Projecting Yield and Utilization Potential of Switchgrass as an Energy Crop

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The potential utilization of switchgrass (*Panicum virgatum* L.) as a cellulosic energy crop was evaluated as a component of a projected future national network of biorefineries designed to increase national reliance on renewable energy from American farms. Empirical data on yields of switchgrass from a network of experimental plots were coupled with data on switchgrass physiology and switchgrass breeding progress to provide reasonable expectations for rates of improvement over yields. Historical breeding

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success with maize (*Zea mays* L.) was found to provide a reasonable model for projected linear rates of yield improvement of switchgrass based on documented progress to date. A physiologically based crop production model, ALMANAC, and an econometric model, POLYSYS, were utilized to estimate variability in switchgrass yield and resource utilization across the eastern two-thirds of the United States. ALMANAC provided yield estimates across 27 regional soil types and 13 years of weather data to estimate variability in relative rates of production and water use between switchgrass and maize. Current and future yield projections were used with POLYSYS to forecast rates of adaptation and economic impacts on regional agricultural markets. Significant positive impacts on US markets, including significant increases in farm income and significant reduction in the need for government subsidies, were projected. This was based on expected technological progress in developing biorefineries that will significantly increase national energy self-sufficiency by producing feed protein, transportation fuel, and electrical power from cellulosic feedstocks.

I. INTRODUCTION

While ethanol from maize (*Zea mays* L.) is the dominant means by which renewable energy is channeled from sunlight to the transportation industry (Shapouri *et al*., 1995), switchgrass (*Panicum virgatum* L.) has become another strong candidate for production of bioenergy. Switchgrass is a native perennial, warm-season grass species within which selection has been practiced for forage and conservation uses over the past half-century (Vogel *et al*., 1985). In 1991 it was selected as a candidate for utilization in production of bioenergy and bioproducts (McLaughlin and Kszos, 2005). Its strongest attributes include high biomass production capability and energy recovery capacity with low energy and material inputs, and excellent compatibility with existing agricultural practices. These qualities, combined with strong soil and water conservation values, and a high capacity to reduce emissions of greenhouse gases have led to switchgrass being considered as a potentially important component of a national energy strategy (McLaughlin *et al*., 2002).

Despite criticism of ethanol production from maize based on low energy efficiency and adverse environmental impacts (Pimmentel *et al*., 2002), maize-based ethanol production has made an important beginning in the reduction of reliance of the United States on imported oil. Maize-based ethanol does displace significantly more oil than is used in its production (Shapouri *et al*., 1995). However, McLaughlin and Walsh (1998) suggested that the efficiency of energy conversion and reduction of greenhouse emissions through production of cellulosic ethanol from switchgrass could exceed that from maize ethanol by more than an order of magnitude. Yet maize remains the standard biofuel feedstock, which provides a base that can ultimately be supplemented by other feedstocks, providing greater economic and environmental efficiencies.

If switchgrass is to provide a viable supplement to ethanol from maize, biomass production levels of switchgrass must be determined as input for a national renewable energy strategy. The Role of Biomass in America's Energy Future (RBAEF) project was initiated to help formulate such a strategy. The RBAEF project represents the most comprehensive effort in the United States to date that has focused on analysis of mature technology for production of energy from biomass. It has involved experts from government and university bioenergy analysis coupled with active involvement of both conservation (Natural Resources Defense Council) and policy (Office of Energy Policy) organizations. The RBAEF project has considered over 20 mature process technology scenarios for production of a broad range of fuels and electrical power from cellosic biomass. Reasonably optimistic forecasts for both biomass production and bioenergy conversion were evaluated for a projected national network of biorefineries that could contribute to national energy self-sufficiency (Greene, 2004). Switchgrass was selected as the model crop for this study and in that context the research described herein has formed a basis for considering what role switchgrass could play in a national energy supply system that incorporated the best foreseeable technology to produce energy and value-added products such as animal feed protein from cellulosic feedstocks. Yield levels will play a key role in the economics of such production and utilization systems as well as in determining the demographics of production.

When discussing methods for increasing plant biomass yield, some terms describing yield must be defined. Two such terms commonly used are "yield potential" and "potential yield." As used in this study, yield potential is the maximum yield (biomass or grain) levels that have been attained at any time for a specific genotype of a crop or grass under field conditions. In contrast, potential yield is the maximum predicted yield based on simulations founded in plausible physics, biochemistry, and physiology of the crop in its normal growing environment (Fischer and Evans, 1999). This yield is considered theoretically and physiologically possible based on maximum light interception and biochemical conversion of solar radiation into dry matter accumulation.

Because maize production is a cornerstone of agricultural economics in North America, the historical improvement of maize yields represents an important standard from which to project future yield gains of other species with comparable production characteristics. Maize yield records for North America extend back more than 100 years and provide a template for both defining and understanding yield improvement through breeding and crop physiological studies (Duvick, 1997; Tollenaar *et al*., 1994). Maize and switchgrass not only share the common trait of being useful bioenergy crops but are also similar in that both are warm-season, C_4 species. However, maize is an annual with only the grain used for ethanol production while switchgrass is a perennial with the entire aboveground biomass used when energy is the endpoint. Maize is a good standard of comparison because of the extensive breeding for increased yields and the extensive physiological research on processes contributing to yield. Investigation of the physiology and breeding history of these two plant species, as related to increased yields, becomes important for studies of yield potential as a theoretical upper limit of yield increases achievable through breeding.

In this chapter, we examine the past record of yield improvement in maize and the basis of those gains to provide a framework for projecting gains in yield of switchgrass. A necessary component of these analyses has been comparisons of the agronomic characteristics, breeding history, and underlying physiology of maize and switchgrass. We had three objectives in initiating this study. First, we wanted to evaluate potential yield improvement in switchgrass using maize breeding advances as a model. Second, we wanted to test and apply a physiologically based crop production model, ALMANAC (Kiniry *et al*., 1992), parametrized to switchgrass physiology to estimate both potential yield and yield potential of switchgrass. Finally, we wanted to describe links between productivity and production costs for regional projections of switchgrass utilization that would require widespread participation of the agricultural community of the United States in supporting renewable energy production. Such participation must be based on switchgrass, providing attractive economic alternatives to conventional crops. For these analyses we have used the econometric model POLYSYS (Ugarte and Ray, 2000).

II. PROJECTING YIELD GAINS IN SWITCHGRASS RELATIVE TO MAIZE

A. Breeding History of Maize

While maize was domesticated more than 7000 years ago (Goodman and AU:1 Brown, 1988), the largest increases in yields occurred in the past 75 years as modern breeding techniques evolved (Duvick, 1997, 1999; Tollenaar *et al*., 1994). Switchgrass breeding has a much shorter history, with selection for yield increases and trait improvement having occurred only in the last few decades. However, this genetically diverse grass is an important component of the North American tallgrass prairies and has undergone thousands of years of natural selection for persistence under the stresses imposed by grazing animals, principally bison (*Bison bison*), and fires (Steinauer and Collins, 1996).

Since 1930, maize yield increases in the United States and Canada have been remarkably linear (Fig. 1) (derived from http://www.nass.usda.gov/Charts_and_Maps/Field_Crops/cornyld.asp). The record of breeding progress in maize extends back over 130 years (Tollenaar *et al.*, 1994) and reflects definitive stages of progress during the evolution of breeding approaches. Breeding strategies have progressed from initial mass selection in open-pollinated populations to the breeding technology capitalizing on hybrid vigor captured in single crosses, double crosses, and finally, three-way crosses. Breeding for hybrid vigor began in maize in the early 1900s, and the introduction of the first double cross hybrids in the 1930s and 1940s provided the largest gains in yields. Yields in the late 1990s achieved levels nearly five times those in the early 1930s and the mean rate of gain was 80–100 kg ha^{-1} year^{-1} for the United States. It is generally considered that, while heterosis has played an important role in maize hybrid yield increase and will continue to contribute to absolute yield gains, the importance of heterosis to absolute gains will likely decrease as inbreeding raises baseline yields (Duvick, 1999).

