A Novel Framework to Classify Marginal Land for Sustainable Biomass Feedstock Production

Gayathri Gopalakrishnan,* M. Cristina Negri, and Seth W. Snyder

To achieve food and energy security, sustainable bioenergy has become an important goal for many countries. The use of marginal lands to produce energy crops is one strategy for achieving this goal, but what is marginal land? Current definitions generally focus on a single criterion, primarily agroeconomic profitability. Herein, we present a framework that incorporates multiple criteria including profitability of current land use, soil health indicators (erosion, flooding, drainage, or high slopes), and environmental degradation resulting from contamination of surface water or groundwater resources. We tested this framework for classifying marginal land in the state of Nebraska and estimated the potential for using marginal land to produce biofuel crops. Our results indicate that approximately 1.6 million ha, or 4 million acres, of land (~8% of total land area) could be classified as marginal on the basis of at least two criteria. Second-generation lignocellulosic bioenergy crops such as switchgrass (*Panicum virgatum* L.), miscanthus (*Miscanthus giganteus*), native prairie grasses, and short-rotation woody crops could be grown on this land in redesigned landscapes that meet energy and environmental needs, without significant impacts on food or feed production. Calculating tradeoffs between the economics of redesigned landscapes and current practices at the field scale is the next step for determining functional designs for integrating biofuel feedstock production into current land management practices.

Landscapes are largely defined by the uses and relationships between people and the environment. Land provides ecological support for native plants and wildlife, sustains ecosystem services, nurtures crops that satisfy human needs for food, feed, fuel, and fiber, and provides physical support for residential, industrial and commercial activities and infrastructure. Social and economic forces influence how land is allocated to the different uses (Dale et al., 2010). Recently, using land to grow crops for bioenergy has become increasingly important in many countries, including the United States. Questions about the availability of land on a global or national scale that can be repurposed for bioenergy and the impacts of such a large-scale conversion on social, economic, and environmental systems have been raised (UN-Energy, 2007; Royal Society, 2008). Developing a sustainable framework for bioenergy has focused on the use of marginal lands to minimize potential food versus fuel conflicts and negative environmental impacts in the form of biodiversity losses, water quality and quantity impacts, and potential increases in greenhouse gas emissions resulting from indirect land-use change.

Some researchers (Campbell et al., 2008; Perlack et al., 2005) have suggested that sufficient marginal farmland is available that can be used for energy crop production without significantly impacting current land uses. Marginal farmland, as defined by these researchers, includes idle or fallow cropland, abandoned farmland, and abandoned pastureland. Campbell et al. (2008) suggested that about 384 to 471 million ha (950 to 1165 million acres) are available globally while approximately 56 to 60 million ha (140 to 150 million acres) could be targeted within the United States. Converting this land to bioenergy crop production could produce 1.4 to 2.1 billion tonnes of biomass globally, with approximately 15% produced in the United States alone. Other types of marginal land have been targeted for energy crop production. Perlack et al. (2005) hypothesized that land currently enrolled in conservation programs in the United States could be utilized for energy crop production. Tilman et al. (2006) suggested the use of native prairie grasses as energy crops which would enable lands converted to bioenergy purposes to meet conservation needs as well. Other researchers have suggested using energy crops to meet energy and environmental requirements by redesigning landscapes to incorporate multifunctionality (Gopalakrishnan et al.,

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*Corresponding author (ggopalakrishnan@anl.gov).
© ASA, CSSA, SSSA
5585 Guilford Rd., Madison, WI 53711 USA

Energy Systems Division, Argonne National Lab., 9700 S. Cass Ave., Argonne, IL 60439.
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Abbreviations: CRP, Conservation Reserve Program; ESRI, Environmental Systems Research Institute; NASS, National Agricultural Statistics Service; NDEQ, Nebraska Department of Environmental Quality.

2009; Karlen, 2010). Gopalakrishnan et al. (2009) presented the concept of using bioenergy crops grown in buffer strips on marginal land near rivers and roadways to capture pollutants and reuse nutrients present in the runoff. A significant area of uncertainty in all of these studies arises from the classification and quantification of marginal land.

