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Interactions among bioenergy feedstock choices, landscape dynamics, and land use

Virginia H. Dale,[1] Keith L. Kline, Lynn L. Wright, Robert D. Perlack, Mark Downing, and Robin L. Graham

Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830 USA

Abstract. Landscape implications of bioenergy feedstock choices are significant and depend on land-use practices and their environmental impacts. Although land-use changes and carbon emissions associated with bioenergy feedstock production are dynamic and complicated, lignocellulosic feedstocks may offer opportunities that enhance sustainability when compared to other transportation fuel alternatives. For bioenergy sustainability, major drivers and concerns revolve around energy security, food production, land productivity, soil carbon and erosion, greenhouse gas emissions, biodiversity, air quality, and water quantity and quality. The many implications of bioenergy feedstock choices require several indicators at multiple scales to provide a more complete accounting of effects. Ultimately, the long-term sustainability of bioenergy feedstock resources (as well as food supplies) throughout the world depends on land-use practices and landscape dynamics. Land-management decisions often invoke trade-offs among potential environmental effects and social and economic factors as well as future opportunities for resource use. The hypothesis being addressed in this paper is that sustainability of bioenergy feedstock production can be achieved via appropriately designed crop residue and perennial lignocellulosic systems. We find that decision makers need scientific advancements and adequate data that both provide quantitative and qualitative measures of the effects of bioenergy feedstock choices at different spatial and temporal scales and allow fair comparisons among available options for renewable liquid fuels.

Key words: bioenergy feedstocks; biomass production; carbon sequestration; hypoxia; indicators; landscape design; land use; scale; sustainability; trade-offs.

Introduction

The proposed increase in bioenergy production and usage has interdependent environmental and socioeconomic impacts (Ragauskas et al. 2006). Many potential technological pathways can connect a wide variety of bioenergy feedstock sources to diverse forms of bioenergy (liquid fuels, chemicals, or power; International Energy Agency 2009). Moreover, local decisions, driven by regional or national policies to adopt alternative feedstock production methods, are strongly coupled with land-use practices, which are a key driver for environmental and socioeconomic changes at various spatial scales (Tolbert 1998). Currently, the complexity and scale dependency of such land-use decisions and their impacts are not defined, understood, or described with adequate clarity to enable policy makers to develop strategies to ensure a sustainable bioenergy future with acceptable environmental and socioeconomic consequences, particularly with current evidence of changing climate conditions (International Energy Agency 2009).

The production and consumption of bioenergy must be sustainable if it is to be successful. Many definitions of sustainability rely on the words of the Brundtland Report (1987) that sustainable development "meets the needs of the present without compromising the ability of future generations to meet their own needs." Lack of a precise definition has ignited intense debate and fostered the concept that it is ethically incorrect to treat the planet as a business in liquidation (Daly 1991). Nevertheless, there is evidence that humanity is not currently using energy resources in a sustainable manner (Wilbanks 2010). Sustainability is essentially a path toward conserving and managing scarce resources, including land, air, water, ecosystems, the biological and human environment, nonrenewable energy resources, species diversity, and other clearly defined providers of ecosystem services. Bioenergy sustainability is the capacity of biofuel development, production, distribution, and use to proceed while maintaining options for future generations. For bioenergy sustainability, major drivers and concerns revolve around energy security, food production, land productivity, soil carbon and erosion, greenhouse gas

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[1] E-mail: dalevh@ornl.gov

emissions, biodiversity, air quality, and water quantity and quality. Given the complexity of interactions of these factors, it is necessary to develop quantitative and qualitative measures to understand the effects of adopting particular options.

The expansion of bioenergy for greater energy independence and security is a key part of the legislation recently passed in the United States (Energy Independence and Security Act [EISA] of 2007; *available online*)[2] and the European Commission's binding renewable energy target in 2020 (Berndes and Hansson 2007). EISA is designed to reduce dependence on imported fossil fuels by fostering reduction of energy use and by increasing the production of renewable fuels that also reduce greenhouse gas emissions. EISA calls for the use of 137 billion liters of biofuels in the United States by 2022 with a mandate for cellulosic and advanced biofuels to provide at least 80 billion of those liters. Under EISA mandates, production of ethanol using corn starch in wet and dry mills is capped at 57 billion liters per year (from a 2010 production level of 50 billion liters; Renewable Fuels Association 2011). Further expansion could have detrimental environmental effects (Graham et al. 1998, Kort et al. 1998, McLaughlin and Walsh 1998, Mann and Tolbert 2000). Therefore, to meet the future demand for advanced biofuels in the United States, new crops and residue collection systems are needed that combine commercially efficient, economically viable, and environmentally sustainable conversion of lignocellulosic materials to ethanol or other transportation fuels (McLaughlin and Kszos 2005, Perlack et al. 2005).

There have been several analyses that assess the possibility of expanding bioenergy to meet growing energy needs. Bioenergy currently provides about 10% of the world's total primary energy supply (50 EJ of bioenergy out of a total of 479 EJ in 2005; i.e., 9.85%, according to International Energy Agency [2009]). Most bioenergy use is in the residential sector (for heating and cooking) and is produced locally. In 2005, bioenergy represented 78% of all global renewable energy produced (International Energy Agency 2007). Biomass is also used to generate gaseous and liquid fuels, and growth in demand for the latter has been significant over the last 10 years (Global Bioenergy Partnership 2007). Residues from farming, plantation forests, and food- and fiber-processing operations that are used in modern bioenergy conversion plants supply approximately 6 EJ/yr. Combustion of about 130 megatons (130 Tg) of municipal solid wastes contributes more than 1 EJ/yr, and landfill gas provides over 0.2 EJ/yr (Intergovernmental Panel on Climate Change 2007). The estimated annual bioenergy potential ranges from 50 to 1100 EJ for 2050, depending on human dietary choices, local soils conditions, and climate change (Hakala et al. 2009, International Energy Agency 2009). All of these estimates are debatable but are presented here as evidence that bioenergy can provide a substantial portion of human energy needs.

The energy-use scenarios implemented in the *Billion Ton Report* (Perlack et al. 2005) found that biofuel feedstocks were sufficient to replace about one-third of 2005 petroleum consumption in the United States by 2030. That estimate was based on the availability of approximately 1.2 billion dry metric tons of biomass feedstock per year from forest lands (335 million metric tons per year) and agricultural lands (908 million metric tons per year). The forest analysis considered equipment recovery limitations and excluded forest lands not accessible by roads and environmentally sensitive areas. The agricultural assumptions included a 50% increase in the 2030 yields of corn, wheat, and other grains; harvesting of 75% of annual selected crop residues; dedicating 22 million hectares of cropland and idle land to perennial energy crops; and using excess manure and other residues for energy. These estimates are currently being updated to provide cost estimates and to account for greater spatial resolution, more conservative assumptions for residue collection to maintain soil carbon, and other factors. The value of the *Billion Ton Report* and several subsequent analyses (Biomass Research and Development Initiative 2008, Lynd et al. 2009) is that they document the potential for bioenergy to provide substantial contributions to human energy needs from specific renewable resources while offering options to protect the environment. A key part of these assessments is consideration of the land used to grow energy crops.

