2009

Biofuels, Land, and Water: A Systems Approach to Sustainability

Gayathri Gopalakrishnan
Argonne National Laboratory

M. Cristina Negri
Argonne National Laboratory

Michael Wang
Argonne National Laboratory

May Wu
Argonne National Laboratory

Seth W. Snyder
Argonne National Laboratory

See next page for additional authors

Biofuels, Land, and Water: A Systems Approach to Sustainability

GAYATHRI GOPALAKRISHNAN,*,† M. CRISTINA NEGRI,† MICHAEL WANG,† MAY WU,† SETH W. SNYDER,† AND LORRAINE LAFRENIERE‡

Energy Systems Division and Environmental Science Division, Argonne National Laboratory, 9700 S. Cass Avenue, Argonne, Illinois 60439

Received March 16, 2009. Revised manuscript received June 07, 2009. Accepted June 18, 2009.

There is a strong societal need to evaluate and understand the sustainability of biofuels, especially because of the significant increases in production mandated by many countries, including the United States. Sustainability will be a strong factor in the regulatory environment and investments in biofuels. Biomass feedstock production is an important contributor to environmental, social, and economic impacts from biofuels. This study presents a systems approach where the agricultural, energy, and environmental sectors are considered as components of a single system, and environmental liabilities are used as recoverable resources for biomass feedstock production. We focus on efficient use of land and water resources. We conducted a spatial analysis evaluating marginal land and degraded water resources to improve feedstock productivity with concomitant environmental restoration for the state of Nebraska. Results indicate that utilizing marginal land resources such as riparian and roadway buffer strips, brownfield sites, and marginal agricultural land could produce enough feedstocks to meet a maximum of 22% of the energy requirements of the state compared to the current supply of 2%. Degraded water resources such as nitrate-contaminated groundwater and wastewater were evaluated as sources of nutrients and water to improve feedstock productivity. Spatial overlap between degraded water and marginal land resources was found to be as high as 96% and could maintain sustainable feedstock production on marginal lands. Other benefits of implementing this strategy include feedstock intensification to decrease biomass transportation costs, restoration of contaminated water resources, and mitigation of greenhouse gas emissions.

Introduction

The development of biofuels as an alternative energy source has become an issue of increasing importance to reduce greenhouse gas emissions to mitigate climate change and to achieve energy security. Initial targets for biofuel production have been developed by many countries, including the United States, those in the European Union, Brazil, India, and China. Current targets range from 2% to 3% in New Zealand and Japan to 25% in Brazil (*1*). In the United States, the Energy Independence Security Act of 2007 mandated the production of 36 billion gallons of biofuels by 2022, including 21 billion gallons of advanced biofuels produced from cellulosic biomass feedstocks. The expansion in biofuel production on local and global scales could result in environmental, social, and economic impacts that are positive and negative. The extent and nature of these impacts may vary through the entire process from feedstock production to conversion, distribution, and end use. The potential impacts of feedstock production are likely to have a significant influence on the sustainability of biofuels (*2, 3*).

The land used for feedstock production is a key factor in determining biofuel sustainability. Many factors, including agricultural subsidies, influence the cost of food commodities and their impact on the poor. However, the use of food crops for energy and the conversion of agricultural lands from food production to biomass feedstock production have the potential to increase these costs and negatively impact the lives of food-insecure people worldwide (*2, 4*). One proposed solution to this problem is producing biofuels from cellulosic feedstock such as native prairie grasses, switchgrass, miscanthus, crop residues, and short rotation woody crops (*5–7*). A second solution focuses on utilizing marginal agricultural land that has been abandoned or set aside for conservation purposes to grow biomass feedstock (*5, 8, 9*). However, concerns about the economic viability and environmental sustainability of these solutions remain. If purpose-grown energy crops such as switchgrass or miscanthus are grown on productive agricultural land, the impact would be similar as direct utilization of food crops.

A key facet of environmental sustainability is the ability of biofuels to mitigate greenhouse gas (GHG) emissions. In terms of the biomass feedstock, the crops are carbon neutral in that the carbon dioxide produced from biofuels was previously absorbed during plant growth and can be carbon negative as a result of increased carbon sequestration in the soil and root biomass (*6, 10, 11*). However, recent studies have suggested that GHG benefits from biomass feedstock would be significantly lower if the effects of direct or indirect land use change are taken into account. GHG benefits derived from bioenergy crops may not completely offset carbon dioxide (CO_2) emissions from the clearing of forest land for new biomass feedstock (*12*). While production and use of any fuel may entail indirect effects, the carbon debt created by land cleared elsewhere to replace displaced food production has stirred a great amount of debate (*13–15*). A recent study indicated that there is significant opportunity to reduce the potential carbon debt and GHG emissions through improved crop and soil management practices, including crop choice, intensity of inputs, harvesting strategy, and tilling practices (*15*).

Crop management practices assume greater significance when evaluating the impact of feedstock production on water resources. Water is an increasingly precious resource that is used in all aspects of society, including agriculture, power, domestic, and industrial sectors. However, demands on water supply are increasing due to growing population, increased per capita use, migration of people, economic activity, and the impacts of climate change. Many regions of the world are experiencing increasing water scarcity. There are suggestions that water quantity *and* quality impacts are likely to be significant as a result of increased biofuel production, especially when grain-based biofuels are the feedstock of choice (*16, 17*).

