosis conditioned by dominance and by the control of multiple traits by a single gene (epistasis). Additional breeding approaches include a novel honeycomb selection design (Fasoulas and Fasoula 1995) being used at the University of Georgia that allows one to select superior plants in the field while considering both genetic and plant-environment interactions.

Basic Research on Propagation Techniques, Physiology, and Molecular Genetics

Research on tissue culture techniques for clonal reproduction of parent plants, physiological measurements of differences in foliar gas exchanges rates , and molecular fingerprinting constitute the tools with which we are trying to augment breeding activities, by gaining basic understanding of fundamental attributes of switchgrass biology.

Tissue Culture Technology. From a starting point of having no existing published protocols for switchgrass tissue culture regeneration, significant advances in developing such technology have been made in this program (Denchev and Conger 1993, 1994, 1995; Alexandrova et al. 1996a, 1996b). At present hundreds of plantlets can be produced from a single parent plant and brought to field-ready status in a period of three months. The recent development of techniques for production of suspension cultures should significantly enhance that capability (Dutta, Gupta, and Conger 1999). These techniques now make possible rapid development of isolated breeding blocks of superior plants for developing narrow genetic base synthetics as well as F_1 hybrids. This technique is currently being used at the University of Tennessee to test genetic gains from crosses involving clonal breeding blocks derived from 2, 4, or 20 elite parents of the variety Alamo.

In addition to its use in clonal propagation for breeding, production of tissue culture plantets and organ-specific differentiating tissues, including flowers as shown in Figure 3 (Alexandrova et al. 1996a), provides new tools to explore genetic transformation in switchgrass (Denchev and Conger 1996). Having such tools in place will be important in incorporating into existing switchgrass varieties new genes that can protect and improve growth or increase resistance to environmental stresses. Collaborative research has already begun to evaluate the feasibility of incorporating growth-enhancing promoters into switchgrass through transformation.

Molecular Genetics. Characterizing the molecular biology of switchgrass through the use of Randomly Amplified Polymorphic DNA (RAPD) markers is being used to provide a tool with which we can develop genetic fingerprints of existing and newly developing switchgrass lines (Gunter et al. 1996). The use of DNA markers as a tool has several uses including defining resident locations of genetic variability within the existing population of switchgrass, tracking the effects of genetic enhancement through breeding on genetic signatures, and examining the genetic stability and variability of switchgrass among commercial seed sources. A final application is the definition of the genetic stability of switchgrass stands as they develop over time in field plantings. To date, RAPD analyses have been used to develop a phylogenic diagram delineating genetic linkages among 18 existing switchgrass accessions in the OSU germplasm nurseries and to identify one low-fidelity commercial seed source for Alamo switchgrass. Studies of genetic drift in field plantings and of seed source variability are continuing.

Gas Exchange Physiology. Measurements of switchgrass foliar physiology, isotopic fractionation of carbon isotopes, and nitrogen uptake have been examined in an effort to provide indicators of resource utilization efficiency that could be used to improve understanding of the capacity of switchgrass to adapt to diverse environmental conditions. Such information can also be and as a potential tool for screening accessions in breeding research. To evaluate variability in leaf physiological potential, gas exchange measurements were obtained for individuals leaves of 25 native accessions of switchgrass and two commercial varieties planted at the OSU germplasm nursery. Significant differences were observed among populations for photosynthesis (P=0.003), transpiration (P=0.001), and water use efficiency (P=0.001) (Wullschleger et al. 1997). Leaf level photosynthetic rates varied by almost a factor of two across accessions, from a high of 30.8 umole /m^2 /s to a minumum of 17.5 umole/ m^2 / s. Water use efficiency, a potential indicator of growth potential under reduced water supply ranged from 2.08 - 3.77 umole CO_2 / mmole H_2O. While higher leaf photosynthetic rates have been found with the faster-growing lowland cultivars in field studies in TX and VA (Sanderson et al., 1995), Wullschleger et al (1996) determined that differences between upland and lowland ecotypes were seasonally and environmentally dependent. During a very dry period in 1993, upland cultivars showed less reduction in photosynthetic rates than their lowland counterparts, reversing the differences among ecotypes observed under more favorable moisture supply earlier in the season.

In subsequent studies, carbon isotope discrimination d13C values were found to be rather constant (-14.6 per mil to -13.1 per mil) across accessions with no statistically significant differences among ploidy levels or ecotypes (Wullschleger et al. 1998), gas exchange physiology was not found to be statistically different between ploidy levels or ecotypes. Additionally leaf nitrogen levels, while they varied widely across accessions (1.33% to 2.25%), did not differ significantly among ecotypes or ploidy levels.

Collectively these measurements indicate that, while differences in single leaf physiological attributes are related to growth potential, the way in which they are integrated at the whole plant level in switchgrass is complex. They are most likely controlled strongly by the seasonal dynamics and plant-to-plant variations in plant and stand-level canopy architecture and allocation patterns that control the distribution of resources between shoots and roots.

Belowground Biomass and Soil Carbon and Nitrogen Dynamics - Allocation of energy to an extensive rooting system is an extremely important aspect of the ecological adaptability, yield potential on marginal sites, and the soil conservation attributes of switchgrass. These attributes are related to nutrient and water uptake potential on degraded agricultural soils, nutrient use efficiency in capturing the benefits of applied fertilizers, and the effects of root growth and turnover on increasing soil carbon, improving soil texture and reducing soil erosion. Profiles of root distribution across 8 locations examined by VPI indicate that live root mass averaged 14.9
Mg /ha in the top 30 cm of the soil profile - approximately 2/3 of the annual harvest of aboveground biomass from these same plots. The maximum root biomass was found in shallow soils in plots in West Tennessee, and at 18.6 Mg/ha exceeded aboveground production at that site by approximately 50%.