While there is recognition that patterns of land cover and land use can have a variety of ecological effects, most current research on bioenergy crops analyzes feedstock production and logistics (harvesting, handling, storage, pretreatment, and transportation) from a supply chain perspective (e.g., U.S. Department of Energy 2009) in the absence of landscape considerations. More effort is needed to integrate research activities and quantitative analysis to take into account the juxtaposition issues, past and future land-use scenarios, and scale dependencies necessary to understand multiple environmental factors and subsequent trade-offs (Graham et al. 1996, U.S. Department of Energy and U.S. Department of Agriculture 2009). This paper begins to address that need by exploring the landscape implications of bioenergy feedstock choices (with a focus on lignocellulosic materials for transportation fuels) because it is critical to develop an approach that will help policy makers understand environmental and socioeconomic consequences of alternative bioenergy feedstock regimes and policies.

Landscape implications of bioenergy feedstock choices are significant

Ultimately, the long-term sustainability of bioenergy production (as well as food supplies) throughout the

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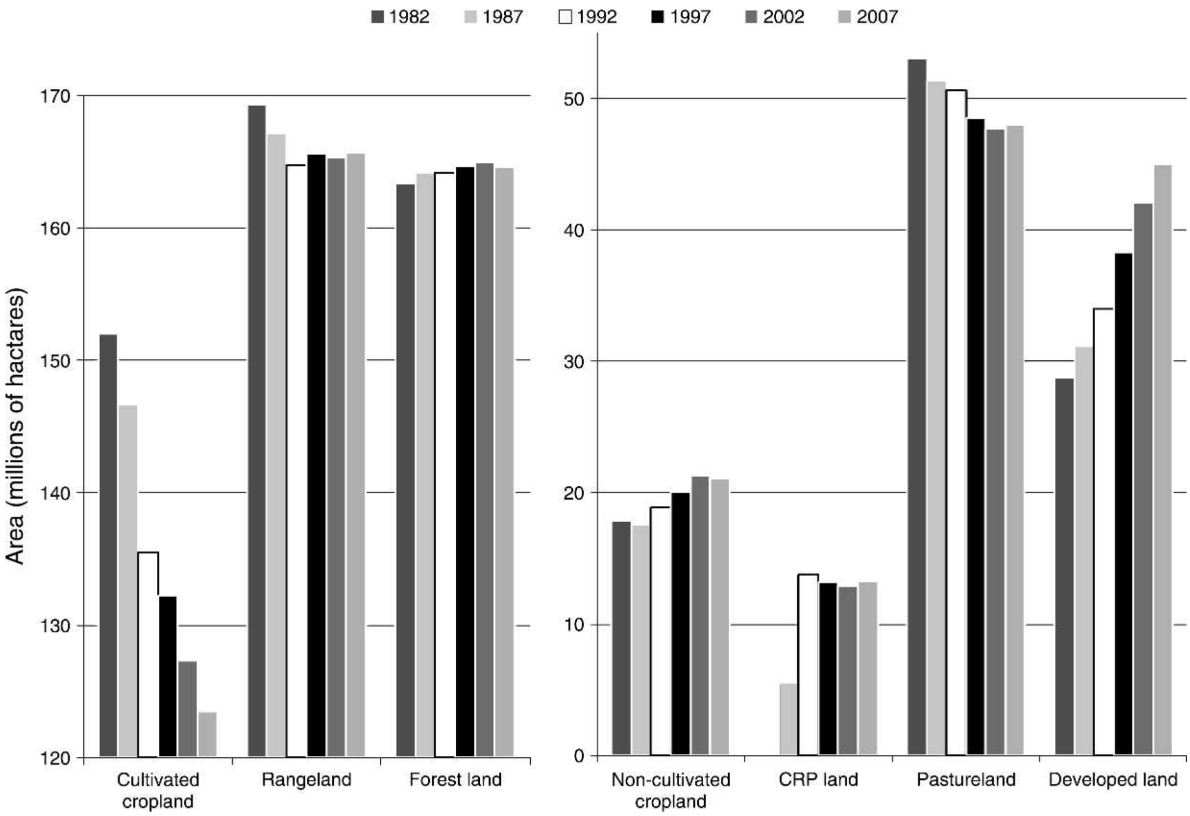

FIG. 1. Land area in the United States in 2007 and earlier based on statistical surveys of natural resource conditions and trends on non-federal land (including privately owned lands, tribal and trust lands, and lands controlled by state and local governments) (from U.S. Department of Agriculture 2009). Cultivated cropland includes land in row crops or close-grown crops and other cultivated cropland (e.g., hay land or pastureland that is in a rotation with row or close-grown crops). Noncultivated cropland includes permanent hay land and horticultural cropland. There has been little change (from 19 to 20 million ha) in other rural land, such as farmsteads and other farm structures, field windbreaks, barren land, and marshland (and so these data are not displayed).

world depends on land-use practices and landscape dynamics. Land-use decisions about what bioenergy crops are grown, where they are grown, and how they are managed determine the effects on carbon sequestration, native plant diversity, food production, greenhouse gas emissions, water and air quality, and other attributes. More importantly, these decisions also affect economic viability. Yet where crops are grown and how they are grown are always in flux (Fig. 1). U.S. cultivated cropland (excluding fallow, land in the Conservation Reserve Program [CRP], cropland pasture, etc.) peaked at 157 million ha in 1949, reached a 57-year low of 132 million ha in 1988 but has continued to decline since then (Lubowski et al. 2006; Fig. 1). Over this same period, rangeland and forest land areas have not changed significantly, while the area of CRP and developed land has increased. There are many forces besides biofuel that have been responsible for these changes.

In the context of bioenergy sustainability, landscape dynamics refers to changes in land use and management for bioenergy feedstocks that enhance ecosystem services over time and space. Such changes in land use can affect on-site and downstream environmental conditions, such as water and air quality (e.g., Chen and Driscoll 2009). They may also affect the juxtaposition of land-cover types and species composition that, in turn, influence pollinator activities, pest populations, the distribution of habitats across the landscape, and the potential for migration and dispersal (e.g., Farwig et al. 2009, Gardiner et al. 2010). On the other hand, both on-site, upstream and downstream conditions, and land-cover patterns influence human decisions about how to use and manage environmental resources such as land and water. Hence, land-use activities are part of a dynamic and interactive system in which environmental conditions affect human choices and vice versa. Furthermore, land-management decisions often invoke trade-offs among potential environmental, social, and economic effects as well as future opportunities for resource use.

The components considered in a landscape approach as proposed here include (1) current and past environmental and socioeconomic conditions and future scenarios; (2) bioenergy feedstock features, including sources, plant species, and management practices (e.g., cultivation, fertilizer, and pesticide applications); (3) interactions with neighboring land uses; and (4) ecological and biogeochemical feedbacks within a landscape. At a regional scale, water availability and quality emerge as key factors, and yet the linkage between water and bioenergy feedstock choices on medium and large scales is poorly quantified and still debated (Dale et al. 2010, Huffaker 2010, National Research Council 2010). An approach that considers both environmental and socioeconomic changes in landscape dynamics provides a way to quantify the influence of alternative bioenergy feedstock choices on water quality and other components of the environment over time.

Many crops can be used for bioenergy feedstocks. While much of current attention in the United States is on the use of corn grain or soybeans, this analysis focuses on lignocellulosic feedstock options because they have numerous environmental benefits (Robertson et al. 2008) and an energy replacement ratio (the energy delivered per unit of fossil energy used in production) several times higher than that of corn grain ethanol (over 10 for cellulosic and about 1.4 for current corn ethanol). The equivalent value of energy delivered by gasoline is approximately 0.8 (U.S. Department of Energy 2006). Lignocellulosic feedstocks refer to the cellulose, hemicellulose, and lignin components of plant material and include municipal wastes and agricultural residues such as corn stover, wheat straw or sugarcane bagasse, dedicated energy crops such as fast-growing perennial grasses or trees, wood residues from logging operations, and fuel-treatment thinnings from forest lands. The hypothesis being addressed in this paper is that sustainability of bioenergy feedstock production can be achieved via appropriately designed lignocellulosic systems. Both crop residues and perennial lignocellulosic plants are considered in this analysis.