The definition of *marginal land* varies widely by country, local conditions, and the organization studying the issue (Dale et al., 2010). Peterson and Galbraith (1932) first defined marginal land from a purely economic perspective as land on the "margins of cultivation." This included the "poorest land which can be remuneratively operated under given price, cost and other conditions." In practice, this term has been broadly used to describe lands that are not under current productive use as opposed to lands that are generating a net profit. In Indonesia, for example, marginal lands include swamplands, wetlands, and peat forests that are currently unproductive from an agroeconomic standpoint but provide carbon sequestration and other environmental benefits (Rossi and Lambrou, 2008). In general, marginality is defined or implied as relative to the agroeconomic profit that could be derived by growing a major crop. Valuation of other potential functions is not currently part of the definition of marginality.

With the establishment of the Conservation Reserve Program (CRP) in the United States, the definition of marginal land broadened to incorporate soil health considerations. Moulton and Richards (1990) defined marginal lands as those lands where the "soil is eroding at a faster rate." For example, land currently enrolled in the CRP is land that has typically been categorized as "highly erosion prone and/or providing valuable conservation benefits" (Lovell and Sullivan, 2006). In recent years, soil productivity indices and erosion indices have been used to better classify land as marginal or not (Larson et al., 1998). Soil productivity indices have been developed by classifying the natural constraints to soil productivity into three major groups (Mueller et al., 2010). The first group of constraints includes the thermal and moisture regimes of the soil; hence, low-productivity soils are first classified on the basis of limitations such as drought, wetness, or a too short vegetation period (Fischer et al., 2002). The second group of constraints includes other internal soil deficiencies that limit the rooting and nutrition of plants and hence their productivity. This includes areas with shallow or stony soils, acidic or saline soils, soils with nutritional deficiencies, or other adverse chemical conditions (Murray et al., 1983; Louwagie et al., 2009). The third group of constraints incorporates topography, which could include soils that are highly erodible, sloped, and/or inaccessible by humans or their machinery (Fischer et al., 2002; Mueller et al., 2010).

Still, these definitions focus on marginality of soil from the perspective of the agroeconomic profit of traditional crops (e.g., grain) grown using current agricultural practices. These definitions fail to acknowledge that land use and quality may change across function, space, and time, with the qualities that make land marginal in one place or for one purpose resulting in land being in fact productive in another location or for a different purpose (Dale et al., 2010). An example is the use of tile drains in the midwestern states of the United States to enable agricultural production. Before the use of tile drains, the land was poorly drained and suitable for indigenous prairie plants and unsuitable for corn (*Zea mays* L.) and other grains because of the lack of drainage. The installation and use of tile drains enabled large-scale production of grain crops, most notably corn and soybean [*Glycine max* (L.) Merr.]. Finally, the increased use of irrigation and fertilization practices in the middle of the 20th century has resulted in lands that were formerly considered marginal to become agroeconomically productive.

Practices that increase land productivity have frequently resulted in significant environmental degradation. Degraded water quality is attributed to increased use of fertilizers (N, P, K) and pesticides that contaminate surface and groundwater (Bennett et al., 2001; Matson et al., 1997; Pimm and Raven, 2000). A key example is the increased size of the hypoxic zone ("dead zone") in the Gulf of Mexico, attributed to nitrate from the Mississippi River Basin (Turner et al., 2008). Water demands associated with agriculture account for approximately 85% of the global water use (Gleick, 2003), and overextraction of groundwater resources due to irrigation requirements is a concern in many parts of the world (Postel, 1992; Tilman et al., 2002). In the United States, irrigation accounts for approximately 50% of water withdrawals and an even larger fraction of consumptive water use (Hutson et al., 2005). Thus, as environmental concerns now form an important component of land use, the definition of marginal land would need to encompass causative environmental degradation directly or through the land–water interface. The externalities of modern agriculture are present in varying degrees on the basis of location and agricultural practices. Locations where impacts of agriculture on ecosystems (primarily water resources) are significant could be classified as marginal from the environmental perspective, even though they may be productive from an agroeconomic standpoint.

