The Americas Journal of Plant Science and Biotechnology ©2007 Global Science Books

Biomass-Bioenergy Crops in the United States: A Changing Paradigm

Jane M-F Johnson[1*] • Mark D. Coleman[2] • Russ Gesch[1] • Abdullah Jaradat[1] • Rob Mitchell[3] • Don Reicosky[1] • W. W. Wilhelm[3]

[1] USDA-Agricultural Research Service, 803 Iowa Ave., Morris, MN 56267, United States
[2] USDA-Forest Service Savannah-River Institute, P.O. Box 700, New Ellenton, SC 29809-0700, United States
[3] USDA-Agricultural Research Service, 117 Keim Hall – UNL, Lincoln, NE 68583, United States

***Corresponding author*: * jane.johnson@ars.usda.gov**

ABSTRACT

The world energy paradigm is changing from one based on petroleum to one based on a mixture of energy platforms. This change is precipitated by a finite petroleum supply, an expanding global demand, and political instability in areas with major petroleum reserves. The mixed energy platform will include an array of renewable energy sources. The agricultural and forestry sectors have the potential to provide several plant-based products. Corn (*Zea mays* L.) grain for ethanol has long been utilized at least in some locations. Soydiesel is an expanding market. Technology is rapidly advancing to utilizing crop biomass, perennial grasses, woody perennials and forest products for the production of ethanol via a cellulosic platform and/or utilizing pyrolysis to generate syngas and other products/co-products. Emerging specialty crops have potential to supply feedstock as well. Altering fundamental aspects of plant growth, development, and responses to biotic and abiotic stresses and the opportunities to increase productivity and conversion-process efficiencies are strategies to expand biomass availability and usage. As this new platform emerges, cellulosic ethanol production brings new concerns: competing uses for crop or crop products, co-products, competition for land base, and management strategies to protect soil, water, and climate resources. As the energy paradigm shifts, the balance among competing needs will be critical to achieve sustainable food, fiber, and energy while protecting the soil resource and the environment. This emphasizes avoiding potential negative environment consequences of new bioenergy technologies and presents strategies on how this may be achieved.

Keywords: bioenergy, ethanol, biodiesel, biomass, herbaceous perennial energy crops, natural resource, renewable energy, soil conservation, woody perennial energy crops
Abbreviations: C, carbon; **CRP**, conservation reserve program; **GHG**, greenhouse gas; **N**, nitrogen; **SOC**, soil organic carbon; **SOM**, soil organic matter; **USDA**, United States Department of Agriculture; **USDOE**, United States Department of Energy; **WPEC**, Woody perennial energy crops

CONTENTS

Received: 17 March, 2007. Accepted: 20 April, 2007.

Special Feature

INTRODUCTION

The use of fossil fuels has accelerated since the dawn of the Industrial Revolution. Demand has increased dramatically in response to an ever-increasing population and by a higher need for energy by mechanization. The United Nations predicts the world's population to exceed eight billion by the year 2030 (United Nations 2005). This expanding population is increasing the demands on finite global natural resources: land, clean-fresh water and air, and fossil energy sources. Anthropogenic factors continue to elevate atmospheric CO_2 concentration, which on average already exceeds 377 ppm in 2006 (Blasing and Smith 2006) a substantial increase from 280 ppm in 1750 (IPCC 2001). The change in atmospheric CO_2 is correlated to the 0.8°C increase in global average surface temperature in the past century, and the current warming rate of about 0.2°C per decade (Hansen *et al.* 2006). The Intergovernmental Panel on Global Change (IPCC 2001; 2007) recently confirmed that the anthropogenic greenhouse effect is real. Impacts of global climate change include increased sea level (Gregory *et al.* 2001; Shepherd and Wingham 2007), change in rainfall distribution, increased storm intensity (Lowe *et al.* 2001; IPCC, 2007), and accelerated species extinction rate (Thomas *et al.* 2004). Potential impacts were dramatically presented to the general public, in the Academy awarding winning movie by Al Gore 'An Inconvenient Truth'. This movie received both praise and criticism, but most importantly brought this topic into the mainstream public arena.

There are two fundamental chemistry challenges now facing humanity: too much C (as CO_2 and CH_4) in the atmosphere, causing global warming and climate change, and too little C in the soil, degrading soil productivity and fertility, and causing environmental concerns. The release or sequestration of C in soils is therefore of prime importance to the global community. Use of C-neutral (causing no net change in atmospheric C concentration) and/or C-negative (causing atmospheric C concentration to decline) fuels and a reduction in energy consumption is needed to solve the global climate change/energy dilemma. Numerous energy alternatives to fossil fuel exist. The new developing energy paradigm will need to be multi-faceted, encompassing multiple renewable energy sources to meet the growing needs. Renewable energy such as biomass, solar, geothermal, wind, ocean thermal and tidal only represents a small percent of the available global energy (Hoffert *et al.* 2002). Biomass, similar to other renewable energy sources, has a low power density about 0.6 W m^{-2} and alone biomass will not contribute significantly to climate stabilization (Hoffert *et al.* 2002). However, biomass can be used to produce C-neutral fuels to power the transportation industry (Hoffert *et al.* 2002). Biomass fuel is C-neutral because they release recently-fixed CO_2, which does not shift the C-cycle. Biomass may generate the same amount of CO_2 as fossil fuels per unit C, but every time a new plant grows it removes that same CO_2 from the atmosphere. In contrast, fossil fuels release ancient C into the atmosphere faster than CO_2 is incorporated into organic forms by autotrophic organisms, thus disrupting the C-cycle balance. The benefits of biomass feedstock are reduced when fossil fuels are used to grow the feedstock (i.e., tillage, fertilizer) and used in the conversion process.

The C-cycle is tightly coupled with climate, the water cycle, nutrient cycles, and the production of biomass by photosynthesis on land and in the oceans. A proper understanding of the global C-cycle is critical for understanding the environmental history of earth and its human inhabitants, and for predicting and guiding their joint future. The biological C-cycle is of the utmost importance (**Fig. 1**) and is differentiated from the fossil C-cycle by the time scale. Fossil C sequestration entails the capture and long-term storage of C of fossil fuels prior to its release to the atmosphere. Fossil fuels (fossil C) are ancient geologically, whereas biofuels are very young geologically and can be effectively managed for improved the C cycling balance; thus, reducing CO_2 concentration in the atmosphere. One example of biological C cycling is the agricultural production of biomass for fuel (**Fig. 1**), which is applicable for herbaceous or woody perennials.

There can be confusion regarding terminology as related to renewable, sustainable, bioenergy, and biomass. Therefore, we felt it was worthwhile to clarify terms early on in this review. The term "renewable" refers to energy platforms of which there is an inexhaustible supply (e.g., sunlight) or that can be replaced or replenished, either by natural processes or by human action. The term "renewable fuel" also includes wind, solar, hydro-electric, geothermal, and others. "Bio-" is a Greek prefix meaning "life" or a living organism and is a modifier or a qualifier that expands meanings to form new words, e.g., biology, or biological. In

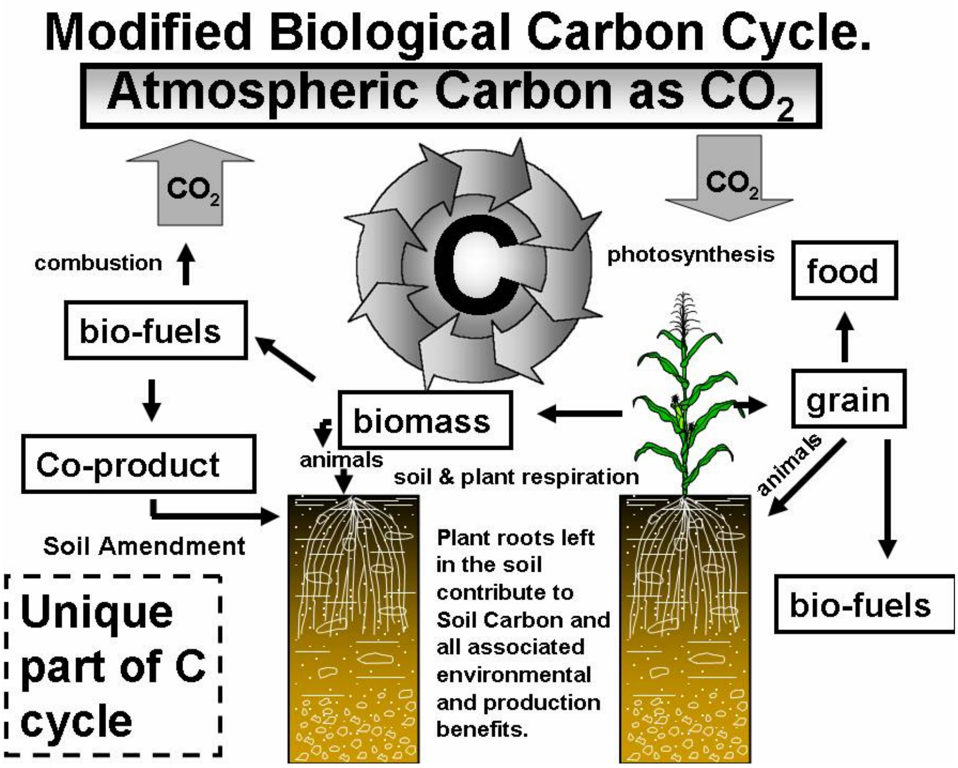

Fig. 1 Schematic representation of the biological carbon cycle.

the context of bioenergy, the prefix "bio-" suggests that the energy platforms were derived from recently living material, and typically excluded fossil fuels (coal, oil, natu-ral gas) even though fossil fuels are derived from ancient plants. "Biofuel" refers to a gas or liquid fuel (e.g., methane and ethanol) made from a broad range of carbonaceous materials such as crop biomass, sugarcane, perennial grasses, wood, wood waste, agricultural waste, fish oils, tar oil, sludge waste, waste alcohol, municipal solid waste, landfill gases, used vegetable oils, and food-processing wastes. We define "biomass" as any organic matter that is available on a recurring basis (excluding old-growth timber), including dedicated energy crops: agricultural food and crop residues (i.e., corn stover), wood and wood wastes and residues, grasses, fibers, and animal wastes, municipal wastes, and other wastes. The term "waste" is a negative and suggests material left over and of little value. However, diverting material from landfills or capturing from landfills transforms "waste" into valuable bioenergy. Many of these materials have intrinsic value for uses beyond converting them into bioenergy. The terms "biomaterial" and "bio-products" are positive, and emphasize the biological nature of the production and processing systems and implies closing the biological C and energy cycle; thereby, establishing a sustainable system.

The major benefit of biofuels is the potential to reduce net CO_2 emissions to the atmosphere. Enhanced C management may make it possible to take CO_2 released from the fossil C cycle and transfer it to the biological C cycle to enhance food, fiber, and bio-fuel production as well as sequester C for enhancing environmental quality. A sustainable bioenergy system has environmental, economic, and social components. A system is not environmentally sound if the natural resources, soil, water, and air are degraded. Degradation can limit their ability to provide environmental service ranging from water resource, wildlife habitat or food and fiber production. A system that is not socially or economically sustainable will not be adopted even if it is environmentally sustainable. Public policy (e.g., subsidies or tax incentives) and education are methods of changing the economic and social sustainability of processes. However, systems that are perceived as economically and socially sustainable do exist even though in the long term they are not environmentally sustainable. The current dependence on fossil fuel is such an example. As we change the energy paradigm, we must address all the environmental, economic, and social components of sustainability to avoid exchanging one non-sustainable system (fossil fuel) for another.

Agriculture and forestry are the primary producers of bioenergy feedstocks. Many recent reports focus primarily on the amount of energy or total biomass available. For example, Berndes *et al*. (2003) predicted the amount of global energy supplied by biomass by 2050 might range from 100 to 400 EJ yr^{-1}; the wide range is attributed to variability in assumptions concerning land availability and yield. Smeets *et al*. (2007) projected a global bioenergy potential 215–1272 EJ yr^{-1} from surplus agricultural land (i.e., land not needed for the production of food and feed) by 2050 depending on the level of advancement of agricultural technology. They recognize these may be overly optimistic estimates and predicted global potential of bioenergy production from agricultural and forestry residues and wastes to be 76–96 EJ yr^{-1} by year 2050. A recent report published by the United States Department of Energy (USDOE) and United States Department of Agriculture (USDA) estimated 1.1 billion Mg of biomass could be produced and harvested annually, in a sustainable manner, from the agricultural and forestry sector for bioenergy and bioproducts (Perlack *et al.* 2005). Comparison among reports frequently requires conversion among biomass, energy, and C content (**Table 1**). The goals of this review are to discuss potential environmental benefits and risks of several important bioenergy feedstocks, to discuss opportunities to increase biomass productivity, to offer a vision for an integrated, sustainable biomass system, and to identify major knowledge gaps that are preventing the system from being implemented today, thus, establishing research priorities.

Agronomic and forestry plants convert solar energy into chemical energy by photosynthesis. Agriculture and forestry have a unique opportunity to both provide biomass for energy and to serve as a net sink for CO_2. In addition to the C captured in the plant biomass, plants transport C belowground where it is used to grow and maintain roots, and as energy for the soil ecosystem and stored as soil organic C. The current hypothesis is that if managed correctly, bioenergy can provide a C-neutral or even C-negative feedstock. As a society, we are increasing the demands for agricultural and forest products to provide bioenergy. A strategy to minimize competition among competing demands is to increase the total amount of biomass or grain products available.

OPPORTUNITIES TO INCREASE PRODUCTIVITY

The yield of agricultural crops has increased dramatically since the late 1930's. For conventional crops, the genetic improvements of partitioning of resources into grain and the ability to respond to improved management are primarily responsible for yield increases since the 1930's (Evans and Fischer 1999; Duvick *et al*. 2004; Duvick 2005). Use of commercial fertilizer and use of pesticide have also contributed to yield improvement (Ruttan 1982). Evans and Fischer (1999) indicate maximum yield potential of certain crops (e.g., corn) has not yet been realized. The genetic yield potential for corn is estimated at 25 Mg ha^{-1} (Tollenaar 1983; Tollenaar and Lee 2002). Much of the observed yield increase in corn is attributed to improved tolerance of high plant population as well improved tolerance of biotic and abiotic stress, rather than to improved yield per plant at low population density (Tokatlidis and Koutroubas 2004). Transgenic crops are now providing herbicide-tolerance and insect-resistance, which may also increase yield potential (Duvick 2005). Harvest index for most crops has increased since the 1930's, but non-the-less total biomass of agronomic crops also increased (Johnson *et al.* 2006b).

Ideally, biomass crops would produce large quantities of biomass containing readily digestible polysaccharides and

Table 1 Common conversion to convert among biomass, energy and C content (http://bioenergy.ornl.gov/papers/misc/energy_conv.html).

Material	Volume	Mass	C content	Energy
		(Mg)	(kg)	(GJ Mg^{-1})
Wood, dry	1.4 m^3	1.0	500	18-22
Wood, 20% moisture	1.4 m^3	1.0	480	15
Agricultural biomass	$6.9^{\dagger}$ -11 m^3	1.0	450	10-17
Ethanol (pure; average density 0.79 Mg m^{-3})	1262 L	1	522	26.7
Biodiesel (Average density 0.88 Mg m^{-3})	1136 L	1	NA	37.8
Crude oil	1113 L	1.0	835-890	42-45
Gasoline	1356 L	1.0	866	43.5
Petroleum diesel (average density 0.84 Mg m^{-3})	1190 L	1.0	870	42.8
Coal (bituminous)		1.0	746	27
Natural gas	1.0 m^{-3}		0.49	34.6

†Baled corn stover (Perlack and Turhollow 2002), other straw (FAO 2004).

tailored composition with value-added chemicals (AEWC 2004; Ragauskas *et al*. 2006). As a prerequisite, biomass crops must have a sustained capacity and effici-ency to capture and convert available solar energy into har-vestable biomass with minimal inputs and minimal environ-mental impact (Sims *et al*. 2006). Conventional food crops (i.e., corn, soybean [*Glycine max* (L.) Merr.], wheat (*Triticum* ssp.)) have a number of disadvantages as biomass crops (Heaton *et al.* 2004); most are annual, requiring large inputs of energy in cultivation, planting, chemical inputs and harvesting each year (Hulsbergen *et al*. 2001), which limits their ability to reduce GHG emission (Farrell *et al*. 2006). Near and mid-term goals for advancing biomass bioenergy include improvement of conventional crops and cropping practices, and the development of a new generation of bioenergy crops that 1) maximize total annual biomass production per unit area; 2) are sustainable while minimizing inputs; 3) are environmentally sound; and 4) maximize the amount of biofuel product per unit of biomass (conversion efficiency) (Kern 2002). The remainder of this section will expand on these goals.

Enhancing the yield of biomass crops

Biomass yield can be defined as the amount of fixed C ha^{-1} yr^{-1}. Achieving the maximal yield of dedicated biomass crops is a significantly different goal than maximizing the seed yield of most annual agronomic crop species, where typically, the maximum number of reproductive or storage organs is the prime component limiting yield. The yield of a dedicated biomass crop, like it is for a forage crop, is a function of the total number of cells per unit area multiplied by the mean amount of accumulated C per cell. Thus, biomass yield can be enhanced by increasing the number of cells ha^{-1} yr^{-1}, the amount of accumulated C per cell, or both (Kern 2002; Rae *et al*. 2004). At the core of the complex system is the problem of achieving either type of enhancement. The real need is to maximize photosynthetic CO_2 fixation to support C accumulation in both grain and biomass (NAS 2000; Larson 2006; Long *et al*. 2006).

Numerous plant traits can be targeted to enhance plant biomass production, including increased photosynthesis, optimized photoperiod response, optimized plant architecture, biotic resistance, abiotic tolerance, floral sterility, regulated dormancy, delayed leaf senescence, greater C allocation to stem diameter instead of height growth, optimal nitrogen (N) acquisition and nutrient use efficiency, and less extensive root system to maximize aboveground biomass (Kern 2002; Sims *et al.* 2006; Long *et al.* 2006; Ragauskas *et al*. 2006). However, in terms of soil management, it may not be desirable to divert biomass to aboveground organs, due to the value of root C for maintaining soil organic carbon (SOC) (Johnson *et al*. 2006a).

One potential limitation on biomass yield is efficiency of light interception and the efficiency with which intercepted light is converted into biomass. Currently, it is estimated that less than 2% of sunlight is initially captured (Raguaskas *et al*. 2006). Improved efficiency may be realized through enhanced photoassimilate production resulting in increased biomass yield (van Camp 2005). Reducing the occurrence of photorespiration in C_3 photosynthetic species by incorporation of C_4 enzymes into C_3 species (Jiao *et al*. 2002), or expression of a heat-tolerant Rubisco activase or expression of an inorganic C transporter would be beneficial (van Camp 2005). These attempts at improving photoassimilate production have had varying degrees of success, as have attempts at genetically modifying the light reactions (van Camp 2005; Raguaskas *et al*. 2006).

Total photosynthetic capacity can be improved by improving light intercept efficiency (e_i) at the plant or canopy level. Interception efficiency depends on the duration, size, and architecture of plant canopy (Ceulemans and Isebrands 1996; Madakadze *et al*. 1999). A crop that can maintain optimum canopy architecture throughout the growing season will absorb the largest proportion of incident radiation (Kern 2002) thereby, enhancing the total photosynthetic capacity (van Camp 2005). The major factor determining e_i in temperate regions is the crop's ability to develop leaves rapidly at the start of the growing season. The complete canopy cover needed to maximize e_i also minimizes the availability of light to weeds and their competitiveness, thus minimizing herbicide requirements. Incorporation of cover crops into a rotation as discussed above increases e_i on a field level by extending the length of time a plant is producing photosynthate. Evergreen woody perennial energy crops (WPEC) like *Pinus* and *Eucalyptus* species also are also favorable by maximizing seasonal use of sunlight.

Understanding the mechanisms underlying the source-sink regulation in plants is needed to force plants to store more C per unit leaf area than they would for normal regular growth and development purposes. For example, short rotation poplar (*Populus* ssp.) appear to accumulate more C per unit leaf area following defoliation (e.g., harvest of biomass) than they normally would without any changes in plant architecture (Rae *et al*. 2004; Larson 2006). When the mechanisms underlying the source-sink regulation are understood, plants can be developed that exhibit significantly larger rates of net photosynthetic CO_2 fixation and larger amounts of total accumulation of C ha^{-1} yr^{-1}. Therefore, a high-priority long-term research goal is to understand mechanisms that regulate net photosynthetic CO_2 fixation. A complementary approach (Seki *et al*. 2003) is to identify factors that regulate plant growth and duration. Different plant species vary widely in growth rates, suggesting that growth rates are under genetic control and, therefore, subject to genetic modification. Several genes have been identified in functional genomics screens that cause significant increase growth rates in different types of plants (NAS 2000; Mahalakshmi and Ortiz 2001). Plants typically invest considerable energy in making reproductive structures, and if flowering can be delayed or prevented, this energy may be transferred into increasing the overall plant biomass (Ragauskas *et al*. 2006). Taking advantage of this genetic variability may create new opportunities to develop highly productive biomass crops.

The amount of biomass that can be produced per unit land area and per unit of investment of other resources, mainly N and water, will determine, to a large extent, the economic yields and energy efficiency of current and future biomass crops (Madakadze *et al*. 1999). Nutrient use efficiency can be optimized by: 1) maximizing of energy flow into biomass via photosynthesis per unit of N invested in the photosynthesis apparatus; 2) maximizing the amount of N and other nutrients translocated out of the photosynthetic source tissues upon their senescence to sink tissues (i.e., storage organs or new photosynthetic tissue); and 3) maximizing nutrient uptake from the soil; which will help minimize both nutrient inputs and loss to the environment (Hulsbergen *et al*. 2001; Tilman *et al*. 2006). With low maintenance perennial biomass species, N availability could become the most limiting factor and could become more pronounced as atmospheric CO_2 concentration continues to increase (Drake *et al*. 1997; Long *et al*. 2006). As discussed in the herbaceous and WPEC sections, management of dedicated biomass crops likely would include fertilizer application.

A substantial proportion of biomass crops may be grown on marginal lands that have suboptimal in water availability, soil quality, or both, to minimize adverse effects on food and feed production (AEWG 2004; Perlack *et al*. 2005). Water availability is a major limiting factor to plant productivity in large parts of the United States (USGS 2006). Irrigation requires significant energy inputs while placing a demand on diminishing fresh water resources. However, in areas near large metropolitan areas, the potential to use gray water from sewage treatment processes may be a way to reap significantly more biomass production from low quality water and land resources. Recent progress in understanding the mechanistic basis of plant drought, salt, and cold tolerance has raised the possibility of modifying plants to enhance productivity under drought and other stresses (Seki *et al*. 2003; Flowers 2004; Tester and Bacic 2005; Sims *et al*. 2006). Plants with C_4 photosynthesis (e.g., corn, switchgrass and *Miscanthus*) typically require less water per unit of CO_2 fixed than do C_3 plants (e.g., wheat and soybean), because C_4 plants can achieve high rates of CO_2 fixation with partially closed stomata, thus reducing water loss (Vogel and Jung 2001; Kern 2002; Long *et al*. 2006). This adaptation using genetic engineering to transfer C_4 photosynthetic machinery to C_3 plants has been attempted with rice (*Oryza sativa* L.; Matsuoka *et al*. 1998; Jiao *et al*. 2002). Long *et al*. (2006) elaborate on the potential and complexity of this transition, concluding that the possibility for success is remote. Different plants exhibit widely different abilities to survive extended periods of drought, indicating that it is possible to develop drought-tolerant biomass crops (Mahalakshmi and Ortiz 2001; Tester and Bacic 2001). Unfortunately, drought tolerance or avoidance mechanism generally result in reduced productivity because of the direct linkage between exchange of CO_2 and water vapor through the stomata and reduced rate of photosynthesis if stomatal openings close to reduce evaporation from the leaf. Reduced evaporation from leaves generally elevates leaf temperature compounding the negative impact of drought on yield. Conservation of water is generally a survival mechanism, not a means to maximum productivity. A priority in dedicated energy crops is to understand mechanisms by which plants survive drought and other abiotic stresses and adapt this knowledge to improving biomass energy crops.

Physiological knowledge of the processes of abiotic stress tolerance, especially in perennial grasses, are still developing, and it is clear that significantly more effort needs to be invested to both complement and guide breeding and genetic programs. The possibilities for increasing tolerance to these stresses are enormous (Seki *et al*. 2003). Although it is notable that the actual production of transgenic plants with demonstrably improved abiotic stress tolerance has been slow (NAS 2000), more progress can be gained by exploiting further the synergies of interfacing of physiological and molecular genetic research. Step changes in tolerance may arise from the introduction of *de novo* characteristics that are apparently absent from a particular gene pool. However, as is frequently the case, a physiological adaptation to tolerate stress is accompanied by a growth and/or yield penalty. Novel solutions (Su and Wu 2004) to avoid this outcome would be to drive expression of the new genes in response to stress by an inducible promoter.

Genomics, proteomics, and metabolomics are being used to improve our understanding of and ability to manipulate the lignin biosynthesis pathway (Vogel and Jung 2001; Casler *et al*. 2002; Seki *et al.* 2003; Dubcovsky 2004; Pedersen *et al*. 2005). Currently, corn stover is pretreated to convert lignocellulose to sugars, but transgenic technologies may provide *in planta* alternatives to pretreatment. Altering cell-wall composition to increase cellulose and decrease lignin could have significant effects on productivity of biomass crops, especially if used as sugar platform feedstock, especially if cellulose eventually can be broken down into glucose molecules efficiently, because we possess far greater knowledge of converting glucose to ethanol than the 5-C sugars in hemicellulose. For example, down regulation of lignin synthesis increased the subsequent digestibility; thus, releasing more sugar for fermentation (Ragauskas *et al*. 2006). Eventually the development of a comprehensive physiological cell-wall model incorporating structural properties with biophysical aspects and knowledge about the proteins involved will help in developing highly productive biomass species whose cell walls are optimized for conversion to biofuels. Therefore, a systems-level understanding of model plants will facilitate improvement of plant cell-wall composition in biomass crops dedicated to conversion into biofuels (Mahalakshmi and Ortiz 2001) without compromising plant viability (Himmel *et al*. 2007).