Water use requirements for biomass feedstock crops will depend on the type of crops, the location where they are grown, and how they are managed (*5, 18*). While the majority

* Corresponding author phone: 630-252-7051; fax: 630-252-1342; e-mail: ggopalakrishnan@anl.gov.
† Energy Systems Division.
‡ Environmental Science Division.

10.1021/es900801u CCC: $40.75

of grain and cellulosic bioenergy crops are not irrigated, their yield is usually dependent on water availability (*19*), and thus water resources may be increasingly tapped to improve productivity. Additionally, qualitative degradation of surface water and groundwater water resources as a result of current agricultural practices could worsen from conversion of land from conservation purposes to biomass feedstock production (*3, 16*). The impacts of this degradation are registered locally, with runoff and percolation of agrochemicals into local surface water and groundwater, and on a larger scale such as the increase in the anoxic zone in the Gulf of Mexico attributed to nitrate from the Mississippi River (*20*). Further, increased application of synthetic and organic nitrate fertilizers to improve biomass feedstock productivity could result in significant GHG emissions through the production of nitrous oxide (N_2O), a GHG with a warming potential that is approximately 300 times greater than CO_2. A recent study suggested that increased N_2O emissions could offset any GHG reductions achieved by biomass feedstock through carbon sequestration and fossil fuel replacement (*21*). N_2O is a natural byproduct of soil nitrification and denitrification that occurs when nitrogen is applied to the soil (*22*). Direct emissions of N_2O from the soil have been expressed as 1.25% of the applied nitrogen, and indirect emissions due to runoff, leaching, and volatilization of the nitrogen from the field have been expressed as 0.75% of the applied nitrogen (*23*).

Management practices also have a strong influence on other environmental concerns resulting from biomass feedstock production. Landscape diversity and ecosystem services (e.g., pest suppression and pollination) provided by more diverse landscapes may be reduced by producing extensive monocultures of feedstock (*5*). Additionally, some bioenergy crops are exotic and potentially invasive (*24, 25*). Excessive removal of crop residue from annual cropping systems could result in soil carbon loss, increased erosion, and decreased soil fertility (*26, 27*). Concerns also exist that excessive thinning of forests would diminish wildlife habitat as well as long-term forest productivity (*5*).

Current approaches to improving the sustainability of biofuels have typically focused on single issues. For example, siting biomass feedstock on marginally productive lands rather than highly productive croplands would minimize competition with food production (*8*). However, marginal lands often require significant inputs of nutrients and water to maintain productivity (*9*). Studies have indicated that water and nutrient requirements can be met through the use of municipal wastewater to grow short-rotation woody bioenergy crops (*28*). These results suggest that closing the loop through the optimization of all resources is essential to minimize conflicts in resource requirements as a result of increased biomass feedstock production.

Here, we present a systems approach to the challenge of biofuel sustainability. In this approach, we consider the agricultural, energy, and environmental sectors as components of a single system and focus on using environmental liabilities as recoverable resources for biomass feedstock production. The specific objective of this study is to improve the sustainability of biomass feedstock production through the use of marginal land and degraded water resources.

We consider land resources that are neither part of existing protected ecosystems nor used for food, fiber, or feed production as marginal land. Four types of marginal land resources are studied in this analysis: (a) abandoned agricultural land and agricultural land that has been set aside for conservation purposes, (b) buffer strips along rivers and streams or riparian buffers, (c) buffer strips along roads or roadway buffers, and (d) brownfield sites that have been contaminated as a result of past practices. Marginal agricultural land has been considered previously for feedstock production. Vegetated buffer strips of grasses and woody trees have been used along roads and streams to mitigate runoff and improve water quality (*29, 30*) and are evaluated here for feedstock production for the first time together with brownfield sites.

Water is defined as degraded once it has been used, whether for domestic, agricultural, industrial, or recreational purposes (*31*). Degraded water resources may be contaminated by a wide range of chemicals from agricultural nutrients such as nitrate and phosphate to pesticides, heavy metals, salts, pathogens, antibiotics, hormones, and organic chemicals (*32*). However, this study focuses on resources that can supply nutrients for biomass feedstock in addition to having significant environmental impacts. Three types of degraded water resources are considered in this analysis: (a) groundwater contaminated by nitrate, (b) wastewater from livestock farms, and (c) wastewater from municipal treatment facilities.

The availability and spatial distribution of these resources are modeled for the state of Nebraska, and the economics and resulting impacts on carbon sequestration, nitrous oxide emissions, habitat fragmentation, and environmental restoration are discussed.

Materials and Methods

The geographic information software ArcGIS v9.2 produced by Environmental Systems Research Institute (ESRI) was used to develop the spatial maps of marginal land and degraded water resources and to determine the dimensions and area of these resources.

We estimated the amount of abandoned agricultural and conservation lands using the most recent data from the 2007 land-use database developed by the U.S. Department of Agriculture, National Agricultural Statistics Service (NASS) (*33*). This database is a geo-referenced, crop-specific land cover data layer with a ground resolution of 56 m produced from satellite imagery for the most recent growing season. We estimated the available area for riparian and roadway buffer strips from the length of the roads and rivers in Nebraska and published values for the width of buffer strips. The width of vegetated buffer strips along rivers and roads is a function of the required level of treatment of runoff, rainfall characteristics, available land, and plant species used (*28, 30*). This study assumes strip widths ranging from 10 to 50 m in order to achieve 50−95% reduction in the concentrations of nutrients, pesticides, and sediments from runoff (*29, 30*).