Sustainably collected amounts of crop residue, such as corn stover, depend on the crop yield, slopes, tillage practices, initial soil organic carbon (SOC) and other nutrient levels, soil types, temperature, and climate conditions. Sustainable collection defined in terms of erosion control has been calculated as the amount of crop residue needed to keep soil loss below the tolerable limit T (Fig. 2; Graham et al. 2007). Sparling et al. (2006) reported that both crop yields and the value of environmental services are greater for soils with greater SOC. A survey of the literature on factors affecting SOC allowed Johnson et al. (2006) to estimate the sustainable range of crop residue needed to prevent loss of SOC in the United States depending on crop production and tillage practices. Wilhelm et al. (2007) compared the studies by Johnson et al. (2006) and Graham et al. (2007) and concluded that more stover is required to maintain SOC than is required to control erosion (except under very high winds; Fig. 3). Nitrogen and other soil nutrients are also important when considering sustainable production and climate-change implications. However, a long-term study in New York demonstrated that corn stover harvest has no adverse effects on soil quality on a silt loam soil in a temperate climate when practiced under no-till management (Moebius-Clune et al. 2008). The crop residue level required to maintain sustainable levels of SOC and nutrients can vary by location. The update to the *Billion Ton Report* that DOE expects to release in 2011 will explicitly account for SOC in the assessment of stover and straw availability over the United States.

Dedicated bioenergy crops have greater potential than crop residues alone for providing a large and sustainable bioenergy feedstock resource in the United States (Perlack et al. 2005, U.S. Department of Agriculture/National Resource Conservation Service 2006, Simpson et al. 2008). Perennial grasses, such as switchgrass (*Panicum virgatum*), and fast-growing trees, such as poplar and cottonwood species (*Populus* sp.), have considerable potential for being environmentally beneficial across most regions of the United States (Wright 1994, Tuskan 1998, McLaughlin and Kszos 2005). The environmental, economic, and climatic conditions in some regions may favor specific crops, such as eucalyptus and tropical grasses (e.g., energy cane) in the southern United States; coppicing willow systems in the northeast and Lake States; and rotations involving energy sorghum, sudangrass, or agave in drier western and southwestern regions. Bioenergy feedstock crop options for most rain-watered crop production regions of the United States (Fig. 4) were first identified in the 1980s and have been updated periodically. One hundred seventy-nine potential feedstocks were evaluated in species-comparison trials located throughout the United States (154 woody crop species and 25 herbaceous species). Several species were selected for further development in bioenergy cropping systems based on a range of characteristics, such as yield potential, adaptability to marginal agricultural soils, genetic improvement potential, and other features (Ferrell et al. 1995). Sorghum, the only annual crop included among these, emerged as a potential dedicated bioenergy crop due to high yield potential, drought tolerance, and adaptability to traditional cropping systems. However, the environmental effects of any proposed feedstock crop will depend on how it is managed, and annuals have the disadvantage of needing to be replanted each year.

The majority of dedicated bioenergy crop options are perennial crops, which inherently offer environmental advantages compared to conventional annual cropping systems. The environmental effects of perennial crops depend on land-management practices (McLaughlin and Walsh 1998, Tolbert 1998, Tolbert and Wright 1998, Tolbert et al. 2000*a*, *b*). Greatest benefits are achieved where minimum tillage and cover-crop management associated with perennial bioenergy crops replace the more intensive tillage and management required for most annual crops. (Of course, land choices should be based on appropriate uses for specific sites and consider

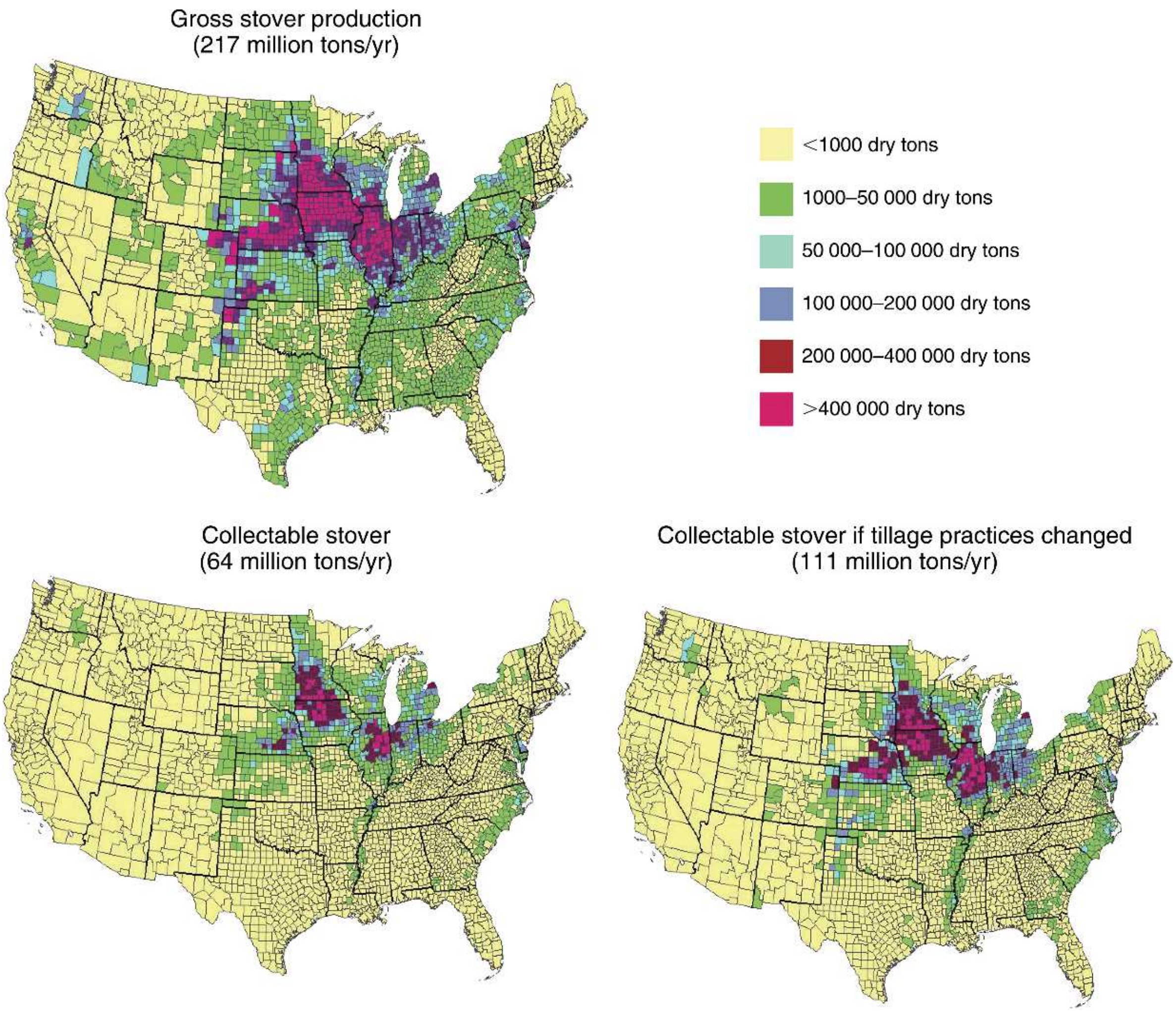

FIG. 2. Map of variability in corn stover production with average corn acreage and harvested grain yields between 1995 and 2000 and with the collectable stover based on erosion constraints (updated from Graham et al. [2007]). Units are metric tons (Mg).