Co-regulation of lignin and cellulose biosynthesis, alteration in lignin structure and in plant cell wall structure could yield important advantages. Advances in plant sciences and genetics are providing researchers with the tools to develop the next generation of biomass crops having increased yield and utility tailored for modern biorefinary operations. However, it is important to remember the heat and power generated by burning lignin in the biorefineries is critical in determining the profitability of the cellulosic ethanol biorefinery (Sheehan *et al*. 2002).

Progress is needed to answer the three key questions: 1) What controls the synthesis and architecture of the plant cell wall; 2) how can we manipulate cell wall structure in biomass crops; and 3) can we identify key traits affecting biomass yield and conversion efficiency and target them for selection and improvement? The organization and interactions among the many polymers of the cell wall are constructed for physical strength and resistance to biotic and abiotic attacks, and therefore, constitutes a barrier to easy and efficient bio-conversion to a usable liquid biofuel (Himmel *et al*. 2007). Screening large populations to identify useful genetic variants to be used as sources for breeding is a slow and time-consuming process, especially for biomass crops most of which are not fully domesticated. However, populations of C_4 perennials such as big blue stem (*Andropogon gerardi* Vitman) can be improved for anaerobic fermentation characteristics in grazing animals in as little as three breeding cycles (Mitchell *et al*. 2005; Vogel *et al*. 2006). Development of markers or DNA polymorphism indicative of desired traits will facilitate this process; thus, allowing breeders to monitor plants for a trait that can be difficult to recognize due to tissue-specific or developmental-stage-specific expression. Using modern molecular genomic applications of modern molecular genomic tools microarrays, single nucleotide polymorphism and comparative databases are being used to support tree breeding and gene transfer efforts enhancing physiological understanding of ecological adaptations (Wullschleger and di Fazio 2003; Lorenz *et al*. 2006; Pavy *et al*. 2007).

Challenges in developing biomass crops

Some of the challenges in developing biomass crops include, but are not limited to (1) better understanding of gene regulation and control of plant metabolic pathways; (2) improving gene modification through functional genomics; (3) developing new screening systems; (4) improving biotechnological method for gene stacking, organelle transformation and molecular evolution; (5) expanding knowledge of C flow at the molecular level; (6) identifying mechanisms of gene switching; (7) developing broad bioinformatics (Mahalakshmi and Ortiz 2001; Kern 2002; AEWG 2004); (8) developing agronomics to effectively and efficiently plant, grow, and harvest; and (9) designing cropping systems with a group of grain and energy crop in a sequence that maintains feedstock supply, grower profitability, environmental services, and sustains soil quality.

Many potential biomass crops require significantly enhanced breeding, testing, and selection to incorporate desired traits and adaptability across a wide range of environments in multiple geographical regions (Casler *et al*. 2002; Kern 2002). The first step in plant breeding for bio-based renewable energy is to identify useful genetic variation for (1) biomass yield and composition; (2) water, N, and radiation use efficiencies, (3) tolerance to abiotic stresses, and (4) resistance to biotic stresses, such as drought, temperature extremes, and salinity. Selection of appropriate crop species and genotypes suited for specific geographical regions may be possible. In the United States, some long-term breeding of switchgrass and poplar has produced large yield gains and these crops are poised to make a large contribution to biofuel production (Heilman and Stettler 1985; Pedersen *et al*. 2005). The second step is to develop methods to correlate desired traits with DNA polymorphisms or markers in order to facilitate selection; this would lead, for example, to accelerated domestication of potential wild biomass species, and to eliminating many years of expensive breeding steps to develop more highly productive plants amenable for processing to biofuels (NAS 2000; Mahalakshmi and Ortiz 2001; Dubcovsky 2004). In addition to targeted breeding, many of these potential biomass crops will require reproductive control (i.e., self-fertility) in the field, either to ensure parentage or prevent gene flow to wild populations (Heaton *et al.* 2004). This is less of an issue for WPEC when they are vegetatively propagated as discussed above; however, many of the same reproduction control issues exist for trees as for herbaceous species.

Many features considered ideal for herbaceous biomass crops are characteristics of invasive weeds, particularly perennial C_4 grasses. A consideration in adapting these grasses for use as dedicated biomass crops is to ensure that the species can be contained as a crop and will not become a problem. Some highly productive perennial grasses such as *Miscanthus* × *giganteus* have been studied intensively in Europe and are thought not to exhibit invasive characteristics (Madakadze *et al.* 1998; Vogel and Jung 2001; Heaton *et al.* 2004). All candidate biomass crops should be studied for potential invasiveness at diverse locations within the United States and provide insights into insects and diseases that might threaten productivity.

Because of the limited breeding experience to date, advances in biomass crop yield and quality can be expected over the next few decades (BTAC 2002). Improved genetic material and management of dedicated biomass crops likely also will improve production. Recently, genetic resources have been developed expanding the understanding of fundamental biological processes responsible for stress tolerance, productivity, symbiotic interactions, and synthesis of biochemical components such as cellulose and lignin in woody species (Stettler *et al.* 1996; Villar *et al.* 1996; Wu *et al.* 1997; Martin *et al.* 2004; Busov *et al.* 2005; Wullschleger *et al.* 2005; Tuskan *et al.* 2006). A major step in the development of genetic resources is the mapping of the *Populus trichocarpa* genome (Tuskan *et al.* 2006). This is only the third plant genome to be mapped, second to *Arabadopsis thaliana* L., a model plant with a minimal genome, and rice, arguably the most commercially important crop plant on a worldwide basis. Having the poplar genome provides opportunities to understand the genetic basis of perennial growth habit and the molecular controls over maturation and wood formation among other significant traits of woody plants (Tuskan *et al.* 2006). These significant traits for a major WPEC species means it is possible to select and develop energy crops for growth, environmental stress tolerance, process compatibility, or unique chemical components required in biorefineries. In combination, the accumulated information on the biology, culture, operations, economics, and genomics of woody crops provides a significant foundation on which to build a bioenergy market.

FEEDSTOCKS: POTENTIAL BENEFITS AND RISKS

Grain ethanol

Cropland represents about 20% of the total land area in the United States (Lubowski *et al.* 2002). In 2005, the majority of agronomic crops was harvested from about 96.2 million ha; with corn, bean (soybean and dry edible (*Phaseolus* L.)), and small grains representing 87% of this acreage (USDA-NASS 2006; **Fig. 2**). Corn and soybean are major grain crops in the United States and are currently used for comercial production of biofuels (i.e., ethanol and biodiesel) for the transportation sector. These crops are heavily subsidized, and are being touted along with wheat as the agricultural feedstocks of choice for biofuels. Therefore, considerably more attention and research has focused on corn and soy-

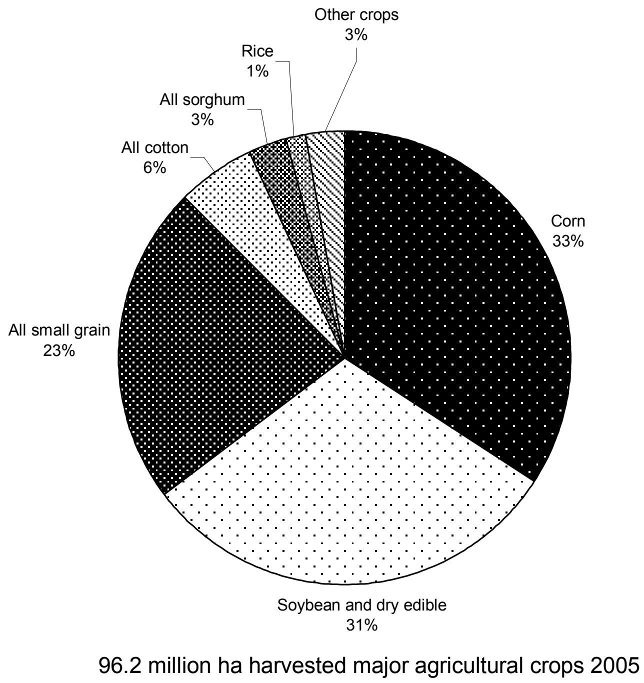

Fig. 2 Distribution of major crops (corn, (*Zea maize* L.), cotton, (*Gossypium hirsutum L.*) edible bean (*Phaseolus* ssp.); rice (*Oryza sativa* L.), sorghum (*Sorghum bicolor* L.), soybean [*Glycine max* (L.) Merr.], among the 96.2 million ha of agricultural lands harvested in 2005. All small grain includes wheat (*Triticum* ssp.), barley (*Hordeum vulgare* L.), rye (*Secale cereale* L.) and oat (*Avena sativa* L.). Other crop includes sugar beet (*Beta vulgaris* L.), potato (*Solanum tuberosum* L.), sweet potato [*Ipomoea batatas* (L.) Poir.], flaxseed (*Linum usitatissimum* L.), canola (*Brassica rapa* L) and sunflower (*Helianthus annuus* L.)(USDA-NASS 2006).

bean as biofuel sources (Pimental and Patzek 2005; Herrera 2006; Hill *et al.* 2006) than alternative or newly developed crops. However, corn and soybean are primary food-crops, which are vitally important to world food security; thus, considerable debate has ensued as to whether it is feasible or even ethical to divert arable land and or food-crops to energy production (Pimental and Patzek 2005). There is still debate over the energy efficiency and environmental ramifications of using high input, highly valued food-crops as an energy source (Hill *et al.* 2006). Apparent disparities among published energy balance estimates for grain ethanol production have been attributed to divergent allocation of energy used in production among ethanol and co-products (Sheehan *et al.* 2002) with net energy balances ranging from negative (Pimentel and Patzek 2005) to positive (e.g., Shapouri *et al.* 2002; Kim and Dale 2005). Farrell *et al.* (2006) recently reanalyzed six reports comparing energy efficiency and environmental impacts. They concluded grain ethanol has small a positive energy balance, such that 5 to 26% of the energy is truly renewable. A healthy debate over the assumptions, allocation of energy and consumption help identify both real drawbacks and potential benefits of this energy platform. By today's standards for any biofuel to be a viable and sustainable substitute for petroleum, it must be economical to produce large quantities without depleting food supplies, provide more energy than is used to produce it, and provide environmental benefits such as reduction of greenhouse gas (GHG) emissions.

The ethanol industry is expanding at an unprecedented rate. In 2005, the United States produced 44.5% and Brazil produced 45.2% of the world's ethanol (32.7 billion L yr^{-1}) (Worldwatch Institute 2006). World wide, sugarcane (*Saccharum officinarum* L.) is the primary feedstock for ethanol production with corn grain as close second (Worldwatch Institute 2006). Ethanol production from sugarcane results in the co-product bagasse and from corn grain it is distiller's grain with solubles, either wet or dry. Perlack *et al.* (2005)

estimated about half of the distiller's grain with solubles are used as animal food. In addition, both can as serve as feedstock for gasification and/or cellulosic ethanol production (Perlack *et al*. 2005; Marris 2006). In Brazil bagasse is used as fuel for distillation and cogeneration of electricity, producing a surplus of power (Dias de Oliveira *et al*. 2005). Life-cycle analysis indicated that production of electricity from bagasse reduces energy-related emissions, while using bagasse as feedstock for cellulosic conserves oil, both environmental benefits (Botha and von Blottnitz 2006).

In the United States, ethanol production, primarily from corn grain, is predicted to reach 26.5 billion L by 2010 (Baker and Zahniser 2006). Twelve percent of the 2004 United States corn crop was used for ethanol production and this percentage is predicted to nearly double by 2010. Baker and Zahniser (2006) anticipate sustained increases on the demand for corn grain will reduce stockpiled corn and cause market shifts like reducing the amount exported, increasing corn prices and encourage addition corn production. Indeed corn prices during the 2006 harvest season increased from $1.97 in July to $3.21 in November (average corn price for Iowa; http://www.agriculture.state.ia.us/historic.html). The Chicago Board of Trade Price for July 2007 delivery was $4.38 on February 20, 2007.

A serious concern about the efficiency of ethanol from corn grain is the large input of N fertilizer used in production of the feedstock. Nitrogenous fertilizer production is very energy and C intensive (Worrell and Block 1994). However, there is exciting research to use wind energy to generate hydrogen and manufacture ammonia for fertilizer being pursued by the University of Minnesota, West Central Research and Outreach Center, Morris, MN (http://wcroc.coafes.umn.edu/To_Devlop_Globally_Unique_Wind_to_Hydrogen.html).

Utilization of wind energy to produce ammonia fertilizer, made in the region where it is needed has many benefits. Wind energy reduces the fossil fuel needed to manufacture N fertilizer and transport the fertilizer. This does not necessarily reduce the cost of N fertilizer production, but can reduce the release of CO_2 from production of the N fertilizer. Reducing the fossil fuels input to corn production will improve net energy return. Reducing fossil fuel use for making N fertilizer does not address the water quality issues related to nutrient and pesticides leaching or volatilization associated especially with corn production. For example, commercial N fertilizer and soil mineralization are considered the largest annual inputs of N into the Mississippi River Basin and Gulf of Mexico (Goolsby and Battaglin 2000). Excess N has been implicated as one of the principal causes for the expanding hypoxic (low oxygen) zone. Others have also questioned the sustainability of corn and soybean production in part due to the increased risk of erosion and the associated movement of N from the field (Randall 2001). Mann *et al*. (2002), Wilhelm *et al*. (2004), and Baker *et al*. (unpublished) have proposed adding cover or companion crops to present corn production practices to help offset N fertilizer needs and reduce amount of off-season movement of nutrients to surface and groundwater.

Biodiesel

Perhaps one of the first biofuels visionaries was Rudolph Diesel (1858-1913) whose invention, the diesel engine, was originally designed to run on vegetable oils (www.ybiofuels.org). The term biodiesel refers to methyl and ethyl esters derived by the transesterification of plant triglycerides and animal fats, providing a liquid fuel similar to No. 2 diesel, with about 88% of the energy in No. 2 diesel (Demirbas 2006). Although other methods of transesterifying vegetable oils have been researched, the oldest and most widely used procedure for making biodiesel is by transesterification using alkaline catalysts (Singh *et al*. 2006).

Energy efficiency and economics of biofuels are major concerns. Estimates based on United States biofuels production show that corn-based ethanol provides a net energy return of only about 25%, while that for biodiesel from soybean is considerably higher at around 93% (Hill *et al*. 2006). The higher energy return for soydiesel is partly due to the greater energy content of the fuel, but largely the result of lower inputs for feedstock production (e.g., fertilizer inputs, energy, and equipment). For biodiesel production, feedstock accounts for about 80% of the operating cost (Demirbas 2006). Naturally, reducing input costs and energy for feedstock production will result in a more economical fuel with a larger net energy return.

Soybean

Soybean production can accentuate soil erosion and loss of SOC. Soil erosion following a soybean crop is usually greater compared to corn (Moldenhauer and Wischmeier 1969; Oschwald and Siemens 1976; Siemens and Oschwald 1976, 1978; Laflen and Moldenhauer 1985). Soybean-associated soil erosion is attributed to less surface biomass, a less stable soil surface populated with smaller aggregates, which are more susceptible to dispersion and surface sealing (Oschwald and Siemens 1976; Siemens and Oschwald 1976, 1978; Fahad *et al*. 1982). After tillage, the soil surface tends to be rougher with more clods following corn or cereal than following soybean. In addition, soybean biomass contributes less C to SOC compared to corn (Layese *et al*. 2002). Exacerbating this issue, the soybean rhizosphere induces a positive priming effect accelerating SOC decomposition, which is not observed with other crops (Fu and Cheng 2002; Cheng *et al*. 2003). The primary effect may be a result of the relatively low C:N ratio of soybean biomass compared to soil organic matter (SOM) or non-legume crop biomass. Generally decomposition of organic material in the soil system is N limited. From an environmental standpoint alternative management practices such as diversifying rotations and including cover crops could minimize C depletion and soil erosion during the soybean phase of the rotation.

The remainder of this section introduces potential alternative and newly developed oilseed crops that could substitute for soybean as a biodiesel source with associated economic, social, and environmental benefits these crops may offer. It is not the intent of this section to provide an exhaustive list of such crops, but merely to highlight some viable options and the advantages they may have over high valued food-crops.

Alternative oil-seed crops

Several species from the mustard family (Brassicaceae) could serve as viable candidates as alternative sources of biodiesel. Oilseed rape (*Brassica napus* L.) is presently a major source of biodiesel in Europe (Demirbas 2006). Brassicaceae species have advantages over soybean that include higher seed oil content and an ability to be grown in harsh climates with fewer agricultural inputs. Some Brassicaceae species (e.g., crambe (*Crambe abyssinica* and lequerella [*Lesquerella fendleri* (S. Wats.)]) are grown primarily for industrial purposes (e.g., lubricants and plasticizers) rather than food uses (Carlson *et al.* 1996; Salywon *et al*. 2005). The seed oil content of soybean is typically around 20% (wt. oil/wt. seed), whereas potential alternatives like oilseed rape, crambe, and camelina (*Camelina sativa* L.) commonly have 30 to 40% seed oil contents (BfEL 2006). Crambe is an oilseed crop that is widely adapted to conditions in the Midwest region of the United States where seed yield were about 1400 kg ha^{-1} (Carlson *et al*. 1996). Camelina recently entered commercial production, and grows quite well in the northern United States with yields around 1700 kg ha^{-1} (Putnam *et al.* 1993). Currently neither crop is grown widely in the United States. However, both are being developed for industrial uses and therefore, will not directly compete with soybean or other edible-oil crops. Importantly, production costs and agricultural inputs for crambe and camelina are lower than high-valued food-crops (Carlson *et al.* 1996; Putnam *et al*. 1993). Their seed yields tend to be lower than soybean, but their higher seed oil content results in greater oil yields on a per hectare basis. Camelina seed oil has recently been shown to make a satisfactory biodiesel with lower productions costs than oilseed rape (Fröhlich and Rice 2005). It is important to note that these newly developed, less domesticated crops may not be as widely adapted to various climates in the United States nor may they currently have as high of yields as crops like soybean, which have benefited from decades of intense genetic manipulation from both private and public sectors.

Pennycress (*Thlaspi arvense* L.) is an annual plant considered to be a weed in the United States, whose seed oil content ranges from 20 to 38% (Hondelmann and Radatz 1984) and could serve a dual role as both a cover crop and biodiesel source. In the upper Midwest, pennycress can be autumn seeded, it emerges in late winter to early spring, sets seed and can be harvested in late May to early June (pers. comm., Terry Isbell, USDA-Agricultural Research Service (ARS)-National Center for Agriculture Utilization Research, Peoria, IL). This leads to the interesting possibility that pennycress could act as a cover crop in early spring to reduce soil erosion, and yet it could be harvested in time to allow planting and harvesting of a warm, short-season crop such as soybean or even short-season corn.

Although virtually any plant oil can be converted to biodiesel, some may have fatty acids with more desirable physical and chemical characteristics. For instance, seed oil of castor bean (*Ricinus communis* L.) and *Lesquerella*, another member of the Brassicaceae, have very high levels of hydroxylated fatty acids that when methyl esterified impart greater lubricity than soybean or oilseed rape methyl esters (Goodrum and Geller 2005). Castor bean was once grown commercially in the United States, but now castor bean oil is imported (Brigham 1993). Average irrigated castor bean yields are 900-1000 kg ha^{-1} with report of 1300 kg ha^{-1} for open-pollinated varieties and exceptional yields of up to 5,000 kg ha^{-1} (Duke 1983). *Lesquerella* is a potential new industrial crop that can be produced in warm, semiarid climates; yields have been as high as 1800 kg ha^{-1} in experimental plots and about 900 kg ha^{-1} in farm scale trials located ub the semi-arid southwestern United States (Dierig *et al*. 1996).

Another prospect for industrial and energy applications is *Cuphea* spp. (plant family Lythraceae). Over the past two decades, breeding efforts with the species *Cuphea viscosissima* Jacq. and *C. lanceolata* W.T. Aiton resulted in a new crop (Knapp 1993; Knapp and Crane 2000), which recently was cultivated in the Midwest for commercial use (Gesch *et al*. 2006). Seed yields in small plot trials of PSR23 averaged 1000 kg ha^{-1} (Gesch *et al.* 2002) and on-farm trial were as high as 744 kg ha^{-1} (Gesch *et al*. 2006). *Cuphea* is different than all traditional oilseed crops grown in the United States because its seed storage oil is mostly composed of saturated small- and medium-chain triglycerides with fatty acid chain lengths of 8- to 14-C long compared to 16-18 C in soybean and sunflower (*Helianthus annuus* L.) (Graham 1989). Within the genus *Cuphea* there are numerous species that greatly emphasize the synthesis and storage of particular fatty acids. For instance, *C. pulcherrima* contains up to 94% caprylic acid (C8:0) and *C. schumannii* 94% capric acid (C10:0) (Graham and Kleiman 1992), *C. palustris* contains 64% myeristic acid (C14:0) and several species have lauric acid (C12:0) contents of 60% and greater (Graham *et al*. 1981).

The physico-chemical nature of *Cuphea* oil may lend itself more useful and economical for production of liquid biofuels. The lower molecular weight and lower viscosity of short- and medium-chain vegetable oils compared to long-chain triglycerides found in traditional oilseed crops may make it possible to use them as a diesel substitute without transesterification (Goodrum and Eiteman 1996). Experimental tests on simulated oil of genetically altered *C. viscosissima*, VS-320, which is high in caprylic acid, indicate that its fuel properties are close to that of methyl esters and No. 2 diesel (Geller *et al*. 1999). Consequently, there would be no need for chemical modification, which would reduce the biofuels production costs and increase net energy return.

A common problem with biodiesel is poor low temperature properties; particularly cloud point (Peterson *et al.* 1997). This problem is also associated with vegetable-based lubricants. However, Cermak and Isbell (2002) showed that estolide 2-ethylhexyl esters synthesized from saturated small- and medium-chain fatty acids (i.e., C4:0-C12:0) resulted in low temperature physical properties superior to some commercially available combustion engine lubricants. Furthermore, estolides and esters synthesized using *Cuphea* (PSR23) seed oil, high in capric acid (C10:0), resulted in cold temperature pour points as low as -41°C (Cermak and Isbell 2004). Perhaps a similar process might eventually be used to improve the cold temperature properties of biodiesel without sacrificing biodegradability of biodiesel by adding low-biodegradable additives. Because *Cuphea* is a rich source of medium-chain triglycerides, it is also being studied for efficient conversion to jet engine biofuel (pers. comm., Ted Aulich, Energy and Environmental Research Center, University of North Dakota).

Use of alternative oilseed crops for biodiesel may have some important advantages over heavily touted soybean. Many oilseed alternatives such as those mentioned in the previous paragraph can be grown on marginal lands with fewer agricultural inputs than soybean or other food crops. Fewer production inputs translate into less leaching and runoff of pollutants, greater reduction in GHG emissions, and possibly a lower costing product to consumers, provided they do not increase the risk of erosion and sufficient yield to make a difference. Furthermore, diversifying agricultural systems with new and alternative crops and lengthening crop rotations will help to reduce insect and weed pests, as well as diseases, again resulting in fewer inputs; thus, improving soil and water quality. Supplementing soybean with alternative oilseeds for biodiesel will lessen the likelihood of depleting food supplies, but undoubtedly there will be some competition for agricultural land, which may be better used for food production. A related issue to resolve is the impact of biomass harvest on soil quality (an issue addressed in other sections of this review).

Lastly, why isn't the United States more actively pursuing alternatives to soybean or other food-use oilseed crops for biodiesel production? A most likely answer is that farmers who produce new and alternative crops, do not receive subsides or crop insurance. Most research dollars have been spent on development and improvement of food-use, rather than industrial crops. Until policies and societal attitudes change, barring catastrophic events, it likely that these crops will continue to take a backseat to corn and soybean.

Cellulosic biomass

Sources of cellulosic biomass are numerous: woody biomass crops and lumber industry wastes, forage crops, industrial and municipal wastes, animal manure, and crop residues (FAO 2004; Perlack *et al*. 2005). Crop biomass, especially corn stover, is thought to be available in sufficient quality to support commercial-sized cellulosic ethanol production (di Pardo 2000; Hettenhaus *et al*. 2000). Wheat is also considered primary feedstock (Nelson 2002). There are regionally important feedstocks such as sugarcane bagasse in Louisiana, rice (*Oryza sativa* L.) straw in California (di Pardo 2000), and perennial grass straw from grass seed production fields in the Pacific Northwest. Individually these regional feedstocks account for only a small percentage of the total biomass feedstock, but collectively can positively impact on fuel needs for the nation (di Pardo 2000). In addition they will be important early feedstocks because they are already collected as a part of current cultural practices. As such, a significant cost in the cellulosic ethanol feedstock chain, collection and staging, is eliminated.

The energy industry speaks of two general methods, or platforms, for converting feedstock into fuel or other products. The platforms are: 1) the sugar platform that utilizes enzyme hydrolysis and produces various chemical and lignin products and 2) the thermochemical platform that includes various kinds of incomplete combustion.

The sugar platform is a series of processes to transform cellulosic feedstock to sugars (hence the name) that are analogous to those used in production of ethanol from grain. Major steps are pretreatment and conditioning, enzymatic hydrolysis, and multi-sugar fermentation (Sheehan *et al.* 2002; USDOE 2006). In the pretreatment step, feedstock is chemically or mechanically modified to initiate release of cellulose and hemicellulose from the ligneous matrix of cell walls. Enzymatic hydrolysis releases constitutive simple sugars; glucose from cellulose and 5-C sugars like xylose from hemicellulose (Sheehan *et al.* 2002; USDOE 2006). The resulting mixture of simple sugars is fermented to produce ethanol or other products butanol and plastic precursors, polylactic acid and 3-hydroxyproprionic acid.

The thermochemical platform involves processes such as gasification, co-firing, slow pyrolysis, fast pyrolysis, and flash pyrolysis (Demirbas and Arin 2002; Yaman 2004). Direct combustion (burning) is an age-old method of converting biomass into heat, but the efficiency is only about 10%, the primary byproducts are CO_2 and ash, which presents a disposal challenge. Gasification, pyrolysis, and related thermochemical technologies greatly improve the energy efficiency compared to combustion (Goldberg 1985).