The river and road networks were mapped using data from NASS and ESRI databases for Nebraska. Roadway networks were divided into main roadways, i.e., national, state, county highways, and minor roadways consisting of local roads. River networks were divided into perennial streams and rivers and seasonal streams. The location of all brownfield sites in 2007 was determined from data produced by the Nebraska Department of Environmental Quality (*34*).

Groundwater samples are described as nitrate-contaminated when levels exceed 10 mg/L, the Environmental Protection Agency (EPA) mandated drinking water limit. A spatial map of areas with nitrate-contaminated groundwater was developed using data produced in 2005, the year that the largest available database was collected (*34*). Spatial maps of all livestock operations and municipal wastewater treatment facilities were developed from data produced in 2007 (*34*).

Feedstock availability for two sample biorefineries was evaluated using two scenarios. Several factors contribute to siting biorefineries, including the capital cost of the refinery, operating costs, transportation costs and constraints, and regulatory restrictions associated with the feedstock and potential environmental impacts. However, the following simplifying assumptions were made for this analysis. We

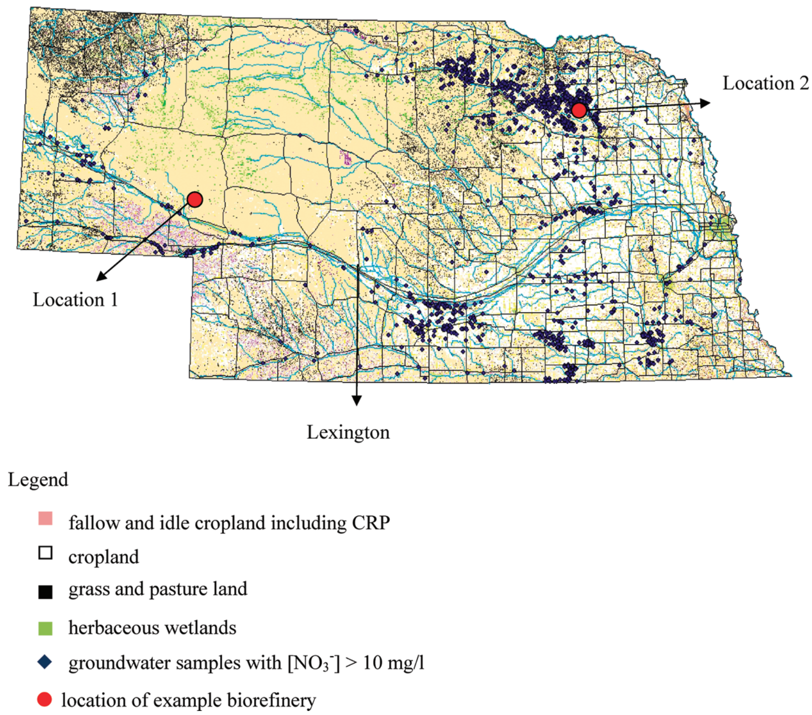

FIGURE 1. Land use, contaminated groundwater, and hypothetical locations of biorefineries for Nebraska (■ fallow and idle cropland including conservation reserve program (CRP), □ cropland, ■ grass and pasture land, ■ herbaceous wetlands, ◆ groundwater samples with [NO_3^-] > 10 mg/L, and ● location of example biorefinery).

assume that the refinery is a plant producing approximately 50 million gallons of ethanol per year, using approximately 0.825 million tons of feedstock annually. The theoretical yield of ethanol per dry ton of feedstock ranges from 90 to 104 gallons of ethanol/dry ton of feedstock depending on the type of feedstock and conversion process. However, we assume a yield of 60 gallons of ethanol/dry ton of feedstock in this study because yields that are 60−90% of the theoretical maximum are achieved in practice (*35*). A second assumption is that all feedstock for the refinery will be obtained within a 25 mile radius (*36*). It is further assumed that no external inputs of nutrients and water are applied to the feedstock, excepting those present in the degraded water sources, and that process energy is supplied by biomass. The locations for the two refineries are shown in Figure 1 and are selected as representative of locations where marginal agricultural land is a significant resource and where it is not.

In the first scenario, marginal land resources within the 25 mile radius of the biorefinery are used to grow feedstock in conventional rain-fed plantations. In the second scenario, degraded water resources near the marginal land resources are used to improve the feedstock yields. Yields for biomass feedstock vary depending on the feedstock, soil type and fertility, climatic conditions, and inputs provided. Values for yields obtained in published studies range from 2 tons of dry matter/acre-yr for switchgrass grown in Nebraska to 4−10 tons of dry matter/acre-yr for short rotation woody crops and 8−12 tons of dry matter/acre-yr for miscanthus (*9, 18, 24, 28*). In this study, we assume that the biomass feedstock grown in an area in Nebraska will be selected to obtain the maximum yield for the given soil and environmental conditions. We assume an average yield of 4 tons of dry matter/acre-yr when conventional rain-fed plantations are used through the state. When degraded water resources containing nutrients are applied to the feedstock, it is assumed that the yield doubles to 8 tons of dry matter/acre-yr (*18, 28*). The area required to supply the refinery when all marginal land resources are considered was estimated for both scenarios. The buffer strip width for roadway and riparian buffers supplying the refinery is assumed to be 50 m, the maximum value used in this study.