trade-offs in diverse needs such as food, fuel, fiber, and habitat as is discussed in later sections of this paper.) Furthermore, environmental improvements from perennial bioenergy crops can be achieved where the nutrient and chemical requirements are less than those for annual crops; native and non-invasive species are planted; and harvesting considers timing of bird nesting and other temporal values (e.g., seasonal water regulation, scenic values, migrations and other wildlife requirements [Tolbert 1998, Tolbert and Wright 1998, Tolbert et al. 2000*a*, *b*]). Perennial crops can provide additional regional-level benefits when they are used as buffers between annual crops and waterways (McLaughlin and Walsh 1998).

Soil carbon and soil tilth have been demonstrated to be improved with perennial crops under several management conditions (Mann and Tolbert 2000, Tolbert et al. 2002). Both conversion from various tillage practices to no-till and from traditional annual crops to perennial energy crops resulted in significant soil improvements. The reduction in disturbance of the soil due to no-till reduces wind and water erosion and allows soil aggregation and fungal-dominated organic-matter-cycling processes to re-establish (Post et al. 2004). Additional soil improvements resulting from perennial crops include increased soil porosity and infiltration, reduced compaction, and reduced risk of soil erosion (Hohenstein and Wright 1994, Ma et al. 2000). The greatest increases in soil carbon occur on poorer-quality sites. Conversions from annual to perennial crops resulted in soil carbon increases primarily in the upper 10 cm, although soil carbon below 60 cm increased when switchgrass plantings had root penetration greater than 120 cm (Garten and Wullschleger 2000, Tolbert et al. 2002).

The viability of perennial crops as bioenergy feedstocks depends on economic as well as environmental factors, for economics affects the nature and extent of landscape modifications. Production of dedicated bioenergy crops will be economically competitive if the net

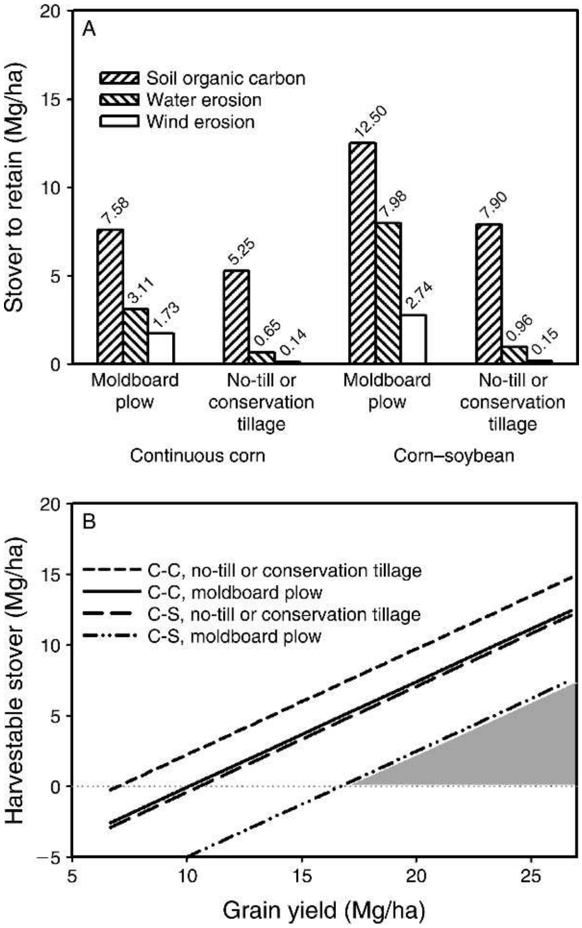

FIG. 3. (A) Estimated amount of corn stover needed to maintain soil organic carbon content (based on Johnson et al. [2006]) using the revised universal soil loss equation, version 2 (RUSLE2; U.S. Department of Agriculture, Agricultural Research Service 2003*a*), to limit water erosion within the accepted tolerance, and to limit wind erosion (as estimated by the wind erosion prediction system (WEPS; U.S. Department of Agriculture, Agricultural Research Service 2003*b*) with various production practices. (B) Estimated amount of harvestable corn stover with various production practices and grain yield levels as limited by the need to maintain soil organic carbon. For example, stover in the shaded area would be harvestable under moldboard plow tillage in a corn–soybean (C-S) rotation (dot-dot-dashed line). Key: long dashed line, harvestable stover under no-till or conservation tillage with a corn–soybean rotation; solid line, harvestable stover under moldboard plow with continuous corn (C-C); short dashed line, harvestable stover under no-till or conservation tillage with continuous corn. The figure is reproduced with permission from Wilhelm et al. (2007).

returns from bioenergy crop production are at least as great as those from other alternatives. The Policy Analysis System (POLYSYS) economic simulation modeling system of the United States agriculture sector has been used to assess the potential economic and land-use change impacts of perennial energy crop production on United States agriculture (e.g., Ugarte and Ray 2000, McLaughlin et al. 2006). Results from these studies suggest that, other things being equal, farm-gate prices of about US$44/dry metric ton would be sufficient for perennial energy crops to compete with the major conventional crops in many areas of the United States (McLaughlin et al. 2002, De La Torre Ugarte et al. 2003, Greene et al. 2004, Biomass Research and Development Initiative 2008). However, higher prices for corn, wheat, and soybeans in recent years, combined with federal programs that insure and support traditional grain production, relegate dedicated energy crops at US$44/dry metric ton to more marginal (i.e., lower-yielding) soils or areas where traditional crops have lost economic appeal. Perennial energy crops may be the most competitive on land currently used as pasture (Biomass Research and Development Initiative 2008). At farm-gate prices of about US$44/dry metric ton, net returns to energy crops are generally higher than the reported regional rental rates for cropland used as pasture. Shifting cropland pasture to perennial energy crops is likely to result in some cropland pasture shifting into hay production or a portion of private rangeland pasture (164 million ha in the United States) shifting to cropland pasture to make up for the lost forage (Biomass Research and Development Initiative 2008, Sanderson and Adler 2008).

Perennial crops offer benefits for farmers when they are grown in a way that improves natural resources and provides synergy with traditional annual crop production. The relationship between benefits provided by traditional crops and those provided by new energy crops means that the location and management of crops needs to be carefully planned. While most perennial crops (like annual crops) will attain their greatest yield under optimum growing conditions, switchgrass was specifically selected as a model crop for bioenergy production because of the capability of some varieties to produce reasonably high and consistent yields on marginal upland (Wright and Turhollow 2010) and because its perennial characteristics would allow production with minimal erosion on highly erodible land (Paine et al. 1996). Thus switchgrass can be grown on land that is not suitable for most food crops and, when managed properly, can enhance environmental conditions. For example, after the initial establishment year, perennial crops grown at relatively tight spacing will minimize erosion on land categorized as highly erodible (Tolbert et al. 2002). Although most varieties of fast-growing energy trees will perform best on well-aerated soils, there appear to be a few varieties that can tolerate saturated soils or flooding for short periods of the year and thus may be good candidates for lowland marginal areas (Gong et al. 2007). Therefore, profitable and sustainable production could be achieved on lower-value cropland with currently identified plant materials and crop-management technologies.