As with most plant systems, root production in the surface soils is a predominant feature of switchgrass development and VPI studies indicate that approximately 50% and 75% of switchgrass roots in the top 90 cm of soil can be found in the the top 15cm and 30cm of the soil profile, respectively. We have analyzed soil carbon gains in the surface horizons across a total of 13 research plots to date to document anticipated increases associated with root turnover and mineralization by switchgrass. These include measurements made after the first 3 years of cultivation in Texas, and after 5 years of cultivation in plots in Virginia and surrounding states.

Preliminary analyses indicate that carbon gains will be comparable to, or greater than the 1.1 MgC/ha-y gains reported for perennial grasses, which included switchgrass, in studies in the Conservation Reserve Program (Gebhardt et al. 1994). Additional studies are ongoing to document gains across deeper profiles and to standardize measurement protocols and minimize sampling variability across sites.

The issue of soil carbon gains and carbon turnover rates has become one of particular importance to energy crops for several reasons. First, soil carbon is well recognized as an extremely important determinant of soil fertility, as it controls both water and nutrient retention and lightens the texture of soils thereby promoting aeration, drainage of excess water, and root growth (Reeves 1997). This is an important issue because energy crops have the potential to improve the quality of agricultural soils depleted by decades of poor cropping management (McLaughlin et al. 1994). In this capacity they qualify as appropriate vegetative cover for fulfilling the soil conservation objectives of the Conservation Reserve Program. For this reason permission had been sought from the USDA and granted for use of existing grasses on 1600 ha of CRP lands as feedstock for power production co-firing tests in Iowa (the Chariton Valley Project). Ultimately plans call for replanting addtional acreages to high yielding switchgrass varieties that will improve the economics of bioenergy production on these lands.

The second issue tied to carbon increments and stability in the soil is that of global climate change. The approximately 30% increase in atmospheric carbon that has occurred during the last century is an important component of a global climate warming trend that is now well established (Thompson 1995; IPCC 1998). The importance of global climate change and the approximately 6 Gigatons (10^9 Mg) of anthropogenic inputs of carbon that enter the atmosphere each year has led to an international plan of reduced carbon emissions formulated in Kyoto, Japan, in 1997. Among the strategies being considered for reducing net increases in atmospheric carbon is increased reliance on energy crops, such as switchgrass, which can both displace fossil carbon inputs, with contemporary carbon removed from the atmosphere, as well as sequestering carbon in soils (Romm et al. 1998; McLaughlin and Walsh 1998).

Increases in soil carbon storage with perennial species offers the possibility of achieving added economic incentives derived from soil carbon storage credits. Isotopic and soil carbon fractionation studies being conducted at Oak Ridge National Laboratory (Garten and Wullschleger 1998) are being conducted to document and better understand the relationship of such gains in soil carbon to long term carbon storage potential. Characterization of the relative amounts of labile and non-labile carbon in the soil pools is being used to provide an indication of the expected longevity of incremental additions to soil carbon pools. In these studies, estimation of the rate of addition of root-derived carbon identified by its isotopic signature, to existing soil carbon pools has provided a preliminary estimate of 25-45 years for the turnover time for carbon derived from switchgrass roots.

EVALUATING THE COMMERCIAL POTENTIAL OF SWITCHGRASS

Bioenergy Markets and Sources

Production of transportation fuels, such as ethanol, and generation of electrical power are the two primary markets for bioenergy. The current biofuels industry in the U.S. is based almost entirely (98%) on conversion of corn to ethanol (Petrulis et al. 1993). At present 1.3 million hectares, approximately 6% of the United States' corn crop, is used in production of approximately 1 billion (B) gallons of ethanol each year. Estimates of future corn production of ethanol have been as high as 5 B gallons per year with potential net benefits to agricultural income of over $1 billion to U.S. farmers (House et al 1993). However, recent analyses suggest that it is unlikely that corn can supply more than 2-2.5 B gallons of ethanol annually because of competing demands for corn. How much this figure will actually increase in the future depends largely on the success of agricultural, economic, and industrial research currently underway, including the development of markets for energy crops. A major consideration in the role that energy crops can play in achieving the goals of improved energy self sufficiency is their efficiency in displacing fossil fuels, a value closely tied to net energy returns. Recent calculations of the net energy gains from ethanol production from a forage crop like switchgrass indicate that both net energy savings and net carbon savings will be achieved much more rapidly than with more energy-expensive processes such as conversion of corn grain to ethanol (McLaughlin and Walsh 1998).

There are two principal sources of biomass-based renewable energy for these fuels - wastes and residues from agriculture and forestry and dedicated energy crops. Wastes such as wood and agricultural residues, municipal wastes, and poultry litter are now typically less expensive to supply to endpoint users, and will likely play an important role in early development of renewable energy supplies. However analyses of future demand for renewable energy indicate that these wastes may be capable of supplying only 14-30% of the total potential production of cellulosic ethanol and only approximately 18-60% of the production potential that could be derived from producing energy crops on currently idled or potentially available agricultural lands (Lynd et al., 1991). Thus dedicated energy crops will be required to meet the demands of a growing renewable energy market. Such crops, grown in the vicinity of the endpoint industrial user and specifically for the conversion process being used, offer important advantages of more systematic control of fuel quality, supply, and price stability than wastes derived from dispersed sources, which will be subject to alternate competitive endpoint uses and associated price fluctuations.