The impressive maize yield gains have come only in part due to genetic improvements. Genetic gains have contributed 50–60% to the overall yield gains achieved with the remainder due to improved management (Duvick, 1999). Gains in maize yield potential have been accompanied by improved physiological characteristics, making plants more resistant to stresses inherent at high-planting density. Understanding roles such changes have played

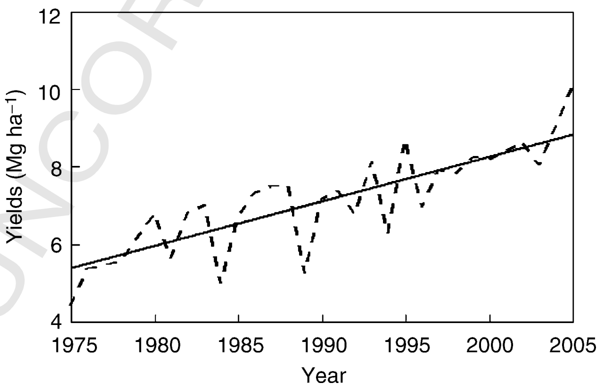

Figure 1 US maize yield gains in the last 30 years.

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in yield gains is important to our objective of estimating how such gains can be mirrored with switchgrass.

B. Breeding Gains with Perennial Grasses Including Switchgrass

Scientific breeding of perennial grasses largely began in the mid-20th century and has been on a much smaller scale than for maize. Consequently, performance gains attributable to sustained breeding of perennial grasses, in general, are much less than for maize. Additionally, the number, scope, and duration of breeding programs have varied greatly with perennial grass species, contributing to substantial differences among species in breeding gains.

Articles addressing genetic gains, made mainly in important cool-season perennial grass species, indicate differences associated with traits, species, and geographic regions (Casler, 2001; Casler *et al.*, 2000; Wilkins and Humphreys, 2003). Casler *et al.* (2000) compared smooth bromegrass (*Bromus inermis* Leyss) cultivars developed in the United States between 1942 and 1995 with cultivars predating 1942. While there were no genetic gains in dry biomass yields (DBY) were detected among the cultivars developed between 1942 and 1995, the DBY of the post 1942 cultivars averaged 0.54 Mg ha^{-1} $year^{-1}$ (7.2%) higher than the DBY of "Lincoln," a direct representative of the first smooth bromegrass introduced into North America. They also reported small gains in brown leaf-spot resistance (0.21 units per decade), *in vitro* dry matter digestibility (IVDMD) (9 g kg^{-1}, 1.4%), and neutral detergent fiber (NDF) (–8 g kg^{-1}, −1.2%). The slow rate of genetic gain for DBY was attributed to the complex polyploid inheritance of smooth bromegrass, breeding emphasis on traits other than forage yield, and relatively little concerted attention from public and private breeders. Casler (2001) reviewed breeding efforts for improved forage nutritional value, reporting enhancements for several different species and indices [increased IVDMD, nylon bag dry matter digestibility (NBDMD), and protein, and decreased acid detergent fiber (ADF) and lignin] ranging from 1 to 7% per cycle. Wilkins and Humphreys (2003) reported that over the past 50 years, gains in DBY of the important forage grass species have been 4–5% per decade in northwestern Europe, but only 0–1% per decade in the United States. Additionally, they state that gains in the dry matter digestibility (DMD) of perennial ryegrass (*Lolium perenne* L.) in the United Kingdom have been 10 g kg^{-1} per decade, whereas in the United States little or no gain has been made, presumably reflecting the continental differences in amount of breeding effort and/or breeding objectives. Common expressions in the previously cited articles are that genetic gains in the perennial grasses have been limited mainly by lack of breeding effort and that the largely unmined genetic diversity within these species offers potential for enormous breeding improvement.

Significant breeding advances have been documented in several warm-season (C_4) perennial grasses for DBY and other attributes. One well-known success story is with bermudagrass [C*ynodon dactylon* L. Pers.]. Bermudagrass breeding initiated by Burton in 1937 at Tifton, GA led to the release of "Coastal" bermudagrass in 1943 (Burton, 1947, 1954). Coastal bermudagrass DBY is nearly twice that of unselected common bermudagrass strains found in the southeastern United States (Adams and Stelly, 1958; Carreker *et al.*, 1972). In addition, Burton (1982, 1985, 1992) and Burton and Mullinix (1998) increased DBY of bahiagrass (*Paspalum notatum* Flügge var *saurae* Parodi) through systematic restricted recurrent phenotypic selection (RRPS). Mean individual spaced plant DBY increased in bahiagrass population "A" from 364 g per plant in cycle 0 to 1767 g per plant in cycle 18, a gain in mean individual plant DBY of 78 g RRPS per cycle. In narrow base population "B," mean spaced plant DBY increased from 823 g per plant in cycle 0 to 1427 g per plant in cycle 10, a gain in mean individual plant DBY of 60 g RRPS per cycle. While RRPS increased the number of high-yielding plants and reduced the number of low-yielding plants in successive cycles, genetic variation for DBY remained high in the populations. Population A RRPS cycle 18 had two plants with DBY of 4540 g and 27 plants with DBY of only 454 g.

Systematic breeding within switchgrass populations specifically for increased DBY is in its infancy, and yield gains of the first few breeding cycles have just been reported (McLaughlin and Kszoz, 2005). Many commonly grown switchgrass cultivars are direct increase of naturally occurring strains (Vogel, 2000, 2004). Examples include the lowland ecotypes "Alamo" and "Kanlow," and the upland ecotypes "Blackwell" and "Cave-in-rock." Cyclic selection in switchgrass for increased nutritive value has been effective and has resulted in the release of "Trailblazer" and "Shawnee," upland type cultivars adapted to the central United States (Vogel, 2004).

The potential for increasing DBY in switchgrass is significant because of the large genetic variation within the species. There is substantial heritable variation in switchgrass for DBY and related performance traits (Hopkins *et al.*, 1993; Newell and Eberhart, 1961; Talbert *et al.*, 1983; Taliaferro *et al.*, 1999; Vogel *et al.*, 1981). Additional basic information generated over the past decade has strengthened understanding of the biology of the species, providing a firm foundation for applied breeding improvement.

Future breeding gains in switchgrass DBY will depend on the amount and consistency of effort expended and on continued refinement of breeding protocols. Better screens are needed to enhance the effectiveness and efficiency of selection. The RRPS protocol, used so successfully with

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bahiagrass, did not achieve the desired results with switchgrass in Nebraska and Oklahoma (Hopkins *et al.*, 1993; Taliaferro, 2002). Two cycles of RRPS failed to increase DBY in an upland population, but did provide linear gains in IVDMD through three cycles (Hopkins *et al.*, 1993). Three cycles of RRPS for increased DBY in each of four populations (two upland and two lowland) gave generally desirable but mixed results in Oklahoma (Taliaferro, 2002). Yield gains per cycle varied from near 0 to a maximum of 6% and were not linear across cycles. Use of RRPS was relatively ineffective in identifying plants of superior breeding value in the establishment year, in large part, because much of the growth during that year is belowground and not readily assessed by these techniques. Some switchgrass breeding programs are now using progeny testing as a basis for selection of plants with superior breeding value for DBY, a process known as genotypic recurrent selection. This procedure has been successful with many crops for many traits but is the most time consuming of the recurrent selection procedures (Fehr, 1987). Four to five years are required for each cycle.

Rapid progress has been made using a novel honeycomb planting design (Fasoula and Fasoula, 1995) to promote phenotypic selection within a lowland switchgrass population developed from Alamo and Kanlow (Bouton, 2002). Data from preliminary testing indicated four synthetic cultivars developed using elite plants selected from the population had 30% yield gains relative to parent populations of Alamo and Kanlow. The selection process occurred over 4 years equated to an annual gain of 7.5%. This compares favorably with early gains in maize improvement in the United States, which ranged from 3.5–6.0% of baseline yields in the 1930s to 1.3–1.8% of those attained in the 1990s (Tollenaar *et al.*, 1994). Average yield gains for maize made over 70 years of breeding for commercial markets in Iowa have, as expected, been lower (0.7–1.2% per year) (Duvick, 1997).