While bioenergy has the potential to be environmentally and socially disruptive in rural communities, it could also form the basis for designing multifunctional landscapes that provide sustainable economic development and provide ecosystem services. In comparison to grain crops, cellulosic crops have been reported to be less dependent on irrigation and fertilization (Tilman et al., 2006). In the correct system, they provide associated discharge water quality benefits if they capture and utilize nutrients. Many biofuel crops are also suitable to grow in land that would be marginal, or subproductive for major agricultural crops. One key feature in designing these landscapes is to develop methods that can identify land that is marginal for conventional crops but not marginal for biofuel crops or other functions, based on economic, soil health, and environmental criteria. Current definitions of marginality have focused on a single criterion. Our objective is to develop an approach that explicitly incorporates all three criteria (current land use, soil health, and environment degradation) to identify marginal land and to test this approach for the state of Nebraska. Nebraska was selected as an example because it has a significant agricultural sector, critical environmental issues (groundwater NO_3–N), and an emerging bioenergy industry that could result in changes in land use and landscape design.

Materials and Methods

Satellite imagery was used to identify and quantify land resources in different categories of marginality. While concerns exist about database errors and incorrect classification of land resources using satellite imagery, this method remains the most widely accepted to date to explore land use and land classification at the state and regional scales.

The geographic information software ArcGIS v9.2 produced by Environmental Systems Research Institute (ESRI) was used to develop the spatial maps of current land use and marginal land categories and to determine the dimensions and area of these resources. The availability and spatial distribution of these resources was mapped for the state of Nebraska. Overlap between the different categories was determined using ArcGIS.

Identification of Marginal Land Resources on the Basis of Soil Health

The USDA–NRCS developed a soil database, STATSGO, to classify land quality. The STATSGO is available on the USDA–NRCS website (http://soildatamart.nrcs.usda.gov/) and was developed primarily for "regional, multistate, river basin, State and multi-county resource planning, management and monitoring" (USDA–NRCS, 1991). The smallest unit of a STATSGO map is called a *mapunit* with a minimum area of 617 ha (1544 acres). This mapunit represents a unique natural arrangement and includes a typical pattern of soil series within its boundaries (USDA–NRCS, 1991). Each mapunit can have a maximum of 21 components (e.g., land quality, rainfall, temperature, soil erodibility, flooding frequency, and topography). A detailed list of the components attached to each mapunit is presented in the STATSGO database summary report (USDA–NRCS, 1991).

In this study, we define marginal land on the basis of soil health criteria as land that is (i) eroded, (primarily moderately and severely eroded), (ii) frequently flooded (>50% chance of flooding in a year), (iii) poorly drained (soil drainage classes 6 and 7), (iv) highly sloped (slope >15°], and (v) of low productivity for the main grain crop (nonirrigated yields of corn <9 tonnes/ha (4 tons/acre), which is approximately 25% of the maximum yields obtained for the state of Nebraksa [USDA–NRCS, 1991]). These criteria were selected as they are prominent factors impacting soil health assessments (Mueller et al., 2010).

Identification of Marginal Land Resources on the Basis of Current Land Use

The most recent data from the 2007 land-use database developed by the USDA, National Agricultural Statistics Service (NASS) and the USDA–NRCS was used to map current land-use patterns (USDA 2007). This database is a raster, georeferenced, crop-specific land-cover data layer with a ground resolution of 56 m produced from satellite imagery for the most recent growing season. The main categories of current land use in Nebraska are rangeland, cropland, grass and pasture land, wetlands, and fallow and idle croplands including CRP land.

Recent suggestions on redesigning landscapes to incorporate sustainable bioenergy crop production on the basis of areas where land is of marginal use include (i) using idle and fallow cropland, including CRP land (Perlack et al., 2005) and (ii) growing the crops in buffer strips along roadways and rivers and streams (Gopalakrishnan et al., 2009). These two categories are used here to define marginal land that could potentially be used for bioenergy crop production.

The river and road networks were mapped using data from the USDA–NASS and ESRI databases (http://www.esri.com/software/arcgis/index.html) for Nebraska. We estimated the available area for riparian and roadway buffer strips from the length of the roads and rivers 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 the plant species used (Borjesson and Berndes, 2006; Bradford et al., 2008). This study assumes strip widths ranging from 10 to 50 m to achieve 50 to 95% reduction in the concentrations of nutrients, pesticides, and sediments from runoff (Corwin and Bradford, 2008; Bradford et al., 2008).