Results and Discussion

The spatial distribution of marginal land resources investigated is presented in Figure 1 and Table S1 of the Supporting Information. Approximately 1.5 million acres were estimated to be marginal agricultural land, i.e., fallow agricultural land and land in the conservation reserve program (CRP land). CRP land alone was estimated at 1.1 million acres for Nebraska in 2007 (*37*). As seen in Figure 1, these resources are located predominantly in the western part of the state, while prime agricultural land is located primarily in the eastern section of the state. Approximately 84% of the 1.5 million acres of marginal agricultural land is located west of the city of Lexington. This result is in agreement with Campbell et al. (*8*), indicating that marginal agricultural land could contribute to biomass feedstock production without impacting food production on prime cropland. However, possible overlap between land classifications (e.g., CRP land classified as cropland or grasslands) is a source of uncertainty in estimating available marginal land resources and merits further investigation.

Existing vegetation on these lands is likely to play a significant role in determining the type of biomass feedstock that can be grown sustainably. Native and introduced grass species were the primary vegetation on more than 90% of CRP land in 2007; the main categories were previously established grass cover (40%), newly established native grasses (26%), and contour grass strips (6%) (*37*). These results suggest that cellulosic feedstock that are primarily native and introduced grass species (e.g., prairie grasses, switchgrass, and miscanthus) could be used to meet energy requirements without impacting other ecosystem services rendered by CRP land.

The roads and rivers were distributed through the state (Figures S1−S2 of the Supporting Information), with main roads and rivers presented in Figure 1, all rivers including seasonal streams in Figure S1 of the Supporting Information, and all roads including minor roads in Figure S2 of the Supporting Information. Significant differences were found in available land for riparian and roadway buffer stripes depending on the width assumed for the buffer strip and the inclusion of minor roads and seasonal streams in the analysis. When only major rivers and roads were considered, available land for riparian buffer strips was estimated between 0.1 and 0.49 million acres and between 0.09 and 0.41 million acres for roadway buffer strips assuming strip widths of 10 and 50 m, respectively. Approximately 39% of riparian buffer areas and 33% of the roadway buffer areas are located west of the city of Lexington, in areas with significant amounts of marginal agricultural land. When minor roads alone were considered, available land increased almost 4-fold from the previous estimate, ranging from 0.96 million acres for strip widths of 10 m to 4.8 million acres when the buffer strip width was assumed at 50 m. Similar results were obtained when seasonal streams were included with available land estimates ranging from 0.5 to 2.1 million acres. As shown in Figures S1 and S2 of the Supporting Information, roads were distributed evenly through the state, while streams were densest in the eastern section of the state. The estimated area from brownfield sites was found to be insignificant for this state (<50000 acres) (*34*).

Biomass resources currently contribute 2% to the total energy requirements of the state of Nebraska (*38*). If CRP land is used for feedstock production, this estimate increases by 3% (Table S2 of the Supporting Information). This estimate is based on the conversion of these lands to perennial energy crops with an average yield of 4 tons of dry biomass/acre and an ethanol yield factor of 60 gallons of ethanol/dry ton of feedstock. The results from the present study indicate that incorporating other sources of marginal land such as riparian and roadway buffer strips could result in available area that is almost 7 times that of available CRP land, without considering yield increases. These resources could either be used as alternatives to CRP land when CRP land is needed to maintain ecosystem services such as protecting soil fertility and minimizing erosion or could be combined to increase available land for biomass feedstock. When all sources of marginal land studied here (CRP land and abandoned agricultural land, roadway and riparian buffers, and brownfield sites) are combined, it is theoretically possible to replace approximately 22% of the energy demand as opposed to using CRP land alone. The viability of these resources will depend on local conditions (e.g., soil fertility, feedstock yield, feasible strip width, and utilizable CRP land) and would need to be evaluated at the field scale for greater accuracy. Additionally, brownfield land availability is minimal for this state but could be significant in other cases. Further, if the theoretical limit of the ethanol yield factor (~100 gallons of ethanol/dry ton of feedstock) could be achieved, biomass resources produced on all marginal lands could replace approximately 37% of the energy requirements of the state.

These estimates are based on the assumed average yield of 4 tons of dry biomass/acre and could change based on yields achieved in practice and by using techniques from agronomy and genetics (*24*). In this study, an increase in yield can be achieved through the application of water and nutrient inputs (*9, 28*) with a concomitant increase in the fraction of energy demand that can be replaced by biofuels. The spatial distribution of all degraded water resources is shown in Figure 1 and in Figures S3 and S4 of the Supporting Information, with nitrate-contaminated groundwater resources presented in Figure 1, livestock wastewater locations in Figure S3 of the Supporting Information, and municipal wastewater locations in Figure S4 of the Supporting Information. Areas with nitrate-contaminated groundwater are located primarily in the eastern section of the state. Approximately 98% of the locations with contaminated groundwater are found east of the city of Livingston as shown in Figure 1 in areas of prime agricultural land. The contaminated groundwater could be used to boost yields of biomass feedstock crops by (a) using traditional irrigation techniques where the groundwater is pumped out and used to irrigate biomass feedstock or (b) passive uptake by the roots of the biomass feedstock crops.