C. Potential Yields in Maize and Switchgrass

Our analyses suggest that upper limit yields (potential yields) of maize and switchgrass are similar. In simplest terms, potential yield is governed by how much radiant energy can be captured by the plant canopy and converted to harvestable biomass over an annual growing season. The key processes regulating potential yield are the leaf canopy size and longevity, and efficiency of canopy interception of radiant energy; the efficiency of conversion of radiant energy to photosynthetic products and plant biomass; and the relative allocation of carbohydrates to the physical and metabolic support of the whole plant system. Loomis and Amthor (1996, 1999) concluded that genetic control of photosynthesis and respiration is complex and relatively stable, such that the basic efficiency of these processes appears little altered by crop domestication and breeding. They estimated that radiation use efficiency (RUE) of maize should be 4.6 g MJ^{-1} of intercepted photosynthetically active radiation. However, measured RUE values with high-yielding maize in the field are only 3.7–3.8 (Kiniry *et al.*, 2004; Lindquist *et al.*, 2005; Tollenaar and Aguilar, 1992).

While neither the upper limits of photosynthesis nor the upper limits of yield potential have changed measurably (Tollenaar and Wu, 1999), the yielding ability of maize in the field has increased dramatically (Fig. 1). This is because maize yields are affected by tolerances to natural stress and responsiveness to management inputs (Fasoula and Fasoula, 2000).

A side benefit of selecting higher maize yield has been increased resistance to stresses associated with high-yield production systems (Duvick, 1997; Tollenaar and Lee, 2002; Tollenaar and Wu, 1999; Tollenaar *et al.*, 1994). Among the performance traits that have improved as maize yields have increased are: increased resistance to competition in high-density plantings (Tokatlidis, 2001); increased resistance to drought stress (Dwyer *et al.*, 1992); improved nitrogen use efficiency (McKay and Barber, 1986); reduced dark respiration (Earl and Tollenaar, 1998); improved source:sink relations (Rajcan and Tollenaar, 1999); improved canopy level efficiency at interception and utilization of radiation (Dwyer *et al.*, 1991); and increased longevity of the productive maize canopy, a phenomenon referred to as "stay-green" (Tollenaar *et al.*, 1994). While these traits have not played significant roles in breeding strategies to date, they could be important for increased future yields of maize or switchgrass. Their improvement for maize has been attributed to the trend in commercial breeding to include testing and selection for performance across diverse testing environments, which included wide variations in these stresses (Tollenaar and Lee, 2002).

Maximum grain yield potential attained by maize under field conditions is in the range of 15–20 Mg ha^{-1} (Tollenaar and Wu, 1999). These data represent record yields from a few individual fields. Maximum regional yields and countrywide commercial yields are lower than these maxima, in the range of 11.2 Mg ha^{-1} for individual counties (National Agricultural Statistical Service, ftp://www.nass.usda.gov/pub/county/byyear/) to 13.3 Mg ha^{-1} (5-year average) for the highest yielding hybrids in Texas (Pietsch *et al.*, 1999). Yield potential of such irrigated maize in the field is 36–48% below potential yield, which has a theoretical maximum of 25 Mg ha^{-1} (Tollenaar, 1983). Average commercial yields of maize between 1980 and 2000 in central North America were considerably less, in the range of 6–7 Mg ha^{-1} (Tollenaar and Lee, 2002).

Yields of switchgrass have been evaluated in the Mid-Atlantic, Southeast, South-Central, and Northern Plains states through a network of field plots designed to evaluate existing commercially available varieties as well as new cultivars developed in an emerging breeding program (Fig. 2). These plots

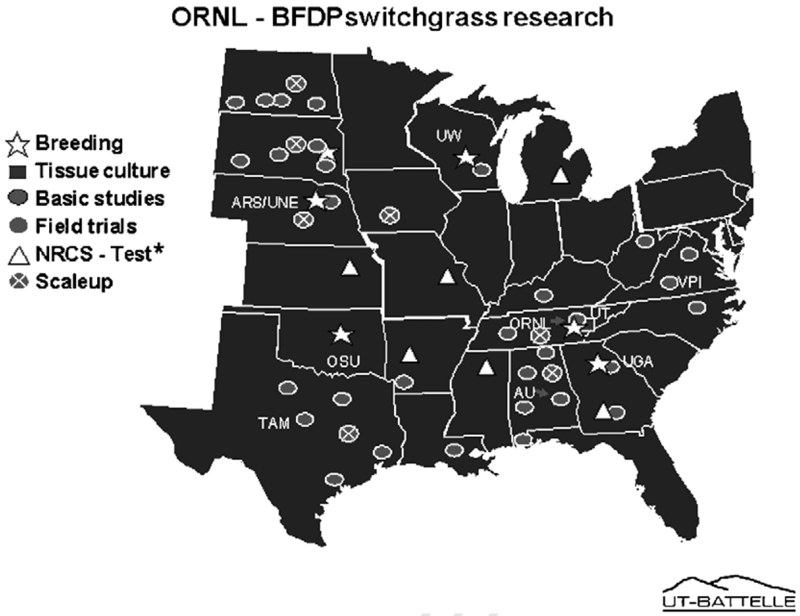

Figure 2 Distribution of yield test sites and basic research activities supporting yield estimates and yield improvement potential in this study (after McLaughlin *et al.*, 1999). The Oak Ridge National Laboratory (ORNL) Bioenergy Feedstock Development Program (BFDP) was a 10-year research program sponsored by the Department of Energy. *ARS-NRDC plant testing centers–variety evaluation. AU:9 AU:10

have served to identify both the most productive varieties for various latitudes and to evaluate the influences of various management regimes, including cutting regimes (one or two harvests per year with variable harvesting dates), nitrogen form and application rates, and row spacing (45–120 cm). Early yield gains of 50% were made by identifying varieties that were best suited to each production region (McLaughlin and Kszos, 2005).

The best available varieties identified over the 1991–2000 test period were the lowland ecotypes Alamo and Kanlow in the southern latitudes; Kanlow and an upland ecotype Cave-in-rock at mid-latitudes; and Cave-in-rock and another upland variety, Summer, in the northern latitudes. Average annual yields of the best adapted varieties in each region over 5–8 years (Table I) have ranged from 13 to 23 Mg ha^{-1} with a maximum individual plot/variety yield of 35 Mg ha^{-1} year^{-1} in Alabama (Sladden *et al.*, 1991). These yields have been produced without irrigation on sites selected to represent agricultural land of moderate quality that would not likely be used for dominant cash crops such as maize or soybeans [*Glycine max* L. Merr.].

Table I
Annual Switchgrass Productivity in a Variety of US Test Environments in the Field

			Yield (Mg ha^{-1} year^{-1})		
Location	Sites	Time (years)	Average	Range	Maximum site
Mid-Atlantic	8	8	13.9	10.9–17.5	27.4
Georgia	2	5	16.2	16.1–16.3	23.2
Alabama	1	13	23.0		34.6
	5	8	12.9	10.4–15.8	24.6
Texas	3	6	13.5	8.1–16.5	24.7
Iowa	1	4	13.1		17.5
Nebraska	1	3	20.6		
North Dakota	2	2	11	9.8–12.2	13.8

Average, range, and maximum 1-year yields of the best switchgrass varieties by site were determined by standard agricultural test plots.