Identification of Marginal Land Resources on the Basis of Environmental Degradation

Multiple considerations could lead to land being classified as environmentally degraded or contributing to degradation. Examples include land that was once part of a protected ecosystem (such as tropical rainforests) but that has been altered to a different use, land that is impacted by invasive species, land that has been contaminated by chemicals or wastes, and land for which the impacts of agriculture on ecosystems, primarily water resources, are significant. Approximately 92% of the land area in Nebraska is in the agricultural sector, and there are very few protected ecosystems in the state (USDA, 2002). However, large-scale agricultural production has also led to contamination of surface and groundwater resources by agricultural chemicals and depletion of the aquifers, especially the Ogallala aquifer (McGuire et al., 2003). The Ogallala aquifer, also known as the High Plains aquifer, covers an area of approximately 45 million ha (174,000 square miles) and is located in Nebraska, South Dakota, Wyoming, Colorado, Kansas, Oklahoma, New Mexico, and Texas. It is an unconfined aquifer and comprises primarily unconsolidated gravel, silt, sand and clay and supplies approximately 30% of the groundwater used in the USA for irrigation (McGuire et al., 2003).

We focus on three factors that have a significant impact in Nebraska to identify environmentally degraded ecosystems where the land directly or the land–water interface is impacted. These factors are (i) brownfield sites consisting of land that has been contaminated with chemicals from prior industrial use, (ii) land where surface water resources (rivers and streams) or groundwater resources are contaminated, and (iii) land where irrigation is significant and could lead to depletion of water resources.

The location of all brownfield sites for 2007 was determined from data produced by the Nebraska Department of Environmental Quality (NDEQ) and is presented in the Supplemental Material (Supplemental Fig. S4) (NDEQ,

2008). The location of surface water bodies where the water quality is sufficiently degraded so that human contact should be avoided (not "swimmable, fishable or drinkable") was determined using the database generated by the USEPA (2002). The area consisting of impaired rivers and streams was estimated using the length of the rivers and streams and buffer widths of 10 to 50 m described previously.

Nitrate is a widespread contaminant in groundwater in Nebraska as a result of fertilizer use by the agricultural sector. Groundwater samples are described as nitrate contaminated when levels exceed 10 mg L^{-1}, the USEPA-mandated drinking water limit. We focus on nitrate-contaminated groundwater in this study as nitrate also serves as a nutrient for bioenergy crops. We developed a spatial map of areas with nitrate-contaminated groundwater ($[NO_3^-] \geq 10$ mg L^{-1}) using data produced in 2005 from monitoring wells, the year that the largest available database was collected (NDEQ, 2007). However, groundwater monitoring data were not available for all areas of the state. The USGS has published a calibrated and validated logistic regression model estimating the probability of nitrate contamination in shallow groundwater. This model uses N inputs to the aquifer (e.g., inorganic fertilizers, manure, atmospheric deposition of N, residential fertilizers, septic systems, and domestic animal waste in urban areas) in combination with soil drainage (e.g., well-drained soils, presence or absence of rock features, depth to seasonally high water table), and land-use properties (e.g., percent of cropland-pasture, human population density) to predict the probability of nitrate concentrations being greater than 4 mg L^{-1} in shallow groundwater (water table < 1.5 m [5 feet] below ground surface) (USGS, 2002). We combined the database developed by NDEQ with model results from the USGS model (Fig. 1). Areas in which nitrate concentrations in monitoring wells were found to be ≥10 mg L^{-1} were areas where the probability of nitrate contamination as predicted by the USGS model was ≥0.8. Thus, in areas where monitoring well data were unavailable, we use the USGS model to estimate the area where there is a high probability (>0.8) of nitrate contamination of the underlying groundwater, resulting in significant environmental degradation (USGS, 2002).

Irrigation could potentially cause overexploitation of water resources and contamination of groundwater aquifers. Approximately 43% of the total harvested cropland in Nebraska is irrigated (USDA, 2002). Approximately 80% of the irrigated land receives irrigation water from groundwater alone, primarily from the High Plains or Ogallala aquifers (McGuire et al., 2003). These withdrawals have resulted in declines in the water table in parts of the aquifer as well as increases in groundwater pollution as a result of nutrients leaching into the aquifers (McGuire et al., 2003). The area of irrigated cropland for Nebraska was calculated using data generated by the USDA (2002); spatial distribution of irrigated areas was not available at a higher level of precision than individual counties. We further assume that if the nonirrigated corn yield is low (<9 tonnes/ha [4 tons/acre]), then that area would necessarily be irrigated by the farmer to maintain profitability.