Thermochemical co-products

The thermochemical technologies provide an opportunity to control the quality of the resulting fuels and at the quality of the resulting ash or char; such that the char retains value as fuel or as a soil amendment. Modern-day pyrolysis is degradation of biomass by heat in the absence of oxygen, which results in the production of char, liquid (BioOil), and non-condensable gases (http://www.dynamotive.com/) (**Fig. 3**). The feedstock characteristics, rate of heating, temperature and residence time during pyrolysis can be manipulated to control the proportions of gas, BioOil and char produced (http://www.dynamotive.com/). The char and BioOil are considered products by the industry, while the non-condensable gases are recycled and supply a major part of the energy required by the process (http://www.dynamotive.com/). BioOil is considered a clean burning, GHG-neutral fuel that will initially be used to replace fossil fuels to generate power and heat in stationary gas turbines, diesel engines and boilers replacing natural gas or coal (http://www.dynamotive.com/). Char is a solid fuel that can be used in kilns, boilers and the briquette industry. The properties of the char depend strongly on the properties of the feedstock material and the pyrolysis conditions (http://www.dynamotive.com/).

The sugar and thermochemical platforms are not mutually exclusive. The unfermented material remaining after cellulosic ethanol production has a high concentration of lignin (Sheehan *et al.* 2002). Johnson *et al.* (2004) demonstrated that the addition of this high lignin material to soils increased humic acid concentration and increased the percentage of water-stable aggregates. However, life-cycle analysis indicate this high lignin byproduct more likely will used to generate electricity or used as feedstock for a thermochemical platform improving the economic and energetic balance for cellulosic ethanol (Sheehan *et al.* 2002).

Soil quality and sustainability issues will be similar regardless of which bioenergy platform is utilized. Guidelines and best management practices will be necessary to protect the soil from erosion, prevent loss of SOM, and retain habitat and other environmental services. The next section will address benefits and potential concerns for annual, herbaceous perennials and wood perennial feedstocks.

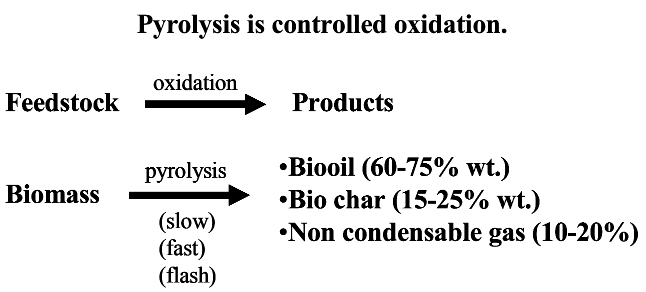

Fig. 3 Schematic representation of biomass pyrolysis http://www.dynamotive.com/.

Feedstock: Annual crops

Corn stover is viewed as the most readily available biomass feedstock (Nelson 2002; Perlack *et al.* 2005). In 2005, corn was harvested from about 33 million ha in the United States, with a national average grain yield of 9.3 Mg ha^{-1}, which corresponds to about 7 Mg ha^{-1} dry stover or nearly 230 Tg of stover produced across the country (**Table 2**). As a result, corn stover has attracted attention as a bioenergy feedstock. However, not all of this biomass can or should be harvested due to soil quality concerns.

Under continuous corn, removal of stover and grain has shown negative effects on SOC of Mollisols in Iowa (Larson *et al.* 1972; Robinson *et al.* 1996), Indiana (Barber 1979), Michigan (Vitosh *et al.* 1997), Wisconsin (Vanotti *et al.* 1997), and Minnesota (Bloom *et al.* 1982; Huggins *et al.* 1998). Removal of crop residues affects soil nutrient content and availability and soil water relations. Barnhart *et al.* (1978) showed that continued removal of corn silage from an Iowa soil resulted in decreased SOM and total N content when compared with plots where grain only was removed. Similarly, Reicosky *et al.* (2002) found that 30 years of autumn moldboard plowing reduced the soil C both when only grain was harvested and when silage was harvested; they suggested soil C would decrease irrespective of residue management if the soil were moldboard plowed. Hooker *et al.* (2005) also found that within a tillage treatment, residue management had little effect on SOC in the surface soil layer (0-5 cm); however, no till combined with stover return maintained greater SOC compared with moldboard plowed treatments.

Crop biomass on the soil surface protects the soil against erosion. Wind and water erosion preferentially transport organic-rich surface horizons; thus, eroding soil and transporting C (Cihacek *et al.* 1993; Fryrear 1995; Gregorich *et al.* 1998; Lal 2003). Larson *et al.* (1978) reported that harvesting crop biomass would directly remove substantial amounts of N and result in additional N loss due to accelerated soil erosion. Loss of N over time would eventually reduce fertility levels. Continued crop biomass removal for biofuels raises concerns about the long-term productivity and sustainability (Wilhelm *et al.* 2004; Johnson *et al.* 2006b). Removal of crop biomass even in the absence of tillage leaves the soil surface exposed and more susceptible to erosive forces (Wilson *et al.* 2004).

Above and below ground crop biomass provide the organic input for building SOM (Johnson *et al.* 2006a). Soil organic matter is responsible for many of the characteristics associated with highly productive soils (Doran *et al.* 1998; Janzen *et al.* 1998; Doran 2002). SOM improves soil aggregation and aggregate stability (Tisdall and Oades 1982; Gollany *et al.* 1991; Tisdall 1996; Six *et al.* 1998), which subsequently impacts soil infiltration, water-holding capacity (Gollany *et al.* 1992), aeration, bulk density (Gollany *et al.* 1992), penetration resistance, and soil tilth. Soil organic matter also impacts chemical properties including pH, nutrient availability and cycling, cation exchange capacity and buffer capacity (Tisdall *et al.* 1986).

Primarily, organic inputs to soil including C are from the unharvested aboveground, belowground biomass and rhizodeposition from cash crop plants and cover crops, and other organic inputs (e.g., animal manure). Total corn root-

Table 2 Harvested area and 2005 yield averages for three most common agronomic crops in the United States, harvest index used to calculate dry biomass yield, minimum biomass input to prevent loss of soil organic C, estimated total biomass produced and potentially harvestable biomass based on preserving SOC.

	Harvested area	Grain yield[†]	Harvest Index[‡]	Biomass Yield[#]	Minimum Biomass Inputs[§]	Total Biomass	Potentially Harvestable Biomass[¶]
Crop	**Million ha**	**Mg ha^{-1}**		**Mg ha^{-1}**	**Mg ha^{-1}**	**Tg**	**Tg**
Corn (*Zea mays* L.)	32.81	9.27	0.53	6.95	5.25	228	57.5
Soybean [*Glycine max* (L.) Merrill]	28.90	2.69	0.46	2.75	7.5	79	0
Wheat (*Triticum* ssp.)	20.30	2.61	0.45	2.27	3.6	56	0

[†]United States yield based on USDA-NASS (2006) reports; corn yield 15.5% moisture, soybean and wheat at 13% moisture.
[‡]Johnson *et al.* (2006a). Harvest index = grain /(grain + aboveground biomass).
[#]Aboveground biomass = {grain – (grain * Harvest index)}/harvest index
[§]Based on Johnson *et al.* (2006a), assumes continuous corn and reduced tillage (chisel or no till), continuous soybean; and continuous wheat (no fallow).
[¶](Biomass yield - minimum biomass input) * harvested area = potentially harvestable biomass.

derived C (C in root biomass plus that in rhizodeposition) contributes 1.5 times to over 3 times more C to SOC than shoot-derived C (Balesdent and Balabane 1996; Allmaras *et al.* 2004; Wilts *et al.* 2004; Hooker *et al.* 2005). Hooker *et al.* (2005) attributed the difference to dissimilar C cycling rates of shoot and root material. Wilhelm *et al.* (2004) noted a critical caveat that even though a larger percentage of root C is incorporated into SOC, it does not negate the importance of shoot biomass in building and maintaining SOC. Despite the importance of roots to the formation of SOC, there is very little information on total biomass (above and belowground) needed to maintain or build SOC; most studies include only aboveground biomass (Johnson *et al.* 2006a).

Johnson *et al.* (2006a) estimated the minimum amounts of biomass input necessary to prevent loss of SOC based on literature values from long-term field-studies (**Fig. 4**). These estimates need to be improved to better account for climatic and soil type effects. They are, however, the first published estimates of minimum biomass input required to maintain productivity (that is, SOC) and provide general guidelines to the cellulosic ethanol industry. It is critical to note these guidelines are stated as absolute amount of biomass input, not as a percentage of the amount produced, as is more commonly stated especially for preventing erosion. The soil C cycle works slowly, but relentlessly. Even though SOC decomposition rates fluctuate with seasonal temperature and water condition, over time a mean rate of input is required to replace C released from the soil system. Johnson *et al.* (2006a, 2006b) based their estimates on long-term (mean) inputs. Crop yields fluctuate over seasons. Maintenance of SOC is a direct function of C input; however, erosion control is more a function of surface cover (usually expressed as percent cover). The USDA-NRCS has a successful history of developing technology to manage soil erosion based on percent cover. Divergent strategies to control erosion and SOC levels complicate delivery of harvest guidelines to the biomass industry.

Recommendations for sustainable harvest rates need to account for both erosion risk and maintaining SOC; stover should not be harvested from lands classified as highly erodible. Consequently, the more limiting constraint, erosion or SOC, should be the determinant for harvestable stover. For example, Graham *et al.* (2007) in the Iowa-Minnesota region recommend 2.45 Mg ha^{-1} stover remain in the field for erosion control, which is about half amount estimated for maintaining soil C in a continuous corn, conservation tillage system (5.25 Mg ha^{-1}) (**Fig. 4**). Providing enough biomass for maintaining SOC constrains the harvest rate. With a stover yield of 7 Mg ha^{-1}, there would be less than 2 Mg ha^{-1} recommended for harvest annually. In a corn-soybean rotation, harvesting corn stover would not be recommended (**Fig. 4**). In most instances managing biomass for SOC will provide sufficient biomass for erosion control.

The method of harvesting corn stover will depend in part if it will serve as feedstock into a sugar or into thermochemical platform. Hoskinson *et al.* (2007) evaluated a prototype one-pass system to harvest grain and stover simultaneously from a cornfield. They evaluated four harvest scenarios (low cut, high-cut top, high-cut bottom, and normal

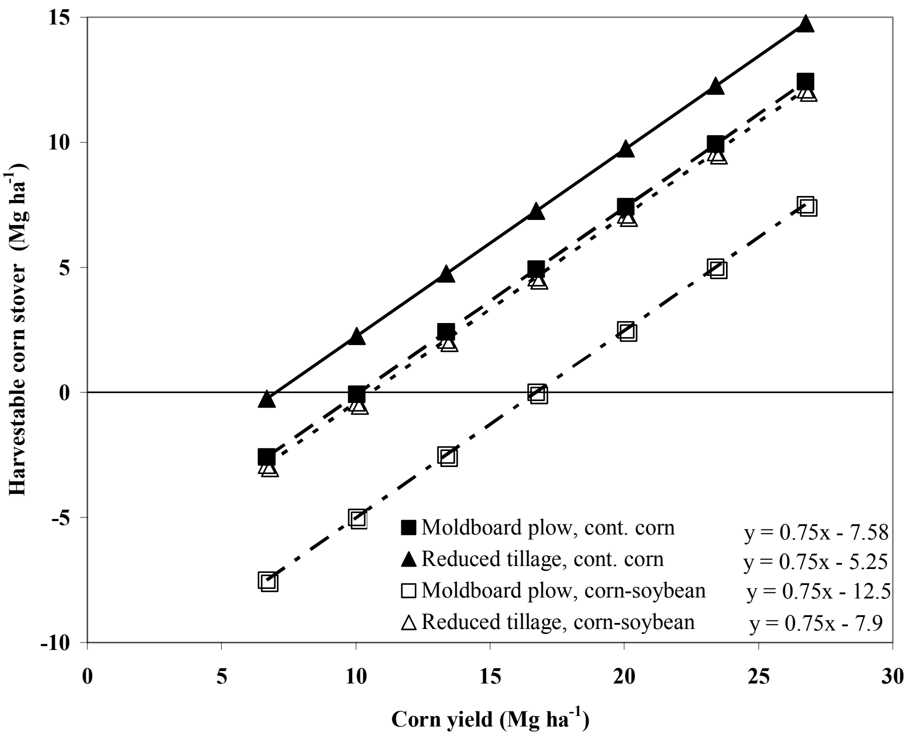

Fig. 4 Estimates of corn (*Zea Maize* L.) stover that could be harvested without reducing SOC, based on Johnson *et al.* (2006a, 2006b). The y-intercept indicates the minimum amount of stover that must remain on the field (during the corn phase of a corn-soybean rotation). This scenario assumes that 2.4 Mg ha^{-1} of soybean [*Glycine max* (L.) Merr.] biomass remained on the field during the soybean phase of the corn-soybean rotation. Reduced tillage data estimated from studies reported in Johnson *et al.* (2006a), which were chisel plowed or no tillage.

cut). Their results indicated harvesting stover (including the cobs) at a height of approximately 40 cm above the soil (normal cut) would be best for farmers and ethanol producers because of faster harvest speed and higher quality cellulosic ethanol feedstock, as well as retaining more biomass on the soil for erosion control than the low-cut scenario. Unfortunately, the mass of stover removed (5.09 Mg ha^{-1}) with this one-pass, normal-cut system left only a fraction of the amount of biomass in the field Johnson *et al.* (2006a, 2006b) estimated necessary to replenish SOC under the conservation tillage-corn-soybean rotation system use in the investigation.

Corn and wheat have dominated the discussion for agricultural biomass feedstock for cellulosic or pyrolysis feedstock (e.g., Nelson 2002; Perlack *et al.* 2005). Other small grains like barley (*Hordeum vulgare* L.), rye (*Secale cereale* L.) oat (*Avena sativa* L.), and soybean straw may also contribute. In the Midwest and Great Plains regions of the United States these crops have the advantage over corn stover as being harvested earlier and drier compared to full-season corn. Thus, there is a longer time period to harvest a drier product. Many of the environmental issues with soybean and small grain straw harvest are similar to corn stover. A minimum amount of biomass needs to be returned to protect the soil from erosion (Graham *et al*. 2007) and from loss of SOC (Johnson *et al*. 2006a, 2006b). In both cases the amount of biomass needed depends on several variables including climate, crop rotation, soil type, slope, and other management factors (Johnson *et al*. 2006a, 2006b; Graham *et al*. 2007). Soybean and small grain produce less biomass compared to corn (Johnson *et al*. 2006a) and soybean appear to exacerbate soil erosion (e.g., Moldenhauer and Wischmeier 1969; Laflen and Moldenhauer 1985) and loss of SOC (Fu and Cheng 2002; Cheng *et al.* 2003).

Wu *et al*. (2004) investigated forage and large biomass soybean cultivars for enhanced production of crop biomass without reducing grain yield. Grain yields of the experimental high biomass lines were 2 to 10% less and biomass was at least 20% more compared to conventional lines (Wu *et al*. 2004). These researchers were optimistic that grain yield of large biomass soybeans could be increased to be competitive with conventional lines. In a preliminary field trial located in West Central Minnesota, with experimental line 97NYCZ 26-1 a maturity group II forage soybean, (courtesy T. Devine, USDA-ARS, Beltsville, MD), had a grain yield of 2.1 Mg ha^{-1} and 4.3 Mg ha^{-1} biomass; group I soybeans in an adjacent field averaged 3.4 Mg ha^{-1} grain yield (Johnson, unpublished data). Typically group I soybean are planted in this part of Minnesota (Hicks *et al.* 2001). The forage soybean biomass material was comprised primarily of stems, as most of the leaves had senesced prior to harvest. The removal of small grain or soybean biomass from the field could be compensated at least partially by the inclusion of cover crops in the rotation.

Cover crops can provide ground cover between harvesting the primary cash crop and the next planting season. Both legumes and nonlegume species may be used, depending upon the cropping systems. The incorporation of cover crops into the rotation can help manage N fertility, reduce erosion risk, suppress weeds, and increase organic C inputs (Singer 2005). Reviews by Reicosky and Forcella (1998) and Dabney *et al*. (2001) discussed the positive impacts of cover crops in cropping systems and their limitations. Briefly, cover crops extend the amount of time photosynthesis occurs, which allows for more C influx (Baker *et al.* 2007); protect soil from wind and erosion by absorbing kinetic energy of raindrops and slowing surface wind speed; and improve N management either by scavenging N or by legume contributing N. The drawbacks of cover crops range from alleopathic effects of some cover crops, competition for moisture in drier climates, and keeping soil colder in cold climates (Reicosky and Forcella 1998). Thus, use of cover crops has been most common in warmer, wetter climates (Dabney *et al.* 2001). Additional field operations to plant a cover crop during the busy harvest season may be a limitation for some producers.

Erosion prevention and C sequestration benefits associated with cover crop use makes their use in conjunction with harvesting biomass appealing; provided that the added complexity to scheduling equipment and manpower to accomplish additional tasks is not limiting. Preventing soil loss from erosion, and increasing the influx of C to the soil by extending the photosynthetic season, builds SOM and improves soil quality (Dabney *et al.* 2001). Cover crops in conjunction with conservation tillage practices sequester more C than conservation tillage alone (Causarano *et al.* 2006). The C input from cover crops was linearly related to soil C concentration (Kuo and Jellum 2002), which is consistent with others who reported linear increases in soil C with increased C inputs (Larson *et al.* 1972; Paustian *et al.* 1997; Follett *et al.* 2005). The question remains can cover crops provide sufficient biomass to prevent erosion and loss of SOM in a biomass removing system. There is not a simple answer to this question. There are several interactions such as: 1) the amount of cash crop biomass produces and harvested, 2) tillage management, 3) grain crop rotation, 4) topography, and 5) climatic regime.

Herbaceous perennials for cellulosic feedstock

Herbaceous perennials such as alfalfa (*Medicago sativa* L.), bermudagrass [*Cynodon dactylon* L. (Pers.)], *Miscanthus*, napiergrass (*Pennisetum purpureum* Schumach.), reed canarygrass (*Phalaris arundinacea* L.), and switchgrass (*Panicum virgatum* L.) have been evaluated for use as dedicated bioenergy feedstocks in the United States. Although none of these species represent a "one-size-fits-all" bioenergy feedstock, each has the potential to be grown feedstock in different regions. Regardless of the species, production of any energy crops require an understanding of the agronomic practices for stand establishment, fertility management, weed control, harvest and storage procedures, and growing season precipitation requirements in rainfed production systems. Legume energy crops such as alfalfa can be grown in a cropping system with corn to provide two agricultural benefits: biomass for energy conversion and biologically-fixed N to increase subsequent crop (e.g., corn) yields.

The USDOE identified switchgrass as the model species for herbaceous perennial feedstocks after considerable evaluation of potential feedstocks (Vogel 1996). Additionally, on January 31, 2006, the President of the United States in his State of the Union Address said, "We must also change how we power our automobiles. We will increase our research in better batteries for hybrid and electric cars, and in pollution-free cars that run on hydrogen. We'll also fund additional research in cutting-edge methods of producing ethanol, not just from corn, but from wood chips and stalks, or switchgrass. Our goal is to make this new kind of ethanol practical and competitive within six years" (http://www.whitehouse.gov/news/releases/2006/01/20060131-10.html).

In his 2007 State of the Union Address, the President reiterated his position by saying, "It's in our vital interest to diversify America's energy supply, … the way forward is through technology. We must continue investing in new methods of producing ethanol … using everything from wood chips to grasses, to agricultural wastes" (http://www.whitehouse.gov/ stateoftheunion/2007/index.html). Consequently, this section will focus on switchgrass as the model perennial grass for bioenergy production. We will consider various approaches used to grow herbaceous energy crops, discuss environmental benefits of these cropping systems, and the advantages associated with herbaceous energy crops.

Switchgrass

The USDOE considers switchgrass a viable bioenergy feedstock because it is broadly adapted and has high yield potential on marginal croplands (Vogel 1996, 2004). This perennial C4 grass is native to North America except for the areas west of the Rocky Mountains and north of 55° north latitude (Vogel 2004). It can be grown very successfully in many of these areas even though it is not native. Switchgrass will be productive in most rain-fed production systems east of the 100th Meridian. Switchgrass is self-incompatible (requiring pollen from different plant to produces seed) and polymorphic (having a wide array of morphological characteristics (e.g., height, leaf size, tendency to tiller)) with distinct lowland and upland ecotypes (Martinez-Reyna and Vogel 2002; Vogel 2004). Lowland ecotypes are found on flood plains and other areas that receive run-on water, whereas upland ecotypes occur in areas that are not subject to inundation (Vogel 2004). Chromosome counts of mitosis in all evaluated plants from lowland ecotypes were tetraploids, whereas plants from upland ecotypes were either octaploids or tetraploids (Hultquist *et al.* 1996; Vogel 2004). Lowland and upland tetraploids are capable of inter-mating and producing true hybrid offspring (Martinez-Reyna *et al*. 2001). These hybrids are promising sources for high-yielding bioenergy feedstocks.

The economic viability of growing switchgrass for bioenergy hinges on establishing an adequate stand in the seeding year. Weed competition is the major reason for switchgrass stand failure (Vogel 2004). Acceptable switchgrass production can be delayed by one or more years because of competition from weeds and poor stand establishment (Schmer *et al.* 2006); however, establishment is improved if weeds are controlled with herbicides (Vogel 2004). Several herbicides have been identified for controlling broadleaves and grasses in switchgrass (Martin *et al*. 1982; Bahler *et al*. 1984; Masters *et al*. 1996; Vogel 2004), which has enabled switchgrass to be fully established within one year of planting (Masters *et al.* 1996). Vogel and Masters (2001) reported a stand frequency (occurrence frequency of the seeded plant species per unit area) of 50% or greater indicated a successful stand, whereas stand frequency from 25 to 50% were marginal to adequate, and stands with less than 25% frequency indicated a partial stand. A study conducted on 12 farms in Nebraska, South Dakota, and North Dakota found switchgrass fields with stand frequency of 40% was considered the threshold indicative of successful establishment needed to support biomass harvesting in subsequent years (Schmer *et al.* 2006). Typically, biomass is not harvested in the establishment year (Schmer *et al.* 2006). Successful switchgrass establishment and persistence requires the roots to develop a symbiotic relationship with arbuscular mycorrhizal fungi (Brejda *et al.* 1998). Most cultivated soils in the United States Central Great Plains contain adequate arbuscular mycorrhizal fungi for symbiosis, but degraded and sandy soils may be mycorrhizal deficient (Brejda 1996).

Meeting the fertility requirements for switchgrass is important for optimizing biomass production and maintaining quality stands. Nitrogen is the primary fertilizer input required by switchgrass. Although switchgrass can tolerate low fertility conditions, it responds to N fertilization with increases in dry matter production, crude protein concentration, *in vitro* dry matter digestibility, and C storage (Rehm *et al*. 1976; Perry and Baltensperger 1979; George *et al*. 1990; Sanderson *et al*. 1999a; Ma *et al*. 2001; Vogel *et al*. 2002).

The amount of applied N required by switchgrass is a function of the yield potential of the site, productivity of the cultivar, and other management practices (Vogel *et al*. 2002). The optimum N rate for 'Alamo' switchgrass ma-naged for biomass yield in Texas was 168 kg N ha^{-1}, and biomass production averaged 14.5 and 10.7 Mg ha^{-1} yr^{-1} at the Stephenville and Beeville, TX locations, respectively (Muir *et al*. 2001). Biomass production declined over time without applied N, and was sustainable only with the application of at least 168 kg N ha^{-1} yr^{-1}. In Alabama, Ma *et al*. (2001) reported switchgrass yields increased to a maximum of 12.0 Mg ha^{-1} as N rate increased up to 224 kg N ha^{-1}, the highest rate of N application in the study.

In general, as N rate increases, switchgrass biomass increases. However, an important concern is the fate of the soil-applied N and its potential to leach from the switchgrass root zone and become a groundwater contaminant. In Nebraska and Iowa, biomass yields of "Cave-in-Rock" switchgrass increased as N rate increased from 0 to 300 kg N ha^{-1} (**Fig. 5**), but residual soil N increased when more than 120 kg N ha^{-1} was applied (Vogel *et al*. 2002). They reported biomass production was optimized with the application of 120 kg N ha^{-1}, the point at which N application approximately offset N removed with the harvested biomass (Vogel *et al*. 2002). They concluded that N fertilizer recommendations in this region should be based on anticipated biomass yield, and approximately 10 to 12 kg ha^{-1} yr^{-1} of applied N is needed for each Mg ha^{-1} yr^{-1} of biomass yield (Vogel *et al*. 2002). Phosphorus (P) may be important for switchgrass growth, but limited response to fertilizer P is often reported (Brejda 2000). Muir *et al*. (2001) reported 'Alamo' switchgrass had no response to applied P when harvested for biomass at two locations in Texas. Switchgrass had no response to applied P in low P soils in Iowa (Hall *et al*. 1982). However, research in Nebraska by Rehm (1984) and Rehm *et al*. (1976) suggested switchgrass might respond to applied P, if P availability from the soil is low.