If these bioenergy crops are to realize their potential as a component of the national energy strategy, they must successfully compete both as crops and as fuels. Landowners will only produce those crops which provide a net economic return that is at least equivalent to conventional crops that they could produce on the same land for an equivalent level of effort. Low management intensity and positive effects on soil quality are important to landowners, but a stable source of income to supplement traditional crop returns will be a major determinant of their willingness to become involved. From the industrial perspective, both fuel cost and quality relative to alternate fossil fuels are essential considerations. An important function of the BFDP strategic plans has been to contribute to national efforts to analyze and continuously update inventories of available land, economic production costs of biofuels, and the levels and fuel characteristics of various biofuels produced within the program (Graham et al. 1995).

Potential Land Availability

At present the U.S. has approximately 178 million (M) hectares categorized as "arable and permanent crop land" (FAO 1996). A smaller fraction of this land has been estimated to be capable of providing yields high enough to compete economically in bioenergy production. Graham (1994) established a baseline production potential of 11.2 Mg /ha -y as the criterion and used national crop production statistics to estimate that up to 131 M ha of crop land would qualify for herbaceous energy crops, such as switchgrass. Of that total, it was estimated that 91M ha would also be suitable for fast growing, short rotation tree crops (Graham 1994).

The amount of land that will actually be used and the rate at which this will occur will be driven by the economics of bioenergy demand. Based on the existence of an estimated 35 M ha of idled land in 1988, the potential land area that could be incorporated into bioenergy crop production by 2012 was estimated at 60 M ha (Lynd et al. 1991). Based on a purchase price of $35/Mg, Ferrell et al.(1995) more recently projected a potential bioenergy crop area of 12 M ha by 2010. More recent estimates made using an agricultural supply and competitive pricing model (POLYSIS) are described below, indicate that energy crops would be competitive on 6-7 M acres at this price (Walsh, 1998).

Bioenergy Crop Prices

Estimates of expected prices for bioenergy crops vary widely by crop, region, and estimation methods, including notably whether transportation costs are included. Walsh (1998a) estimated production costs to vary from $22 per dry Mg to $110 Mg^{-1} and transportation costs to range from $ 5 Mg^{-1} to $8 Mg^{-1} for a 25 mile transport distance. On a national scale ORNL estimates of bioenergy supply prices were $30-40 Mg^{-1} at low (near term demand rates) A more detailed estimate of both bioenergy supply rates and prices has now been provided through the use of optimization models which consider the comparative economics of production of bioenergy and conventional crops (Walsh 1998b). This approach has the benefit of integrating many factors that determine prices of specific bioenergy crops and their capacity to compete with conventional crops within their regions, as well as evaluating the regional differences in land availability and cost. These are factors that will be important in determining the feasibility of locating bioenergy facilities of various sizes in a particular region. These analyses have been used to provide estimates for the year 2007 of the total cropping area over which energy crops could compete successfully with conventional crops for two pricing options and three energy crops , switchgrass, hybrid poplar, and willow, as shown in Table 4. These analyses indicate that switchgrass would compete successfully with conventional crops on approximately 98% of the 3.9 M ha that would be available at a price of $38.5/Mg ($35/ton) for switchgrass (and identical prices per unit of energy content for the two other crops) . As that price increased to $55/Mg, total acreage increases to 7 M ha and the representation of switchgrass remained at a the same relatively high percentage (97%) of the total. Total production of energy crops was estimated at 45 Mt and 79 Mt at the two respective pricing options. Longer term projections have indicated that other species such as hybrid polar may become increasingly competitive economically over time as production and harvesting technology improves (Walsh 1998b).

From the perspective of impacts on current agricultural production, the crops that are most likely to be supplanted by the more competitive economics of switchgrass production on 3.9 M ha of agricultural land (pricing option 1 in Table 4) are predominantly non-alfalfa hay (2044 k ha), wheat (672 k ha), oats (328 k ha), and alfalfa hay (255 k ha). Only 85 k ha of corn would be displaced in this scenario.

Bioenergy Conversion

There are three principal technological endpoints for bioenergy crops: conversion to liquid fuels, combustion alone or in combination with fossil fuels to produce heat , steam, or electricity, and finally gasification to simpler gas products that can be used in a variety of endpoint processes. Energy crops such as switchgrass and hybrid poplar are classified as lignocellulosic crops because it is primarily the cell walls that are digested to form sugars, which can subsequently be fermented to produce liquid fuels.This is in contrast to energy recovery from corn grain, where digestion and fermentation of starch to produce sugars and ethanol is a well-established technology (Wyman 1993). The rationale for developing lignocellulosic crops for energy is that less intensive production techniques and poorer quality land can be used for these crops, thereby avoiding competition with food production on better quality land. A potential limitation of some biofuels is that biochemical composition, energy content, and contamination with alkalai metals can limit their usefulness for some industrial applications (Miles et al. 1993). An analysis of the energy content and the level of alkalai and ash and combustion properties of switchgrass (Table 5) indicates that switchgrass is a versatile feedstock that is well suited to be used in combustion, gasification, and liquid fuel production (McLaughlin et al. 1996).