Results and Discussion

The spatial distribution of marginal land categories for the state of Nebraska is presented in Fig. 1, for soil health, land use, and environmental categories, respectively. The availability of marginal land for each category is presented in Table 1. The overlap between the different categories could help identify land that is suitable for producing sustainable biofuel crops that could provide environmental services while meeting energy needs.

The distribution of marginal land categories based on soil health criteria is shown in Fig. 1a and Table 1a, with individual categories presented in Supplemental Fig. S1–S3. Areas with eroded soil and areas where the nonirrigated yield of corn was poor formed the largest categories, comprising approximately 0.64 million ha (1.6 million acres) each, followed by land classified as poorly drained at 0.5 million ha (1.25 million acres). Approximately 2 million ha (5 million acres) were determined to be marginal land based on the soil health criteria. However, as shown in Fig. 1a, there is significant overlap between the different categories. Approximately 48% of the area classified as eroded land was also highly sloped. Similarly, approximately 30% of the land classified as poorly drained was also classified as frequently flooded. The use of tile drains in these areas improves drainage and hence ensures agricultural productivity, even though the land is classified as marginal on the basis of soil health. This study has focused on five components classifying land as marginal based on soil health; other factors may become important in different states and countries and would need to be included.

The land-use and land-cover map for the state of Nebraska and estimated areas for marginal land based on land use were previously quantified by Gopalakrishnan et al. (2009) and are presented in Fig. 1b and Table 1b. Approximately 1.24 to 3.64 million ha (3.1–9.1 million acres) could be classified as marginally economically productive for grains (corn). Marginal agricultural land comprises approximately 0.6 million ha (1.5 million acres) of land that is unproductive (idle or fallow cropland) but not enrolled in CRP, as well as land that is enrolled in CRP. Vegetated buffer strips along roadways which range between 0.4 and 2 million ha (1 and 5 million acres) based on buffer width (Gopalakrishnan et al., 2009), are currently not economically productive and have significant costs associated with maintenance (NCHRP 2005). Riparian buffer strips may be enrolled in CRP or be unproductive or be part of other land-use categories such as rangeland or cropland. This land may or may not be economically marginal depending on yields of existing crops, rental payments from CRP, and other potential uses such as hunting or fishing.

Land that is environmentally marginal as defined earlier is presented in Fig. 1c, with estimated areas given in Table 1c. Approximately 12 million ha (30 million acres) could be classified as environmentally marginal, with areas associated with nitrate-contaminated groundwater comprising approximately 8.4 million ha (21 million acres) and irrigated cropland consisting of approximately 3.2 million ha (8 million acres). This land constitutes the vast majority of Nebraska's cropland and thus highlights the tradeoffs between increased environmental impacts and maintaining agricultural productivity on the same land. This also highlights the importance

of identifying and classifying land as marginal using a broader set of criteria than only economic productivity. While nitrate is used as the contaminant of concern in this study due to the potential for reuse as a nutrient by energy crops, other contaminants (e.g., pesticides) could be included in future studies when defining environmentally marginal land. Brownfields were found to be insignificant for Nebraska, consisting of <20,000 ha (50,000 acres), but could be important in other states. Approximately 0.01 to 0.06 million ha (0.03–0.14 million acres) of land were found adjacent to rivers and streams that were classified as impaired by the USEPA. However, this area is a function of the buffer width estimated around these surface water bodies and could vary significantly depending on conditions in the field. There was significant overlap between land where the surface water was impaired and areas with nitrate-contaminated groundwater. Approximately 94% of the land with impaired surface water was also found to have contaminated groundwater resources.

Results presented in Table 1 indicate that a maximum of 16 million ha (40 million acres) of land could be classified as marginal in Nebraska, with approximately 1.6 million ha (4 million acres) identified as marginal based on two criteria (Table 1d). Overlap was present between the different marginal land categories shown in Table 1d. For example, land that was eroded and marginally productive for agricultural land was frequently highly sloped as well. Similarly, land in riparian buffer strips was often poorly drained and frequently flooded.