Maximizing dry matter production is the primary ob-

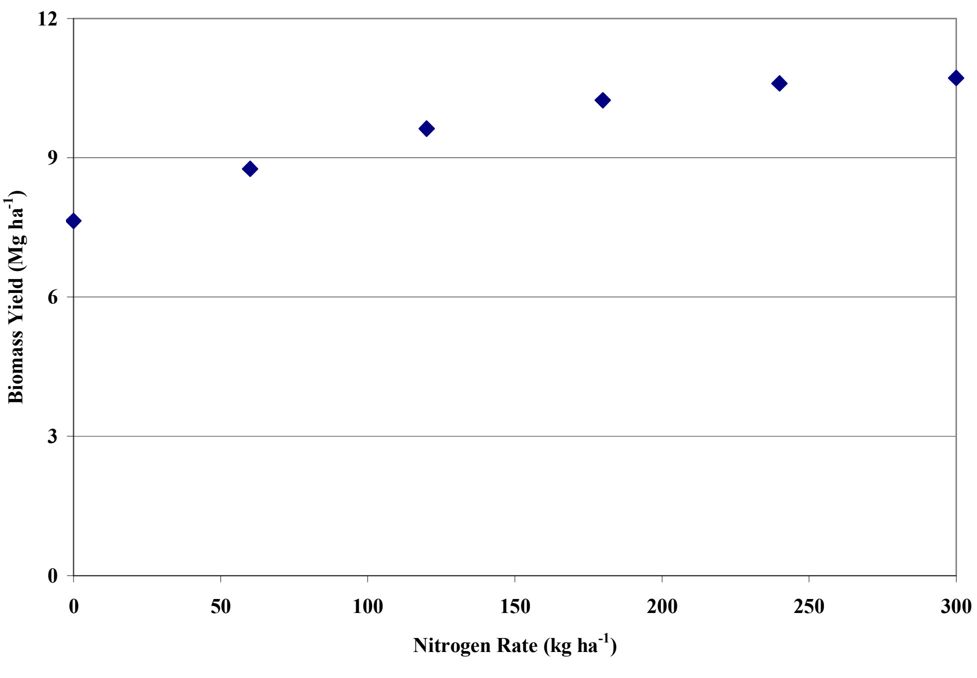

Fig. 5 Switchgrass (*Panicum virgatum* L.) N response curve developed from first harvest 'Cave-in-Rock' switchgrass grown in 1994 and 1995 at Mead, NE and Ames, IA. (Vogel *et al*. 2002).

jective when harvesting biomass for feedstocks. In general, a single harvest during the growing season maximizes switchgrass biomass recovery. For example, Sanderson *et al*. (1999a; 1999b) harvested several switchgrass strains once or twice per growing season at five locations for four years in Texas. They concluded that 'Alamo' was the best-adapted commercially available switchgrass cultivar for biomass feedstock production in Texas, and that a single harvest in autumn maintained stands and maximized biomass production. Yields ranged from 8 to 20 Mg ha^{-1} yr^{-1}, and SOC increased by 42% from 11.1 to 15. 8 g kg^{-1} in the upper 30 cm of soil between 1992 and 1996, indicating that switchgrass grown for bioenergy has good potential for storing soil C (Sanderson *et al*. 1999b). In Nebraska and Iowa, Vogel *et al*. (2002) conducted an intensive harvest management study consisting of either one or two harvests per year. Optimum biomass yields of 'Cave-in-Rock' switchgrass were attained with a single harvest during anthesis (R3 to R5; Vogel *et al*. 2002). Biomass yields ranged from 10.5 to 12.6 Mg ha^{-1} yr^{-1}, and quality stands were maintained throughout the three-year study. In South Dakota, Conservation Reserve Program (CRP) lands dominated by switchgrass, Mulkey *et al*. (2006) recommended applying 56 kg N ha^{-1} in the spring and harvesting once after a killing frost to maintain stands and optimize biomass production. In North Dakota, Frank *et al*. (2004) applied 67 kg N ha^{-1} in the autumn and harvested at the soil level for a three year average biomass yield of 6.4 and 9.1 Mg ha^{-1} for "Dacotah" and "Sunburst," respectively. Maturity of switchgrass biomass influences biomass quality and the potential glucose recovery for ethanol fermentation (Dien *et al*. 2006). These studies indicate that a single annual harvest will optimize efficiency; harvest timing needs to be considered for stand maintenance and optimizing cellulosic ethanol yield.

Environmental benefits of perennial grasses

Growing perennial grasses can protect soil, water and air quality, provide fully sustainable production systems, sequester C, create wildlife habitat, increase landscape and biological diversity, and return marginal farmland to production. Growing switchgrass for bioenergy feedstock may increase wildlife habitat, increase farm revenues, and increase C sequestration (Sanderson *et al*. 1996; McLaughlin and Walsh 1998; McLaughlin *et al*. 2002). Switchgrass root density (Mg root ha^{-1}) in the surface 15 cm is twice that of alfalfa, more than 3-fold greater than corn, an order of magnitude greater than soybean and roughly two orders of magnitude greater than cuphea (Johnson *et al*. 2007). Frank *et al.* (2004) reported that soil C increased at a rate of 1.01 kg C m^{-2} yr^{-1} and switchgrass in the United States northern Great Plains have the potential to store significant quantities of soil C. Liebig *et al.* (2005) reported that switchgrass stored 12 Mg ha^{-1} more C in the 30 to 90 cm depth than croplands in a paired field experiment in North Dakota, South Dakota, and Minnesota. Lee *et al*. (2007) reported that switchgrass grown in South Dakota CRP stored soil C at a rate of 2.4 to 4.0 Mg yr^{-1} in the 0-90 cm depth and C storage varied by N form. In addition to increasing SOC, the perennial habit of switchgrass increases the residence time of C stored in living material, especially belowground.

Perennial herbaceous energy crops provide several challenges. A stable and consistent feedstock supply must be available year-round to the ethanol plant. For the producer, perennial herbaceous energy crops must be profitable, they must fit into existing farming operations, they must be easy to store and deliver to the ethanol plant without loss of quality. Extension efforts are needed to provide to producers with agronomics and best management practices for growing perennial herbaceous energy crops. Perennial herbaceous energy crops have potential for improvement, and present a unique opportunity for cultural and environmental change on the agricultural landscape. There are numerous environmental benefits to perennial herbaceous cropping systems that can improve agricultural land use practices including stabilizing soils and reducing soil erosion, improving water quality, increasing, and improving wildlife habitat, and storing C to mitigate GHG emissions. All of these benefits can be achieved, provided agronomic, genomic, and operational aspects of perennial herbaceous cropping systems are fully developed and accepted by farmers. We speculate that herbaceous perennial energy crops may be used in conjunction with row crops to distribute workload and feedstock availability. Annuals likely would be harvested in autumn and perennial grasses could be harvested in early spring, while they are dry, similar to when native prairies typically are burned. This may help reduce need for feedstock storage by providing feedstock at different times during the year. The quality of switchgrass in the spring compared to autumn harvest needs to be ascertained.

Woody perennial energy crops

Biomass can be produced from fast growing trees using intensive management practices. Here we use the term woody perennial energy crops (WPEC) to distinguish them from herbaceous perennial energy crops. The woody biomass produced from these perennial energy crops is easy to store and handle, has high density and low ash content, and mixes well with other woody feedstock such as forest harvest residue or mill waste.

Intensive tree plantation management uses improved genetic stock, competition control, fertilization, and even irrigation to enhance productivity. Although such practices are common in agriculture, they have recently been adopted for tree culture. In traditional forestry, naturally regenerated or planted seedlings are expected to out-compete other vegetation and grow to the extent resources within the site provide. Growth rates of WPEC trees are fast enough to allow rotation time between planting and harvesting within three to ten years compared to several decades for traditional silviculture (Lemus and Lal 2005). There are clear advantages of producing biomass for energy or even traditional woody products using short-rotation intensively-managed woody crop systems. There are also positive and negative environmental consequences for WPEC systems. There is public concern that adopting wood as an alternative energy source will result in greater harvesting of native forested lands with significant loss of ecosystem services and declining biological diversity. However, there is a large knowledge base on which to build productive and sustainable woody feedstock system. Growing regimes for WPEC can focus biomass production on marginal lands and provide numerous environmental advantages for agricultural landscapes while simultaneously relieving pressure from natural forests.

Wood is an obvious alternative energy source. Prior to the widespread adoption of coal and petroleum energy, wood, and charcoal supplied virtually all of the energy consumed in the United States (EIA 2006a). Wood still plays a significant role today, even though it is considered an alternative energy source for home heating and industrial drying. In 2006, wood provided over 80% of the renewable energy consumed in the United States, with 60% was consumed by the wood products industry, and 40% used for domestic and other commercial uses (EIA 2006b). In the decades leading up to the Arab oil embargo, there was recognition that intensive forest management practices could vastly improve forest productivity (Schreiner 1945; McAlpine *et al*. 1966; Ek and Dawson 1976; McMinn and Nutter 1981; Dickmann 2006). Work supported largely through the USDA Forest Service and the forest products industry demonstrated both the genetic potential of select forest tree species and the positive consequences of agronomic practices. Foresters and the wood products industry recognized that a greater proportion of our energy supplies could be derived from wood as an alternative to fossil fuels and promoted woody biomass as a source for power and liquid fuels (Dickmann 2006).

Many promising wood energy conversion technologies emerged from alternative energy programs (e.g., Reed and Lerner 1973). The USDOE Short Rotation Woody Crops

Program, which was later named the Bioenergy Feedstock Development Program supplied necessary funding for greater development of short-rotation woody cropping systems and eventually focused on poplar (*Populus* spp.) and willow (*Salix* ssp.) as model tree species, while other tree species were also considered (Kszos *et al*. 2001). Numerous reports and summary publications are available describing the program's activities in genetic selection and improvement, cultural practices, operational and logistical support, environmental assessment and monitoring, resource analysis and assessment, economic and policy analysis, as well as analytical and database tools (Ranney *et al*. 1987a, 1987b; Tuskan 1998; Kszos *et al*. 2001). At the same time a number of organizations encouraged information exchange and communications between government, academic, and industrial researchers, including International Energy Agency (http://www.ieabioenergy.com/; http://www.short rotationcrops.com/), the International Poplar Commission (http:// efor.ucl.ac.be/ipc/), the International Union of Forest Research Organizations (IUFRO; http://www.iufro.org/), and the SRWC Operations Working Group (http://www. woody crops.org/) (Dickmann 2006).

In the remainder of this section we will summarize the major approaches used to grow WPEC in North America, with some international examples of applications, and discuss the environmental benefits of these cropping systems.

WPEC cropping systems

Woody perennial energy crops, also known as short rotation woody crops involve several different approaches based on the type of tree grown. The types considered here include large-stature widely-spaced hardwoods; low-stature, densely-spaced coppice culture; and intensively managed pine. Successful implementation of each of these types of woody crops includes common agronomic features of improved genetic material, high quality planting stock, effective competition control, and adequate water and nutrient supplies (Dickmann and Stuart 1983; Standiford and Ledig 1983; Willebrand *et al*. 1993; Borders and Bailey 2001; Stanturf *et al*. 2001). Pest control is also beneficial to susceptible varieties; however, most effective pest control strategies involve deployment of resistant varieties, which contribute to a superior genotype's production potential (Coyle *et al*. 2002).

The greatest gains in woody crop production potential have been from selection and breeding of superior varieties. Selection, clonal propagation and hybridization have doubled productivity for *Populus* and *Eucalyptus* species (Heilman and Stettler 1985; Zobel *et al*. 1987). Any gains made through selection and breeding can be retained without loss through recombination, because these species are easily propagated vegetatively. Sustained genetic improvement has been possible for fast growing hardwoods because of the short generation time to reproductive maturity and continued commercial interest. While significant gains have been achieved for prominent commercial softwood species such as southern yellow pines (e.g., *Pinus taeda* L., *Pinus palustris*), genetic improvements are not expected to be as rapid when breeding long-lived perennial species compared to agronomic crops. Currently, second-generation genetic improvements are being deployed for loblolly pine (*P. taeda* L.). Larger gains are expected at a faster pace in the future as softwood clonal forestry techniques are further developed (Schmidtling *et al*. 2002). Genetic selection and breeding programs for hardwoods such as willow, sycamore (*Platanus)*, and sweetgum (*Liquidambar*) have been initiated, but are not as advanced as poplar and *Eucalyptus* (Larsson 1998; Schmidtling *et al*. 2002; Volk *et al*. 2006). Given adequate commercial interest in developing specific traits such as high productivity, disease resistance, stress tolerance, specific chemical properties, large gains can be obtained through breeding programs. Functional genomics offers opportunities for both basic and applied understanding of ecological adaptations of woody crop species (di Fazio 2005).

Competition control is fundamental to agronomy; however, it has not been widely used in forestry until recently. Management of forest regeneration has focused on encouraging natural regeneration of desirable species, or planting of competitive early successional crop trees, typically softwood species, that eventually overtop less desirable species. This legacy of minimal site preparation and establishment requirements suggests that competition control efforts are not required for establishment of tree crops. However, several research efforts demonstrate the necessity of effective competition control for hardwood establishment (Hansen *et al*. 1984; Cogliastro *et al*. 1993; Stanturf *et al*. 2001; Schuler *et al.* 2004). Even for softwood species there is increasing recognition that competition control results in large gains in productivity (Powers and Reynolds 1999; Fox 2000; Jokela *et al*. 2004). Poor competitive ability of hardwoods, and productivity targets of woody crops, in general, makes the use of competition control a necessity. There are safe and effective herbicides available for both hardwoods and conifers that aid in controlling competition with minimal expense (Stanturf *et al*. 2001; Moorhead 2006). When weed pressure is low, one herbicide application per year only for the first two or three years and none after canopy closure maybe sufficient. With high weed pressure two applications per year might be required for the first couple of years. The frequency of application over the course of a three to ten year rotation is small relative to annual agronomic crops resulting in less environmental impacts.

Achieving maximum productivity for WPEC requires availability of adequate soil nutrients and water. While high productivity can be achieved on high quality agricultural sites and higher productivity is associated with greater nutrient demand for some woody crop in the genus *Populu*s and willow other woody crops such as pines and eucalypts do not demand large quantities of nutrient resources for a given amount of productivity due to the on-site recycling of nutrients. Annual N supply requirements range up to 170 to over 200 kg N ha^{-1} yr^{-1} for highly productive (>20 Mg ha^{-1} yr^{-1}) poplar (Heilman *et al*. 1996). Woody perennial energy crops species with modest production rates (<10 Mg ha^{-1} yr^{-1}) require less than 120 kg N ha^{-1} yr^{-1}. Much of the annual nutrient requirement of WPEC, including poplar, can be supplied by sites having moderate quality (Reich *et al.* 1997) or can be added on lower quality sites. Little or no response to fertilization is common in forestry experiments due to adequate site availability and internal cycling of acquired nutrients (Binkley 1986; Hansen *et al*. 1988). High yields are expected on productive farmland without fertilizer, especially when high nutrient containing leaves remain on sight and rotations greater than 10 years. Marginal farmlands however require some regular, low-rate fertilizer addition to achieve maximum production especially for those trees with high nutrient demand such as poplars. Fertilization rates of 30 to 50 kg N annually can achieve 80% to more than a 3-fold growth increases if applied annually (Heilman and Xie 1993; Jokela *et al*. 2004; Coleman *et al*. 2006). Proportion-ally greater fertilizer will be necessary as production rates increase (Heilman *et al*. 1996). Application frequency varies from once per rotation to once per irrigation cycle (Binkley 1986; Allen *et al*. 1990; van Miegroet *et al*. 1994; Stanturf *et al*. 2001). Higher rates are applied when fertilization occurs only once or twice during the rotation, but the capacity of the site to retain high nutrient amounts is important to consider avoiding off-site transport by run-off or leaching. Supplying fertilizer with irrigation involves splitting annual applications among all treatment dates (Ingestad 1987). The low nutrient concentrations provide significant improvements to site nutrient retention while supporting greater yields (van Miegroet *et al.* 1994). Identifying critical nutrient demand periods during the rotation may avoid the high cost of multiple split application or the consequences of off-site transport. Commonly, fertilizer is applied at planting and at mid-rotation. Fertilization at planting that is applied directly in the planting hole achieves the best results (van den Driessche 1999) because more is available to the crop rather than the competition. During establishment, nutrient requirements are met by root exploration of the site and any applied fertilizer provides minimal benefit. Mid-rotation demand is greatest at the time of canopy closure and intra-specific root competition. Small annual applications at canopy closure achieve greater growth response compared to an equivalent amount applied in a single year (Coleman *et al*. 2006). However, significant work is still required to optimize fertilizer rates and timing during WPEC rotations. In addition the recent discovery of nitrogen-fixing endophytic bacteria (*Rhizobium tropici*) in nonlegumous popular may shed light on success of this species in marginal lands (Doty *et al*. 2005).

Supplemental irrigation is required in arid climates where high light environments and warm temperatures help to achieve very high production rates (Pereira *et al*. 1989; Myers *et al*. 1996; Stanton *et al.* 2002). Plantation-growth rates can be maintained in humid climates by planting drought-resistant trees (Coleman *et al*. 2004a), and poorly drained sites will support high productivity rates if soil aeration is not restricted during the growing season (Stanturf *et al*. 2001; Stanton *et al*. 2002; Eisenbies *et al*. 2006). The most effective approach to meeting WPEC moisture requirements is to match the genotype to the climate. For instance both *Eucalyptus* and *Poplar* have drought-hardy clones (e.g., Gebre *et al*. 1998), which can be selected, bred, or inserted to produce genotypes appropriate for a wider range of climatic conditions.

Although all woody crops have similar characteristics including improved genetic material, effective weed control, and requirement for sufficient nutrient and water supplies, there are unique differences among cropping systems. The following sections describe the major woody cropping systems appropriate for energy feedstock production.

Hardwoods

Hardwoods grown in short rotation culture are commonly raised to large stature trees. Appropriate species are included within poplar, *Eucalyptus*, sycamore, maple (*Acer*), alder (*Alnus*), and locust (*Robinia*), among others. Production rates for large-stature hardwoods range from 5 to over 20 Mg ha^{-1} yr^{-1} (Skolmen 1983; Perlack *et al*. 1995; Coyle and Coleman 2005; Dickmann 2006). Although the site quality and management treatments control average productivity, the piece size and the rotation length required to reach the site-carrying capacity is largely determined by tree-spacing (Steinbeck and Nwoboshi 1980; Heilman and Peabody 1981; Bernardo *et al.* 1998). The target piece size depends on the desired product. Hardwoods spaced at lower density (700 to 1500 trees ha^{-1}) achieve larger stature before inter-tree competition slows growth after 10 to 15 years. Large individual tree size allows multiple products including energy wood, pulp chips, and solid wood products. Such a multi-product approach is used to maximize profit from each rotation and energy wood is only one product component of this type of cropping system.

Hardwoods grown at higher density (1500-2000 trees ha^{-1}) will result in faster site occupation and shorter rotations. At close spacing, trees reach the site-carrying capacity and reach maximum annual growth rates at six to eight years, which result in smaller individual trees. These smalller trees are appropriate as energy or pulpwood. The minimum size for this cropping system is determined by operational constraints. Trees smaller than 10-cm diameter can not be harvested efficiently with conventional felling and bunching equipment (Stokes and Hartsough 1993) and pulp mills are unwilling to accept smaller material because pulp yield is small and the fiber tensile strength is low compared to older wood (Francis *et al*. 2006). Higher density plantings are possible and they are described under coppice culture below.

Propagation of hardwoods can be accomplished through bare-root nursery production of favorable seed sources, or mixed seed sources, and vegetative propagation using greenwood cuttings from hedge orchards or by using hardwood cuttings from stool-beds. Rooting of hardwood cuttings in nurseries is also used on sites where rooting in the field is unfavorable. Traditional propagation involving bare-root nursery stock is well established for both forestry and horticultural applications (Williams 1976; Duryea *et al*. 1984). Establishment of low-density hardwood stands includes using bare-root or containerized nursery stock for species such as *Eucalyptus*, sycamore, sweetgum, maple and locust. However, individual seedlings can be costly and significantly increase establishment cost as planting density increases. Poplar species are easily propagated using dormant stem cuttings (FAO 1979b; Dickmann and Stuart 1983; Stanturf *et al*. 2001). Stem cuttings taken from ramets grown in stool-beds can be produced in large quantities and at low cost, consequently lowering establishment costs. Rooting of greenwood cuttings is also possible for high-value, genetically improved stock material although they can be expensive to produce. Vegetative propagation allows for the maintenance of any genetic gains achieved through selection, breeding, and gene insertion. This advantageous propagation characteristic is one of the most important features favoring *Poplar* spp. for WPEC.

Coppice

Coppice culture involves stump resprouting following removal of aboveground stems. Hardwood trees such as willow (*Salix*), *Eucalyptus*, poplar, locust, elm (*Alnus*), sycamore and birch (*Betula*) will initiate new shoots from dormant buds when induced by wounding (Sennerby-Forsse *et al.* 1992). Coppice WPEC have been well developed using willow (Willebrand *et al*. 1993; Volk *et al*. 2006). Average production rates for coppice willow range from 10 to 24 Mg ha^{-1} yr^{-1} (Perlack *et al*. 1995; Kopp *et al*. 2001). Low-stature shrub willow is planted in densely-spaced (10,000-20,000 trees ha^{-1}) dual-row plantings that allow machinery to move over coppice stools for harvest and treatments. The stem portion is removed at 3-4 year harvest intervals. After harvest, herbicide and fertilizer are applied and the shoots are allowed to regrow. Vigorous growth is achieved, often exceeding growth from the initial planting rotation, and high production is maintained for up to 25 years. Low-density large-stature trees harvested with conventional forestry equipment will coppice successfully, especially *Eucalyptus* in tropical climates. However, the capacity of dormant buds is suppressed as trees age (Sennerby-Forsse *et al*. 1992), which results in lower production from coppicing with longer rotations. There is also strong sensitivity to the season of harvest, and the requirement for year-round harvest and the desire to replace old genotypes with more favorable ones has discouraged the use of coppice regeneration in poplar (Stanton *et al*. 2002).

Worldwide willow coppice culture is a well-established WPEC production system. Shrub willow is grown on over 15,000 ha in Sweden and 1,750 ha in the United Kingdom where some plantings are near district-heating and combined heat and power facilities for fuel supplies (pers. comm., N.E. Nordh representative from Sweden and K. Richards representative from the United Kingdom, respectively presented at the International Energy Association Task 30 meeting, 8 Nov. 2004, Charleston, SC). Research in New York state has established nearly 300 ha (Volk *et al.* 2006). This research program has demonstrated the advantages for power production by co-firing coppice-willow biomass with coal at two separate facilities, documenting reductions in chemical and particulate pollutants. Similar efforts developing willow coppice are occurring in other countries including United Kingdom, Canada, and New Zealand (Mitchell *et al*. 1999; Sims *et al*. 2001; Bullard *et al*. 2002; Labrecque and Teodorescu 2005). Costs for producing biomass using willow-coppice culture are becoming competitive with fossil fuels by considering the most productive cropping schemes (Willebrand *et al*. 1993; Bullard *et al*. 2002) and improvements in harvesting efficiency (Culshaw and Stokes 1995). Willow has proved effective in cleaning contaminants from polluted soil and water (Mirck *et al.* 2005), for stream bank stabilization (Lee *et al.* 2000), and as living snow fences (Volk *et al.* 2006).

Numerous *Eucalyptus* species have been investigated for growth in coppice culture as WPEC and other uses throughout the world (FAO 1979a; Standiford and Ledig 1983; Whitesell *et al.* 1992; Sims *et al.* 2001; Wildy and Pate 2002; Little and Gardner 2003). For instance, Brazil maintains 3.2 million ha of *Eucalyptus* plantations to produce charcoal and fiber for steel and pulp industries, wood chips and pellets for commercial energy uses, and electricity from forest residues (Walter *et al.* 2004). The Brazilian *Eucalyptus* plantations are harvested as many as three times in rotations of 5 to 8 years before re-planting is required. The Australian representative, B. George to the International Energy Association Task 30 meeting (8 Nov., 2004, Charleston, SC) noted during his presentation that the Narrogin Integrated Mallee Processing Plant in Western Australia has demonstrated the use of coppiced oil mallee (*E. kochii*) for multiple products including oil extracts, energy and charcoal production. In the United States, significant efforts in Florida and California have considered *Eucalyptus* species for energy production (Standiford and Ledig 1983; Rockwood *et al.* 2006), and the Hawaiian forest inventory includes over 6,000 ha of short-rotation coppice *E. grandis* (Martin and Nakamura 2001) much of which has been targeted toward energy production (Whitesell *et al.* 1992).

Sycamore (*Platanus occidentalis*) has shown promise for coppice culture in an early demonstration of WPEC growing system known as silage sycamore (McAlpine *et al.* 1966; Steinbeck *et al.* 1972). This pioneering effort demonstrated that closer spaced trees, even though individually smaller, would maintain greater biomass than wider spaced trees of larger individual size (Dickmann 2006). *P. occidentalis* has good growth potential (Coyle and Coleman 2005; Davis and Trettin 2006); however, widespread use is hindered due to bacterial leaf scorch disease that occurs after three to five years following planting (Henneberger *et al.* 2004).

Intensive pine silviculture

There are 12 million ha of pine plantations growing in the southeastern United States (Conner and Hartsell 2002) and 0.65 million ha planted annually (Siry 2002). Productivity of managed southern pine plantations currently ranges from 11 to 18 Mg ha^{-1} yr^{-1} (Stanturf *et al.* 2003). Similar to hardwoods described above, pine silviculture includes low-density spacing 700-to 2000 tree ha^{-1} to achieve large stature trees in 12 to 20 year rotations. In addition to intensive plantation forestry using native southern yellow pine grown in southeastern United States, similar high productivity rates have been achieved internationally by introducing non-native species in temperate and tropical climates (Fox 2000). Pine is typically grown for high-value timber and pulp markets, but as those markets are becoming constricted in some regions by international competition, there is significant interest in finding new markets for small diameter (<15 cm) pine to increase natural resource management options.

Pine silviculture has intensified to meet product demands and lower production costs. Intensive pine silviculture includes use of select and advanced generation genotypes (Allen *et al.* 2005; McKeand *et al.* 2006); the capacity to grow large quantities of seedlings from bare-root and containerized stock in nurseries (Duryea and Landis 1984); for planting on diverse sites prepared to optimize seedling growth by managing site water balance through bedding techniques (Eisenbies *et al.* 2006); and through control of competing vegetation using a suite of effective herbicides (Moorhead 2006). Fertilization prescriptions (macro and micronutrient as needed) matched to soil nutrient availability have achieved large growth benefits so that now much of the commercial pine forestland receives some level of mineral nutrient supplements (Fox *et al.* 2006). For example, a one-time at mid-rotation application in eight years of 168 to 224 kg ha^{-1} N plus 28 kg ha^{-1} P provides growth gain of 30% compared to no fertilizer (Fox *et al.* 2006). Forest operations involve equipment and techniques that are highly developed for efficient site preparation, planting, treating, and harvesting. This technology is designed for the existing state of the resource base and product requirement, but is also capable of adapting to a changing resource base such as a shift toward WPEC (Rummer 2002).

This shift away from low input forestry to intensive forestry including standard agronomic techniques, elite genetic stock, effective site preparation, competition control, fertilization, and irrigation demonstrates the capacity for hardwoods, coppice and pines to meet energy production demands. Additionally, understanding of impacts resulting from past practices has made the forestry community acutely aware of environmental impacts of land management (Carter and Foster 2006). This fact and the emerging understanding of forest technology to supply environmental services have developed a wealth of information on the environmental impacts and opportunities of WPEC.