While U.S. renewable energy policies (Energy Independence and Security Act of 2007, see footnote 2) are stimulating the development of biofuels and bioenergy facilities, it will take time to develop appropriate

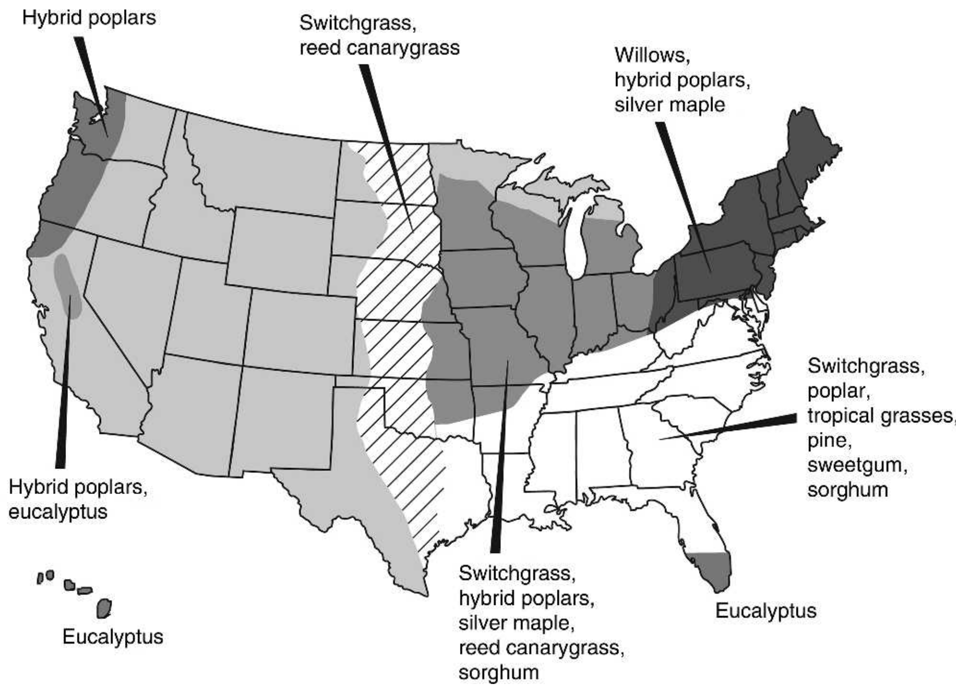

FIG. 4. Map of recommended biofuel feedstock plantings in the United States (updated from Wright [1994]).

cellulosic feedstocks and production systems that meet environmental criteria for advanced biofuels. More research is needed to find a greater number of plant varieties, associated planting schemes, and rotation systems that are suited to local conditions and can improve the productivity of marginal croplands, pastures, and complementary traditional crops. Also, even if excellent varieties for bioenergy crops were available now, it could require nearly a decade to get the market-demand, nursery, and seed production infrastructure in place to support planting large areas with bioenergy crops. This infrastructure development requirement will allow time to develop better guidelines and indicators for assuring sustainable production of these crops.

Socioeconomic effects of bioenergy feedstocks affect sustainability

Societal effects of bioenergy feedstock choices include effects on energy and food security, fiber, employment, farm income, rural life style, mitigation and adaptation to climate change, scenery, infrastructure, recreation, and other tastes and preferences. Each of these effects may differ in direction, intensity, and extent depending on the site-specific conditions and the context in which the bioenergy crop is grown (past land use and soil erosion, existence of a market for the energy crops, etc.). A key reason for investing in lignocellulosic bioenergy production systems is reflected by the inclusion of "independence" and "security" in the titles of the two U.S. federal laws passed to promote renewable fuels in 2005 and 2007. U.S. policy goals include reducing dependency on imported oil and providing a renewable option to ease a transition away from fossil fuels as they become increasingly scarce.

Although food security became a concern when food prices spiked in 2008, biofuels were not a strong influence on those food price increases. The higher food prices coincided with increasing use of U.S. corn for ethanol, and the media were quick to blame biofuels for the high costs of food. The relationships among higher petroleum prices (which drive up prices for food and other commodities) and biofuel production (which help moderate the effects of higher imported oil costs), combined with other feedbacks and interactions among corn grain uses and co-products in feed, food, and fuel, make cause-and-effect calculations difficult and complex. Studies suggest that the higher global energy prices themselves combined with growing world demand, an extended period of low prices that led to falling stocks, bad weather, and speculation all played significant roles in food price increases (Abbott et al. 2009, Gilbert 2010). The U.S. Department of Agriculture estimated that biofuels could have directly caused food prices to rise by 0.1–0.2% in 2007, and up to 0.9% after estimating indirect effects via the cost of animal feed affects on meat. Others estimated biofuel production contributed about 5% of the increase in global food prices between April 2007 and April 2008 (Kline et al. 2009), and the Congressional Budget Office calculated that U.S. ethanol contributed to an increase in the price of a bushel of corn of 50 to 80 cents, directly increasing U.S. expenditures on food by about 0.1% and that increases were passed on to consumers of meat, another 0.2–0.4% (Congressional Budget Office 2009). Also complicating the issue is that biofuel markets provide incentives to invest in improved technologies and more-efficient production, which reduce long-term prices for consumers in competitive markets and increase yields. Furthermore, globally traded agricultural commodities are subject to price volatility caused by fluctuations in weather and policies. By expanding into diverse markets (e.g., food, fuel, feed, and fiber), overall production increases and outputs can shift among sectors in response to markets. For example, expanded corn and sugarcane productivity offers more flexibility to adjust to temporary shocks and thereby to provide more stable prices for producers and consumers alike. In the United States, most corn is used for animal feed. About one-third of the feed protein value of corn used for ethanol production remains available in ethanol co-products, including distillers' dried grains (DDG), corn gluten feed, corn gluten meal, and corn oil (U.S. Department of Agriculture, Economic Research Service 2009).

One of the major social opportunities for bioenergy production is in increasing employment, farm incomes, and value-added industries by replacing an imported fossil fuel with new domestic markets for crops and processing (e.g., Porter et al. 2009). As energy crop production expands, there will be opportunities to collect the empirical evidence needed to document the social costs and benefits of bioenergy crops as compared with other energy options. The accompanying co-product production streams coming from these integrated biorefineries are inputs to other biochemicals and energy systems and, thereby, provide farm and other income-producing labor. Furthermore, by offering employment and income opportunities in developing countries, bioenergy feedstocks can help establish economic stability and thus reduce the recurring use of fire on previously cleared land as well as pressures to clear more land (Nepstad et al. 2001, Mather 2007, Tschakert et al. 2007, Kline et al. 2009).

Biofuels may also be a more cost-effective approach to solving a broad set of related development problems. United Nations Environment Program (2009) notes that, for the same dollar invested to address climate change, additional economic and environmental benefits could be delivered from improved water quality, soil stabilization, and new "green jobs" related to natural-resource management. And the International Energy Agency (2009) has estimated that "Bioenergy could sustainably contribute between a quarter and a third of global primary energy supply in 2050 … providing opportunities for social and economic development in rural communities, and improving the management of resources and wastes."