D. Whole Plant Production in Maize and Switchgrass

Because harvested maize grain crop represents allocation of a portion of the captured and converted solar energy from the maize canopy, one must also know the harvest index (grain weight divided by total aboveground plant weight) to calculate total productivity of the maize crop. This is particularly relevant in comparing results of yield increase of a grain crop, like maize, with a cellulosic crop, like switchgrass, where total biomass production is the major emphasis. The harvest index of maize is 50–54% (Escharte and Andrade, 2003; Kiniry *et al.*, 2002, 2004; Tollenaar, 1992). Unlike the increasing harvest index values that have tracked the trend in yield gains in some of the cereal grains, such as wheat (Fischer *et al.*, 1998), the harvest index of maize has remained largely unchanged (Tollenaar, 1989). With a maximum theoretical yield for maize of 25 Mg ha^{-1} and a harvest index of 54% (Escharte and Andrade, 2003; Kiniry *et al.*, 2004), the calculated maximum aboveground productivity of maize is 46.3 Mg ha^{-1}. Potential yield of maize on an individual plant basis is considered to have remained largely unchanged over the last several decades of yield increase (Duvick, 1997). What has improved is the performance of leaf canopies under intensive management for high yields.

Estimates of maximum potential yields of switchgrass are similar to those of maize. Initial estimates of potential yields of switchgrass came from a space-planted nursery in eastern Tennessee at a location with the highest overall yields attained during the yield trials. Individual plants grown on a 1.2 m × 1.2 m spacing were harvested and weighed to determine size distribution within a 1000-plant nursery initiated from seedlings produced in the greenhouse from tissue culture explants (Conger *et al.*, 1996). These plots produced some of the highest yields in the test network in 1995. Estimates of the upper limits of field-scale yields based on the distribution of yields within the stand projected a maximum of 48.6 Mg ha^{-1} year^{-1} (based on a population at the level of the highest yielding plant). Similar calculations based on the mode and average yields of individual plants were 22.8 and 20.6 Mg ha^{-1} year^{-1}, respectively.

The estimates of maximum annual potential yields of maize (46.3 Mg ha^{-1} year^{-1}) and switchgrass biomass (48.6 Mg ha^{-1} year^{-1}) (Table II) are

Table II
Some Physiologically Based Production Characteristics of Switchgrass Based on Field Measurements of Accessions at a Germplasm Nursery in Tennessee and Oklahoma (see text)

Maximum single-plant yield in a space-planted nursery from a 1000-plant nursery in tennessee (projected from 1.2 m × 1.2 m spaced planting)		
Average yield all plants:		20.6 Mg ha^{-1} year^{-1}
Most frequent yield:		22.9 Mg ha^{-1} year^{-1}
Highest yielding plant:		7.0 kg
"Max plot"[a]:		48.6 Mg ha^{-1} year^{-1}
Physiological characteristics		
Single-leaf photosynthesis	Range:	17.5–30.8 μmol m^{-2} s^{-1}
	Top 3:	30.5
	Alamo:	27.9
Transpiration	Range:	6.2–13.0 mmol m^{-2} s^{-1}
	Top 3:	11.83
	Alamo:	8.2
Stomatal conductance	Range:	0.16–0.30 mol m^{-2} s^{-1}
	Top 3:	0.29
	Alamo:	0.23
Water use efficiency (Ps/Tr)	Range:	2.08–3.77 μmol mmol^{-1}
	Top3(WUE):	3.71
	Top 3(Ps):	2.67
	Alamo:	3.6
Dark respiration (4 varieties at 3 sites)	Range:	1.76–2.24 μmol m^{-2} s^{-1}
	3 Site average:	2.12
	Alamo:	1.98
Seasonal PS Phenology	Alamo:	Photosynthesis
Stephensville, Texas, 1993	Early (May 18):	30.6 μmol m^{-2} s^{-1}
	Later (July 16):	18.1
	Cave-in-rock	
	Early (May 18):	27
	Later (July 16):	16.2

[a]This is a projection of the yield potential of a field of plants all of which have the productive potential of the best plant in this 0.40 ha unirrigated test plot with a 1.2 m × 1.2 m planting density.
WUE, water use efficiency; Ps, photosynthesis; Tr, transpiration.
AU:11 Source: Wullschleger *et al.* (1996a,b).

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remarkably similar, despite the differences in life strategy. Although both have the efficient C_4 metabolism, the perennial life strategy of switchgrass dictates that the species' persistence rests strongly on energy storage and mobilization from a much larger root system than the annual crop maize, which invests half of annual dry matter accumulation in grain. Estimates of the root mass of switchgrass from excavation studies at eight sites in the mid-Atlantic region averaged 15.1 Mg ha^{-1} and ranged from 31% to 60% of the total biomass above and below ground at harvest (Parrish *et al.*, 2003). Similar work with Alamo switchgrass roots sampled with soil coring at final harvest in Texas showed that 30% and 37% of the total biomass were in the roots in a wet year and 60% and 73% in a dry year (Kiniry *et al.*, 1999).

III. PROJECTING SWITCHGRASS PERFORMANCE IN TIME AND SPACE WITH THE ALMANAC MODEL

A. Physiological and Ecological Traits of Switchgrass

While physiological criteria have had limited utility in increasing maize yields, the effects of maize breeding for increased yield on physiological traits indicate that such characteristics may be valuable in targeting increased yield in future breeding efforts when applied with the tools of molecular biology (Tollenaar *et al.*, 1994). As a C_4 species, switchgrass has high carbon fixation efficiency per unit of radiant energy absorbed. At 0.060 mol CO_2 E^{-1}, the quantum yield (moles of CO_2 absorbed per micromole) is only slightly below that of maize (0.062 mol CO_2 E^{-1}) (Ehleringer and Pearcy, 1983). Additional physiological characterization of switchgrass has been obtained from measurements within a switchgrass germplasm nursery near Stillwater, Oklahoma (Table III). Measurements included characterization of leaf level exchange of CO_2 and H_2O, and seasonal changes in rates of photosynthesis. From such measurements, it was determined that there was high intraspecific variability in physiological characteristics of switchgrass cultivars and both the highest photosynthetic rates and water use efficiencies were clearly associated with highest yields among the 45 varieties tested. Additional traits of switchgrass that are considered by the ALMANAC model (Kiniry *et al.*, 1996) in estimating switchgrass yield potential include canopy bioenergetics and developmental characteristics, nutrient requirements at different growth stages, and contributions to soil quality (soil erosion, soil nutrient status, and soil carbon status). These traits influence total carbon fixation and production potential, life cycle

Table III
Comparison of Simulated Annual Yields of Switchgrass with Actual Yields in Research Plots at Four US Regional Locations

		Dry matter yield (Mg ha^{-1} $year^{-1}$)	
Location	Management	Research plot	ALMANAC simulation
Blacksburg, VA	5-year mean	12.3	12.0
Mead, NE	2-year mean	13.4	13.8
Beeville, TX	1993	11.8	11.7
	1994	11.7	15.7
Tallassee, AL	9-year mean-2 cut	10.5	10.6
	9-year mean-1 cut	10.1	10.2

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energetics, production economics, and potential environmental benefits from switchgrass production as a biofuel.

The high investment by switchgrass and other perennial species in root biomass for storage and recovery of nutrients, diverting fixed carbon from harvestable aboveground biomass, represents an important agronomic benefit of these species. It leads to lower requirements for supplemental water and nutrients and hence more stable and cost-effective yields. In addition, the high root turnover in the soil can increase soil organic carbon, which improves soil quality, and both soil and water conservation (Garten and Wullschleger, 2000; McLaughlin and Walsh, 1998). Ultimately, optimization of switchgrass production to balance the mixture of resource use efficiency, total energy and bioproduct recovery, production economics, and fuel quality should be important components of an implementation strategy for utilization of cellulosic crops in bioenergy and bioproduct production.