Environmental consequences and benefits of WPEC

To understand the consequences and benefits of WPEC, it is important to compare environmental impacts relative to other land uses (Ranney and Mann 1994). In the case of WPEC, the comparisons must be made relative to both forests and agricultural systems because woody crops are intensive forestry operations that apply agricultural methods. They are likely to be located on the margins between agriculture and forestry. We will compare WPEC with working forests that are managed for commodity production and not natural undisturbed old-growth. Although there are significant ecological and physiological distinctions between naturally occurring old-growth forest and second-growth plantations (Bond and Franklin 2002), the opportunity presented by WPEC is to focus production of forest products in agricultural areas and not to replace natural forests. Concentrating wood production at the margins between agricultural and forestlands preserves both high-value agricultural land for food production and natural forests for social and ecological services. The appropriate comparisons to assess environmental impacts of WPEC are then with management practices of both adjacent agricultural and working forestlands.

Off-site soil and nutrient transport

Woody perennial energy crops have potential to both retain sediments and nutrient through soil stabilization by the perennial root system, but allow off-site transport during harvest and crop reestablishment phases. Soil stabilization has long been recognized as a favorable characteristic of tree plantings (Carter and Foster 2006). Tree root systems are concentrated in the upper surface layers (Gale and Grigal 1987) where they hold and protect soil from the action of wind and water. Tree plantings have been used as shelter belts to prevent soil erosion and to stabilize stream banks (Lowrance *et al.* 2002; Brandle *et al.* 2004). There are obvious soil protection advantages of using widely-spaced long-rotation perennial crop plants that remain in place for several years protecting the soil. There are also advantages of using coppice crops that do not require site preparation and soil disturbance for more than two decades.

Problems with erosion and off site transport occurred in earlier forestry operations raised concerns about the sustainability of forest operations. Rapid revegetation and the development of best management practices avoided erosion and runoff and improved adjacent surface water quality (Fox 2000; Carter and Foster 2006). Memories of early land use practices and continued concerns over forest harvest impacts on stream quality and fish habitat lead to continued public concern over intensive forestry management practices. However, proper management can avoid such problems and even reduce nutrient losses using the stabilization and filtering capacity of perennial tree root systems.

Woody crops also compare favorably to agronomic and herbaceous energy crops in most instances studied. Woody perennial energy crops stands have been shown to protect against loss of nutrients compared to corn or switchgrass (Tolbert *et al.* 2000; Nyakatawa *et al.* 2006). Soil erosion from WPEC is generally lower than row crops (Ranney and Mann 1994) although greater sediment loss occurred in tilled WPEC when compared to no-till corn or previously established switchgrass, due to lack of adequate soil cover (Nyakatawa *et al.* 2006). Stream banks having riparian buffers consisting of willow and poplar trees decreased erosion more than 70% relative to stream banks running through unprotected crop fields (Zaimes *et al.* 2004).

The tree root system is an effective filter for plant nutrients and organic compounds moving in ground water or applied to the soil surface (Stanton *et al.* 2002; Mirck *et al.* 2005). Although species and genotypes of *Poplar* and *Eucalyptus* can display high nutrient use efficiency, when provided with high nutrient availability they are capable of acquiring large amounts of nutrients, increasing internal concentrations, and growing proportionally (Jia and Ingestad 1984; Coleman *et al.* 1998). In fact, poplar and willow have frequently been used for stream bank protection and as riparian buffers (Lee *et al.* 2000; Schultz *et al.* 2000; Volk *et al.* 2006). Poplar trees planted as riparian buffers maintain greater rooting density to a greater depth than corn or soybean planted in the same position relative to the stream (Tufekcioglu *et al.* 1998). Nutrient accumulation by hardwoods such as poplar and willow from soil is high compared to other trees (Heilman *et al.* 1996; Pregitzer and Friend 1996), but even southern pines show high nutrient accumulation rates (Adegbidi *et al.* 2005) that place large nutrient demands on site. This high rate of nutrient uptake is due to relatively high root length densities as well as high ion uptake rates (BassiriRad 2000). Conifer trees typically have coarser roots and lower rooting density than deciduous hardwoods (Bauhus and Messier 1999; Coleman *et al.* 2000; Pregitzer *et al.* 2002). Low root length density yet with equally high nutrient acquisition demonstrates that fast growing conifers have higher uptake per unit root length than hardwoods and indicates that they may have a greater dependence on mycorrhizal associations (Bauhus and Messier 1999). Regardless of the mechanisms and symbiotic relationships, this capacity for high rates of nutrient accumulation in both hardwoods and conifers is an advantage for nutrient removal.

Further evidence for WPEC to maintain or improve water quality can be found by using fast growing woody crops to filter contaminants or degrade harmful organic compounds. Many WPEC have been used for filtering nutrients from effluent, landfill leachates or irrigation runoff water (Schultz *et al.* 2000; Aronsson and Perttu 2001; Licht and Isebrands 2005; Zalesny *et al.* 2006). Use of contaminated effluent or other sources of reclaimed water provides dual environmental services, when those sources provide water and nutrient resources to support WPEC growth (Hansen *et al.* 1980; Laughton *et al.* 1990; Myers *et al.* 1996; Falkiner and Polglase 1999; Snow *et al.* 1999; Moffat *et al.* 2001; Zalesny *et al.* 2006). Trees have also been used to extract heavy metals and other contaminants from former industrial sites, commercial spills and other types of soil contaminants (Wang *et al.* 1999; Hammer *et al.* 2003; Robinson *et al.* 2003; Vervaeke *et al.* 2003; Sebastiani *et al.* 2004; Kuzovkina and Quigley 2005; Laureysens *et al.* 2005; Pilipovic *et al.* 2005; Vandecasteele *et al.* 2005). Given the capacity of trees to degrade harmful organics and to sequester toxic metal compounds there is large potential for use of WPEC to improve site quality over abandoned or marginal farmland, and to reclaim former industrial acres to produce renewable and sustainable energy (Licht and Isebrands 2005). Properly managed WPEC can have important protective benefits in the agricultural landscape and restorative benefits on contaminated lands.

Long-term site productivity

Maintenance of site productivity involves retention of soil and nutrients and building of the soil quality by additions of organic matter. Losses of soil and nutrients from WPEC mainly occur during harvesting and reestablishment. Building of soil quality results from the development and growth of the WPEC stand. Site quality must be maintained through proper site management during conversion (harvest and reestablishment). Proper site preparation and rapid reestablishment of the next crop is critical for soil protection including maintenance of SOM, soil physical properties such as porosity and bulk density (Fox 2000). Forestry site preparation practices such as, shearing and raking residual organic matter into piles is known to degrade site quality (Carter and Foster 2006). Shear and pile site preparation, still common today, can displace nutrient rich topsoil resulting in lower productivity. Such problems may be avoided by clearing previous vegetation during harvesting to decrease the need to pile debris, followed by chemical suppression of competing vegetation and burning. These steps have proven to be an effective means to maintain productivity of the site quality at minimal expense (Fox 2000; Carter and Foster 2006).

Concern has also been expressed over degrading site quality by nutrient removal at harvest, especially when whole-tree harvesting for bioenergy feedstocks compared to stem only harvest for solid wood and pulp products (Fox 2000; Carter and Forest 2006). Meta analysis of research studies showed there is an 18% increase in soil C and N resulting from stem-only harvesting, while there is a 6% decline with whole-tree harvesting (Johnson and Curtis 2001). There are no detectable limits on subsequent rates of forest productivity (Mann *et al.* 1988; Fox 2000). In the case of WPEC more frequent removals will occur than on longer rotation forest management. Fertilizer amendments exceed aboveground removals because much of the biomass grown is returned to the soil by deciduous ephemeral tissue having high nutrient content (see below). The cycling of this tissue helps to maintain and even enhance soil nutrient levels. Consequently, if the nutrient content of WPEC are properly managed to achieve productivity goals during crop rotations there will be positive impacts on soil quality and any removal during harvest will not impact site productivity.

Organic material is deposited on sites growing operational forests and WPEC through aboveground litterfall, root turnover, and residual stump material after harvest. Annual leaf litter fall of WPEC can be as much as one quarter of annual above ground production (Davis and Trettin 2006) and belowground production of woody plants is equal or greater than total above ground production (Vogt 1991) with the average fine root having a residence time commonly less than a year (Eissenstat and Yanai 1997). The deposited organic matter from above and belowground result in greater detritus deposition, which supports a diverse belowground ecosystem that includes abundant microbes and mesofauna (Coleman *et al.* 1992) similar to as discussed above in respect to annual crops. However, since SOM is used as an energy source by an abundant belowground ecology, the amount of C added to the soil as organic matter or labile C compounds are equivalent to the amount of C lost through soil respiration (Raich and Nadelhoffer 1989; Giardina and Ryan 2002). Disturbance of plant inputs during stand establishment can result in declines in SOM content (Grigal and Berguson 1998) and have negative impacts on soil quality unless vegetation inputs are rapidly restored. There is a large addition of organic matter during harvest of large-stature hardwoods and pine, if the stump and roots are left in place. This residual organic matter will slowly decompose as the autotrophic input from the new crop increase as part of the biological C-cycle (**Fig. 1**). These simultaneous processes provide managers with an organic matter reserve during conversion. Organic matter may actually accumulate over successive rotations. Carbon in soils growing WPEC has been shown to increase relative to agricultural fields (Hansen 1993; Tolbert *et al.* 2002); although, this has been difficult to consistently document (Garten 2002; Coleman *et al*. 2004b). Yet, there is great potential for C sequestration using WPEC. Biomass crops used for energy production will not only offset fossil fuel C emissions, but fields used to grow energy crops can also be C sinks.

Biodiversity and habitat quality

Establishment of tree crops creates structure on the landscape that is used for cover, foraging and breeding habitat for wildlife. Woody perennial energy crops were shown to have wildlife populations equivalent to less intensive forest plantations and greater than adjacent agricultural fields (Sage and Robertson 1996; Twedt and Portwood 1997; Londo *et al*. 2005). The edge structure of woody crop plantations is favored by raptors (Moser and Hilpp 2003). Small mammal populations are greater in young poplar plantations (3-4 years) than older plantations due to greater ground vegetation (Moser *et al*. 2002). Faster growing poplar plantations have higher diversity and greater breeding bird counts than slower growing oak (*Quercus*) reforestation sites, and the rapid establishment of structure in poplar creates rapid increases in bird populations compared to adjacent agricultural fields (Twedt *et al*. 2002). Providing the structure of multi-aged stands across the agricultural landscape will enhance diversity relative to an agricultural landscape consisting of row crops and hay fields.

Intensively managed forests have a number of favorable ecological characteristics that maintain or enhance site conditions relative to old-field conditions. These characteristics include soil stabilization, organic matter inputs, filtering by the root systems and development of aboveground structure for wildlife habitat. Harvesting operations disrupts these favorable conditions and care must be taken to minimize negative environmental consequences. Most notably off site transport and excessive loss of SOM. Reestablishment practices that minimize soil disturbance and retain debris to protect soil will minimize impacts during stand conversion. These soil impacts and habitat shifts during harvesting can also be minimized by maintaining a variety of WPEC stands with each of the age classes so that the area disturbed during any year is a fraction of the total land base.

OTHER ISSUES

Thermochemical co-products, C sequestration and soil quality

Another aspect of biomass for bioenergy is the production of by-products or co-products. This section will discuss uses of by-products or co-products formed. Co-products are differentiated from by-products in that co-products have intrinsic value either as energy or for C sequestration. The wet or dry solubles after grain ethanol fermentation are used as animal feed; any excess could be biomass feedstock for a thermochemical platform (Perlack *et al*. 2005), the high lignin by-product of cellulosic fermentation likely will be thermochemical feedstock (Sheehan *et al*. 2002). Thermochemical processes generate ash or char.

There are a variety of products and terms that will be defined before continuing this discussion. Generally, the term black C applies to various carbonaceous products of incomplete biomass combustion, including char, charcoal, and soot (Goldberg 1985). The chemical properties of these materials vary tremendously along this continuum from the fly ash, a by-product of direct combustion of fossil or biomass fuels, which is trapped by electrostatic precipitators to char that is biologically active. We here-after refer to biologically active char as bio char.

Fossil-fuel fly-ash has little nutrient value as a soil amendment. Palumbo *et al*. (2004) reviewed prospects for enhancing C sequestration and reclamation of degraded lands with fossil-fuel combustion by-products. Degraded lands are often characterized by acidic pH, low levels of key nutrients, poor soil structure, and limited moisture-retention capacity. Land application of fly-ash may change soil pH and nutrient availability. Fly-ash varies greatly in elemental composition and pH ranges from 4 to 11 (Furr *et al*. 1977). Some ash materials have been considered for soil amendments in agricultural production systems because these ashes contain a broad spectrum of elements, both essential and toxic (Davison *et al*. 1974; Furr *et al*. 1977). Numerous plant response studies have been conducted evaluating various forms of fly ash as a soil amendment (Martens 1971; Chang *et al*. 1977; Menon *et al*. 1993; Cox *et al*. 2001); in general it contributed phosphorus but few other nutrients. For example, amending soil with sewage-sludge incinerator ash provided plant-available phosphorus (Bierman *et al*. 1995).

In contrast to the relatively limited value of fly-ash; bio char can act as a soil conditioner enhancing plant growth by supplying and, more importantly, retaining nutrients and by providing other services such as improving soil physical, chemical and biological properties (Glaser *et al*. 2002; Lehmann *et al*. 2003b, 2006; Lehman and Rondon 2006). A key advantage of bio char with respect to soil ecosystem functions is that is more efficient in improving soil fertility and nutrient retention than un-charred organic matter (Sombroek *et al*. 1993; Lehman and Rondon 2006). The longevity of bio char in ecosystems is an important question since only a long half-life will ensure a relevant amount of C sequestration. Bio char from biomass-pyrolysis contains a significant amount of highly adsorbent elementary C. Therefore, it can be combined with N and other plant nutrients to form a slow-release fertilizer (Day *et al*. 2002, 2003). A char-NH_4HCO_3-combined fertilizer is probably the best product that could maximally enhance sequestration of C into soils while providing a slow-release fertilizer for plant growth (Lee e*t al*. 2003); thereby, decreasing leeching and run-off potential and possible reduce emissions of N_2O. The highly active bio char adsorbs pesticides and other potential pollutants (Lehmann *et al*. 2006). Proper management of the bio char can favorably affect the C cycle once we understand how to create the ideal bio char properties, which optimize its benefits.

There are challenges related to using bio char as soil amendment. Bio char like ash or char in general, has a low density making transport and application a challenge. Existing equipment for spreading and incorporating fertilizer is designed for higher density compounds little affected by wind during surface application. The low density of the bio char may require application and a slurry form or partial incorporation to minimize wind losses. In addition to physical limitations, depending on the feedstock it can be highly alkaline. Ash/char remaining after pyrolysis of corn stover has a pH >10 (Johnson *et al*. unpublished data). High pH can be detrimental to plant growth. In addition, high pH (10-12) can solublize existing SOM (Stevenson 1994). Clearly, there are knowledge and technical issues to resolve prior to commercial utilization of bio char as a soil amendment.

Studying the Amazon dark earth soils may provide insight on utilization of bio char. Amazonian dark earths (Terra Preta de Indio or Indian Black Earth) refer to certain dark soils in the Brazilian Amazon region and other South American countries. It is thought these soils were established by pre-Columbian Indians from 500 to 2500 years ago, but abandoned after the invasion of Europeans (Smith 1980; Woods *et al*. 2000). These soils have an elevated C content that has persisted for hundreds of years after the sites were abandoned. Amazonian dark earths have high C contents of up to 150 g C kg^{-1} soil in comparison to the surrounding soils with 20-30 g C kg^{-1} soil (Smith 1980; Glaser *et al*. 2001). Additionally, organic matter enriched soil can be as deep as 1-2 m (average 40-50 cm) compared to 10-20 cm in the surrounding soil (Smith 1980; Glaser *et al*. 2001). Therefore, the total C stored in these soils can be one order of magnitude higher than in adjacent soils. The reason for the high stability of the soil C is currently under discussion; however, so-called black C is considered probable reason for the high stability (Glaser *et al*. 2001). Based on the similarity of the black C in the Amazonian dark earths to charcoal, Smith (1980) suggested that these soils were generated through accumulation or purposeful application of organic C from incomplete combustion.

In addition to their high SOC contents as mentioned above, Amazonian dark earths are characterized by high P contents reaching 200-400 mg P kg^{-1}, and higher cation exchange capacity, pH and base saturation than surrounding soils (Smith 1980; Sombroek *et al.* 1993; Glaser *et al.* 2001; Lehmann *et al.* 2003a, 2003b; Liang *et al.* 2006). Thus, these soils are highly fertile (Lehmann *et al.* 2003a, 2003b).

Important lessons can be learned from the recalcitrance of black C and its effects on the biogeochemistry of soils. Given the apparent ubiquity of black C established by several authors (Schmidt and Noack 2000; Skjemstad *et al.* 2002; Fowles 2007), refinements of global C models and sequestration estimates may be necessary. Further, the potential for enhancing sequestration by active management of black C or bio char could be established with important linkages to energy production and land use.

The feedstock and pyrolysis conditions can be manipulated to produce biologically active char or bio char. Perhaps we can learn how to create Amazonian dark earth soils, which sequester C and are highly productive. Generation of bio char may require sacrificing some of the energy co-product. Therefore, the developing industry and we as a society are challenged value co-products for there ability to sequester C – thus improve soil quality beyond their energy value.

Energy and conservation policy in the United States

In view of the emerging need for renewable bioenergy, United States agriculture will have to respond to new economic drivers and take advantage of new technological advances. Much of the current legislation with respect to renewable fuels places emphasis on developing techniques and efficiencies. The Renewable Fuels for Energy Security Act of 2001, the Reliable Fuels Act, the Fuels Security Act of 2005, and the 2005 Energy Policy Act place emphasis on technical and engineering aspects developing renewable fuels. The 2005 Energy Policy Act provides cellulosic ethanol incentives to reach a goal of 946 million L of ethanol in 2013. Grant programs for research and credit-trading programs are part of this legislation.

Existing legislation in the United States needs to be further developed and integrated with resource conservation programs to address the long-term life-cycle analysis of the biological C-cycle. Two primary areas of concern are CO_2 emissions from fuel utilization and soil C retention or sequestration for sustainable production systems. These two areas are intimately linked and enhanced through C management. A sustainable biofuel production system needs these policies to be linked with existing United States conservation programs summarized in **Table 3**. The USDA and United States Forest Service programs provide incentives and support voluntary actions by private land-owners in targeting GHG emission and C sequestration through a portfolio of beneficial conservation programs. Many of these programs are focused on protecting our soil, water, and air resources for agricultural production. However, since the role of feedstock production for biofuels as part of the C-cycle is now being relegated to agriculture and agroforestry, the emphasis on resource conservation cannot be over stated. Much of the current emphasis is on soil erosion and water quality control. The concern for air quality and increased CO_2 emissions is rapidly increasing with potential long-term ramifications related to global climate change. The increase in CO_2 emissions from fossil fuel can be partially offset by C sequestration practices, which maintain soil and environmental quality. The biological C-cycle must be managed to reduce CO_2 emissions and for food, fiber and biofuel production. The C-cycle impacts all of us and requires careful management of the C captured by crops that produce food and fiber for human and animal consumption. The linkage of renewable fuel legislation and resource conservation becomes even more critical as production and use expands across the country.

There is a strong need to assess the impact of bioenergy crops on existing SOM pools and how they may impact current and potential C sequestration. Policies are needed to bring together aspects of C management through renewable fuels and the bio char utilized for the benefit of mankind. Modeling by Rokityanskiy *et al.* (2007) indicated that C sequestration policy can make a significant contribution to the global portfolio of efficient climate mitigation policies, dependent upon carbon prices. Regulatory approval of bio char as a fertilizer or soil amendment is necessary to improve the economics of the bioenergy production systems. Tax incentives or C credits for farmers that use char or produce char as a soil amendment may provide the necessary incentives. Encouraging the promotion of purchasing biofuels (renewable fuels) with tax credits or other incentives can enhance the development through renewable fuel standards. There is a need to develop process standards for the co-products of biofuel production, such as chars, that can be used to enhance environmental quality. The same set of standards can be utilized to control GHG emission emphasizing balance between energy production and CO_2 emission. Research is urgently needed to determine the commercial potential of pyrolysis co-products for biological C sequestration.

There is a need to establish soil quality standards for crop residue removal that will enable maintenance of C in the soil for sustainable production and environmental quality (Wilhelm *et al.* 2004; Johnson *et al.* 2006a). There is a critical need to balance biomass feedstocks for energy production and soil sustainability. Government policies are needed to coordinate research programs to develop a research agenda that allows a balanced land and water use for bioenergy and human food production without jeopardizing soil and water resources.

Policy is a crucial component in bringing this new technology to market and addressing related high priority socio-economic issues. National sustainability criteria are needed so that the public incentives bring about environmentally sustainable production and utilization of biofuels to replace our dependence on imported fossil fuels. The national policies must provide an integrated approach to addressing the social, technical, environmental, and political issues associated with biofuel production and utilization. The potential social and environmental impacts of biofuels suggest that large-scale use of biofuels carries significant ecological risks, especially indiscriminate use of agricultural crop biomass. Government incentives could be used to minimize competition between food and fuel crops and to discourage expansion onto ecologically sensitive lands. On the other hand, biofuels have the potential to increase energy security, create new economic opportunities in rural areas, and reduce local pollution and GHG emission. The common commodity that links bioenergy production and ecosystem sustainability is C. Carbon is the "C" that starts "C"onservation of our valuable resources and must be explicitly managed for ecosystem sustainability that must be emphasized in existing and new policies.

Soil C is the foundation of soil quality essential for a sustainable global biofuel/bioenergy and food production systems. Soil quality is the foundation of our life, economy, and environment. To strengthen bioenergy crops' impact on SOC sequestration, the C sink must become long lasting. Policy must focus on establishing permanent or indefinite C sinks, preventing C losses, and agreeing on C measures. Society needs to recognize that the benefits of C sequestration justify the cost. A systematic assessment of the roles of bioenergy crops in the C-cycle is important to valuing the potential of SOC sequestration (Lemus and Lal 2005). The potential for pyrolysis bio char to meet these requirements, as a high-grade soil amendment needs to be fully evaluated and considered in policy development. While the bioenergy

Table 3 A portfolio of beneficial Government conservation programs that point to C-cycle management.

Program*	Primary Objective	Role of Carbon
ACP, Agriculture Conservation Program	Initiated in an effort to reduce soil loss and agricultural contributions to water pollution from both runoff and direct discharge, program provides cost-share funds for approved practices that provide long-term and community-wide benefits.	Carbon improves soil physical properties to enhance water infiltration and minimizing runoff carrying potential pollutants.
CRP, Conservation Reserve Program	Provides technical and financial assistance to eligible farmers and ranchers to address soil, water, and related natural resource concerns on their lands in an environmentally beneficial and cost-effective manner.	Soil carbon sequestration and reduced CO_2 emissions for enhanced environmental quality.
CSP, Conservation Security Program	A voluntary program that provides financial and technical assistance to producers who advance the conservation and improvement of soil, water, air, energy, plant and animal life, and other conservation purposes on Tribal and private working agricultural lands.	Soil C sequestration and reduced CO_2 emissions involving energy considerations for improved soil conservation
WRP, Wetlands Reserve Program	A voluntary program offering landowners the opportunity to protect, restore, and enhance wetlands on their property, to achieve the greatest wetland functions and values, along with optimum wildlife habitat.	Carbon is the primary energy source for the smaller fauna in the wildlife habitat and the anaerobic conditions serve to sequester more C than agricultural landscapes.
WHIP, Wildlife Habitat Enhancement Program	A voluntary program for people who want to develop and improve wildlife habitat primarily on private land, provides both technical and financial assistance to establish and improve fish and wildlife habitat.	Carbon is the primary energy source for the smaller fauna at the start of the predatory food chain.
CREP, Conservation Reserve Enhancement Program	A voluntary program to farmers to improve water quality and wildlife habitat by offering financial incentives, cost-share and rental payments by restoring riparian buffers, filter strips and wetlands through the installation of approved conservation practices.	Carbon contributes to numerous beneficial conservation practices, such as minimizing runoff and maximizing infiltration, to reduce agricultural runoff and pollutant transport.
EQIP, Environmental Quality Incentive Program	A voluntary conservation program for farmers and ranchers that promotes agricultural production and environmental quality as compatible national goals, offers financial and technical help to assist eligible participants install or implement structural and management practices on eligible agricultural land.	Carbon contributes to numerous beneficial conservation practices, such as minimizing runoff and maximizing infiltration, for better water control at the watershed scale.
GRP, Grassland Reserve Program	A voluntary program offering landowners the opportunity to protect, restore, and enhance grasslands on their property.	Carbon provided by the root systems perennial species enhances soil quality and provides conservation benefits on land marginal for crop production.
USDA 2002 Farm Bill Section 9600 Rural Development Renewable Energy Systems and Energy Efficiency Improvements	This program currently funds grants and loan guarantees to agricultural producers and rural small business for assistance with purchasing renewable energy systems and making energy efficiency improvements.	The chemical bonds of the C compounds (biomass) used in renewable energy systems provide useful energy and carbonaceous byproducts with near zero net emissions of CO_2.
USDA/DOE/EPA AgSTAR	A voluntary outreach program effort jointly designed to sponsor and encourages the use of methane recovery (biogas) technologies at the confined animal feeding operations that manage manure as liquids or slurries, technologies reduce methane emissions while achieving other environmental benefits.	Carbon is the primary element in methane and is part of the biological C-cycle; C properly managed in manures can reduce GHG.
Federal Farm Bill 2007	To be determined.	Speculation: More emphasis on greenhouse gas reduction and resource conservation.
SIP, Stewardship Incentive Program	Provides technical and financial assistance to encourage non-industrial private forest landowners to keep their lands and natural resources productive and healthy.	
HFRP, Healthy Forests Reserve Program	A voluntary program established for the purpose of restoring and enhancing forest ecosystems to: 1) promote the recovery of threatened and endangered species, 2) improve biodiversity; and 3) enhance carbon sequestration.	

* Information in the above table was obtained from the respective web sites for each piece of legislation available through http://www.nrcs.usda.gov/programs/index_alph.html.
** The roles of C listed reflect scientific expertise and opinions of the authors.

crops represent an important new source of income for farmers, policies must be in place to encourage farmers to adopt sustainable practices that decreased soil C losses. Now we must balance aspects of renewable energy production and ecosystem sustainability through total C management in all parts of the biological C-cycle for a sustained quality of life.