Multiple implications of biofuel choices require ecological indicators at appropriate scales

Indicators are needed to assess the sustainability of bioenergy systems. Although agronomists rely on a variety of field measures of soil quality and production to assess agricultural practices, ecological measures need to be at the field, watershed, regional, and global scales in order to capture potential effects on land productivity, soil carbon and erosion, greenhouse gas emissions, biodiversity, air quality, and water quantity and quality, which also vary across spatial and temporal scales.

The larger regional implications of local bioenergy feedstock choices are illustrated by their potential effects on hypoxia in the Northern Gulf of Mexico (Donner and Kucharik 2008, Dale et al. 2010). Hypoxia is the condition under which dissolved oxygen concentrations in shallow coastal and estuarine systems decrease below the level required to support many estuarine and marine organisms (generally less than 2 mg/L). Hypoxic conditions result from complex interactions among climate, weather, basin morphology, circulation patterns, water retention times, freshwater inflows, stratification, mixing, and nutrient loadings. Excessive nutrients promote algae blooms that deplete dissolved oxygen, and marine organisms either die or flee the hypoxic zone.

Hypoxia provides an example of the importance of spatial scale when measuring effects of bioenergy feedstock options. Choices of feedstock are typically made at the field scale. Environmental effects may occur at the field (often measured at the "edge of field"), at the hydrological response unit, at the level of small watersheds, and at the scale of the entire river basins. This variation in scale effects illustrates the need to have indicators of diverse ecosystem services at the corresponding scales. Metrics for evaluating the effects of bioenergy feedstock crop choices as well as effects of other land-use practices are needed at all relevant scales, both temporally and spatially. Even so, strategically placed U.S. Geological Survey water-quality sample stations in the Mississippi River basin have been discontinued.

Hypoxia occurs naturally in many waterways, but the size of the Gulf of Mexico's hypoxic zone has grown considerable over the past 50 years in association with land-use changes (Committee on Environment and Natural Resources Research 2000, Osterman et al. 2005). Increases in the size of the hypoxic zone are associated with the growth of nitrogen fertilizer use in the upper Midwest over several decades (Goolsby et al. 1999). Opportunities exist for N and P reduction via lignocellulosic bioenergy feedstocks that require little fertilizer and can absorb runoffs with their deep perennial root systems (Simpson et al. 2008, Almaraz et al. 2009). Conversion to alternative cropping systems using perennials or alternative rotation systems as well as environmentally sustainable approaches to bioenergy feedstock crop production (e.g., no-till farming, reduced use of fertilizer, and riparian buffers) can reduce both nutrient input and the movement of nutrients and sediments to waterways (Costello et al. 2009, Dale et al. 2010).

Water quality studies provide supporting evidence that conversion of marginal cropland to perennial lignocellulosic energy crops can reduce amounts of fertilizer use and chemical runoff, which can aid in reducing the size of the hypoxia zone in the Gulf of Mexico. For example, an evaluation of subsurface movements of chemicals in side-by-side plantings of hybrid poplar, switchgrass, and wheat from established plots in Minnesota found no detectable movement of herbicides from poplars or switchgrass plantings during the study (Perry et al. 1998). Nitrogen exports from hybrid poplar and switchgrass were higher or similar to wheat in the first year of establishment (68.5, 26.1, and 21.3 $kg \cdot ha^{-1} \cdot yr^{-1}$, respectively); but, by the second year, exports under poplar were zero; and switchgrass and wheat had similar levels of export (2.5 and 2.6 $kg \cdot ha^{-1} \cdot yr^{-1}$, respectively). Phosphorus exports from poplar and switchgrass stands were 0.02 and 0.033 $kg \cdot ha^{-1} \cdot yr^{-1}$ in the first year and negligible in the second year. There was no movement of nutrients below the rooting zone of either crop (Perry et al. 1998, Shanks 2002). A second study simultaneously compared sediment loss and nutrient transport with various bioenergy feedstock crops in small watersheds in Alabama, Tennessee, and Mississippi over five years (Joslin and Schoenholtz 1997, Tolbert et al. 2002). The comparisons were between cottonwood and conventionally tilled cotton in Mississippi; between sweetgum (with and without cover crops), switchgrass, and no-till corn in Alabama; and between sycamore and corn in Tennessee. Since each site had unique soil rainfall conditions and management conditions, the specific amounts of sediment and nutrient losses are not easily comparable (Thornton et al. 1997, Tolbert et al. 2000*a*, Nyakatawa et al. 2006). However, in all years in Mississippi, and all but establishment years in Tennessee and Alabama, sediment runoff and nutrient transport were reduced under tree crops and switchgrass relative to the agricultural crops. For tree crops, the reductions were greatest with cottonwood, then sycamore, and finally sweetgum—largely related to the rate of growth and site-occupation rates of the tree species. Tillage treatments of the agricultural crop used in the comparisons also affected the results (Tolbert et al. 2000*b*). Over the five years of comparison in Alabama, nitrate runoff under sweetgum was either similar to (in one year) up to nearly four times less than nitrate runoff under no-till corn (Nyakatawa et al. 2006). While more studies are needed in more locations, these similar results from the North Central and Southeastern regions of the United States provide reason to believe that deployment of perennial bioenergy crops over large areas of the landscape would aid in reducing the level of hypoxia in the Gulf of Mexico. These studies illustrate the types of research that need to be implemented and the indicators that should be measured in order to document how local farm activities can affect regional environmental conditions that are a part of sustainable bioenergy production.

Land-use change and associated carbon emissions are complicated

Bioenergy sustainability requires understanding how bioenergy use can affect a variety of indicators, but special attention has been given to carbon emissions. Yet the greenhouse gas emissions associated with biofuels and land-use change are fraught with uncertainty and disagreement (General Accounting Office 2009, Le Quéré et al. 2010). The data for fossil fuels (and cement), on the other hand, are clearer. There is agreement in the research community that fossil fuels are responsible for the vast majority of global CO_2 emissions (80–92%) and that their share is increasing as the world's economies become more fossil-energy intensive (Canadell et al. 2007, van de Werf et al. 2009, Le Quéré et al. 2010). Fossil-fuel predominance in global greenhouse gas emissions is further increased relative to land use as the world's forest cover reaches equilibrium or shows slight net increases in area because of regrowth and reforestation's surpassing areas deforested (FAO 2006, 2007, Kauppi et al. 2006, Grainger 2008, 2009).

Land can help address climate change in two basic ways: by producing bioenergy to substitute for fossil fuels and by serving as a sink to capture and store atmospheric carbon in soils and aboveground biomass. These two pathways are not mutually exclusive (International Energy Agency 2009). In the first, greenhouse gas emissions from burning fossil fuels are replaced with a bioenergy source that offsets the carbon released to the atmosphere from combustion with the carbon captured from the atmosphere when the feedstock grew. Bioenergy is not only renewable in this sense, but it can facilitate expansion of the sink pathway by creating incentives to manage and protect forests and other growing stocks. Bioenergy feedstock production can also add carbon to depleted soils and improve the soil's capacity for future carbon uptake. The Executive Director of the United Nations Environment Program noted in 2009 that, "Earth's living systems might be capable of sequestering more than 50 gigatones of carbon over the coming decades with the right market signals." Thus, bioenergy can make important contributions to terrestrial capacity to serve as a carbon sink. These benefits will be enhanced when sustainable feedstocks are placed on degraded lands or on landscapes that would burn periodically or be mismanaged in the absence of market signals supporting biofuel production. A key bioenergy sustainability concern is thus sufficient availability of land. Several studies estimate that abandoned land covers 400–500 million hectares globally (e.g., Campbell et al. 2008); and if these lands were used for biofuel production, they could significantly increase carbon sequestration and help avoid and offset the air pollution and greenhouse gas emissions generated when hundreds of millions of hectares burn each year (UNESCO-SCOPE 2009).