B. Parametrization of the ALMANAC Model

ALMANAC is a physiologically based crop production model designed to quantify key plant–environment interactions that influence productivity and resource use by a wide variety of agricultural crops (Kiniry *et al*., 1992). Parametrization of ALMANAC for estimating switchgrass productivity was based on previous work with Alamo switchgrass at several sites in Texas (Kiniry *et al*., 1996). Work at locations outside of Texas involved developing appropriate soil parameters to characterize water and nutrient supply potential of each location, and working with the degree days to maturity and the potential leaf area index (LAI) to provide realistic simulations of growth rates and growth dynamics. The model simulates the soil water balance, which requires realistic values for soil depth, soil water–holding capacity, and runoff curve number. Water availability for plant growth is simulated as a function of plant demand, atmospheric demand, rainfall input, and soil water drainage from the upper soil layers. Dry matter production is simulated with light interception using the Beer's law (Monsi and Saeki, 1953) and daily predictions of LAI. A realistic value for potential LAI is needed for each site. Stresses, such as drought or nutrient deficiency, can reduce LAI and biomass in the model.

For analyses in this chapter, ALMANAC was used to check assumptions, concerning current and potential yields of switchgrass across regions for which biocellulosic energy supply estimates were of interest. Four representative US locations were selected from a region-wide network of test locations for switchgrass productivity (McLaughlin and Kszos, 2005) with the idea of using published switchgrass yields to calibrate simulated yields before extending simulations across broader regions. These sites and responsible investigators were Beeville, TX (Bill Occumpaugh), the E.V. Smith site research stations near Tallassee, AL (David Bransby), an eastern Nebraska site near Nickerson, NE (Ken Vogel), and Blacksburg, VA (David Parrish).

Plant parameters used in these simulations included RUE and light extinction coefficient (k) for Beer's Law. The RUE was 4.7 g MJ^{-1} intercepted PAR and the k was -0.33 for all locations. These values were derived from field measurements at Temple, TX (Kiniry *et al.*, 1999). We assumed the potential LAI was near 6.0 for the longer growing season locations and about half as large for the shortest growing season, driest location. Potential LAI was 5.8 for three of the locations and 2.7 for Mead, NE. The base temperature for calculation of growing degree days was 12°C, with an optimum of 25°C (Van Esbroeck, 1996). Values for degree days to maturity were calculated using the actual weather data for the sites. The values for degree days to maturity each year were 2600 in Alabama and Texas, 1400 in Nebraska, and 1100 in Virginia.

C. Simulated Yields from ALMANAC Versus Actual Yields Within the Region

AU:2,3 Working with USDA-NRCS soils data and NOAA weather data, we were able to simulate switchgrass yields for these four locations. When compared with available measured Alamo switchgrass yields, ALMANAC yield simulations were found to be in good agreement with yields attained in field test plots at these four locations (Table III).

Switchgrass yield potential was simulated with ALMANAC in this project to both estimate upper yield limits in the field under nonlimiting water and nutrient supply and to provide estimates of time-averaged regional yields that considered both temporal variability in climate and spatial variability in soils within regions. Simulated upper limit yields under field conditions with water and nutrient limitations removed were in the range of 50 Mg ha^{-1} $year^{-1}$ (results not shown), very similar to the scaled maximum plant yield observed in the Tennessee clonal nursery (Table II). Field-scale-yield simulations with ALMANAC, which included both weather-dependent variations over time (13 years) and spatial variability across 27 soil types, have provided estimations of both the level and variability of yields to be expected under typical climatic variability across the study region as shown in Fig. 3. Both minimum and average yields within a region shown in Fig. 3 will be important in establishing required acreage to supply a biorefinery plant with adequate feedstock. The higher ratio of minimum to average yield levels associated with the climate and soils in the Southeast and South-Central states shown in Fig. 3 suggest that the same land area in those states would provide a more dependable supply of feedstock than in the upper Midwest.

Estimates of water use efficiency (WUE) in switchgrass based on empirical data have also been used with ALMANAC both to explore the adequacy of rainfall across the region to supply moisture demands of high-yielding switchgrass and to compare switchgrass WUE with the demands of maize. In the first instance we calculated the adequacy of rainfall amounts across the study region to supply the moisture demands of the increased yields estimated to be possible by year 2025 based on breeding studies. Based on ALMANAC simulations of total crop water use (transpiration and

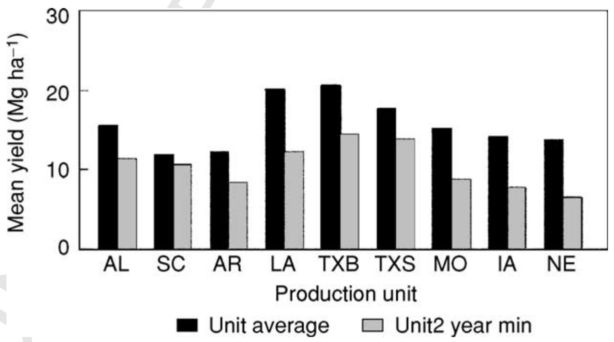

Figure 3 Potential variability in yields will be important to scaling feedstock production areas to maintain a continuous supply to large biorefinery systems. Here the ALMANAC model has been used to interface currently achieved yield levels in test plots with the influences of both soil type and climate variation to express the relative "risk" of lower than average feedstock supply capacity for each production unit.

evapotranspiration), moisture levels projected to be available from 13-year-average annual rainfall were projected to be adequate to meet the annual demands of switchgrass at projected yield levels (Fig. 4). By plotting projected yields across the region based on current yields, climate, and soil data (Fig. 5), estimates of changes in WUE with increasing yield can be also derived with ALMANAC. Higher values for WUE were clearly associated with higher yields ($P < 0.01$), thus, we can expect improved WUE to be an offshoot of improved yields through breeding. This may make projected

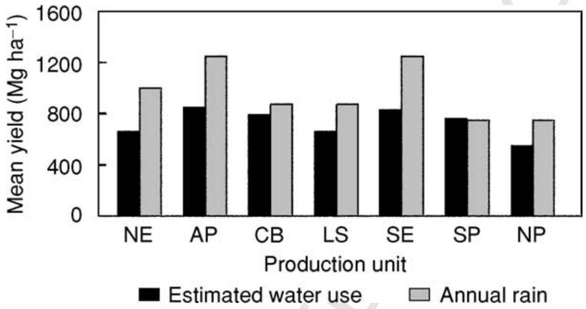

Figure 4 Estimated annual water use from ALMANAC for seven production regions at yield levels projected for 2025 suggests that average annual rainfall (13-year average) will exceed plant requirements in all areas except the US Southern Plains, where studies suggest that intermittent irrigation may strongly increase yields. The POLYSYS regions in the United States are Northeast (NE), Appalachia (AP), Corn Belt (CB), Lake States (LS), Southeast (SE), Southern Plains (SP), and Northern Plains (NP).

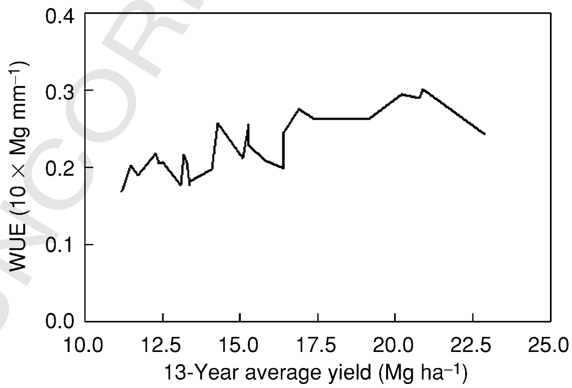

Figure 5 Calculated WUE from 13-year average switchgrass production simulated across 27 soil types by ALMANAC.

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water demand (Fig. 4) somewhat less than we assumed. Such simulations will require additional field data for validation but are compatible with physiological measurements of switchgrass under field conditions in a breeding nursery (Table III).