CONCLUSION

A paradigm shift is underway altering how energy is consumed and produced. Corn-grain ethanol alone cannot and will not solve the foreign energy dependency issues in the United States. However, it may serve as a portion or interim bridge at least on a regional level. The source of biomass feedstock needs to reflect what is available in a region. The first source of biomass energy should be those materials that would otherwise be put in landfills. This includes such materials as bagasse, cull fruits and vegetables, food processsing wastes, saw dust, used vegetable oils just to name a few. Agricultural biomass (stover, straw) only should be harvested for bioenergy once the needs for protecting soil needs have been satisfied. High inputs of pesticides and herbicide, limited belowground biomass also limits the amount of these feedstocks that should be harvested. Perennial biomass crops (grasses and woody) have several advantages over annual crops. First, perennials typically need fewer inputs (fertilizer or herbicide), thus cause fewer off-site consequences. Second, their perennial nature results in annual inputs of leaf litter and more belowground biomass compared to annual crops to build SOC. Third, tillage is reduced or eliminated reducing oxidation of soil C and risk of erosion. Fourth, perennial species provide wildlife habitat, adding an additional ecosystem service.

Energy conservation and conservation of natural resources (soil, water and air) are critical. Assume for a moment that ethanol from either grain or biomass is as thermodynamically efficient as possible. There is a finite amount of land available to support an expanding population with food and fiber needs. Now that land will also need to supply bioenergy feedstocks. Our insatiable energy appetite must be curbed. While it is painful to pay the higher prices for gasoline, higher prices do have the benefit of making people think about their driving habits and alternative fuels. When the cost of heating/cooling a home goes up, the cost motivates consumers to become more energy efficient. These changes put the poorest members of society at risk, because the choice may be among heat, food, or medicine. At some point, we as a society must accept the fact that the resources of our planet are finite and there are global consequences of failing to do so. Severity of the consequences increases the longer we wait to take action toward sustainable energy use.

Scientists have a moral and social responsibility to educate the general public, including policy-makers, of the benefits and risks associated with the paradigm shift. Researchers must present science in a manner that is truthful, clear, understandable, and unbiased. Debate on the economics and environmental balance are useful in identifying the 'truth' and testing the validity of our assumptions. The time to protect our planet is now.

Based on the present energy usage rate of the United States, our petroleum addiction is not likely to be overcome by any one alternative fuel, at least in the near future. The solar energy supply to the earth has essentially boundless potential, in human timeframes. Unfortunately, its energy received is diffuse and we need concentrated forms. Agriculture and forestry are ways to capture and concentrate the ultimate supply. It is our challenge to do the concentrating effectively. Conservation and efficient energy use are not merely idealistic concepts, but are inevitable for survival. Nevertheless, bioenergy can and will help to make a significant reduction in our dependence on petroleum both foreign and domestic. The linkage of various renewable technologies such as solar, hydro, geothermal, and harnessing wind energy to generate hydrogen to make ammonia fertilizer improves the energy efficiency of both grain and cellulosic ethanol. As the paradigm shifts, it will be come important to maximize conservation of energy and natural resources, maximize energy conversion efficiencies and integrate technologies to minimize GHG emissions, improve C sequestration, and provide food and fuel for a growing global population.

ACKNOWLEDGEMENTS

Thanks to B. Burmeister for proof-reading.

REFERENCES

Adegbidi HG, Jokela EJ, Comerford NB (2005) Factors influencing production efficiency of intensively managed loblolly pine plantations in a 1- to 4-year-old chronosequence. *Forest Ecology and Management* **218**, 245-258

Agricultural Energy Working Group (AEWG) (2004) 25 x 25: Agriculture's Role in Ensuring U.S. Energy Independence. Available online: www.bio.org/ind/25x25.pdf

Allen HL, Dougherty PM, Campbell RG (1990) Manipulation of water and nutrients - practice and opportunity in southern U.S. pine forests. *Forest Ecology and Management* **30**, 437-453

Allen HL, Fox TR, Campbell RG (2005) What is ahead for intensive pine plantation silviculture in the South? *Southern Journal of Applied Forestry* **29**, 62-69

Allmaras RR, Linden DR, Clapp CE (2004) Corn residue transformations into root and soil carbon as related to nitrogen, tillage, and stover management. *Soil Science Society of America Journal* **68**, 1366-1375

Aronsson P and Perttu K (2001) Willow vegetation filters for wastewater treatment and soil remediation combined with biomass production. *Forestry Chronicle* **77**, 293-299

Bahler CC, Vogel KP, Moser LE (1984) Atrazine tolerance in warm-season grass seedlings *Agronomy Journal* **76**, 891-895

Baker A, Zahniser S (2006) *Ethanol reshapes corn market*. USDA-Economic Research Service. Available online: http://www.ers.usda.gov/AmberWaves/April06/Features/Ethanol.htm

Balesdent J, Balabane M (1996) Major contribution of roots to soil carbon storage inferred from maize cultivated soils. *Soil Biology and Biochemistry* **28**, 1261-1263

Barber SA (1979) Corn residue management and soil organic matter. *Agronomy Journal* **71**, 625-627

Barnhart SL, Schrader WD, Webb JR (1978) Comparison of soil properties under continuous corn grain and silage cropping systems. *Agronomy Journal* **70**, 835-837

BassiriRad H (2000) Kinetics of nutrient uptake by roots: responses to global change. *New Phytologist* **147**, 155-169

Bauhus J, Messier C (1999) Soil exploitation strategies of fine roots in different tree species of the southern boreal forest of eastern Canada. *Canadian Journal of Forest Research* **29**, 260-273

Bernardo AL, Reis MGF, Reis GG, Harrison RB, Firme DJ (1998) Effect of spacing on growth and biomass distribution in *Eucalyptus camaldulensis*, *E. pellita* and *E. urophylla* plantations in southeastern Brazil. *Forest Ecology and Management* **104**, 1-13

Berndes G, Hoogwijk M, van den Broek R (2003) The contribution of biomass in the future global energy supply: A review of 17 studies. *Biomass and Bioenergy* **25**, 1-28

BfEL (2006) *Seed Oil Fatty Acids Data Base*, Federal Research Centre for Nutrition and Food (BfEL), Germany, Available online: http://www.bagkf.de/sofa/

Bierman PM, Rosen CJ, Bloom PR, Nater EA (1995) Soil solution chemistry of sewage-sludge incinerator ash and phosphate fertilizer amended soil. *Journal of Environmental Quality* **24**, 279-285

Binkley D (1986) *Forest Nutrition Management*, John Wiley and Sons, New York, 290 pp

Biomass Technical Advisory Committee (BTAC) (2002) Vision for bioenergy and biobased products in the United States. Available online: www.climatevision.gov/sectors/elecricpower/ pdfs/bioenergy_vision.pdf

Blasing TJ, Smith K (2006) *Recent Greenhouse Gas Concentrations*, Oak Ridge National Laboratory, United State Department of Energy. Available online: http://cdiac.ornl.gov/pns/ current_ghg.html

Bloom PR, Schuh WM, Malzer GL, Nelson WW, Evans SD (1982) Effect of nitrogen fertilizer and corn residue management on organic matter in Minnesota Mollisols. *Agronomy Journal* **74**, 161-163

Bond BJ, Franklin JF (2002) Aging in Pacific Northwest forests: a selection of recent research. *Tree Physiology* **22**, 73-76

Borders BE, Bailey RL (2001) Loblolly pine - pushing the limits of growth. *Southern Journal of Applied Forestry* **25**, 69-74

Botha T, von Blottnitz H (2006) A comparison of the environmental benefits of bagasse-derived electricity and fuel ethanol on a life-cycle basis. *Energy Policy* **34**, 2654-2661

Brandle JR, Hodges L, Zhou XH (2004) Windbreaks in North American agricultural systems. *Agroforestry Systems* **61-62**, 65-78

Brejda JJ (1996) Evaluation of arbuscular mycorrhiza populations for enhancing switchgrass yield and nutrient uptake. PhD Thesis, University of Nebraska, Lincoln, 161 pp

Brejda JJ (2000) Fertilization of native warm-season grasses. In: Moore KT, Anderson B (Eds) *Native Warm-Season Grasses: Research Trends and Issues*, Crop Science Society of America, Special Publication 30, CSSA and ASA, Madison, WI, pp 177-200

Brejda JJ, Moser LE, Vogel KP (1998) Evaluation of switchgrass rhizosphere microflora for enhancing seedling yield and nutrient uptake. *Agronomy Journal* **90**, 753-758

Brigham RD (1993) Castor: Return of an old crop. In: Janick J, Simon JE (Eds) *New Crops*, Wiley, New York, pp 380-383

Bullard MJ, Mustill SJ, McMillan SD, Nixon PMI, Carver P, Britt CP (2002) Yield improvements through modification of planting density and harvest frequency in short rotation coppice *Salix* spp. - 1. Yield response in two morphologically diverse varieties. *Biomass and Bioenergy* **22**, 15-25

Busov VB, Brunner AM, Meilan R, Filichkin S, Ganio L, Gandhi S, Strauss SH (2005) Genetic transformation: a powerful tool for dissection of adaptive traits in trees. *New Phytologist* **167**, 9-18

Carlson KD, Gardner JC, Anderson, VL, Hanzel JJ (1996) Crambe: New crop success. In: Janick J (Ed) *Progress in New Crops*, ASHS Press, Alexandria, VA, pp 306-322

Carter MC, Foster CD (2006) Milestones and millstones: A retrospective on

50 years of research to improve productivity in loblolly pine plantations. *Forest Ecology and Management* **227**, 137-144

Casler MD, Buxton DR, Vogel KP (2002) Genetic modification of lignin concentration affects fitness of perennial plants. *Theoretical and Applied Genetics* **104**, 127-131

Causarano HJ, Franzluebbers AJ, Reeves DW, Shaw JN (2006) Soil organic carbon sequestration in cotton production systems of the Southeastern United States: A review. *Journal of Environmental Quality* **35**, 1374-1383

Ceulemans R, Isebrands J (1996) Carbon acquisiton and allocation. In: Stettler RF, Bradsha HD, Heilman PE, Hinckley TM (Eds) *Biology of Populus and its Implications for Management and Conservation*, NRC Research Press, Ottawa, pp 355-399

Cermak SC, Isbell TA (2002) Physical properties of saturated estolides and their 2-ethylhexyl esters. *Industrial Crop Production* **16**, 119-127

Cermak, SC, Isbell TA (2004) Synthesis and physical properties of cuphea-oleic estolides and esters. *Journal of the American Oil Chemists' Society* **81**, 297-303

Chang A, Lund L, Page A, Warneke J (1977) Physical properties of fly ash-amended soils. *Journal of Environmental Quality* **6**, 267-270

Cheng WX, Johnson DW, Fu SL (2003) Rhizosphere effects on decomposition: Controls of plant species, phenology, and fertilization. *Soil Science Society of America Journal* **67**, 1418-1427

Cihacek LJ, Sweeney MD, Deibert EJ (1993) Characterization of wind erosion sediments in the Red River Valley of North Dakota. *Journal of Environmental Quality* **22**, 305-310

Cogliastro A, Gagnon D, Bouchard A (1993) Effect of sylvicultural site and treatment on growth, biomass allocation and nitrogen uptake by seedlings of 4 hardwoods in plantations of Southeastern Quebec. *Canadian Journal of Forest Research* **23**, 199-209

Coleman DC, Odum EP, Crossley DA (1992) Soil biology, soil ecology, and global change. *Biology and Fertility of Soils* **14**, 104-111

Coleman MD, Coyle DR, Blake J, Britton K, Buford M, Campbell RG, Cox J, Cregg B, Daniels D, Jacobson M, Johnson K, McDonald T, McLeod K, Nelson E, Robison D, Rummer R, Sanchez F, Stanturf J, Stokes B, Trettin C, Tuskan J, Wright L, Wullschleger S (2004a) Production of short rotation woody crops grown with a range of nutrient and water availability: Establishment report and first-year responses. USDA Forest Service, Southern Research Station, Asheville, NC, USA, General Technical Report, SRS- 72, 21 pp

Coleman MD, Dickson RE, Isebrands JG (1998) Growth and physiology of aspen supplied with different fertilizer addition rates. *Physiologia Plantarum* **103**, 513-526

Coleman MD, Dickson RE, Isebrands JG (2000) Contrasting fine-root production, survival and soil CO_2 efflux in pine and poplar plantations. *Plant and Soil* **225**, 129-139

Coleman MD, Isebrands JG, Tolsted DN, Tolbert VR (2004b) Comparing soil carbon of short rotation poplar plantations with agricultural crops and woodlots in North Central United States. *Environmental Management* **33**, S299-S308

Coleman MD, Tolsted D, Nichols T, Johnson WD, Ween EG, Houghtaling T (2006) Post-establishment fertilization of Minnesota hybrid poplar plantations. *Biomass and Bioenergy* **30**, 740-749

Conner RC, Hartsell AJ 2002 Forest Area and Conditions. In Southern forest resource assessment. In: Wear DN, Greis JG (Eds) *General Technical Report SRS-53*. USDA-Forest Service, Southern Research Station, Asheville, NC, pp 357-401

Cox D, Bezdicek D, Fauci M (2001) Effects of compost, coal ash, and straw amendments on restoring the quality of eroded Palouse soil. *Biology and Fertility of Soils* **33**, 365-372

Coyle DR, Coleman MD (2005) Forest production responses to irrigation and fertilization are not explained by shifts in allocation. *Forest Ecology and Management* **208**, 137-152

Coyle DR, McMillin JD, Hall RB, Hart ER (2002) Deployment of tree resistance to insects in short rotation *Populus* plantations. In: Wagner MR, Clancy KM, Leiutier F, Paine TD (Eds) *Mechanisms and Deployment of Resistance in Trees to Insects*, Kluwer Academic Publishers, Boston, MA, pp 189-215

Culshaw D, Stokes B (1995) Mechanisation of short rotation forestry. *Biomass and Bioenergy* **9**, 127-140

Dabney SM, Delgado JA, Reeves DW (2001) Using winter cover crops to improve soil and water quality. *Communications in Soil Science and Plant Analysis* **32**, 1221-1250

Davis AA, Trettin CC (2006) Sycamore and sweetgum plantation productivity on former agricultural land in South Carolina. *Biomass and Bioenergy* **30**, 769-777

Davison RL, Natusch DFS, Wallace JR, Evans CA Jr. (1974) Trace elements in fly ash. Dependence of concentration on particle size. *Environonmental Science and Technology* **8**, 1107-1113

Day D, Evans RJ, Lee JW, Reicosky DC (2003) Economical CO_2, SOx and Nox capture from fossil fuel utilization with combined renewable hydrogen production and large scale carbon sequestration. *IIASA Abstracts*. International Institute for Applied Systems Analysis (IIASA). Available online: http://www.iiasa.ac.at/Research/ECS/IEW2003/index.html

Day D, Evans B, Lee JW, Reicosky DC (2002) The development of a slow-release sequestering fertilizer, by an integrated process of hydrogen production from biomass, and the direct sequestration of fossil fuel CO_2 emissions. *Proc. USDA Symposium on Natural Resource Management to Offset Greenhouse Gas Emissions*, Raleigh, NC,19-21, November 2002, p 161

Demirbas A (2006) Biodiesel production via non-catalytic SCF method and biodiesel fuel characteristics. *Energy Conversion and Management* **47**, 2271-2282

Demirbas A, Arin G (2002) An overview of biomass pyrolysis. *Energy Sources* **24**, 471-482

Dias de Oliveira M, Vaughan B, Rykiel E (2005) Ethanol as fuel: Energy, carbon dioxide balances, and ecological footprint. *Bioscience* **55**, 593-602

Dickmann DI (2006) Silviculture and biology of short-rotation woody crops in temperate regions: Then and now. *Biomass and Bioenergy* **30**, 696-705

Dickmann DI, Stuart KW (1983) *The Culture of Poplars in Eastern North America*, Michigan State University Press, East Lansing, MI, 168 pp

Dien B, Jung HG, Vogel KP, Casler MD, Lamb JFS, Weimer PJ, Iten L, Mitchell RB, Sarath G (2006) Chemical composition and response to dilute-acid pretreatment and enzymatic saccharification of alfalfa, reed canarygrass, and switchgrass. *Biomass and Bioenergy* **30**, 880-891

Dierig DA, Coffelt TA, Nakayama FS, Thompson AE (1996) Lesquerell and vernonia: Oilseeds for arid lands. In Janick J (Ed) *Progress in New Crops*, ASHS Press, Alexandria, VA, pp 347-354

di Fazio SP (2005) A pioneer perspective on adaptation. *New Phytologist* **165**, 661-664

di Pardo J (2000) *Outlook for biomass ethanol production and demand. Energy Information Agency, Washington, DC*. Available online: http://www.eia.doe.gov/oiaf/analysispaper/pdf/biomass.pdf

Doran JW (2002) Soil health and global sustainability: translating science into practice. *Agricultural Ecosystems and Environment* **88**, 119-127

Doran JW, Elliot ET, Paustian K (1998) Soil microbial activity, nitrogen cycling, and long-term changes in organic carbon pools as related to fallow tillage management. *Soil and Tillage Research* **49**, 3-18

Doty SL, Dosher MR, Singleton GL, Moore AL, van Aken B, Stettler RF, Strand SE, Gordon MP (2005) Identification of an endophytic *Rhizobium* in stems of *Populus*. *Symbiosis* **39**, 27-35

Drake BJ, Gonzalez-Meler MA, Long SP (1997) More efficient plants: A consequence of rising atmospheric CO_2? *Annual Review of Plant Physiology and Plant Molecular Biology* **48**, 609-639

Dubcovsky J (2004) Marker-assisted selection in public breeding programs: The wheat experience. *Crop Science* **44**, 1895-1898

Duke J (1983) *Handbook of Energy Crops*. University of Purdue, Center for New Crops and Plant Products. Available online: http://www.hort.purdue.edu/newcrop/duke_energy/Ricinus_communis.html#Yields%20and%20Economics

Duryea ML, Landis TD (1984) *Oregon State University Nursery Technology Cooperative and United States Forest Service. Pacific Northwest Region. 1984 Forest nursery manual: Production of bareroot seedlings*, M. Nijhoff/W. Junk Publishers for Oregon State University, Forest Research Laboratory, Corvallis, OR, Boston, MA 385 pp

Duvick DN (2005) The contribution of breeding to yield advances in *Zea maize* (L.). *Advances in Agronomy* **86**, 83-145

Duvick DN, Smith JSC, Cooper M (2004) Changes in performance parentage, and genetic diversity of successful corn hybrids, 1930-2000. In Smith CW, Betrán J, Runge ECA (Eds) *Corn, Origin, History, Technology, and Production*, John Wiley and Sons, Canada, Mississauga, Ontario, pp 65-98

Eisenbies MH, Burger JA, Aust WM, Patterson SC, Fox TR (2006) Assessing change in soil-site productivity of intensively managed loblolly pine plantations. *Soil Science Society of America Journal* **70**, 130-140

Eissenstat DM, Yanai RD (1997) The ecology of root lifespan. *Advances in Ecological Research* **27**, 1-60

Ek AR, Dawson DH (1976) Actual and projected growth and yields of *Populus* 'tristis-l', under intensive culture. *Canadian Journal of Forest Research* **6**, 132-144

Energy Information Agency (EIA) (2006a) Annual Energy Review. *Energy Information Agency*. Available online: http://www.eia.doe.gov/emeu/aer/contents.html

Energy Information Agency (EIA) (2006b) Monthly Energy Review. *Energy Information Agency*. Available online: http://www.eia.doe.gov/emeu/mer/pdf/pages/see_7.pdf

Evans LT, Fischer RA (1999) Yield potential: Its definition, measurement, and significance. *Crop Science* **39**, 1544-155

Fahad AA, Mielke LN, Flowerday AD, Swartzendruber D (1982) Soil physical properties as affected by soybean and other cropping sequences. *Soil Science Society America Journal* **46**, 377-381

Falkiner RA, Polglase PJ (1999) Fate of applied phosphorus in an effluent-irrigated *Pinus radiata* plantation. *Australian Journal of Soil Research* **37**, 1095-1106

FAO (1979a) *Eucalypts for Planting*, FAO, Rome, 677 pp

FAO (1979b) *Poplars and Willows in Wood Production and Land Use*, FAO, Rome, 328 pp

FAO (2004) *Unified Bioenergy terminology*. Food and Agriculture Organization of the United Nations - Forestry Department, Wood Energy Programme. Available online: http://ftp.fao.org/docrep/fao/007/j4504e/j4504e00.pdf

Farrell AE, Plevin RJ, Turner BT, Jones AD, O'Hare M, Kammen DM (2006) Ethanol can contribute to energy and environmental goals. *Science* **311**, 506-508

Flowers TJ (2004) Improving crop salt tolerance *Journal of Experimental Botany* **55**, 307-319

Follett RF, Castellanos JZ, Buenger ED (2005) Carbon dynamics and sequestration in an irrigated Vertisol in Central Mexico. *Soil and Tillage Research* **83**, 148-158

Fox TR (2000) Sustained productivity in intensively managed forest plantations. *Forest Ecology and Management* **138**, 187-202

Fox TR, Allen HL, Albaugh TJ, Rubilar R, Carlson CA (2006) Forest fertilization in southern pine plantations. *Better Crops* **90**, 12-15

Fowles M (2007) Black carbon sequestration as an alternative to bioenergy. *Biomass and Bioenergy* **31**, 426-432

Francis RC, Hanna RB, Shin SJ, Brown AF, Riemenschneider DE (2006) Papermaking characteristics of three *Populus* clones grown in the north-central United States. *Biomass and Bioenergy* **30**, 803-808

Frank AB, Berdahl JD, Hanson JD, Liebig MA, Johnson HA (2004) Biomass and carbon partitioning in switchgrass. *Crop Science* **44**, 1391-1396

Fröhlich A, Rice B (2005) Evaluation of *Camelina sativa* oil as a feedstock for biodiesel production. *Industrial Crops Production* **21**, 25-31

Fryrear DW (1995) Soil losses by wind erosion. *Soil Science Society of America Journal* **59**, 668-672

Fu SL, Cheng WX (2002) Rhizosphere priming effects on the decomposition of soil organic matter in C-4 and C-3 grassland soils. *Plant and Soil* **238**, 289-294

Furr AK, Parkinson TF, Hinrichs RA, van Campen DR, Bache CA, Gutenmann WH, St. John LE Jr., Pakkala IS, Lisk DJ (1977) National survey of elements and radioactivity in fly ashes. Absorption of elements by cabbage grown in fly ash-soil mixtures. *Environmental Science and Technology* **11**, 1194-1201

Gale MR, Grigal DF (1987) Vertical root distributions of northern tree species in relation to successional status. *Canadian Journal of Forest Research* **17**, 829-834

Garten CT (2002) Soil carbon storage beneath recently established tree plantations in Tennessee and South Carolina, USA. *Biomass and Bioenergy* **23**, 93-102

Gebre GM, Tschaplinski TJ, Tuskan GA, Todd DE (1998) Drought resistance of two hybrid *Populus* clones grown under irrigation in large-scale plantations. *Tree Physiology* **18**, 645-652

Geller DP, Goodrum JW, Knapp SJ (1999) Fuel properties of oil from genetically altered *Cuphea viscosissima*. *Industrial Crop Production* **9**, 85-91

George JR, Reigh GS, Mullen RE, Hunczak JJ (1990) Switchgrass herbage and seed yield and quality with partial spring defoliation. *Crop Science* **30**, 845-849

Gesch RW, Forcella F, Barbour NW, Phillips B, Voorhees WB (2002) Yield and growth response of Cuphea to sowing date. *Crop Science* **42**, 1959-1965

Gesch RW, Forcella F, Olness AE, Archer DW, Hebard A (2006) Agricultural management of cuphea and potential for commercial production in the United States. *Industrial Crops Production* **24**, 300-306

Giardina CP, Ryan MG (2002) Total belowground carbon allocation in a fast-growing *Eucalyptus* plantation estimated using a carbon balance approach. *Ecosystems* **5**, 487-499

Glaser B, Haumaier L, Guggenberger G, Zech W (2001) The Terra Preta phenomenon – a model for sustainable agriculture in the humid tropics. *Naturwissenschaften* **88**, 37-41

Glaser B, Lehmann J, Zech W (2002) Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal - A review. *Biology and Fertility of Soils* **35**, 219-230

Goldberg ED (1985) *Black Carbon in the Environment: Properties and Distribution*, John Wiley and Sons, New York, 198 pp

Gollany HT, Schumacher TE, Evenson PD, Lindstrom MJ, Lemme GD (1991) Aggregate stability of an eroded and desurfaced Typic Argiustoll. *Soil Science Society of America Journal* **55**, 811-816

Gollany HT, Schumacher TE, Lindstrom MJ, Evenson P, Lemme GD (1992) Topsoil thickness and desurfacing effects on properties and productivity of a typic Argiustoll. *Soil Science Society of America Journal* **56**, 220-225

Goodrum JW, Eiteman MA (1996) Physical properties of low molecular weight triglycerides for the development of bio-diesel fuel models. *Bioresource Technology* **56**, 55-60

Goodrum, JW, Geller DP (2005) Influence of fatty acid methyl esters from hydroxylated vegetable oils on diesel fuel lubricity. *Bioresource Technology* **96**, 851-855

Goolsby DA, Battaglin WA (2000) *Nitrogen in the Mississippi basin-estimating sources and predicting flux to the Gulf of Mexico. USGS Fact Sheet 135-00*. United States - Geological Survey. Available online: http://ks.water.usgs.gov/Kansas/pubs/fact-sheets/fs.135-00.html

Graham RL, Nelson R, Sheehan J, Perlack RD, Wright LL (2007) Current and potential U.S. corn stover supplies. *Agronomy Journal* **99**, 1-11

Graham SA (1989) *Cuphea*: A new plant source of medium-chain fatty acids. *Critical Reviews in Food Science and Nutrition* **28**, 139-173

Graham SA, Hirsinger F, Röbbelen G (1981) Fatty acids of *Cuphea* (Lythraceae) seed lipids and their systematic significance. *American Journal of Botany* **68**, 908-917

Graham SA, Kleiman R (1992) Composition of seed oils in some Latin American *Cuphea* (Lythraceae). *Industrial Crops Production* **1**, 31-34

Gregorich EG, Greer KR, Anderson DW, Liang BC (1998) Carbon distribution and losses: Erosion and deposition effects. *Soil and Tillage Research* **47**, 291-302