Traditional irrigation would require energy for pumping and is likely to further exacerbate water table declines in the state. Passive uptake of the contaminated groundwater by feedstock will depend on the accessibility of the groundwater and the depth to which plant roots can penetrate. Approximately 90% of the contaminated groundwater samples were taken in areas with shallow groundwater where the depth to water is less than 50 ft (*34*). At least a portion of these resources may be accessible by deep-rooting biomass feedstock such as short rotation woody crops and grasses (*39*). Studies have shown that approximately 28% of available groundwater resources in the United States are contaminated with nitrate and would need to be treated prior to use for drinking water (*40*). Our results suggest that these resources could be used as alternative in situ sources of water and nutrients for biomass feedstock production. However, hydrological modeling at the watershed scale will be required to design the feedstock system in order to ensure sustainable withdrawal of groundwater.

As shown in Figures S3 and S4 of the Supporting Information, there is significant overlap between areas with nitrate contaminated groundwater and locations of livestock farms but not between the locations of municipal wastewater facilities. Livestock farms include hog, cattle, and poultry farms and are found primarily in the eastern section of the state, while municipal wastewater plants are clustered around the cities, primarily near the two largest cities of Omaha and Lincoln. Livestock farms range from small family farms with less than 50 animals to large confined feedlot operations with more than 100000 animals and generate between hundreds to millions of gallons of wastewater per day depending on the type and number of animals (*32, 41*). Municipal wastewater treatment plants in Nebraska have capacities ranging from thousands to millions of gallons per day depending on the population base served (*34*).

The waste streams are typically treated to limits regulated by state and federal environmental agencies, with the treated water discharged to surface water bodies and organic solids applied to agricultural fields as fertilizers. However, a significant fraction of wastewater generated from both of these resources is not used for irrigation and land application and is a likely source of nonpoint source pollution (*31*). This fraction could potentially be used for irrigation and fertilization of biomass feedstock. Increases of 50−100% in the yields of two cellulosic bioenergy crops, willows, and switchgrass were reported when the crops were irrigated and fertilized with nutrients conventionally and using municipal wastewater (*9, 19, 28*). Nutrient and water inputs are especially important when biomass feedstock is grown on marginal land, which is of low fertility and hence low productivity (*9*). The use of degraded water resources could result in economically sustainable production of bioenergy crops on marginal land as yields are increased through the use of inputs recycled from waste streams. However, potential risks from antibiotics, supplements, estrogen, and pharmaceutical compounds found in degraded water could be significant and need further investigation. Impacts from accumulation of pollutants in biomass feedstock and soil also warrant further research. Nutrient management plans would need to be developed at the state level to ensure effective use of the inputs with minimal environmental impacts.

TABLE 1. Percentage of Feedstock Requirements Obtained from Marginal Land and Water Resources for a Single Biorefinery

scenario	biorefinery	marginal agricultural land (%)	major roadway and riparian buffers (%)	minor roadway and riparian buffers (%)
1 (no degraded water resources used)	location 1	48	9	34
2 (degraded water resources used)	location 1	97	18	68
1 (no degraded water resources used)	location 2	<1	9	29
2 (degraded water resources used)	location 2	<1	18	58

Spatial overlap between the marginal land and degraded water resources is important in maximizing feedstock productivity, while minimizing transportation costs of the water resources to the biomass feedstock. For the state of Nebraska, approximately 2% of the CRP land, 44% of the riparian buffers, and 50% of the roadway buffers overlap with areas of nitrate-contaminated groundwater and livestock farms. This suggests that roadway and riparian buffer strips can be used in conjunction with nitrate-contaminated groundwater and livestock wastewater on the basis of current data. Municipal wastewater use will depend on which land resource is closest and can be used.

The land and feedstock availability for a single biorefinery when marginal land and degraded water resources are used is presented in Table 1 and Table S3 of the Supporting Information. At location 1, at least three-fourths of the feedstock requirements can be met using all sources of marginal land and more than the required amount of feedstock can be produced if degraded water resources are used. However, degraded water sources in this area are primarily municipal wastewater treatment plants, and the refinery would need to be located close to one. At location 2, the contribution of marginal agricultural land is insignificant (<1%), and 19−58% of the feedstock requirements can be met from buffer strips based on the use of degraded water resources. Here, degraded water sources are easier to access compared to location 1 as this is the area where more than 98% of the livestock facilities and nitrate-contaminated groundwater are present. At both locations, incorporating buffer strips in addition to marginal agricultural land resulted in increasing the available feedstock by a minimum of 9%. These results indicate that the systems approach could present biorefineries, farmers, and other stakeholders with multiple options by (a) enabling the use of cropland for food production, (b) decreasing feedstock transportation costs through intensified land use from buffers, and (c) increasing refinery capacity if required by improving yields and utilizing alternative resources. The trade-offs involved in these options and the economic and technical feasibility of harvesting biomass along dispersed strips as opposed to conventional large farms will need to be further evaluated.