In a second application of ALMANAC's projections of WUE, we compared the relative water use of switchgrass and maize. Across all regions, the WUE ratio of switchgrass to maize was 40% higher on a biomass production basis and over 300% higher on the basis of biomass production for bioenergy (grain only for maize). In this application we have contrasted total crop water used by both cropping systems across 27 soil types, 13 years, and 9 test regions. We compared WUE calculated both in terms of whole plant yield and on the basis of biomass actually used in energy conversion (Fig. 6). In the primary maize production regions of the Midwest, WUE expressed as total biomass production per unit of water used for maize and switchgrass is highly influenced by soil type, but these WUE values for the two species were similar overall. As one moves outside this region, however, the relative WUE is much higher for switchgrass than for maize. However, the grain is typically the only plant part of maize used for ethanol production. Because maize grain is only about half of the total aboveground biomass, maize grain WUE necessarily is less favorable relative to switchgrass.

Finally, switchgrass yield estimates with ALMANAC have been used in providing important validation of yield assumptions in the region with an econometric model, POLYSYS (Ugarte and Ray, 2000). The POLYSYS

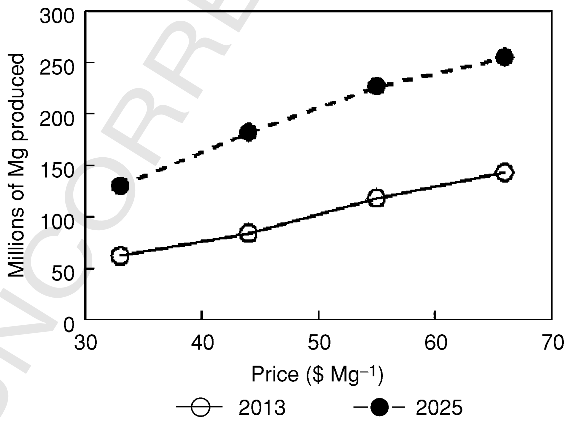

Figure 6 Relationship between price offered to farmers for switchgrass and total switchgrass production at 10 and 20 years after an aggressive breeding program is projected to begin. The increase in total production in 2025 is due to rather modest increase in average yield of 4.48 Mg ha^{-1} $year^{-1}$ (from 11.4 to 15.9 Mg ha^{-1} $year^{-1}$ in 10 years).

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model was used to evaluate the potential effects of yield and price of switchgrass on the US agricultural economy as discussed later.

IV. ASSESSING ECONOMIC IMPACTS OF WIDESPREAD DEPLOYMENT OF SWITCHGRASS IN A NATIONAL BIOENERGY PROGRAM

Regional analyses of the economic impacts of widespread utilization of a bioenergy crop have been assessed with POLYSYS, an econometric model developed for evaluating regional crop production economics (Ugarte and Ray, 2000). The POLYSYS model incorporates crop production data across 305 agricultural districts within the eastern two-thirds of the United States for which USDA baseline crop production data are available. The model integrates data on crop yields, production costs, and sale prices to evaluate relative profitability and market penetration. Such information is important for policy analysis but can also reveal important information about relationships among price, yield, demand, and production demographics. The POLYSYS analyses indicated that average yields of a crop like switchgrass, which will likely be grown on marginal lands, will be influenced by the price paid for switchgrass (McLaughlin *et al*., 2002). Average US switchgrass yield was predicted to decrease from 11 to 9.0 Mg ha^{-1} $year^{-1}$ as the farm gate price increased from \$30.3 Mg^{-1} and 3.1 million ha of supply area to \$52.37 Mg^{-1} and 21 million ha of production (McLaughlin *et al*., 2002). This effect results from the influence of price on the minimum site quality on which the crop can be profitably grown and, hence, the minimum yield that will be economically viable in the induced supply stream. To project future yields of switchgrass we have assumed that, like maize, a steady rate of yield improvement of base yield levels can be maintained over multiple decades with a sustained and vigorous breeding program. Based on 3–5% per year gain demonstrated for some upland switchgrass varieties in the Midwest (Taliaferro, 2002) and the 7.5% per year gain for lowland varieties realized in a single study in the southeastern United States (Bouton, 2002), we estimated three average rates of improvement of baseline yield levels: one for upland varieties best adapted to the cooler, shorter growing season of the Northern Plains and Lake States (1.5% gain per year above baseline); an intermediate rate of 3% per year for the Cornbelt with intermediate conditions; and the highest rates (5% per year for lowland varieties grown in the southeastern United States). These improvement rates represent the mid to upper range of improvement for commercial varieties based on past breeding research (McLaughlin and Kszos, 2005).

Projected yields will be heavily dependent on the baseline yields used to calculate them. We used ALMANAC to estimate means and ranges of yields for three soil types within each of nine Agricultural Supply Districts upon which POLYSYS is based. Since POLYSYS yields are estimated field-scale yields based on expert opinion of agronomists within the regions, we penalized the ALMANAC yield estimates for each of nine POLYSYS subregions by 30% to adjust for overestimation of field-scale yields by smaller research plots. These adjusted yields generated with actual soils and 13 years of meteorological data are compared with the regional baseline POLYSYS yields in Table IV. Also included in this table are estimated yield gains for each of the respective regions in response to 10 years (2015) and 20 years (2025) of breeding at gain rates matched to regions as discussed earlier. Averaged annual yields of switchgrass estimated for 27 soil types in nine states by ALMANAC and aggregated into the three test regions in Table IV were 12.22 Mg ha^{-1} year^{-1}, 4% higher than baseline yields in POLYSYS for these same regions. Thus, we considered POLYSYS baseline and projected yields as reasonable estimates of field-scale yields to be expected over larger regions in the United States.

In this study, we used POLYSYS to evaluate the influence of projected yield increase on the availability, price, and economic impacts of producing switchgrass as a feedstock for biorefineries in the RBAEF project. The endpoint time periods for estimation in this application were the years

Table IV
Estimates of Annual Dry Matter Yield Potential for each of Seven US Production Regions Based on Annual Increase 1.5–5% per Year Over Current Baselines Yields

US production region	Baseline yields (Mg ha^{-1} year^{-1})	Almanac yields (Mg ha^{-1} year^{-1})	Annual gains (year^{-1})	Projected future yields (Mg ha^{-1} year^{-1})	
	Averages (ranges)	Averages[a]	(%)	2015	2025
Northeast	10.89 (7.8–12.3)		1.5	12.6	14.20
Appalachia	13.06 (9.8–14.76)		5	19.6	26.2
Corn Belt	13.37 (11.07–15.05)	12.15	3	17.4	21.5
Lake States	10.73 (7.83–13.42)		1.5	12.4	14.0
Southeast	12.28 (7.60–14.42)	10.47	5	18.5	24.6
Southern Plains	9.61 (5.70–13.37)	14.04	5	14.5	19.3
Northern Plains	7.76 (4.47–12.28)		1.5	8.9	10.1

[a]Yields were estimated with the ALMANAC model for six counties in each of three Agricultural Statistical Districts within each of the designated regions. Yields from ALMANAC represent averages of 13 years of simulation with a range of soil types and actual annual meteorological conditions with those regions.

2013 and 2025. The 2013 estimation provided a 10-year maximum forward projection from a 2003 USDA forecasting baseline available at the time these analyses began (i.e., the initiation year was 2004). Yield gains during this time period were at the rate specified in Table IV. The second projection endpoint, 2025, required extension beyond the USDA forecasts. For this application, the USDA forecasting framework was fixed at 2013 levels and dynamic factors were rates of yield gain (constant increase per year at 2013 levels) and prices offered for switchgrass. Agricultural policy changes were restricted to assumptions about allowable export markets (constant or variable) and associated crop prices influenced by supply and demand. Annual rates of yield gain through breeding (Table IV) were considered to extend for a total of 22 years from the 2003 baseline for this application. With the POLYSYS model we combined anticipated rates of yield increase with a range of projected feedstock prices. Outputs from these simulations included total area on which switchgrass would likely be grown based on its relative profitability to farmers compared to conventional crops within each production region; the average yields and total production of switchgrass on these areas; changes in net returns to agriculture from switchgrass and other crops; and finally, reductions in government price support needed as a result of improved prices and farm income.