Fermentation to Fuels . Much of the early emphasis on biofuels has been on production of ethanol as a transportation fuel (Lynd et al. 1991). DOE has sponsored a significant research effort to produce ethanol from lignocellulosic crops through the SSF (Simultaneous Saccharification and Fermentation) processs (Wyman 1993), a combination of chemical and/or physical digestion followed by microbial fermentation. In the SSF process biofuels are broken down to structurally less complex organic residues that can be enzymatically converted to sugars and then fermented by microbes to produce ethanol. This is a relatively expensive technology because of the costs of acids and enzymes used in digestion. Ethanol yields are limited to 50-80% of possible levels, partly because lignin cannot be broken down by this process. On the other hand, recovered lignin has a high energy content and can be used as an energy input to the ethanol recovery process in SSF (Tyson et al 1994). Pilot scale testing of this technology is underway with the first commercial plant targeted for the year 2005.

Gasification . Another technology for producing both ethanol and a variety of other liquid fuels and chemical products is gasification. Gasification is a process that has been available for many years as a means of converting coal, natural gas, or solid wastes into simpler synthesis gases, primarily hydrogen and carbon monoxide. Syngas can then be burned to produce heat or chemically synthesized into a wide variety of secondary products, including ethanol, diesel fuels, and chemical solvents used in industrial processes. Gasification has the benefit of converting essentially all of the carbon in biomass, including lignin, into synthetic gases.

While the conventional syngas technology, the Fischer-Tropsch system used high heat and temperature to synthesize secondary products, there are newer systems currently under development that use the biological capacity of microrganisms in reaction cells to produce synthetic products such as acetic acid, ethanol, and many other useful organic chemicals

(Kaufman 1996). The advantage of these biological reaction cells, is that they operate at near ambient temperatures and pressures, resulting in greatly reduced costs, and with greater chemical specificity than the Fischer-Tropsch process. Talks have now begun with private industry to incorporate this new technology in to ethanol production plants and several locations in the Southeastern U.S. are currently under consideration for an initial smaller- scale commercial facility.

Combustion. The final category of biofuel use is in combustion to produce heat or electrical power. At present there are approximately 7000 megawatts (MW) of power produced from biomass in the U.S. (DOE 1996). This is derived largely (90 %) from wood wastes at wood processing plants operated by the timber industry around the U.S. A much broader use of wood and other biomass energy from dedicated feedstocks is envisioned in the future. Factors that will be important to the quantities and types of feedstocks utilized are fuels quality (low ash), energy content per unit cost, and regional availability. Dedicated forage crops also offer a source of high energy feedstock for power production (Bransby 1996). For switchgrass production, the cost per unit of renewable energy produced has been estimated to be lowest in the Southeastern U.S. ($1.78-$2.03 per million BTU (MBTU)) and in the southern plains ($1.95 -2.50 per MBTU, Walsh 1994).

To help achieve a concerted national program to promote the development and use of biomass power, the U.S. DOE in 1991 formed the National Biomass Power Program . This program is strongly based on collaboration with the U.S. Department of Agriculture (USDA) and private industry to form the government-industry partnerships necessary to achieve success. This effort promotes both direct combustion of biomass feedstocks co-fired in electric boilers with coal and other fuels, as well as gasification, an energetically more efficient process.

While wood wastes form the greatest fraction of current biomass-derived power production, there is great interest in using forage grasses for biopower as well. The DOE has recently embarked on three cooperative efforts to evaluate forage crops for power production. One involves the use of switchgrass in power generation (6 MW) with the Chariton Valley (Iowa) Resource Conservation and Development Agency. The second involves a joint effort with the Minnesota Valley Alfalfa Producers to produce electricity (from alfalfa stems) and animal feed from alfalfa leaves. A third supports tests by the Southern Research Institute in Alabama to evaluate cofiring switchgrass with coal in power production. These first commercial scale implementation efforts should provide valuable information on agricultural, sociological, and economic issues involved in a regional biomass power program.

SUMMARY AND CONCLUSIONS

Over the past 7 years research designed to evaluate and improve switchgrass as a bioenergy crop has been conducted by a team of government and university researchers in the southeast and central U.S.. This effort is part of the DOE- sponsored Bioenergy Feedstock Development Program at Oak Ridge National Laboratory and has been focused in the areas of yield improvement through management and breeding, physiological and genetic characterization, and applications of biotechnology for regeneration and breeding research. Switchgrasss, a warm season prairie grass, was chosen as the model species because of its perennial growth habit, high yield potential, compatibility with conventional farming practices, and high value in improving soil conservation and quality. Variety trials centered in Virginia, Alabama, and Texas have identified three excellent high-yielding switchgrass varieties. The varieties include Alamo, in the deep South, Kanlow at intermediate latitudes, and Cave-in-Rock for the upper Midwest. Yields of fully established stands of best adapted varieties have averaged approximately 16 $Mg*ha^{-1}$ in research plots across 18 testing sites, and minimum costs of \$1.78-\$2.03 $MBtu^{-1}$ have been estimated for farm-scale production in the Southeast. Management research has been directed at documenting nitrogen, row spacing, and cutting regimes to maximize sustained yields. Significant gains in soil carbon have been documented for switchgrass across a wide range of sites and associated gains in soil quality and erosion control are anticipated in connection with long term production of this species. Breeding research has focused on developing and characterizing an extensive germplasm collection, characterizing breeding behavior traits, and both narrow and broader base selection for yield improvement for both marginal and better quality soils. Tissue culture techniques have been developed to permit rapid clonal propogation of select switchgrass lines and to offer opportunities for application of advanced biotechnological tools. Energy budgets indicate that significant gains in energy return and carbon emissions reduction can be achieved with switchgrass as a biofuel.