In addition to the direct economic benefits of improving feedstock productivity and minimizing feedstock transportation distances to the biorefinery, indirect cost savings are also achieved with this approach. The manufacture of fertilizers accounts for 37−67% of the fossil energy required in feedstock production and a significant fraction of the cost (*42*). The approach presented here could result in saving almost all the energy requirements and costs by recycling nutrients from degraded water sources. Furthermore, the national costs associated with remediating contaminated groundwater range from $480 million to $1 trillion (*43*), and the costs of eutrophication and degradation of surface water bodies from nonpoint source pollution are approximately $2.2 billion (*44*). These costs could be substantially reduced when biomass feedstock is used to clean the contaminated groundwater and buffer strips with biomass feedstock are used to mitigate nonpoint source pollution.

While the potential economic benefits of the systems approach are evident, the environmental benefits merit discussion. A primary benefit lies in water quality improvements through the restoration of contaminated aquifers and mitigation of nonpoint source pollution through runoff capture. Remediation of the aquifers will be a byproduct of passive uptake of contaminated groundwater by biomass feedstock or extracting the groundwater and irrigating the crops. Restoration of contaminated groundwater has been demonstrated at several phytoremediation sites growing short rotation woody biomass crops (*45*) but will need to be evaluated for other cellulosic feedstock. Vegetated buffer strips utilizing grasses have been found to capture up to 95% of the pollutants contained in runoff, depending on the width of the strip, slope, and the choice of feedstock (*29*), and will need to be evaluated for other cellulosic feedstock. Additionally, the impact on runoff capture and aquifer remediation when biomass feedstock is harvested is unknown and needs investigation.

In addition to water quality benefits, carbon sequestration benefits could be significant, depending on the crop chosen and the existing land use. Previous studies at the field scale have indicated that between 0.2 and 4.7 Mg of carbon/ha-yr could be sequestered by cellulosic feedstock such as short rotation woody crops, switchgrass, prairie grasses, and miscanthus (*7, 9, 10*). Opportunities to increase sequestered carbon arise when marginal land is not vegetated or has vegetation that can be replaced by feedstock with greater carbon sequestration potential in soil and root biomass. This is a likely scenario in the case of roadway and riparian buffers and brownfield sites. Where the marginal land is already vegetated, replacement of existing plants with biomass feedstock could lead to loss of carbon and would need to be carefully evaluated. Even if existing vegetation is replaced by biomass feedstock, proper crop management practices developed to yield higher soil organic carbon levels compared to pre-existing vegetation would ensure that biomass feedstocks are carbon negative at best and carbon neutral at worst (*15*). However, the amount of carbon sequestration at a field depends on multiple factors, including existing soil carbon concentration, soil type, climate, precipitation, management, annual biomass production, and root density and merits investigation for multiple agro−ecosystems using this approach.

Another important environmental benefit would be reductions in nitrous oxide (N_2O) emissions, direct and indirect. Reductions in direct emissions could occur from integrating animal waste and crop production and through use of nitrate-contaminated groundwater that obviates or significantly reduces the need for direct fertilization. Studies have indicated N_2O emissions were decreased by almost 17% for traditional crops through the integration of livestock waste and crop production (*46*), and similar results are possible for biomass feedstock. The reduction in emissions for a zero N input system (no fertilizers applied) of grain-based feedstock ranged from 18% to 85%, depending on existing soil conditions, crop uptake, and climate (*22*), and similar reductions are possible for cellulosic feedstock that obtain nutrients and water through passive uptake of nitrate-contaminated groundwater. Additionally, assuming that all nitrate present in the leachate and runoff from existing cropland is captured using biomass feedstock as buffers and in passive uptake systems, N_2O emissions could be decreased by an additional 38%. This estimate is based on the assumption that indirect emissions contribute 0.75% of the applied N in fertilizers and direct emissions contribute 1.25% (*23*). However, the uncertainty associated with determining these emissions is large as direct measurements of N_2O in multiple agro−ecosystems at the field are lacking.

A further advantage of this systems approach is the possibility of improving wildlife habitat and biodiversity through the development of buffer strips and biomass feedstock fields as habitat corridors. Studies have shown that increases in bird species and mammalian species result when shelterbelts, edge covers, and small corridors of forestland are provided amidst cropland (*47*). However, the benefits when biomass feedstock crops are used will need to be evaluated at the field and depend on the species being protected, type of crop used, and habitat strategy.

In summary, the systems approach has the potential to significantly improve the economic, social, and environmental sustainability of biofuels. The inclusion of other sources of marginal land could contribute significantly to feedstock production for bioenergy. If the crops grown on these lands are irrigated and fertilized using degraded water resources, feedstock production could be further increased with concomitant environmental benefits obtained through the reuse and restoration of these resources. An important area of future research is the quantification of the carbon and nitrogen cycles at the field scale, especially nitrous oxide emissions. This approach will need to be tested in the field, but the initial analysis shows promise for developing a sustainable bioenergy infrastructure without significant changes in existing processes.

Acknowledgments

Funding from the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy is gratefully acknowledged.