Results of the POLYSYS simulations (Table V) indicated that introduction of switchgrass as a bioenergy crop could have major and positive implications for the US agriculture. The level of these impacts will be influenced both by yield increase and by the price offered for switchgrass. At a minimum price of \$33 Mg^{-1}, over 4.9 million ha are anticipated to be in production after the first 10 years (2013), producing 130 million Mg $year^{-1}$.

Table V
Switchgrass-Planted Hectares, Production, Average Yield, Change in Net Crop Revenue and Average Annual Savings in Government Payments at Four Price Levels in Years 2013 and 2025 (Under Increasing Exports Baseline Assumption)

Switchgrass price (\$ Mg^{-1})	Millions of hectares planted		National production (millions of Mg $year^{-1}$)		Average yield (Mg ha^{-1} $year^{-1}$)		Change in net crop revenue (millions of \$)		Average annual savings in government payments (millions of \$)	
	2013	2025	2013	2025	2013	2025	2013	2025	2013	2025
33	5.1	7.6	62	130	11.95	17.18	3991	4936	775	1129
44	7.4	11.4	84	182	11.35	15.90	6609	11,982	1647	1661
55	10.6	14.9	118	227	11.12	15.25	13,690	20,587	2217	2011
66	12.9	17.1	143	255	11.10	14.91	24,045	31,492	2419	2135

At \$66 Mg^{-1} these figures more than double in 2013 and more than triple by 2025. Net farm income increases dramatically due to both improved profitability derived from substituting switchgrass for less productive crops as well as improved prices for other crops. The range in this projected effect is from \$3.99 billion at \$33 Mg^{-1} in 2013 to \$32.5 billion at \$66 Mg^{-1} in 2025. Combined with and resulting from improved farm income are substantial reductions in the need for government subsidy payments. The magnitude of these reductions prorated to the quantity of switchgrass produced is on the order of \$8.26 Mg^{-1} of switchgrass produced. Total benefits to agriculture of switchgrass produced under this scenario would be \$123 Mg^{-1} or nearly twice the price offered for switchgrass as a bioenergy feedstock at the \$66 Mg^{-1} level in 2025.

The relative effectiveness of price and yield on farm profitability are of particular interest relative to the emphasis of this paper on breeding potential of switchgrass. Yields attained by 2013 and 2025 in Table V are lower than the projected yields based on breeding progress in Table IV. This is because POLYSY is a dynamic modeling tool that incorporates new and improved seed at the time when demand develops and fields planted to those seed sources remain in production for 10 years before they are planted to newer seed sources that become available later. Thus, the innate yield potential of fields in production in 2013 will be an aggregate of seed sources planted from 1 to 10 years earlier.

Increasing yields through breeding as well as increasing the price offered to farmers for switchgrass can have dramatic effects on total switchgrass production (Fig. 6). Because of the dynamic nature of switchgrass introduction into the marketplace discussed earlier, average switchgrass yields are projected to be only marginally improved by 2013. The geometric average yield across regions in the baseline condition in Table IV was 11.33 Mg ha^{-1} $year^{-1}$. For this application we reduced this baseline yield by 10% by increasing the cutting height from 10 to 15 cm.[1]

By 2014 the average simulated yield varies between 11.10 and 11.95 Mg ha^{-1} $year^{-1}$, a 10% increase over baseline. By 2025 the gain is an additional 45% to 15.81 Mg ha^{-1} $year^{-1}$. Projections of the effects of an aggressive and successful breeding program must consider the time it will take to incorporate genetically improved material into a large-scale production system. Because switchgrass takes 2–3 years to attain maximum yields after planting, reestablishing a switchgrass field with an improved variety will reduce average yields over a 10-year cycle by around 15% from levels that might have been attained at full yield capacity for 10 years.

[1]This translates into a baseline yield of 10.20 Mg ha^{-1} $year^{-1}$ after imposing the 10% harvest penalty, resulting from increasing cutting height from 10 to 15 cm in the POLYSYS runs for this application.

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The other major variable that will influence the rate of development of biofuels supply systems is the regional variability in production potential, a result of both land production capacity and regional economic factors which favor specific crops. Based on regional variability in production potential for the United States at ($44 Mg^{-1}) in 2015 and 2025 (Figs. 7 and 8), potential productivity within the eastern half for the United States varies from 0 to over 4.5 million Mg within individual POLYSYS production units. Numerous locations are already projected to be able to supply more than the 1.59 million Mg $year^{-1}$ required to fuel a 4540 Mg day^{-1} biorefinery of the type being proposed by the RBAEF project by 2013. This is based on a modest fuel price of $40 dry Mg $^{-1}$ and relatively small effective increases in yield potential over present levels. In Fig. 9A and B the combined effects of projected yield increases to 2025, increasing the delivered price of switchgrass to $66 Mg $^{-1}$, and altering agricultural export policy are considered. Combined price and yield increase in 2025 would significantly increase the production density of switchgrass (Fig. 8 vs Fig. 9A) and the total production by approximately threefolds (see also Fig. 6). In addition, changes in crop export limits posed on conventional crops with which switchgrass would compete for land can also influence switchgrass production levels.

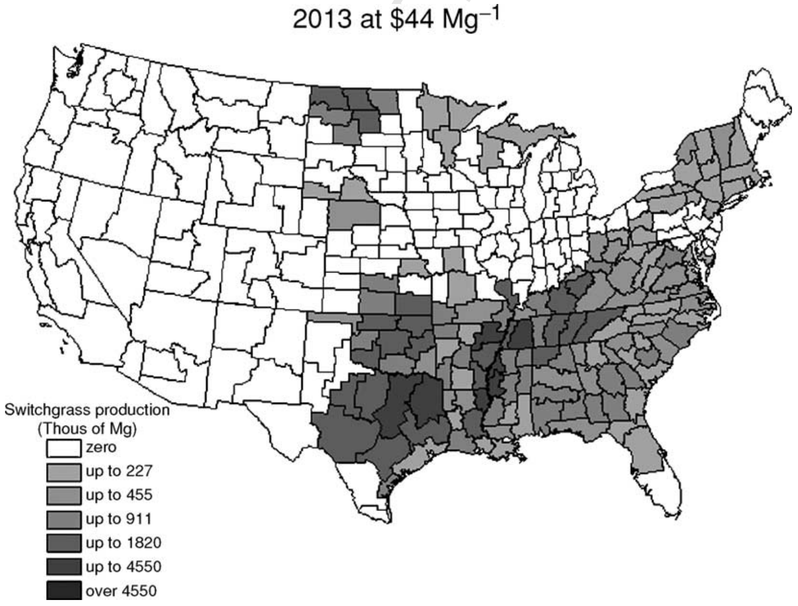

Figure 7 For year 2013, projected switchgrass production density at a delivered price of $44 Mg^{-1} at projected yield levels using POLYSYS simulations of market penetration. Export levels of other crops are allowed to increase as switchgrass production increases.

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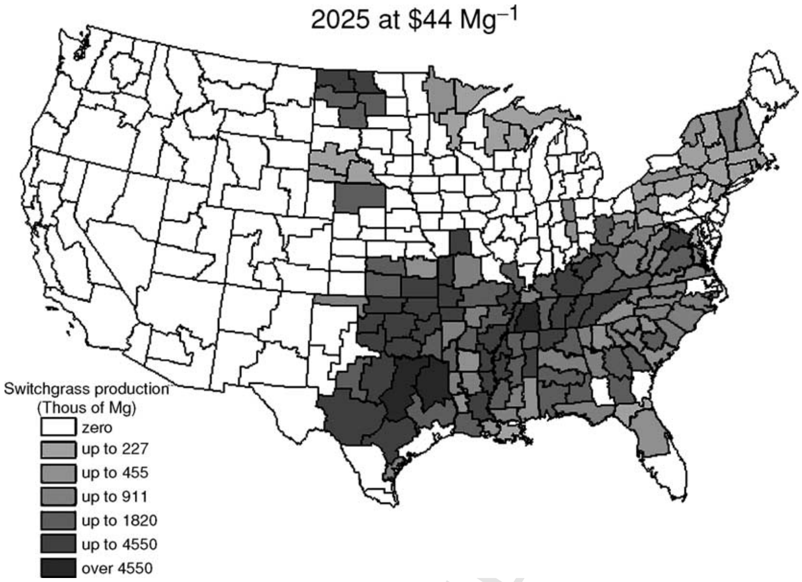

Figure 8 For year 2025, projected switchgrass production density at a delivered price of $44 Mg^{-1} at projected yield levels with yields increased by intensive breeding efforts using POLYSYS simulations of market penetration. Export levels of other crops are allowed to increase as switchgrass production increases.