Gregory JM, Church JA, Boer GJ, Dixon KW, Flato GM, Jackett DR, Lowe JA, Farrell SPO, Roeckner E, Russell GL, Stouffer RJ, Winton M (2001) Comparison of results from several AOGCMs for global and regional sea-level change 1900-2100. *Climate Dynamics* **18**, 225-240

Grigal DF, Berguson WE (1998) Soil carbon changes associated with short-rotation systems. *Biomass and Bioenergy* **14**, 371-377

Hall KE, George JR, Riedel RR (1982) Herbage dry matter yields of switchgrass, big bluestem, and indiangrass with N fertilization. *Agronomy Journal* **74**, 47-51

Hammer D, Kayser A, Keller C (2003) Phytoextraction of Cd and Zn with *Salix viminalis* in field trials. *Soil Use and Management* **19**, 187-192

Hansen E, Netzer D, Rietveld WJ (1984) Weed control for establishing intensively cultured hybrid poplar plantations. *Research Note NC-317*. St. Paul, MN: U.S. Dept. of Agriculture, Forest Service, North Central Forest Experiment Station. Available online: http://www.ncrs.fs.fed.us/pubs/1805

Hansen EA (1993) Soil carbon sequestration beneath hybrid poplar plantations in the north central United States. *Biomass and Bioenergy* **5**, 431-436

Hansen EA, Dawson DH, Tolsted DN (1980) Irrigation of intensively cultured plantations with paper mill effluent. *Tappi Journal* **63**, 139-143

Hansen EA, McLaughlin RA, Pope PE (1988) Biomass and nitrogen dynamics of hybrid poplar on two different soils: implications for fertilization strategy. *Canadian Journal of Forest Research* **18**, 223-230

Hansen J, Sato M, Ruedy R, Lo K, Lea DW, Medina-Elizade M (2006) Global temperature change. *Proceedings of the National Academy of Sciences USA* **103**, 14288-14293

Heaton E, Voigt T, Long SP (2004) A quantitative review comparing yields of two candidate C_4 perennial biomass crops in relation to nitrogen, temperature, and water. *Biomass and Bioenergy* **27**, 21-30

Heilman P, Peabody DV (1981) Effect of harvest cycle and spacing on productivity of black cottonwood in intensive culture. *Canadian Journal of Forest Research* **11**, 118-123

Heilman PE, Xie FG (1993) Influence of nitrogen on growth and productivity of short-rotation *Populus trichocarpa* × *Populus deltoides* hybrids. *Canadian Journal of Forest Research* **23**, 1863-1869

Heilman PE, Hinckley TM, Roberts DA, Ceulemand R (1996) Production physiology. In: Stettler RF, Bradshaw HD, Heilman PE, Hinckley TMO (Eds) *Biology of Populus and its Implications for Management and Conservation*, NRC Research Press, Ottawa, pp 458-489

Heilman PE, Stettler RF (1985) Genetic variation and productivity of *Populus trichocarpa* and its hybrids. II. Biomass production in a 4-year plantation. *Canadian Journal of Forest Research* **15**, 384-388

Henneberger TSM, Stevenson KL, Britton KO, Chang CJ (2004) Distribution of *Xylella fastidiosa* in Sycamore associated with low temperature and host resistance. *Plant Disease* **88**, 951-960

Herrera S (2006) Bonkers about biofuels. *Science Biotechnology* **24**, 755-760

Hettenhaus JR, Wooley R, Wiselogel A (2000) *Biomass commercialization prospects in the next 2 to 5 years: Biomass colloquies 2000 NREL/ACO-9-29-039-01*. National Renewable Energy Laboratory, Golden, CO. Available online: http://www.nrel.gov/docs/fy01osti /28886.pdf

Hicks DR, Naeve SL, Hexum D (2001) *Corn and Soybean Planting Considerations for 2001*. University of Minnesota. Available online: http://www.soybeans.umn.edu/resources/news/news_5-08-01.htm

Hill J, Nelson E, Tilman D, Polasky S, Tiffany D (2006) Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proceedings of the National Academy of Sciences USA* **103**, 11206-11210

Himmel ME, Ding S-Y, Johnson DK, Adney WS, Nimlos MR, Brady JW, Foust TD (2007) Biomass recalcitrance: Engineering plants and enzymes for biofuels production. *Science* **315**, 804-807

Hoffert MI, Caldeira K, Benford G, Criswell DR, Green C, Herzog H, Jain AK, Kheshgi HS, Lackner KS, Lewis JS, Lightfoot HD, Manheimer W, Mankins JC, Mauel ME, Perkins LJ, Schlesinger ME, Volk T, Wigley TML (2002) Advanced technology paths to global climate stability: energy for a greenhouse planet. *Science* **298**, 981-987

Hondelmann W, Radatz W (1984) Variation in some plant and seedoil characteristics of pennycress (*Thlaspi arvense* L.). *Zeitschrift fur Pflanzenzuchtung* **92**, 328-342

Hooker BA, Morris TF, Peters R, Cardon ZG (2005) Long-term effects of tillage and corn stalk return on soil carbon dynamics. *Soil Science Society America Journal* **69**, 188-196

Hoskinson RL, Karlen DL, Birrell SJ, Radtke CW, Wilhelm WW (2007) Engineering, nutrient removal, and feedstock conversion evaluations of four corn stover harvest scenarios. *Biomass and Bioenergy* **31**, 126-136

Huggins DR, Buyanovky GA, Wagner GH, Brown JR, Darmody RG, Peck TR, Lesoing GW, Vanotti MB, Bundy LG (1998) Soil organic C in the tallgrass prairie-derived region of the corn belt: effects of long-term crop management. *Soil and Tillage Research* **47**, 219-234

Hulsbergen KJ, Feil B, Biermann S, Rathke GW, Kalk WD, Diepenbrock W (2001) A method of energy balancing in crop production and its application in a long-term fertilizer trial. *Agriculture Ecosystem and Environment* **86**, 303-321

Hultquist SJ, Vogel KP, Lee DJ, Arumuganathan K, Kaeppler S (1996) Chloroplast DNA and nuclear DNA content variations among cultivars of switchgrass, *Panicum virgatum* L. *Crop Science* **36**, 1049-1052

Ingestad T (1987) New concepts on soil fertility and plant nutrition as illustrated by research on forest trees and stands. *Geoderma* **40**, 237-252

IPCC (2001) Climate Change 2001: The Scientific Basis. Contributions of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change. In: Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA (Eds) Cambridge University Press, Cambridge, UK, 881 pp

IPCC (2007) *Intergovernmental Panel on Climate Change WGI, Fourth Assessment report, Climate Change 2007: The Physical Science Basis, Summary for Policymakers*. IPCC, Available online: http://www.ipcc.ch/SPM2feb07.pdf

Janzen HH, Campbell CA, Gergorich EG, Ellert BH (1998) Soil carbon dynamics in Canadian agroecosystems. In: Lal R, Kimble R, Follet R, Stewart BA (Eds) *Soil Processes and the Carbon Cycle*, CRC Press, Boca Raton, FL, pp 57-80

Jia H, Ingestad T (1984) Nutrient requirements and stress response of *Populus simonii* and *Paulownia tomentosa*. *Physiologia Plantarum* **62**, 117-124

Jiao D, Huang X, Li X, Chi W, Kuang T, Zhang Q, Ku MSB, Cho D (2002) Photosynthetic characteristics and tolerance to photo-oxidation of transgenic rice expressing C4 photosynthesis enzymes. *Photosynthesis Research* **72**, 85-93

Johnson DW, Curtis PS (2001) Effects of forest management on soil C and N storage: meta analysis. *Forest Ecology and Management* **140**, 227-238

Johnson JMF, Allmaras RR, Reicosky DC (2006a) Estimating source carbon from crop residues, roots and rhizodeposits using the national grain-yield database. *Agronomy Journal* **98**, 622-636

Johnson JMF, Barbour NW, Weyers SL (2007) Chemical composition of crop biomass impacts its decomposition. *Soil Science Society of America Journal* **71**, 155-162

Johnson JMF, Reicosky DC, Allmaras RR, Archer D, Wilhelm WW (2006b) A matter of balance: Conservation and renewable energy. *Journal of Soil and Water Conservation* **61**, 120A-125A

Johnson JMF, Reicosky D, Sharratt B, Lindstrom M, Voorhees W, Carpenter-Boggs L (2004) Characterization of soil amended with the by-product of corn stover fermentation. *Soil Science Society of America Journal* **68**, 139-147

Jokela EJ, Dougherty PM, Martin TA (2004) Production dynamics of intensively managed loblolly pine stands in the southern United States: a synthesis of seven long-term experiments. *Forest Ecology and Management* **192**, 117-130

Kern, M (2002) Food, feed, fiber, fuel and industrial products of the future: Challenges and opportunities. Understanding the strategic potential of plant genetic engineering. *Journal of Agronomy and Crop Science* **188**, 291-305

Kim S, Dale BE (2005) Environmental aspects of ethanol derived from no-tilled corn grain: nonrenewable energy consumption and greenhouse gas emissions. *Biomass and Bioenergy* **28**, 475-489

Knapp SJ, Crane JM (2000) Registration of reduced seed shattering *Cuphea* germplasm PSR23. *Crop Science* **41**, 299-300

Knapp SJ (1993). Breakthroughs towards the domestication of *Cuphea*. In: Janick J, Simon JE (Eds) *New Crops*, Wiley, NY, pp 372-379

Kopp RF, Abrahamson LP, White EH, Volk TA, Nowak CA, Fillhart RC (2001) Willow biomass production during ten successive annual harvests. *Biomass and Bioenergy* **20**, 1-7

Kszos LA, Downing ME, Wright LL, Cushman JH, McLaughlin SB, Tolbert VR, Tuskan GA, Walsh ME (2001) Bioenergy Feedstock Development Program Status Report. ORNL/TM-2000/292. Available online: http://www.ornl.gov/~webworks/cppr/y2001/rpt/108677_.pdf

Kuo S, Jellum EJ (2002) Influence of winter cover crop and residue management on soil nitrogen availability and corn. *Agronomy Journal* **94**, 501-508

Kuzovkina YA, Quigley MF (2005) Willows beyond wetlands: Uses of *Salix* L. species for environmental projects. *Water, Air and Soil Pollution* **162**, 183-204

Labrecque M, Teodorescu TI (2005) Field performance and biomass production of 12 willow and poplar clones in short-rotation coppice in southern Quebec (Canada). *Biomass and Bioenergy* **29**, 1-9

Laflen JM, Moldenhauer WC (1985) Soybean production and soil erosion problems-North America. Shibles R (Ed) *World Soybean Research Conf.* III, Westview Press, Inc., Boulder, CO, pp 1166-1174

Lal R (2003) Soil erosion and the global carbon budget. *Environment International* **29**, 437-450

Larson ED (2006) Lifecycle analyses of greenhouse gas impacts of biofuels for transport. Presentation at "*Energy Week, The World Bank*" Washington, D.C. Available online: worldbank.org/EXTENERGY/Resources/336805-1137702984816/2135734-1142446048455/EricLarson.ppt

Larson WE, Clapp CE, Pierre WH, Morachan YB (1972) Effects of increasing amounts of organic residues on continuous corn. II. Organic carbon, nitrogen, phosphorus and sulfur. *Agronomy Journal* **64**, 204-208

Larson WE, Holt RF, Carlson CW (1978) Residues for soil conservation. In: Oschwald WR (Ed) *Crop Residue Management Systems*, ASA Special Publication 31, American Society of Agronomy, Madison, WI, pp 1-15

Larsson S (1998) Genetic improvement of willow for short-rotation coppice. *Biomass and Bioenergy* **15**, 23-26

Laughton PJ, Papadopol CS, Jaciw P (1990) Zero discharge through innovative application of intensive silviculture to effluent disposal from a small Canadian wastewater treatment plant. *Water Science and Technology* **22**, 217-224

Laureysens I, De Temmerman L, Hastir T, van Gysel M, Ceulemans R (2005) Clonal variation in heavy metal accumulation and biomass production in a poplar coppice culture. II. Vertical distribution and phytoextraction potential. *Environmental Pollution* **133**, 541-551

Layese MF, Clapp CE, Allmaras RR, Linden DR, Copeland SM, Molina JAE, Dowdy RH (2002). Current and relic carbon using natural abundance 13C. *Soil Science Society of America Journal* **167**, 315-326

Lee DK, Owens VN, Doolittle JJ (2007) Switchgrass and soil carbon sequestration response to ammonium nitrate, manure, and harvest frequency on Conservation Reserve Program land. *Agronomy Journal* **99**, 462-468

Lee JW, Li R (2003) Integration of coal fired energy systems with CO_2 sequestration through NH_4HCO_3 production. *Energy Conversion and Management* **44**, 1535-1546

Lee KH, Isenhart TM, Schultz RC, Mickelson SK (2000) Multispecies riparian buffers trap sediment and nutrients during rainfall simulations. *Journal of Environmental Quality* **29**, 1200-1205

Lehmann J, da Silva JP Jr., Steiner C, Nehls T, Zech W, Glaser B (2003a) Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. *Plant and Soil* **249**, 343-357

Lehmann J, Gaunt J, Rondon M (2006) Bio-char sequestration in terrestrial ecosystems – a review. *Mitigation and Adaptation Strategies for Global Climate Change* **11**, 403-427

Lehmann J, Kern DC, Glaser B, Woods WI (2003b) *Amazonian Dark Earths: Origin, Properties, Management*, Kluwer Academic Publishers, Dordrecht, The Netherlands, 523 pp

Lehmann J, Rondon M (2006) Bio-char soil management on highly weathered soils in the humid tropics. In: Uphoff N, Ball AS, Fernandes E, Herren H, Husson O, Laing M, Palm C, Pretty J, Sanchez P (Eds) *Bio-Char Soil Management on Highly Weathered Soils in the Humid Tropics*, CRC Press, Boca Raton, FL, pp 517-530

Lemus R, Lal R (2005) Bioenergy crops and carbon sequestration. *Critical Reviews in Plant Sciences* **24**, 1-21

Licht LA, Isebrands JG (2005) Linking phytoremediated pollutant removal to biomass economic opportunities. *Biomass and Bioenergy* **28**, 203-218

Liebig MA, Johnson HA, Hanson JD, Frank AB (2005) Soil carbon under switchgrass stands and cultivated cropland. *Biomass and Bioenergy* **28**, 347-354

Liang BC, Lehmann J, Solomon D, Kinyangi J, Grossman J, O'Neill B, Skjemstad JO, Thies J, Luizão FJ, Petersen J, Neves EG (2006) Black carbon increases cation exchange capacity in soils. *Soil Science Society of America Journal* **70**, 1719-1730

Little KM, Gardner RAW (2003) Coppicing ability of 20 Eucalyptus species grown at two high-altitude sites in South Africa. *Canadian Journal of Forest Research-Revue Canadienne de Recherche Forestiere* **33**, 181-189

Londo M, Dekker J, ter Keurs W (2005) Willow short-rotation coppice for energy and breeding birds: an exploration of potentials in relation to management. *Biomass and Bioenergy* **28**, 281-293

Long SP, Zhu XG, Naidu SL, Ort DR (2006) Can improvement in photosynthesis increase crop yields? *Plant, Cell and Environment* **29**, 315-330

Lorenz WW, Sun F, Liang C, Kolychev D, Wang HM, Zhao X, Cordonnier-Pratt MM, Pratt LH, Dean JFD (2006) Water stress-responsive genes in loblolly pine (*Pinus taeda*) roots identified by analyses of expressed sequence tag libraries. *Tree Physiology* **26**, 1-16

Lowe JA, Gregory JM, Flather RA (2001) Changes in the occurrence of storm surges around the United Kingdom under a future climate scenario using a dynamic storm surge model driven by the Hadley Centre climate models. *Climate Dynamics* **18**, 179-188

Lowrance R, Dabney S, Schultz R (2002) Improving water and soil quality with conservation buffers. *Journal of Soil and Water Conservation* **57**, 36A-43A

Lubowski RN, Versterby M, Buchholz S, Baez A, Roberts MJ (2002) *Major uses of land in the United States, 2002/EIB14*. Economic Research Service, USDA. Available online: http://www.ers.usda.gov/publications/EIB14/eib14a.pdf

Ma Z, Wood CW, Bransby DI (2001) Impact of row spacing, nitrogen rate, and time on carbon partitioning of switchgrass. *Biomass and Bioenergy* **20**, 413-419

Madakadze IC, Coulman BE, McElroy AR, Stewart KA, Smith DL (1998) Evaluation of selected warm-season grasses for biomass production in areas with short growing season. *Bioresource Technology* **65**, 1-12

Madakadze IC, Stewart KA, Peterson PR, Coulman BE, Smith DL (1999) Switchgrass biomass and chemical composition for biofuel in eastern Canada.

Agronomy Journal **91**, 696-701

Mahalakshmi V, Ortiz R (2001) Plant genomics and agriculture: From model organisms to crops, the role of data mining for gene discovery. *Electronic Journal of Biotechnology* **4**, 1-10

Mann LK, Johnson DW, West DC, Cole DW, Hornbeck JW, Martin CW, Riekerk H, Smith CT, Swank WT, Tritton LM, Vanlear DH (1988) Effects of whole-tree and stem-only clearcutting on postharvest hydrologic losses, nutrient capital, and regrowth. *Forest Science* **34**, 412-428

Mann LK, Tolbert VR, Cushman J (2002) Potential environmental effects of corn (*Zea mays* L.) stover removal with emphasis on SOM and erosion: a review. *Agriculture, Ecosystems and Environment* **89**, 149-166

Marris E (2006) Sugar cane and ethanol: Drink the best and drive the rest. *Nature* **444**, 670-672

Martens D (1971) Availability of plant nutrients in fly ash. *Compost Science and Utilization* **12**, 15-19

Martin DA, Nakamura R (2001) Hawaii forestry: a special report on Hawaii's privately-owned forest lands. Hawaii Agricultural Statistics Service, Hawaii Department of Agriculture, Honolulu, HI, 2 pp

Martin F, Tuskan GA, DiFazio SP, Lammers P, Newcombe G, Podila GK (2004) Symbiotic sequencing for the Populus mesocosm. *New Phytologist* **161**, 330-335

Martin AR, Moomaw RS, Vogel KP (1982) Warm-season grass establishment with atrazine. *Agronomy Journal* **74**, 916-920

Martinez-Reyna JM, Vogel KP (2002) Incompatibility systems in switchgrass. *Crop Science* **42**, 1800-1805

Martinez-Reyna JM, Vogel KP, Caha C, Lee DJ (2001) Meiotic stability, chloroplast DNA polymorphisms, and morphological traits of upland x lowland switchgrass reciprocal hybrids. *Crop Science* **41**, 1579-1583

Masters RA, Nissen SJ, Gaussoin RE, Beran DD, Stougaard RN (1996) Imidazolinone herbicides improve restoration of Great Plains grasslands. *Weed Technology* **10**, 392-403

Matsuoka M, Nomura M, Agarie S, Miyao-Tokutomi M, Ku MSB (1998) Evolution of C4 photosynthetic genes and overexpression of maize C4 genes in rice. *Journal of Plant Research* **111**, 333-337

McAlpine RG, Brown CL, Herrick AM, Ruark HE (1966) "Silage" sycamore. *Forest Farmer* **26**, 6-7, 16

McKeand SE, Jokela EJ, Huber DA, Byram TD, Allen HL, Li BL, Mullin TJ (2006) Performance of improved genotypes of loblolly pine across different soils, climates, and silvicultural inputs. *Forest Ecology and Management* **227**, 178-184

McLaughlin SB, Ugarte D, Garten CT, Lynd LR, Sanderson MA, Tolbert VR, Wolf DD (2002) High-value renewable energy from prairie grasses. *Environmental Science and Technology* **36**, 2122-2129

McLaughlin S, Walsh M (1998) Evaluating environmental consequences of producing herbaceous crops for bioenergy. *Biomass and Bioenergy* **14**, 317-324

McMinn JW, Nutter WL (1981) Energy wood harvesting. A study of promises and pitfalls. *Georgia Forest Research Paper* **17**, 6 pp

Menon M, Sajwan K, Ghuman G, James JT, Chandra K (1993) Fly-ash amended compost as a manure for agricultural crops. *Journal of Environmental Science and Health* **28**, 2167-2182

Mirck J, Isebrands JG, Verwijst T, Ledin S (2005) Development of short-rotation willow coppice systems for environmental purposes in Sweden. *Biomass and Bioenergy* **28**, 219-228

Mitchell CP, Stevens EA, Watters MP (1999) Short-rotation forestry – operations, productivity and costs based on experience gained in the UK. *Forest Ecology and Management* **121**, 123-136

Mitchell RB, Vogel KP, Klopfenstein TJ, Anderson BE, Masters RA (2005) Grazing evaluation of big bluestem bred for improved forage yield and digestibility. *Crop Science* **45**, 2288-2292

Moffat AJ, Armstrong AT, Ockleston J (2001) The optimization of sewage sludge and effluent disposal on energy crops of short rotation hybrid poplar. *Biomass and Bioenergy* **20**, 161-169

Moldenhauer WC, Wischmeier WH (1969) Soybeans in corn-soybean rotations permit erosion but put blame on corn. *Crops and Soils* **21**, 20

Moorhead DJ (2006) Forest herbicides. Available online: http://www.ent.uga.edu/pmh/Com_Trees.pdf, p 5-11

Moser BW, Hilpp GK (2003) Wintering raptor use of hybrid poplar plantations in northeastern Oregon. *Journal of Raptor Research* **37**, 286-291

Moser BW, Pipas MJ, Witmer GW, Engeman RM (2002) Small mammal use of hybrid poplar plantations relative to stand age. *Northwest Science* **76**, 158-165

Muir JP, Sanderson MA, Ocumpaugh WR, Jones RM, Reed RL (2001) Biomass production of 'Alamo' switchgrass in response to nitrogen, phosphorus, and row spacing. *Agronomy Journal* **93**, 896-901

Mulkey VR, Owens VN, Lee DK (2006) Management of switchgrass-dominated Conservation Reserve Program lands for biomass production in South Dakota. *Crop Science* **46**, 712-720

Myers BJ, Theiveyanathan S, O'Brien ND, Bond WJ (1996) Growth and water use of *Eucalyptus grandis* and *Pinus radiata* plantations irrigated with effluent. *Tree Physiology* **16**, 211-219

National Academy Sciences (NAS) (2000) *Transgenic Plants and World Agriculture Report prepared under the auspices of the Royal Society of London, the U.S. National Academy of Sciences, the Brazilian Academy of Sciences, the Chinese Academy of Sciences, the Indian National Science Academy, the Mexican Academy of Sciences and the Third World Academy of Sciences*. National Academy Press. Available online: http://www.nap.edu/catalog/9889.html#toc

Nelson RG (2002) Resource assessment and removal analysis for corn stover and wheat straw in the Eastern and Midwestern United States – rainfall and wind-induced soil erosion methodology. *Biomass and Bioenergy* **22**, 349-363

Nyakatawa EZ, Mays DA, Tolbert VR, Green TH, Bingham L (2006) Runoff, sediment, nitrogen, and phosphorus losses from agricultural land converted to sweetgum and switchgrass bioenergy feedstock production in north Alabama. *Biomass and Bioenergy* **30**, 655-664

Oschwald WR, Siemens JC (1976) Soil erosion after soybeans. In: Hill LD (Ed) *World Soybean Research. Proc. World Soybean Research Conference*, Interstate Printers and Publishers, Danville, IL, pp 74-81

Palumbo AV, McCarthy JF, Amonette JE, Fisher LS, Wullschleger SD, Daniels WL (2004) Prospects for enhancing carbon sequestration and reclamation of degraded lands with fossil-fuel combustion by-products. *Advances in Environmental Research* **8**, 425-438

Paustian K, Collins HP, Paul EA (1997) Management controls on soil carbon. In: Paul EA, Paustian K, Elliott ET, Cole CV (Eds) *Soil Organic Matter in Temperate Agroecosystems: Long-Term Experiments in North America*, CRC Press, Boca Raton, FL, pp 15-49

Pavy N, Johnson JJ, Crow JA, Paule C, Kunau T, MacKay J, Retzel EF (2007) ForestTreeDB: A database dedicated to the mining of tree transcriptomes. *Nucleic Acids Research* **35**, D888-D894

Pedersen JF, Vogel KP, Funnell D (2005) Impact of reduced lignin on plant fitness. *Crop Science* **45**, 812-819

Pereira JS, Linder S, Araújo MC, Pereira H, Ericsson T, Borralho N, Leal LC (1989) Optimization of biomass production in *Eucalyptus globulus* plantations - A case study. In: Pereira JS, Landsberg JJ (Eds) *Biomass Production by Fast-Growing Trees,* Kluwer, Dordrecht, The Netherlands, pp 101-121

Perlack RD, Turhollow A (2002) *Assessment options for the collection, handling and storage of corn stover*. Oak Ridge National Laboratory, US Department of Energy. Available online: http://bioenergy.ornl.gov/pdfs/ornltm-200244.pdf

Perlack RD, Wright LL, Huston MA, Schramm WE (1995) Biomass fuel from woody crops for electric power generation. ORNL-6871. Oak Ridge National Laboratory, Oak Ridge, TN. Available online: http://bioenergy.ornl.gov/reports/fuelwood/toc.html

Perlack RD, Wright LL, Turhollow A, Graham RL, Stokes B, Erbach DC (2005) *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply*. USDOE and USDA. Available online: http://www.eere.energy.gov/biomass/pdfs/final_billionton_vision_report2. pdf

Perry LJ, Baltensperger DD (1979) Leaf and stem yields and forage quality of three N-fertilized warm-season grasses. *Agronomy Journal* **71**, 355-358

Peterson CL, Reece DL, Hammond BL, Thompson J, Beck SM (1997) Processing, characterization, and performance of eight fuels from lipids. *Applied Engineering in Agriculture* **13**, 71-79

Pilipovic A, Nikolic N, Orlovic S, Petrovic N, Krstic B (2005) Cadmium phytoextraction potential of poplar clones (Populus spp.). *Zeitschrift Fur Naturforschung C-a Journal of Biosciences* **60**, 247-251

Pimentel D, Patzek TW (2005) Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower. *Natural Resources Research* **14**, 65-76

Powers RF, Reynolds PE (1999) Ten-year responses of ponderosa pine plantations to repeated vegetation and nutrient control along an environmental gradient *Canadian Journal Forestry Research* **29**, 1027-1038