Supporting Information Available

Four figures show all streams and roads and spatial distribution of all livestock operations and municipal wastewater treatment plants in Nebraska. Three tables list the marginal land resources for Nebraska, energy contribution from biomass using marginal land resources, and land and feedstock availability within a 25 mi radius for an example biorefinery. This material is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

(1) Ruth, L. Bio or bust? *EMBO Rep.* **2008**, *9*, 130−133.
(2) Sustainable Bioenergy: A Framework for Decision Makers. United Nations, 2007. http://esa.un.org/un-energy/pdf/susdev.Biofuels.FAO.pdf.
(3) Sustainable Biofuels: Prospects and Challenges. The Royal Society, 2008. http://royalsociety.org/document.asp?tip=1=7366.
(4) Johansson, D. J.; Azar, C. A scenario-based analysis of land competition between food and bioenergy production in the United States. *Climatic Change.* **2007**, *82* (3−4), 267–291.
(5) Robertson, P. G.; Dale, V. H.; Doering, O. C.; Hamburg, S. P.; Melillo, J. M.; Wander, M. M.; Parton, W. J.; Adler, P. A.; Barney, J. N.; Cruse, R. M.; Duke, C. S.; Fearnside, P. M.; Follett, R. F.; Gibbs, H. K.; Goldemberg, J.; Mladenoff, D. J.; Ojima, D.; Palmer, M. W.; Sharpley, A.; Wallace, L.; Weathers, K. C.; Wiens, J. A.; Wilhelm, W. W. Sustainable biofuels redux. *Science.* **2008**, *322*, 49–50.
(6) Hill, J.; Nelson, E.; Tilman, D.; Polasky, S.; Tiffany, D. Environmental, economic and energetic costs and benefits of biodiesel and ethanol biofuels. *Proc. Natl. Acad. Sci. U.S.A.* **2006**, *103* (30), 11206–11210.
(7) Tilman, D.; Hill, J.; Lehman, C. Carbon-negative biofuels from low-input high diversity grassland biomass. *Science.* **2006**, *314*, 1598–1600.
(8) Campbell, J. E.; Lobell, D. B.; Genova, R. C.; Field, C. B. The global potential of bioenergy on abandoned agricultural lands. *Environ. Sci. Technol.* **2008**, *42* (15), 5791–5794.
(9) Schmer, M. R.; Vogel, K. P.; Mitchell, R. B.; Perrin, R. K. Net energy of cellulosic ethanol from switchgrass. *Proc. Natl. Acad. Sci. U.S.A.* **2008**, *105* (2), 464–469.
(10) Lemus, R.; Lal, R. Bioenergy crops and carbon sequestration. *Crit. Rev. Plant Sci.* **2005**, *24*, 1–21.
(11) Huo, H.; Wang, M.; Bloyd, C.; Putsche, V. Life-cycle assessment of energy use and greenhouse gas emissions of soybean-derived biodiesel and renewable fuels. *Environ. Sci. Technol.* **2009**, *43* (3), 750–756.
(12) Righelato, R.; Spracklen, D. V. Environment: Carbon mitigation by biofuels or by saving and restoring forests. *Science.* **2007**, *317*, 902–904.
(13) Fargione, J.; Hill, J.; Tilman, D.; Polasky, S.; Hawthorne, P. Land clearing and the biofuel carbon debt. *Science.* **2008**, *219*, 1235–1238.
(14) Searchinger, T.; Heimlich, R.; Houghton, R. A.; Dong, F.; Elobeid, A.; Fabiosa, J.; Tokgoz, S.; Hayes, D.; Yu, T.-H. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science.* **2008**, *319* (5867), 1238–1240.
(15) Kim, H.; Kim, S.; Dale, B. E. Biofuels, land use change, and greenhouse gas emissions: Some unexplored variables. *Environ. Sci. Technol.* **2009**, *43* (3), 961–967.
(16) *Water Implications of Biofuels Production in the United States*; National Research Council, National Academy Press: Washington, DC, 2008; http://www.nap.edu/catalog/12039.html.
(17) Berndes, G. Bioenergy and water: The implications of large-scale bioenergy production for water use and supply. *Global Environ. Change.* **2002**, *12*, 253–271.
(18) Perlack R. D.; Wright L. L.; Turhollow A. F.; Graham R. L.; Stokes B. J.; Erbach D. C. *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply*; Technical Report A357634; Oak Ridge National Laboratory: Oak Ridge, TN, 2005.
(19) Linderson, M. L.; Iritz, Z.; Lindroth, A. The effect of water availability on stand-level productivity, transpiration, water use efficiency, and radiation use efficiency of field grown willow clones. *Biomass Bioenergy* **2007**, *31*, 460–468.
(20) Turner, R. E.; Rabalais, N. N.; Justic, D. Gulf of Mexico hypoxia: Alternate states and a legacy. *Environ. Sci. Technol.* **2008**, *42* (7), 2323–2327.
(21) Crutzen, P. J.; Mosier, A. R.; Smith, K. A.; Winiwarter, W. N_2O release from agro−biofuel production negates global warming reduction by replacing fossil fuels. *Atmos. Chem. Phy.* **2008**, *8*, 389–395.
(22) Smeets, E. M. W.; Bouman, L. F.; Stehfest, E.; Van Vuuren, D. P.; Posthuma, A. Contribution of N_2O to the greenhouse gas balance of first-generation biofuels. *Glob. Change Biol.* **2009**, *15*, 1–23.
(23) Bouman, A. F. Direct emission of nitrous oxide from agricultural soils. *Nutr. Cycling Agroecosyst.* **1996**, *46*, 53–70.
(24) Heaton, E.; Dohleman, F.; Long, S. Meeting U.S. biofuel goals with less land: The potential of miscanthus. *Glob. Change Biol.* **2008**, *14*, 2000–2014.
(25) Barney, J.; DiTomaso, J. Non-native species and bioenergy: Are we cultivating the next invader? *Bioscience* **2008**, *58*, 64–70.
(26) Wilhelm, W. W.; Johnson, J. M. F.; Karlen, D. L.; Lightle, D. T. Corn stover to sustain soil organic carbon further constrains biomass supply. *Agron. J.* **2007**, *99*, 1665.
(27) Graham, R. L.; Nelson, R.; Sheehan, J.; Perlack, R. D.; Wright, L. L. Current and potential U.S. corn stover supplies. *Agron. J.* **2007**, *99*, 1–11.
(28) Borjesson, P.; Berndes, G. The prospects for willow plantations for wastewater treatment in Sweden. *Biomass Bioenergy* **2006**, *30*, 428–438.
(29) Morschel, J.; Fox, D. M.; Bruno, J.-F. Limiting sediment deposition on roadways: Topographic controls on vulnerable roads and cost analysis of planting grass buffer strips. *Environ. Sci. Policy* **2004**, *7*, 39–45.
(30) Liu, X.; Zhang, X.; Zhang, M. Major factors influencing the efficacy of vegetated buffers on sediment trapping: A review and analysis. *J. Environ. Qual.* **2008**, *37*, 1667–1674.
(31) Corwin, D. L.; Bradford, S. A. Environmental impacts and sustainability of degraded water reuse. *J. Environ. Qual.* **2008**, *37*, S1–S7.
(32) Bradford, S. A.; Segal, E.; Zheng, W.; Wang, Q.; Hutchins, S. R. Reuse of concentrated animal feeding operation wastewater on agricultural lands. *J. Environ. Qual.* **2008**, *37*, S97–S115.
(33) Cropland Data Layer, United States. U.S. Department of Agriculture, National Agricultural Statistics Service2007. http://datagateway.nrcs.usda.gov/.