The POLYSYS simulations indicate that with unlimited export of these crops as assumed in Figs. 7, 8, and 9A, prices of these crops will rise as the land base on which they are grown shrinks and demand increases. As a consequence, conventional crops would become more competitive with switchgrass. By limiting exports of these crops, prices of these crops would be lower and switchgrass would become relatively more competitive. A flat export policy further increases the competitive potential and production density of switchgrass (Fig. 9B).

Feedstock supply will be a vital component of efforts to achieve increased energy self-sufficiency on a national scale. Such systems will ultimately require utilization of multiple feedstocks to maximize US bioenergy and bioproduct potential. Dedicated feedstocks, such as switchgrass, should play an important supply-stabilizing role in such systems, and an aggressive breeding program building on past progress will be important in developing full production capacity. Recognition of the high efficiency of switchgrass in production of bioenergy per unit of input of both energy and water should be important considerations in maximizing energy production potential. Early comparisons of energy budgets of switchgrass and maize (McLaughlin

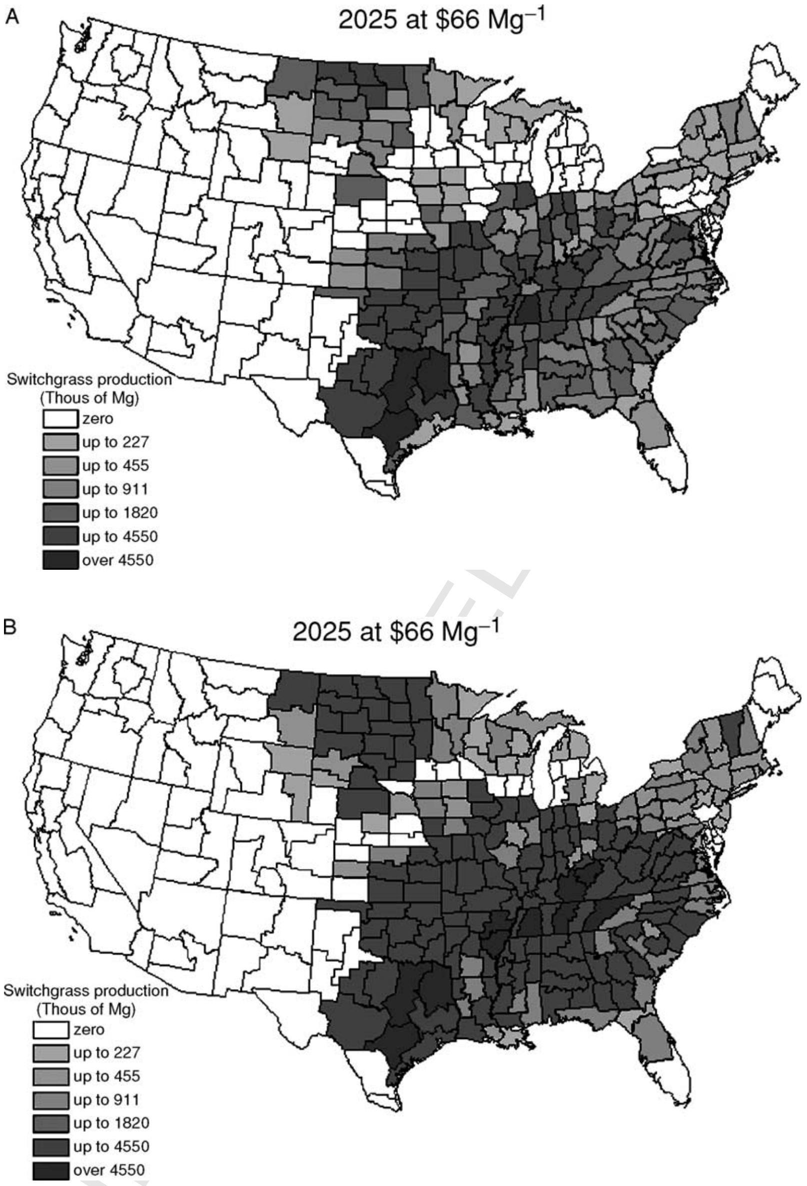

Figure 9 (A) With increasing exports of other crops, POLYSYS projection of regional switchgrass production density with both increasing price (delivered price of \$66 Mg^{-1}) at yield levels projected to be obtained by year 2025 by intensive breeding efforts. (B) Identical to Fig. 9A, but with constant exports of other crops.

and Walsh, 1998) indicated that energy gains from producing and converting switchgrass bioenergy to ethanol energy will be large (over threefold) for switchgrass. The input energy to produce switchgrass is only about 8% of the output energy in the biomass. With projected yield improvements described here, we expect this input energy to decrease even further. In addition, the favorable WUE of switchgrass should make it increasingly attractive in maximizing energy output efficiency on a landscape level. In the shorter term, strategic location of initial plants in regions with high innate production potential using the best available varieties should allow earlier initial deployment of commercial scale plants and testing of economically viable feedstock supply systems.

V. CONCLUSIONS

Similarities in the physiology and early breeding success between maize and switchgrass indicate that an aggressive breeding program similar to that of maize could lead to a doubling of yield of the best lowland varieties in 20–30 years to around 22 Mg ha^{-1} year^{-1} on areas of high production potential. The ALMANAC model and the POLYSYS model were used to make regional forecasts of the increase in switchgrass in regions having conventional agricultural markets. These models simulated the total dry tonnage of switchgrass production, the increase in farm income, and reductions in the level of government subsidies needed. Within 10 years of initiating intensive breeding efforts, even at relatively lower switchgrass prices of \$44 Mg^{-1}, significant increase in farm income (\$24 billion) and government subsidy reductions (\$1.6 billion) are projected at yields only 10% higher than current capacity. Significant opportunities would exist for locating the first 4540 Mg day^{-1} biorefinery even at this early stage. After 20 years of yield improvement it is estimated that, at a price of \$66 Mg^{-1}, 254 million Mg of switchgrass would be produced on more than 17 million ha of cropland on which switchgrass would be more profitable than conventional crops. This production is projected to increase net farm income by \$31 billion and reduce the need for government subsidies by \$21 billion. An aggressive switchgrass breeding program using modern breeding techniques, including molecular biology, would provide significant economic gains to the nation as it searches for avenues of greater energy self-sufficiency. The lag time for incorporating the best new varieties into perennial grass agriculture systems dictates that such efforts should be initiated very early in the planning cycle to maximize their effects.

Finally, the coupling of research results in basic physiology, breeding, yield management, and modeling production demographics and economics described here has been most useful in feeding national energy policy analysis in the RBAEF project. The results have contributed significantly to RBAEF analyses and recommendations, several of which were included in the Energy Policy Act (2005), and these results have important implications for future agronomic research and development. On the one hand they suggest that a large fraction of this nation's transportation energy requirements could be met with bioenergy feedstock production on currently managed lands with little or no additional land requirements. On the other hand they suggest that it can be very useful to address significant policy issues by coupling basic agronomic research with linked simulation models at multiple scales.

ACKNOWLEDGMENTS

This research is part of a larger project entitled Role of Biomass in America's Energy Future (RBAEF). This larger project has been led by Dr. Lee Lynd of Dartmouth College and represents a multi-institutional, multidisciplinary effort to provide credible forecasting of the extent to which the United States could rely in the future on cellulosic fuels such as switchgrass to reduce dependence on imported oil.

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