The bioenergy industry is still in its infancy in terms of its impacts on national energy use. However the potential of biofuels to contribute to a national energy strategy is substantial. The benefits to the nation of providing cleaner burning fuels that improve both regional and global air quality while improving soil and water quality should be obvious. Combined with the improvements in farm economy, which can be expected with the production of energy on American farms and increased income for American farmers, bioenergy crops offer a "win-win" option for the planners of Americas future energy strategy. Bioenergy crops can be expected to become increasingly competitive in the future as the diversity of products possible from reformulation of biochemical constituents is developed through processes such as gasification and bioreactor technology. There are promising signs that the utility industry has recognized the value of cleaner burning renewable fuels which reduce environmental and political liabilities associated with relying totally on fossil fuels. Attainment of the potential for significantly greater participation of biofuels in national energy supply curves will require continued research on producing and improving energy crops more economically , continued improvement of the bioconversion technology to increase the diversity and value of end products, and a commitment of policy makers to improvement of environmental quality, which is measured in both long and short- term time frames.

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Table 5. Chemical and physical properties of switchgrass as a biofuel relative to selected alternate fuels (after McLaughlin et al. 1996).

Table 1. Effects of harvest timing on yield of two switchgrass varieties in research plots at Auburn , AL under single and two-cut harvest management schemes . Yield in megagrams per hectare (tonne/ha). Data from S. Sladden and D. Bransby). Plots were established in 1992.

Number of Harvests	Timing	Cultivar	Yield in Mg/ha-y 1997	1993-1997 (Total)
2	May + November	Alamo	8.4	56.0
		Cave-in-Rock	3.7	32.8
2	June + November	Alamo	6.0	69.6
		Cave-in-Rock	0.9	43.8
2	July + November	Alamo	23.8	135.8
		Cave-in-Rock	9.5	69.0
1	August	Alamo	23.2	135.5
		Cave-in-Rock	7.5	58.5
1	September	Alamo	40.3	135.7
		Cave-in-Rock	12.4	62.3
1	0ctober	Alamo	23.9	114.4
		Cave-in-Rock	12.4	61.9

Table 2. A comparison of nitrogen uptake and yield with three switchgrass varieties reveals much lower N use in the single-cut systems. Nitrogen was applied at 110 kg/ha to all plots in the spring.

Source: J. Reynolds and D. Wolf, VPI studies at Knoxville during 1995.

Variety	N Content ($kg \cdot Mg^{-1}$)			Totals			
	2-cut system		Single cut	Yields (Mg/ha)		N-use (kg/ha)	
	1	2		2 cut	1 cut	2 cut	1 cut
Alamo	8.3	4.5	2.6	24.2	20.2	160	52
Kanlow	8.9	3.2	2.5	22.4	20.1	152	51
Cave-In-Rock	8.8	3.1	1.7	22.9	16.3	157	28

Table 3. Comparative gains in breeding for improved yield of switchgrass with 2 cycles of Recurrent Restricted Phenotypic Selection (RRPS) and with a single cycle of narrow base synthetic selection. Four breeding populations—northern lowland (NL), southern lowland (SL), northern upland (NU), and southern upland (SU) are compared to the starting parent population in solid seeded stands in the first and second years after establishment at Perkins (OK). (Source: C. C. Taliaferro.)

Cycle	Yield			
	Kanlow (NL) (Mg/ha) (% of parent population)	Alamo (SL) (Mg/ha) (% of parent population)	Pathfinder (NU) (Mg/ha) (% of parent population)	Caddo (SU) (Mg/ha) (% of parent population)
Parent population	8.9 (100)	10.4 (100)	6.6 (100)	7.5 (100)
RRPS Cycle 1	10.2 (115)**	10.3 (99)	5.8 (88)	7.7 (102)
RRPS Cycle 2	10.8 (121)***	9.9 (96)	6.8 (105)	7.9 (105)
Synthetic	11.7 (131)***	11.8 (113)	6.6 (101)	8.8 (118)*

*$P \leq 0.10$, **$P \leq 0.05$, ***$P \leq 0.01$ for comparisons with the parent population.

Table 4. Comparative land area projected by an econometric model to be available for energy crop production for each of three candidate energy crops at two prices levels paid to the producer (farmgate). Prices are based on a uniform cost per unit of energy and were set at $ the same per unit of energy for each of the three cropping options compared. Source: Walsh et al., 1998.

Energy crop	Price ($/Mg)	Land area (M ha)	Biofuel quantity (MMg)	Price ($/Mg)	Land Area (M ha)	Biofuel Quantity (MMg)
Switchgrass	38.5	3.9	45	55	7.0	79
Hybrid Poplar	42.3	0.024	0.63	60.3	0.32	1.2
Willow	37.0	0.032	0.69	58.2	0.77	1.3
Total Production		3.95	46.3		8.1	81.5

Table 5.Chemical and physical properties of switchgrass as a biofuel relative to selected alternate fuels (Source: McLaughlin et al. 1996).