As shown in Table 1, land that is environmentally marginal comprised the largest fraction of marginal land. Clearly, conflicts exist between the three different categories used to define marginal land and emerge when the definition for marginality is broadened in scope. For example, land where the groundwater is contaminated with nitrate or the streams are impaired is also land that is productive for corn using modern irrigation and fertilization methods. In this case, land that is environmentally

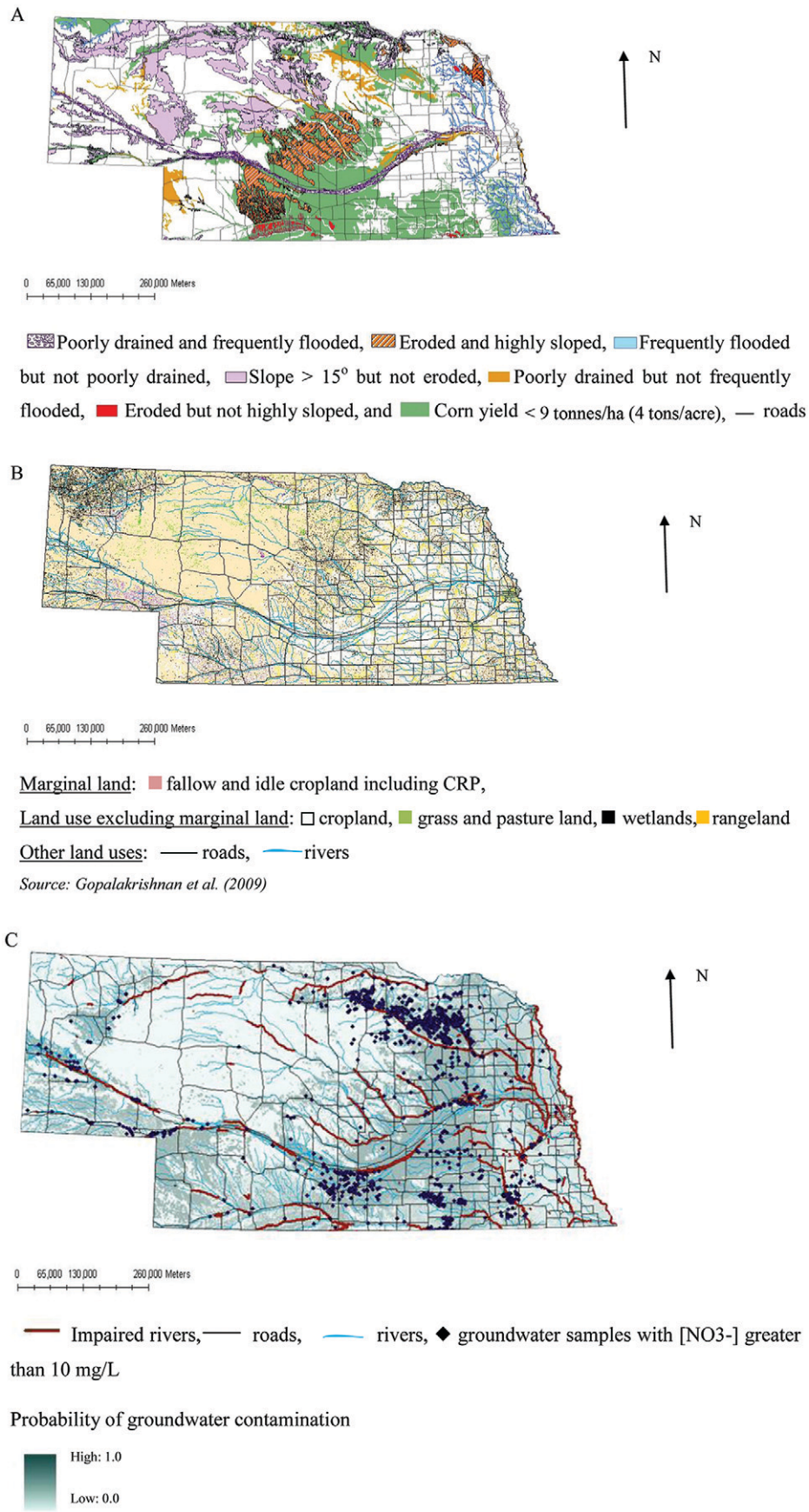

Fig. 1. Spatial distribution of marginal land in Nebraska based on (a) soil health, (b) current land use, and (c) environmental degradation criteria. Spatial distribution data were unavailable for irrigated cropland.

marginal is important for food or feed production. Tradeoffs between existing land use and management practices and developing alternative practices to redesign the landscape need to be developed.