(34) Interpretative Maps and Data for Nebraska. Nebraska Department of Environmental Quality (NDEQ), 2008. http://deqims.deq.state.ne.us/DEQ/.

(35) Sanchez, O. J.; Cardona, C. A. Trends in biotechnological production of ethanol from different feedstocks. *Bioresour. Technol.* **2008**, *99*, 5270–5295.

(36) Khanna, M.; Dhungana, B.; Clifton-Brown, J. Costs of producing miscanthus and switchgrass for bioenergy in Illinois. *Biomass Bioenergy* **2008**, *32*, 482–493.

(37) *Land Use for Land Enrolled in the Conservation Reserve Program*; Nebraska Farm Service Agency: Omaha, NE, 2008.

(38) *State Energy Data Report*; Nebraska Energy Office: Lincoln, NE, 2008. http://www.neo.ne.gov/statshtml/92.htm.

(39) Collins, D. B. G.; Bras, R. L. Plant rooting strategies in water-limited ecosystems. *Water Resour. Res.* **2007**, *43*, 1–10.

(40) Rupert, M. G. Decadal-scale changes of nitrate in ground water of the United States: 1988−2004. *J. Environ. Qual.* **2008**, *37*, S-240–S-248.

(41) *Development Document for the Proposed Revisions to the National Pollutant Discharge Elimination System Regulation and the Effluent Guidelines for Concentrated Animal Feeding Operation (CAFOs)*; Rep. 821-R-01-003; U.S. Environmental Protection Agency: Washington, DC, 2001.

(42) Heller, M. C.; Keoleian, G. A.; Volk, T. A. Life cycle assessment of a willow bioenergy cropping system. *Biomass Bioenergy* **2003**, *25*, 147–165.

(43) *In Situ Bioremediation: When Does It Work*? National Research Council, National Academy Press, Washington, DC, 1993.

(44) Dodds, W. K.; Bouska, W. W.; Eitzmann, J. L.; Pilger, T. J.; Pitts, K. L.; Riley, A. J.; Schloesser, J. T.; Thornbrugh, D. J. Eutrophication of U.S. freshwaters: Analysis of potential economic damages. *Environ. Sci. Technol.* **2009**, *43* (1), 12–19.

(45) McCutcheon S. C.; Schnoor J. L. *Phytoremediation: Transformation and Control of Contaminants*; Wiley−Interscience, Inc.: Hoboken, NJ, 2003.

(46) Mosier, A. R.; Duxbury, J. M.; Freney, J. R.; Heinemeyer, O.; Minami, K. Assessing and mitigating N_2O emissions from agricultural soils. *Clim. Change.* **1998**, *40*, 7–38.

(47) Pierce, R. A.; Farrand, D. T.; Kurtx, W. B. Projecting the bird community response resulting from the adoption of shelterbelt agroforestry practices in eastern Nebraksa. *Agroforestry Sys.* **2001**, *53*, 333–350.

ES900801U