Fuel property	Units	Switchgrass Value	Alternate fuel Value	Alternate fuel Fuel type
Energy content (dry)	Gj·Mg^{-1}	18.4	19.6	Wood
			27.4	Coal
Moisture content (harvest)	%	15	45	Poplar
Energy density (harvest)	Gj·Mg^{-1}	15.6	10.8	Poplar
Net energy recovery	Gj·Mg^{-1}	18	17.3	Poplar
Storage density				
(6' x 5') round bale	kg·m^{-3}	133	150	Poplar chips
(4' x 5') round bale	(dry weight)	105		
Chopped		108		
Holocellulose	%	54–67	49–66	Poplar
Ethanol recovery	L·kg^{-1}	280	205	Poplar
Combustion ash	%	4.5–5.8	1.6	Poplar
Ash fusion temperature	°C	1016	1350	Poplar
			1287	Coal
Sulfur content	%	0.12	0.03	Wood
			1.8	Coal

Notes. Energy content of switchgrass was determined from 6 samples from Iowa. Bale density and chopped density of switchgrass are from Alabama (D. Bransby, Auburn). Poplar chip density is from studies of White et al. (1984). Poplar energy moisture content, combustion ash and ash fusion temperatures are from NREL, as are ash fusion temperatures and sulfur contents of all fuels. Energy density is the energy per unit of wet harvest weight. Net energy recovery considers energy lost in drying fuel prior to combustion. Holocellulose content of switchgrass is from 7 varieties in AL (Sladden et al. 1991) and from 7 hybrid poplar varieties in PA (Bowersox et al. 1979). Ethanol yields are averages of SSF recovery on 3 analyses per species using a standard recovery procedure for all feedstocks. Ethanol yields can likely be improved somewhat by tailoring reaction mixtures to each specific feedstock, thus those should be considered preliminary measures of potential recovery.

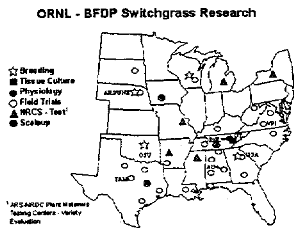

FIGURE 1

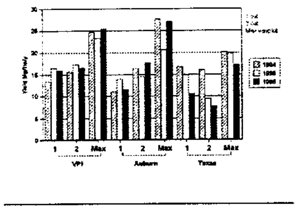

FIGURE 2

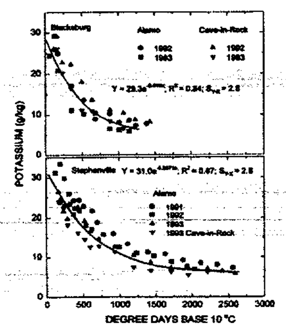

FIGURE 3

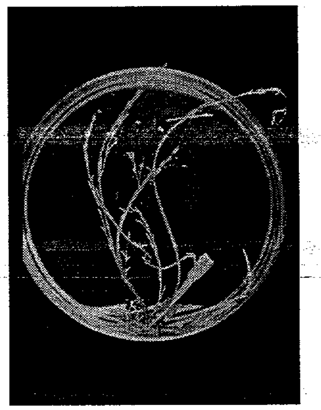

FIGURE 4

Electronic copies of these figures are available from S.M. upon request.