Despite the potential benefits of sustainable bioenergy plantings and availability of marginal land, claims have been made that land use associated with biofuels induces "indirect land-use change" with such enormous consequences that biofuels would be "worse than petroleum" (Searchinger et al. 2008). The assertions about indirect land-use change depend on assumptions and simple economic models that do not consider the key factors of yield change in reducing new land conversion, corn ethanol by-products, the availability of cropland within the United States to grow corn for ethanol, and the role of crop management (Gnansounou et al. 2009, Keeney and Hertel 2009, Kim et al. 2009). Numerous empirical studies show that land-use change is not a result of a single crop market but rather is driven by interactions among cultural, technological, biophysical, political, economic, and demographic forces within a defined spatial and temporal context (Contreras-Hermosilla 2000, Dale et al. 2000, Lambin et al. 2001, 2003, United Nations Environment Program 2001, de Sherbinin 2002, Geist and Lambin 2002, Kauppi et al. 2006, Chomitz et al. 2007, Scouvart et al. 2007). Land-use changes and associated carbon emissions are much more complex than portrayed in the models used to infer indirect land-use effects (Kline and Dale 2008, Kim et al. 2009).

Those simple economic models also depend on the premise that policies promoting the exploration, drilling, production, and transport of fossil fuels does not have any indirect land-use effects while biofuel policies do. Throughout the world, land-use change in remote forest ecosystems is aided and accelerated by the exploration for fossil fuels (Finer et al. 2008, 2009, Laurance et al. 2009, Suarez 2009, Finer and Orta-Martinez 2010).

Furthermore, net emissions associated with land-use effects of bioenergy may be far lower than postulations based on assumed forest carbon values and land classification after deforestation had already occurred (Morton et al. 2006, Sousa 2006), which by definition omit carbon losses, removal, and incremental degradation that typically occur long before conversion. The estimated indirect impacts also depend on low yield assumptions that neglect increases in crop yields realized in the United States as biofuel markets developed (U.S. Department of Agriculture Economic Research Service 2009), the potential to increase yields substantially elsewhere if markets provide incentives, and the actual yields documented in expanding agricultural landscapes that supply global markets such as Brazil. Nor do these models consider the availability of large areas of underutilized land (FAO and IIASA 2007) or what happens to that land (e.g., extensive and repeated fires and degradation) in the absence of incentives to manage it for biomass production. Analyses of rural land suitable for rain-irrigated agriculture show that between 20 and 40 million km^2 could be put into production after excluding closed forests, nature reserves, urban, and currently cultivated areas (Bruinsma 2002, FAO and IIASA 2007). This non-forest area vastly eclipses (by a factor of roughly 300) the 108 000 km^2 of new cultivation that Searchinger et al. (2008) projected to offset U.S. biofuel production.

In addition, the influence of soils on emissions was not adequately considered by Searchinger et al. (2008), for they assume that conversion to lignocellulosic bioenergy crops emits 25% of the carbon in soils [citing the meta analysis by Guo and Gifford (2002) yet not considering the increases in soil carbon with conversion as reported in the same study]. Furthermore, using marginal land for cellulosic production is not considered in the analysis by Guo and Gifford (2002) but has been identified repeatedly as a top priority (e.g., Campbell et al. 2008, European Union 2009, International Energy Agency 2009, Tilman et al. 2009). Studies in South America demonstrate that deep-rooted perennial bioenergy feedstocks in the tropics could enhance soil carbon storage by 0.5–1 $Mg \cdot ha^{-1} \cdot yr^{-1}$ on already cleared land (Fisher et al. 1994). Most land-use-change studies consider the role of soil in CO_2 release but exclude its potential role in carbon storage.

Neither Searchinger et al. (2008) nor Fargione et al. (2008) consider the carbon-cycle implications of current land-use trends, including emissions from regular use of burning as a recurrent land-management practice in developing countries. The increasing contribution of burning to atmospheric CO_2 concentrations primarily results from burning tropical savannas and forests (Santilli et al. 2005, FAO 2006, Mouillot et al. 2006). The practice of repeated fires allows people to maintain clearance and land claims; yet the cost to the environment (de Mendonça et al. 2004) is not tallied. The 10.8 million ha estimated by Searchinger et al. (2008) as needed to offset future bioenergy feedstock represents about 3% of the 250–400 million hectares burned each year from 2000 to 2005, as reported by Tansey et al. (2004) and Giglio et al. (2006).

It is essential to understand the processes and relative importance of the forces behind land clearing and conversion in order to be able to model the influence of bioenergy feedstocks on these forces and related carbon emissions. Yet, to date, there are no models that capture these influences (Center for BioEnergy Sustainability, Oak Ridge National Laboratory 2009). Historical data on land use (as opposed to land cover) typically do not exist, especially in developing countries, or are available only at a coarse scale or for a simple two-point comparison in time for a restricted area. The interpretation of land-cover data is further compromised by the use of different sensors over time, varying classification schemes, imprecise definitions of land-cover classes, and varying quality standards, leading to tremendous uncertainties (Grainger 2008, 2009, Center for BioEnergy Sustainability, Oak Ridge National Laboratory 2009). While the interpretation of land-cover data can help us estimate where changes take place, it conveys no information about *why* changes take place. For example, a change among three simple categories (forest, pasture, and cropland) is often calculated by comparing images at two points in time. Such change analysis records a single step, and, in the case of some studies, the latter "status" is assumed to "cause" the change. Given that assumption and current data, any change from forest must, by definition, become "agriculture" (e.g., crops or pasture) and the "conclusion" that agriculture caused deforestation is guaranteed. Yet this approach cannot inform how key ecological factors (above- and belowground carbon stocks, nitrogen fluxes, biodiversity, evapotranspiration rates, greenhouse gas emissions, runoff, etc.) were actually changing incrementally over time. These changes can be significant and move in multiple directions in response to varying intensities of use, fire, and other natural and anthropogenic disturbances. Nevertheless, land-cover data are used by modelers in an attempt to infer land-use changes without mention of the limitations of these data, the fact that there is no empirical support or causal analysis of the drivers of change, and with little discussion of the effects and degree of error that the approximations and replacements (of "land use" for "land cover" for example) may have on the resulting model projections. The bottom line is that, to date, global equilibrium economic models and analysis of satellite imagery have not been capable of representing the social, economic, and environmental effects driving land-use changes and emissions (Kline and Dale 2008, Center for BioEnergy Sustainability, Oak Ridge National Laboratory 2009). Lacking empirical validation, these models and techniques generate estimates that are dependent upon user beliefs, assumptions, and input specifications (Gnansounou et al. 2009, Keeney and Hertel 2009, Oladosu and Kline 2010).