Pregitzer KS, DeForest JL, Burton AJ, Allen MF, Ruess RW, Hendrick RL (2002) Fine root architecture of nine North American trees. *Ecological Monographs* **72**, 293-309

Pregitzer KS, Friend AL (1996) The structure and function of *Populus* root systems. In: Stettler RF, Bradshaw HD, Heilman PE, Hinckley TM (Eds) *Biology of Populus*, NRC Research Press, National Research Council of Canada, Ottawa, ON, pp 331-354

Putnam, DH, Budin JT, Field LA, Breene WM (1993) *Camelina*: A promising low-input oilseed. In: Janick J, Simon JE (Eds) *New Crops*, Wiley, New York, pp 314-322

Rae AM, Robinson KM, Street NR (2004) Morphological and physiological traits influencing biomass production in short-rotation coppice poplar. *Canadian Journal of Forest Research* **34**, 1488-1498

Ragauskas AJ, Williams CK, Davison BH, Britovsek G, Cairney J, Eckert CA, Frederick WJJ, Hallet JP, Leak DJ, Liotta CL, Mielenz JR, Murphy R, Templer R (2006) The path forward for biofuels and biomaterials. *Science* **311**, 484-489

Raich JW, Nadelhoffer KJ (1989) Belowground allocation in forest ecosystems: Global trends. *Ecology* **70**, 1346-1354

Randall GW (2001) *COMMENTARY: Intensive corn-soybean agriculture is not sustainable*. Land Stewardship Project. Available online: http://www.landstewardshipproject.org/pr/newsr_010927.html

Ranney JW, Mann LK (1994) Environmental considerations in energy crop production. *Biomass and Bioenergy* **6**, 211-228

Ranney JW, Wright LL, Layton PA (1987a) Hardwood energy crops: the technology of intensive culture. *Journal of Forestry* **85**, 17-28

Ranney JW, Wright LL, Layton PA, McNabb WA, Wenzel CR, Curtin DT (1987b) Short rotation woody crops program: Annual progress report for 1986. *Oak Ridge National Laboratory, Oak Ridge, Tennessee, Technical Report ORNL* 6348, 59 pp

Reed TB, Lerner RM (1973) Methanol: A versatile fuel for immediate use: methanol can be made from gas, coal, or wood. It is stored and used in existing equipment. *Science* **182**, 1299-1304

Rehm, GW (1984) Yield and quality of a warm-season grass mixture treated with N, P, and atrazine. *Agronomy Journal* **76**, 731-734

Rehm, GW, Sorensen RC, Moline WJ (1976) Time and rate of fertilizer application for seeded warm-season and bluegrass pastures. I. Yield and botanical composition. *Agronomy Journal* **68**, 759-764

Reich PB, Grigal DF, Aber JD, Gower ST (1997) Nitrogen mineralization and productivity in 50 hardwood and conifer stands on diverse soils. *Ecology* **78**, 335-347

Reicosky DC, Evans SD, Cambardella CA, Allmaras RR, Wilts AR, Huggins DR (2002) Continuous corn with moldboard tillage: Residue and fertility effects on soil carbon. *Journal of Soil and Water Conservation* **57**, 277-284

Reicosky DC, Forcella F (1998) Cover crops and soil quality interactions in agroecosystems. *Journal of Soil and Water Conservation* **53**, 224-229

Robinson B, Green S, Mills T, Clothier B, van der Velde M, Laplane R, Fung L, Deurer M, Hurst S, Thayalakumaran T, van den Dijssel C (2003) Phytoremediation: using plants as biopumps to improve degraded environments. *Australian Journal of Soil Research* **41**, 599-611

Robinson CA, Cruse RM, Ghaffarzadeh M (1996) Cropping systems and nitrogen effects on Mollisol organic carbon. *Soil Science Society of America Journal* **60**, 264-269

Rockwood DL, Carter DR, Langholtz MH, Stricker JA (2006) *Eucalyptus* and *Populus* short rotation woody crops for phosphate mined lands in Florida USA. *Biomass and Bioenergy* **30**, 728-734

Rokityanskiy D, Benitez PC, Kraxner F, McCallum I, Obersteiner M, Rametsteiner E, Yamagata Y (2007) Geographically explicit global modeling of land-use change, carbon sequestration, and biomass supply. *Technological Forecasting and Social Change* **60**, 572-583

Rummer B (2002) Forest operations technology. In: Wear DN, Greis JG (Eds) *Southern Forest Resource Assessment. General Technical Report. SRS-53*, USDA-Forest Service, Southern Research Station, Asheville, NC, pp 341-353

Ruttan VW (1982) *Agricultural Research Policy*, University of Minnesota Press, Minneapolis, MN, 369 pp

Sage RB, Robertson PA (1996) Factors affecting songbird communities using new short rotation coppice habitats in spring. *Bird Study* **43**, 201-213

Salywon AM, Dierig DA, Rebman JP, Jasso-de-Rodriguez D (2005) Evaluation of new *Lesquerella* and *Physaria* (Brassicaceae) oilseed germplasm. *American Journal of Botany* **92**, 53-62

Sanderson MA, Read JC, Reed RL (1999a) Harvest management of switchgrass for biomass feedstock and forage production. *Agronomy Journal* **91**, 5-10

Sanderson MA, Reed R, McLaughlin S, Wullschleger S, Conger B, Parrish D, Wolf D, Taliaferro C, Hopkins A, Ocumpaugh W, Hussey M, Read J, Tischler C (1996) Switchgrass as a sustainable bioenergy crop. *Bioresource Technology* **56**, 83-93

Sanderson, MA, Reed R, Ocumpaugh WR, Hussey MA, van Esbroeck G, Read J, Tischler C, Hons FM (1999b) Switchgrass cultivars and germplasm for biomass feedstock production in Texas. *Bioresource Technology* **67**, 209-219

Schmer MR, Vogel KP, Mitchell RB, Moser LE, Eskridge KM, Perrin RK (2006) Establishment stand thresholds for switchgrass grown as a bioenergy crop. *Crop Science* **46**, 157-161

Schmidt MWI, Noack AG (2000) Black carbon in soils and sediments: analysis, distribution, implications, and current challenges. *Global Biogeochemical Cycles* **14**, 777-793

Schmidtling RC, Robison TL, McKeand SE, Rousseau RJ, Allen HL, Goldfarb B (2002) The role of genetics and tree improvement in southern forest productivity. In: Rauscher HM, Johnsen K (Eds) *Southern Forest Science: Past, Present, and Future. General Technical Report. SRS*-75. USDA-Forest Service, Southern Research Station, Asheville, NC, pp 97-108

Schreiner EJ (1945) How sod affects establishment of hybrid poplar plantations. *Journal of Forestry* **43**, 412-427

Schuler JL, Robison DJ, Quicke HE (2004) Assessing the use of chopper herbicide for establishing hardwood plantations on a cutover site. *Southern Journal of Applied Forestry* **28**, 163-170

Schultz RC, Colletti JP, Isenhart TM, Marquez CO, Simpkins WW, Ball CJ (2000) Riparian forest buffer practices. In: Garrett HE, Rietveld WJ, Fisher RF (Eds) *North American Agroforestry: An Integrated Science and Practice*, American Society of Agronomy, Inc, Madison, WI, pp 189-281

Sebastiani L, Scebba F, Tognetti R (2004) Heavy metal accumulation and growth responses in poplar clones Eridano (*Populus deltoides* × *maximowiczii*) and I-214 (*P.* × *euramericana*) exposed to industrial waste. *Environmental and Experimental Botany* **52**, 79-88

Seki M, Kamei A, Yamaguchi-Shinozaki K, Shinozaki K (2003) Molecular response to drought, salinity, and frost: common and different paths of plant protection. *Current Opinions in Biotechnology* **14**, 194-199

Sennerby-Forsse L, Ferm A, Kauppi A (1992) Coppicing ability and sustainability. In: Mitchell CP, Ford-Robertson JB, Hinckley T, Sennerby-Forsse L (Eds) *Ecophysiology of Short Rotation Forest Crops*, Elselvier, London, pp 146-173

Sheehan J, Aden A, Riley C, Paustian K, Killian K, Brenner J, Lightle D, Nelson R, Walsh M, Cushman J (2002) *Is ethanol from corn stover sustainable? Adventures in cyber-farming: A life cycle assessment of the production of ethanol from corn stover for use in a flexible fuel vehicle*, United States Department of Energy - National Renewable Energy Laboratory, Golden, CO, 330 pp

Shepherd A, Wingham D (2007) Recent sea-level contributions of the Antarctic and Greenland ice sheets. *Science* **315**, 1529-1532

Siemens JC, Oschwald WR (1976) Erosion for corn tillage systems. *Transactions of Society of Agricultural Engineers* **19**, 69-72

Siemens JC, Oschwald WR (1978) Corn-soybean tillage systems: erosion control, effects on crop production, costs. *Transactions of Society of Agricultural Engineers* **21**, 293-302

Sims REH, Maiava TG, Bullock BT (2001) Short rotation coppice tree species selection for woody biomass production in New Zealand. *Biomass and Bioenergy* **20**, 329-335

Sims RH, Hastings A, Schlamadinger B, Taylor G, Smith P (2006) Energy crops: Current status and future prospects. *Global Energy Biology* **12**, 2054-2076

Singer JW (2005) *Small grain cover crops for corn and soybean*. Iowa State University, University Extension. Available online: http://www.extension.iastate.edu/Publications/PM1999.pdf

Singh A, He B, Thompson J, van Gerpen J (2006) Process optimization of biofuel production using alkaline catalysts. *Applied Engineering in Agriculture* **22**, 597-600

Siry JP (2002) Intensive timber management practices. In: Wear DN, Greis JG (Eds) *Southern Forest Resource Assessment. General Technical Report SRS-53*. USDA-Forest Service, Southern Research Station, Asheville, NC, pp 327-340

Six J, Elliott ET, Paustian K, Doran JW (1998) Aggregation and soil organic matter accumulation in cultivated and native grassland soils. *Soil Science Society of America Journal* **62**, 1367-1377

Skjemstad JO, Reicosky DC, Wilts AR, McGowan JA (2002) Charcoal carbon in US agricultural soils. *Soil Science Society of America Journal* **66**, 1249-1255

Skolmen RG (1983) Growth and yield of some eucalyptus of interest to California. In: Standiford RB, Ledig FT (Eds) *Proceedings of a Workshop on Eucalyptus in California* June 14-16, 1983, Sacramento, California. *General Technical Report PSW-69*. Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Berkeley, CA, pp 49-57

Smeets EMW, Faaij APC, Lewandowski IM, Turkenburg WC (2007) A bottom-up assessment and review of global bio-energy potentials to 2050. *Progress in Energy and Combustion Science* **33**, 56-106

Snow VO, Smith CJ, Polglase PJ, Probert ME (1999) Nitrogen dynamics in a eucalypt plantation irrigated with sewage effluent or bore water. *Australian Journal of Soil Research* **37**, 527-544

Sombroek W, Nachtergaele FO, Hebel A (1993) Amounts, dynamics and sequestering of carbon in tropical and subtropical soils. *Ambio* **22**, 417-426

Standiford RB, Ledig FT (1983) Proceedings of a Workshop on *Eucalyptus* in California June 14-16, 1983, Sacramento, California. Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, Berkeley, CA, *Gen. Tech. Rep. PSW 69*, 128 pp

Stanton B, Eaton J, Johnson J, Rice D, Schuette B, Moser B (2002) Hybrid poplar in the Pacific Northwest - The effects of market-driven management. *Journal of Forestry* **100**, 28-33

Stanturf JA, Kellison RC, Broerman FS, Jones SB (2003) Productivity of Southern pine plantations: Where are we and how did we get here? *Journal of Forestry* **101**, 26-31

Stanturf JA, van Oosten C, Netzer DA, Coleman MD, Portwood CJ (2001) Ecology and silviculture of poplar plantations. In: Dickmann DI, Isebrands JG, Eckenwalder JE, Richardson J (Eds) *Poplar Culture in North America*, NRC Research Press, Ottawa, Ontario, Canada, pp 153-206

Steinbeck K, Nwoboshi LC (1980) Rootstock mass of coppiced *Platanus occidentalis* as affected by spacing and rotation length. *Forest Science* **26**, 545-547

Steinbeck K, McAlpine RG, May JT (1972) Short rotation culture of sycamore - status report. *Journal of Forestry* **70**, 210-213

Stettler RF, Bradshaw HD, Heilman PE, Hinckley TM (1996) Biology of *Populus* and its implications for management and conservation. NRC Research Press, Ottawa, Ontario, Canada, 539 pp

Stevenson FJ (1994) *Humic Chemistry: Genesis, Composition, Reactions*, John Wiley and Sons, New York, 496 pp

Stokes BJ, Hartsough BR (1993) Development and analysis of SRIC harvesting systems. In: *First Biomass Conference of the Americas: Energy, Environment, Agriculture, and Industry*, National Renewable Energy Laboratory, Golden CO, pp 302-308

Su J, Wu R (2004) Stress-inducible synthesis of proline in transgenic rice confers faster growth under stress conditions than that with constitutive synthesis. *Plant Science* **166**, 941-948

Tester M, Bacic AA (2005) Abiotic stress tolerance in grasses. From model plants to crop plants. *Plant Physiology* **137**, 791-793

Thomas CD, Cameron A, Green RE, Bakkenes M, Beaumont LJ, Collingham YC, Erasmus BFN, de Siqueira MF, Grainger A, Hannah L, Hughes L, Huntley B, van Jaarsveld AS, Midgley GF, Miles L, Ortega-Huerta MA, Peterson AT, Phillips OL, Williams SE (2004) Extinction risk from climate change. *Nature* **427**, 145-148

Tilman D, Hill J, Lehman C (2006) Carbon-negative biofuels from low-input high-diversity grassland biomass. *Science* **314**, 1598-1600

Tisdall JM (1996) Formation of soil aggregates and accumulation of soil organic matter. In: Carter MR, Stewart BA (Eds) *Structure and Organic Matter Storage in Agricultural Soils*, CRC/Lewis Publishers, Boca Raton, FL, pp 57-96

Tisdall JM, Nelson WL, Beaton JD (1986) *Soil Fertility and Fertilizers*, MacMillan Publishing Company, New York, pp 754

Tisdall JM, Oades JM (1982) Organic matter and water-stable aggregates in soils. *Journal of Soil Science* **33**, 141-163

Tokatlidis IS, Koutroubas SD (2004) A review of maize hybrids: Dependence on high plant populations and its implications for crop yield stability. *Field Crops Research* **88**, 103-114

Tolbert VR, Mays DA, Houston A, Tyler DD, Perry CH, Brooks KE, Thornton FC, Bock BB, Joslin JD, Trettin CC, Isebrands J (2000) Ensuring environmentally sustainable production of dedicated biomass feedstocks. *Bioenergy 2000*, 15-19 October 2000, Buffalo, New York. Available online: http://bioenergy.ornl.gov/papers/bioen00/tolbert.html

Tolbert VR, Todd DE, Mann LK, Jawdy CM, Mays DA, Malik R, Bandaranayake W, Houston A, Tyler D, Pettry DE (2002) Changes in soil quality and below-ground carbon storage with conversion of traditional agricultural crop lands to bioenergy crop production. *Environmental Pollution* **116**, S97-S106

Tollenaar M (1983) Potential vegetative productivity in Canada. *Canadian Journal of Plant Science* **63**, 1-10

Tollenaar M, Lee AF (2002) Yield potential, yield stability and stress tolerance in maize. *Field Crops Research* **75**, 161-169

Tufekcioglu A, Raich JW, Isenhart TM, Schultz RC (1998) Fine root dynamics, coarse root biomass, root distribution, and soil respiration in a multispecies riparian buffer in Central Iowa, USA. *Agroforestry Systems* **44**, 163-174

Tuskan GA, DiFazio S, Jansson S, Bohlmann J, Grigoriev I, Hellsten U, Putnam N, Ralph S, Rombauts S, Salamov A, Schein J, Sterck L, Aerts A, Bhalerao RR, Bhalerao R P, Blaudez D, Boerjan W, Brun A, Brunner A, Busov V, Campbell M, Carlson J, Chalot M, Chapman J, Chen GL, Cooper D, Coutinho PM, Couturier J, Covert S, Cronk Q, Cunningham R, Davis J, Degroeve S, Dejardin A, Depamphilis C, Detter J, Dirks B, Dubchak I, Duplessis S, Ehlting J, Ellis B, Gendler K, Goodstein D, Gribskov M, Grimwood J, Groover A, Gunter L, Hamberger B, Heinze B, Helariutta Y, Henrissat B, Holligan D, Holt R, Huang W, Islam-Faridi N, Jones S, Jones-Rhoades M, Jorgensen R, Joshi C, Kangasjarvi J, Karlsson J, Kelleher C, Kirkpatrick R, Kirst M, Kohler A, Kalluri U, Larimer F, Leebens-Mack J, Leple J C, Locascio P, Lou Y, Lucas S, Martin F, Montanini B, Napoli C, Nelson DR, Nelson C, Nieminen K, Nilsson O, Pereda V, Peter G, Philippe R, Pilate G, Poliakov A, Razumovskaya J, Richardson P, Rinaldi C, Ritland K, Rouze P, Ryaboy D, Schmutz J, Schrader J, Segerman B, Shin H, Siddiqui A, Sterky F, Terry A, Tsai CJ, Uberbacher E, Unneberg P, Vahala J, Wall K, Wessler S, Yang G, Yin T, Douglas C, Marra M, Sandberg G, de Peer YV, Rokhsar D (2006) The genome of black cottonwood, *Populus trichocarpa* (Torr. & Gray). *Science* **313**, 1596-1604

Tuskan GA (1998) Short-rotation woody crop supply systems in the United States: What do we know and what do we need to know? *Biomass and Bioenergy* **14**, 307-315

Twedt DJ, Portwood J (1997) Bottomland hardwood reforestation for Neotropical migratory birds: Are we missing the forest for the trees. *Wildlife Society Bulletin* **25**, 647-652

Twedt DJ, Wilson RR, Henne-Kerr JL, Grosshuesch DA (2002) Avian response to bottomland hardwood reforestation: The first 10 years. *Restoration Ecology* **10**, 645-655

United Nations (2005) *World Population Prospects: The 2005 Revision and World Urbanization Prospects: The 2005 Revision*. Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat. Available online: http://esa.un.org/unpp

USDOE (2006) *ABC of Biomass*. United States Department of Energy, Energy Efficiency and Renewable Energy. Available online: http://www1.eere.energy.gov/biomass/abcs_biofuels.html

USGS (2006) *Water Use in the United States*. United State Geological Survey. Available online: http://nationalatlas.gov/articles/water/a_wateruse.html

USDA-NASS (2006) *USDA-National Agricultural Statistics Services, Historical Data*. United States Department of Agriculture - National Agriculture Statistic Service, Research and Development Division. Available online: http://www.nass.usda.gov/Publications/Track_Records/index.asp

van Camp W (2005) Yield enhancement genes: Seeds for growth. *Current Opinion in Biotechnology* **16**, 147-153

van den Driessche R (1999) First-year growth response of four *populus trichocarpa × Populus deltoides* clones to fertilizer placement and level *Canadian Journal of Forest Research* **29**, 554-562

van Miegroet H, Norby RJ, Tschaplinski TJ (1994) Nitrogen fertilization strategies in short-rotation sycamore. *Forest Ecology and Management* **64**, 13-24

Vandecasteele B, Meers E, Vervaeke P, de Vos B, Quataert P, Tack FMG (2005) Growth and trace metal accumulation of two *Salix* clones on sediment-derived soils with increasing contamination levels. *Chemosphere* **58**, 995-1002

Vanotti MB, Bundy LG, Peterson AE (1997) Nitrogen fertilizer and legume-cereal rotation effects on soil productivity and organic matter dynamics in Wisconsin. In: Paul EA, Paustian K, Elliot ET Cole CV (Eds) *Soil Organic Matter in Temperate Agroecosystems*, CRC Press, Boca Raton, FL, pp 105-119

Vervaeke P, Luyssaert S, Mertens J, Meers E, Tack FMG, Lust N (2003) Phytoremediation prospects of willow stands on contaminated sediment: A field trial. *Environmental Pollution* **126**, 275-282

Villar M, Lefevre F, Bradshaw HD, du Cros ET (1996) Molecular genetics of rust resistance in poplars (*Melampsora larici-populina Kleb/Populus* sp) by bulked segregant analysis in a 2×2 factorial mating design. *Genetics* **143**, 531-536

Vitosh ML, Lucas RE, Silva GH (1997) Long-term effects of fertilizer and manure on corn yield, soil carbon, and other soil chemical properties in Michigan. In: Paul EA, Paustian K, Elliot ET, Cole CV (Eds) *Soil Organic Matter in Temperate Agroecosystems*, CRC Press, Boca Raton, FL, pp 129-139

Vogel KP (1996). Energy production from forages (or American agriculture – Back to the future). *Journal of Soil and Water Conservation* **51**, 137-139

Vogel KP (2004) Switchgrass. In: Moser LE, Sollenberger L, Burson B (Eds) *Warm-season (C_4) grasses*. ASA-CSSA-SSSA Monograph. Madison, WI, pp 561-588

Vogel KP, Brejda JJ, Walters DT, Buxton DR (2002) Switchgrass biomass production in the Midwest USA: Harvest and nitrogen management. *Agronomy Journal* **94**, 413-420

Vogel KP, Jung HG (2001) Genetic modification of herbaceous plants for feed and fuel. *Critical Reviews in Plant Sciences* **20**, 15-49

Vogel KP, Masters RA (2001) Frequency Grid - A simple tool for measuring grassland establishment. *Journal of Range Management* **54**, 653-655

Vogel KP, Mitchell RB, Klopfenstein TJ, Anderson BE (2006) Registration of 'Bonanza' big bluestems. *Crop Science* **46**, 2313-2314

Vogt K 1991 Carbon budgets of temperate forest ecosystems. *Tree Physiology* **9**, 69-86

Volk TA, Abrahamson LP, Nowak CA, Smart LB, Tharakan PJ, White EH (2006) The development of short-rotation willow in the northeastern United States for bioenergy and bioproducts, agroforestry and phytoremediation. *Biomass and Bioenergy* **30**, 715-727

Walter A, Dolzan P, Piacente E (2004) Biomass energy and bio-energy trade: Historic developments in Brazil and current opportunities. State University of Campinas, Campinas, Brazil, *Country Report: Brazil – Task 40 – Sustainable Bio-energy Trade*, 35 pp

Wang X, Newman LA, Gordon MP, Strand SE (1999) Biodegradation of carbon tetrachloride by poplar trees: Results from cell culture and field experiments. In: Leeson A, Allenman BC (Eds) *Phytoremediation and Innovative Strategies for Specialized Remedial Applications,* Battelle Press, Columbus, OH, pp 133-138

Whitesell CD, DeBell DS, Schubert TH, Strand RF, Crabb TB (1992) Short-rotation management of *Eucalyptus*: guidelines for plantations in Hawaii. USDA Forest Service, Pacific Southwest Research Station, Albany, CA, USA, *General Technical Report PSW-137*, 30 pp

Wildy DT, Pate JS (2002) Quantifying above- and below-ground growth responses of the western Australian oil mallee, *Eucalyptus kochii* subsp *plenissima*, to contrasting decapitation regimes. *Annals of Botany* **90**, 185-197

Wilhelm WW, Johnson JMF, Hatfield JL, Voorhees WB, Linden DR (2004) Crop and soil productivity response to corn residue removal: A literature review. *Agronomy Journal* **96**, 1-17

Willebrand E, Ledin S, Verwijst T (1993) Willow coppice systems in short rotation forestry: effects of plant spacing, rotation length and clonal composition on biomass production. *Biomass and Bioenergy* **4**, 323-331

Williams RD (1976) Hardwood nurseryman's guide. *USDA-Forest Service, Agricultural Handbook 473*; for sale Supt. of documents, U.S. Govt. Print. Office, Washington, 78 pp

Wilson GV, Dabney SM, McGregor KC, Barkoll BD (2004) Tillage and residue effects on runoff and erosion dynamics. *Transactions of the American Society of Agricultural Engineers* **47**, 119-128

Wilts AR, Reicosky DC, Allmaras RR, Clapp CE (2004) Long-term corn residue effects: Harvest alternatives, soil carbon turnover, and root-derived carbon. *Soil Science Society of America Journal* **68**, 1342-1351

Worldwatch Institute (2006) *Biofuels for Transportation: Selected Trends and Facts*. Worldwatch Institute. Available online: http://www.worldwatch.org/node/4081

Worrell E, Block K (1994) Energy savings in the nitrogen fertilizer industry in the Netherlands. *Energy* **19**, 195-209

Wu R, Bradshaw HD, Stettler RF (1997) Molecular genetics of growth and development in *Populus (Salicaceae*). 5. Mapping quantitative trait loci affecting leaf variation. *American Journal of Botany* **84**, 143-153

Wu SX, Lu YC, McMurtrey JE, Weesies G, Devine TE, Foster GR (2004) Soil conservation benefits of large biomass soybean (LBS) for increasing crop residue cover. *Journal of Sustainable Agriculture* **24**, 107-128

Wullschleger S, Yin TM, DiFazio SP, Tschaplinski TJ, Gunter LE, Davis MF, Tuskan GA (2005) Phenotypic variation in growth and biomass distribution for two advanced-generation pedigrees of hybrid poplar. *Canadian Journal of Forest Research* **35**, 1779-1789

Wullschleger SD, Difazio SP (2003) Emerging use of gene expression microarrays in plant physiology. *Comparative and Functional Genomics* **4**, 216-224

Yaman S (2004) Pyrolysis of biomass to produce fuels and chemical feedstocks. *Energy Conversion and Management* **45**, 651-671

Zaimes GN, Schultz RC, Isenhart TM (2004) Stream bank erosion adjacent to riparian forest buffers, row-crop fields, and continuously-grazed pastures along Bear Creek in central Iowa. *Journal of Soil and Water Conservation* **59**, 19-27

Zalesny RS, Wiese AH, Bauer EO, Riemenschneider DE (2006) Sapflow of hybrid poplar (*Populus nigra* L. × *P. maximowiczii* A. Henry 'NM6') during phytoremediation of landfill leachate. *Biomass and Bioenergy* **30**, 784-793

Zobel B, van Wyk G, Stahl P (1987) *Growing Exotic Forests*, Wiley, New York, 508 pp