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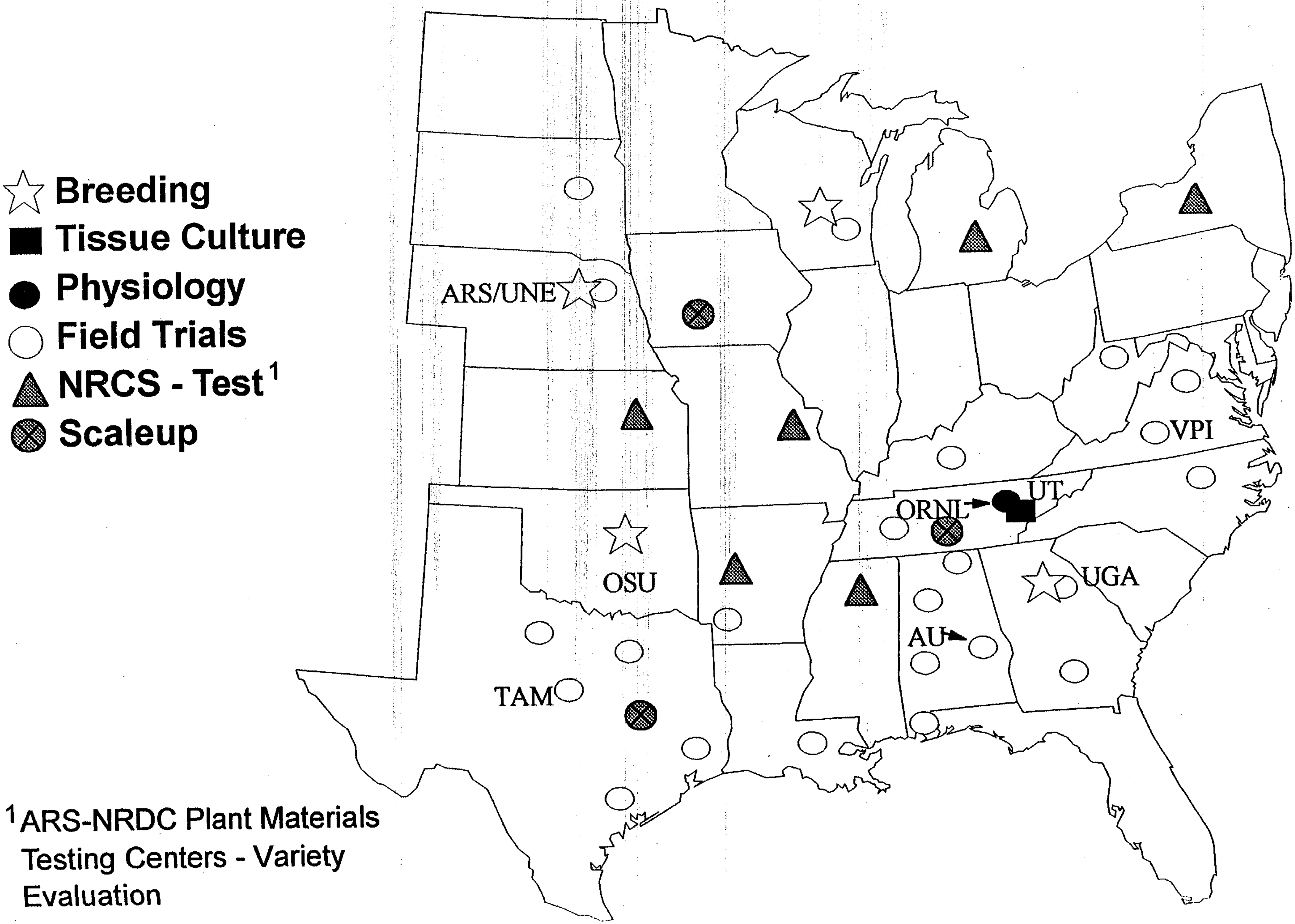
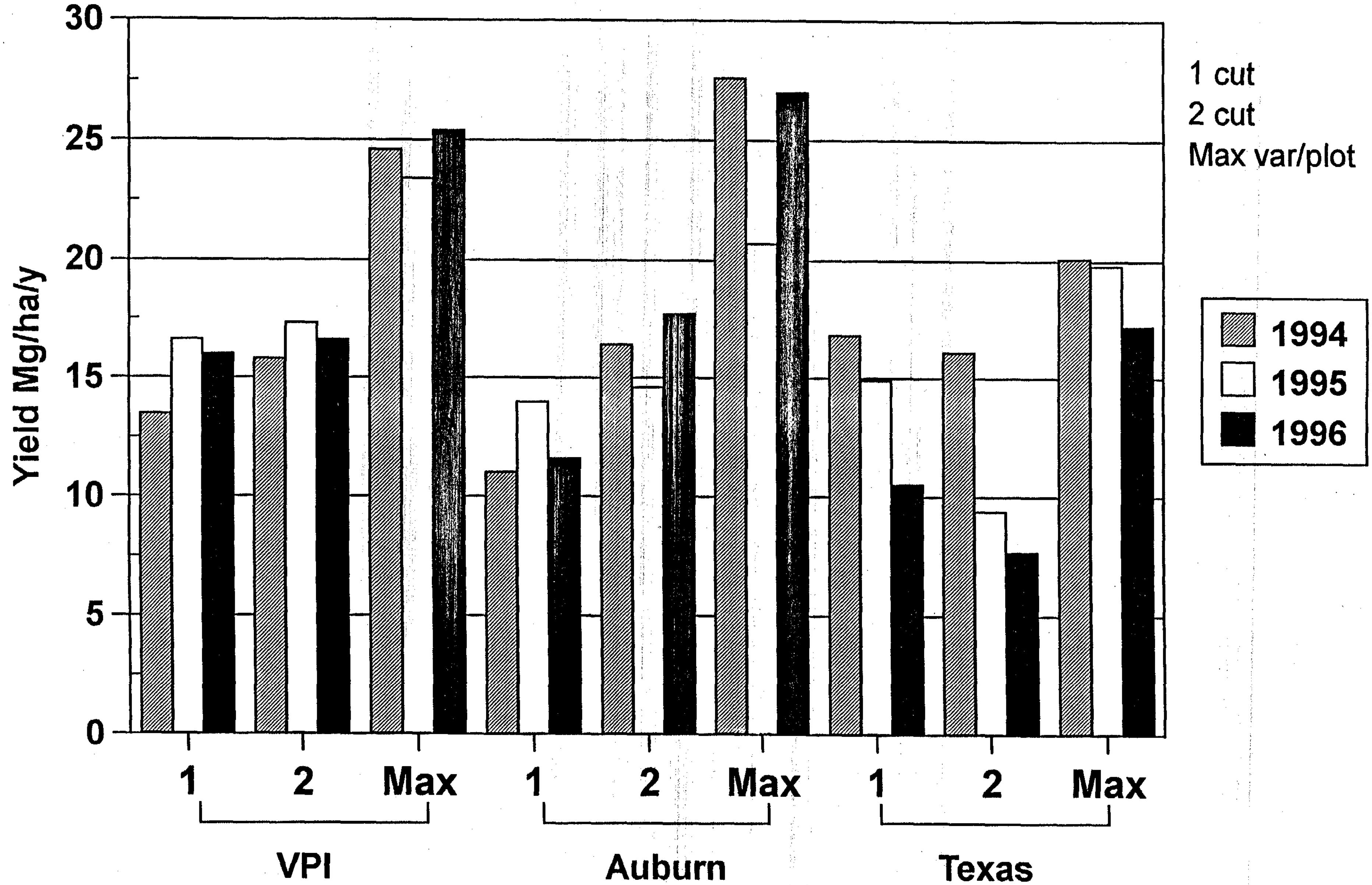
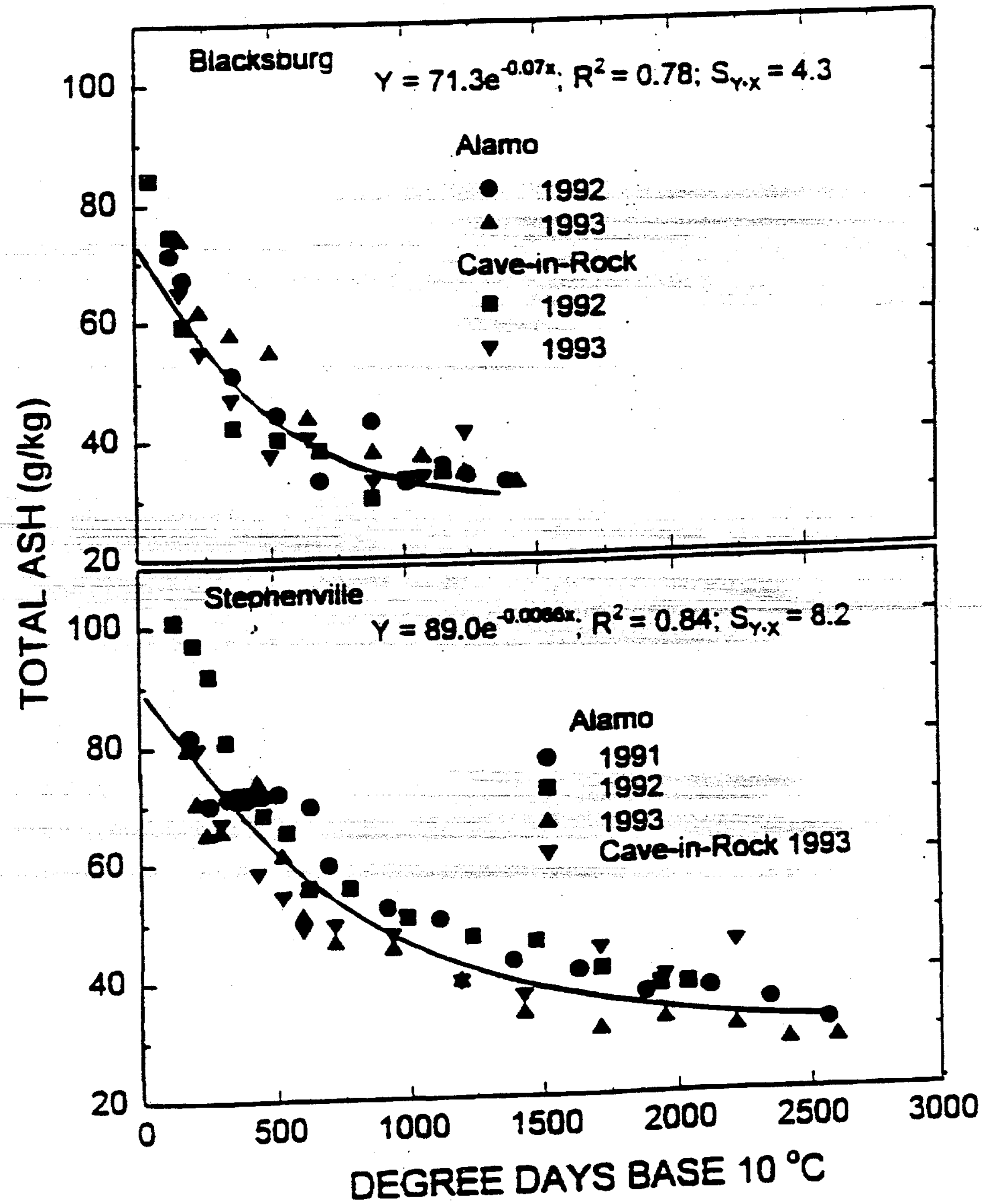