In summary, it is critical to understand that land-use change is a dynamic process occurring at spatial scales that far exceed societal needs for cropland and on temporal scales that begin earlier and will continue far longer than the time frames considered in analyses of indirect land effects of bioenergy. Because of poverty, governance, and other issues, forest conversion will continue in many parts of the world, regardless of bioenergy policies or feedstock production. But policies that stress legal compliance and sustainability and that add value to forest resources can slow deforestation rates and contribute to forest expansion (e.g., Knoke et al. 2009). This perspective provides an alternate interpretation about the potential impacts of bioenergy on carbon emissions. Under proper management, in appropriate locations, and using previously cleared lands, we hypothesize that sustainable local bioenergy feedstock production in the tropics can decrease carbon emissions by fostering the replacement of fossil fuels by biofuels, reducing land-burning, and enhancing soil carbon sequestration, while providing a predictable livelihood for poor farmers. While this hypothesis needs to be tested, it is supported by the success of community-based land management that fosters sustainability by reducing deforestation pressure while enhancing the ability of the local people to make a living on the land. For example, Knoke et al. (2009) found in southern Ecuador that an economic-ecological land-use diversification approach combined with reforestation of tropical "wastelands" both reduced deforestation by 45% and increased farmers' profits by 65%. Their approach of transforming formerly unproductive wastelands into productive land use could be adopted by bioenergy systems and used as a means to reduce deforestation pressure, enhance soil carbon sequestration, and reduce the carbon emission associated with slash and burn agriculture. The Ecuador case was implemented using inexpensive microcredits (at interest rates below 6%) and offering farmers alternative land-use opportunities (Knoke et al. 2009). From a regional perspective, local initiatives are a more relevant driver for land-use changes than are global economic forces. A question for any region is how the local social, political, economic, and environmental forces act to influence land management decisions.

Opportunity to design bioenergy system choices to optimize socioeconomic and ecologic benefits

A key challenge is whether bioenergy systems can be sustainable under prevailing social, political, economic, and environmental forces. To answer this question in a holistic sense requires attention to feedstock type, management, location, extent, and many other environmental factors. This holistic perspective must consider the complete bioenergy system from the feedstock production to transport, conversion, production, and market delivery within larger landscape dynamics.

To develop and implement such a sustainable bioenergy infrastructure requires determining: (1) What are the environmental implications of different feedstock options? (2) What are the opportunities/constraints for feedstock locations (that is, where should they be produced or collected)? (3) What forms of bioenergy (fuels, heat, power, and other biochemical co-products) should be produced? (4) And where should bioenergy conversion facilities be located?

Trade-offs exist across space and time among the economic, ecological, and social consequences of alternative choices. For example, increased biofuel production from corn grain ethanol production at a local scale may mean more pesticide use and negative effects on human health, at a regional scale may mean increased nutrient flux and thus degraded water quality, and at the scale of the Mississippi River watershed may mean a larger hypoxia zone in the Gulf of Mexico and declines of shrimp harvest. Furthermore, changing climate conditions will likely influence possible crop choice and energy needs. On the other hand, increased biofuel production using perennials integrated in a sustainable system of rotations and buffer strips to complement other crops could reduce the use and costs of pesticides at a local scale, absorb soil nutrients and improve water quality at a regional scale, and mitigate hypoxia in the Gulf.

Landscape designs for bioenergy feedstocks should take into account environmental and socioeconomic dynamics and consequences with consideration of alternative bioenergy regimes and policies. The approach should consider the benefits and costs of trade-offs in implications of major decision; be at the appropriate spatial and temporal resolution; include the potential for spatial optimization; and be sensitive to the economic, social, and environmental context. To develop a landscape design, land managers must consider (1) what the environmental impacts on water and air quality, carbon sequestration, and native plants and animals and their habitats are; (2) what are the appropriate spatial and temporal scales at which to examine environmental effects; and (3) how potential trade-offs in environmental costs and benefits can be considered.

Forman (1995) suggested that under ideal land management, decisions should be based first on water and biodiversity concerns; second on food cultivation, grazing, and wood products; third on sewage and other wastes; and fourth on homes and industry. In the case of bioenergy issues, climate mitigation is also important and would likely be in the first category. In reality, planning under such pristine conditions is not possible; rather extant development of the region constrains opportunities for land management. In fact, urban expansion is the major land-use pressure on crops used for food, fuel, and fiber (e.g., Martin et al. 2008, U.S. Department of Agriculture 2009). However, even given current land uses, there are places where energy crops can provide farmers with new opportunities (e.g., in eastern Tennessee, switchgrass is touted by farm extension agents as a viable crop for the future). Devising policies and incentives that place appropriate, relative market values on the array of products and ecosystem services offered by the landscape is one way to move toward more sustainable land-use patterns.

The challenge in designing bioenergy choices to optimize socioeconomic and ecological benefits is to consider trade-offs in different costs and benefits. With proper management, perennial lignocellulosic feedstocks can enhance carbon sequestration, provide habitat, enhance biodiversity, and improve soil and water quality as compared to annual grain crops (Wright 1994, Tolbert et al. 1997, 2000, 2002, McLaughlin and Walsh 1998, Wright and Turhollow 2010). Bioenergy systems integrated with rural development programs can improve land-tenure rights and arrest detrimental land-use practices. Providing technical assistance to increase yields and manage land can enhance farm incomes, food security, carbon sequestration, and sustainable living—all of which reduce pressure to clear new land (Erskine 1991, Lal 2010). When these factors are considered, properly designed and integrated bioenergy systems can lead to significant net improvements in greenhouse gas emissions and other environmental benefits. Steps toward this goal are to develop (1) multi-metric spatial-optimization models that identify characteristics of places and (2) land management practices that consider and compare these factors. Our research team and several other groups are in the process of developing such models, but there are few empirical data against which to validate or test such approaches, and obtaining those data will take years. In the absence of such models and data, this manuscript has assembled major findings from several case studies. We recognize that these studies cannot capture the complexity of potential interactions between bioenergy feedstock choices, landscape dynamics, and land use. Instead, we hope that this analysis stimulates others to consider ways to model and measure implications on sustainability of these complex relationships because policy makers need a better understanding of effects of bioenergy expansion.

Conclusions

Bioenergy is a recognized way to achieve greater energy security and independence. As such, its use is expected to increase in future decades. Therefore, there is a strong need to understand ways in which bioenergy crops can be grown in a sustainable manner. Environmental implications of bioenergy choices are extensive, complex, intertwined, and dependent on both endogenous and exogenous factors and have not been analyzed with scientific rigor. Major choices include cropping systems, supply-driven issues, and technological conversion to fuels, chemicals, or power energy. The implications of these choices range from effects at the level of individual fields, hydrological response units, small watersheds, and large watersheds (as big as the 48% of the United States that drains into the Gulf of Mexico) to potentially the entire world, and they vary based on feedstocks, production technology, transport decision, and end products.

The complexity of these issues calls for a systematic approach to understand the interactions between different implications and other forces affecting bioenergy production and land-use changes. Models need to include key processes affecting land-use and management choices and should be validated and tested against empirical data. Information needs to be collected on the causes and effects of land-use change, in general, and bioenergy feedstock choices, in particular. Much of the information needed is at watershed and regional scales, where data is often sparse but benefits of bioenergy options may be high. Furthermore, sustainable ways to address bioenergy needs will be place-based and depend on specific crop and management decisions as well as on the context (soils, past land-use practices, adjacent land uses, policy options and constraints, prevailing air and water quality, etc.). Many implications of biofuel and cropping-system choices also require multiple indicators at the different relevant spatial and temporal scales. The opportunity to design lignocellulosic bioenergy feedstock systems to optimize socioeconomic, ecologic, and other benefits must build from the growing scientific understanding of effects of bioenergy choices at different scales, quantitative metrics, and ways that allow society and decision makers to understand and address environmental trade-offs.

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