[1] ARS-NRDC Plant Materials Testing Centers - Variety Evaluation



Yield Mg/ha/y
30
25
20
15
10
5
0
1
2
Max
1
2
Max
1
2
Max
VPI
Auburn
Texas
1 cut
2 cut
Max var/plot
1994
1995
1996

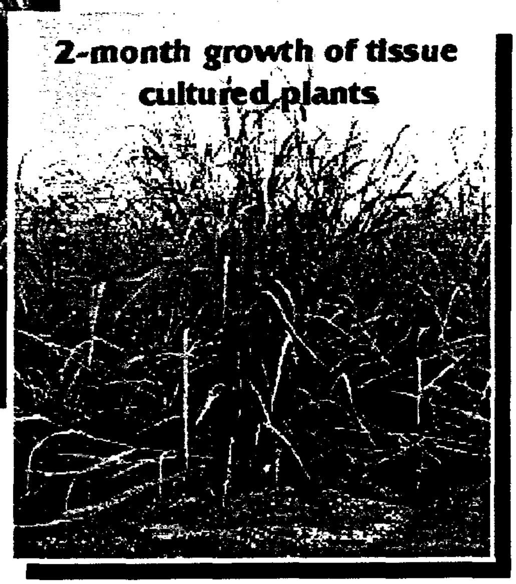
Delayed Harvesting Can Significantly Reduce Total Ash Content



Concentration of total ash in switchgrass at Blacksburg, VA and Stephenville, TX. Each data point is the mean of two (1992 and 1993 at Blacksburg and 1993 at Stephenville) or four (1991 and 1992 at Stephenville) replicates.

Switchgrass Advanced Technology Research

Switchgrass inflorescence produced by tissue culture



2-month growth of tissue cultured plants