There is significant overlap between all three categories used to define marginal land in the eastern half of the state, where corn and soybeans are the main crops. Approximately 20% of this area consists of land with relatively low corn productivity, eroded land, and frequently flooded land and would thus be economically marginal for grain production. Groundwater in this area is also contaminated with nitrate, and the rivers and streams are impaired. This area could potentially be targeted first for bioenergy crop production using second-generation lignocellulosic crops such as switchgrass (*Panicum virgatum* L.), miscanthus, and short-rotation woody crops that are expected to have limited environmental impacts (Tilman et al., 2006; Schmer et al., 2008). Gopalakrishnan et al. (2009) indicated that between 0.2 and 0.8 million ha (0.5–2 million acres) of land could be converted to energy crop production through the use of riparian buffer strips. As indicated in Fig. 1a, approximately 0.2 and 0.72 million ha (0.5–1.8 million acres) of land along the streams and rivers is classified as frequently flooded or poorly drained and hence marginal. This is land where corn may have low productivity (Lovell and Sullivan, 2006; USDA–NRCS, 1991) but that could be productive for short-rotation woody energy crops such as willow (*Salix* spp.) and poplar (*Populus* spp.) trees that are adapted to riparian environments. Furthermore, these energy crops could filter and reuse agricultural nutrients in the runoff from farm fields, thus improving water quality and providing environmental services. This would enable the farmer to use the land productively while simultaneously meeting energy and environmental needs. Because this area has relatively low corn productivity, losses in grain production as a result of this land-use change would probably be insignificant. However, the tradeoff between current and new land uses in terms of revenue at the farm scale and environmental services and indirect land-use change effects at the larger scale needs to be quantified.

Other areas exist where overlap occurs between two of the categories used to classify land as marginal. Approximately 52% of eroded land is also categorized as marginal agricultural land (idle and fallow cropland and CRP land). Most areas classified as frequently flooded were found near rivers and streams (Supplemental Fig. S3) and could be used in riparian buffer strips. Approximately 28% of rivers and streams in Nebraska are impaired and thus could be classified as environmentally degraded. Land in riparian buffer strips associated with these impaired streams could also be classified as land that is marginally productive for grain crops. Approximately 40% of the area with low corn yield overlaps with areas with nitrate-contaminated groundwater.

Areas with farmland classified as idle or fallow cropland, including land enrolled in CRP, are found primarily in the western and southern sections of the state (Fig. 1). Approximately

Table 1. Estimates of marginal land in Nebraska based on (a) soil health, (b) current land use, (c) environmental degradation, and (d) overlap between 2 criteria.†

Marginal land	Estimated area‡
	million ha (million acres)
a. Marginal land based on soil health criteria	
Eroded	0.66 (1.64)
Poorly drained	0.50 (1.25)
Slope > 15°	0.35 (0.88)
Corn yield < 9 tonnes/ha (4 tons/acre)	0.64 (1.60)
Frequently flooded	0.20 (0.49)
b. Marginal land based on current land-use criteria	
Marginal agricultural land, including CRP land§	0.60 (1.5)
Riparian buffer strips	0.24–1 (0.6–2.5)
Roadway buffer strips	0.4–2.04 (1.0–5.1)
c. Marginal land based on environmental degradation criteria	
Impaired streams buffer strips	0.01–0.06 (0.03–0.14)
Area with nitrate-contaminated groundwater	8.4 (21)
Brownfield sites	<0.20 (0.05)
Irrigated cropland	3.44 (8.60)
d. Marginal land based on 2 criteria¶	
Eroded and highly sloped	0.32 (0.79)
Poorly drained and frequently flooded	0.15 (0.38)
Eroded and marginal agricultural (idle and fallow cropland, including CRP)	0.31 (0.78)
Poorly drained and riparian buffer strips	0.49 (1.23)
Impaired streams and riparian buffer strips	0.06 (0.14)
Low corn yield and irrigated land	0.64 (1.60)
Low corn yield and nitrate-contaminated groundwater	0.26 (0.66)

† Source: Gopalakrishnan et al. (2009).

‡ Estimated area of buffer strips are given as a range based on strip widths of 10 or 50 m, respectively.

§ CRP, Conservation Reserve Program.

¶ Overlaps are present between the categories listed in this section.

40% of this land overlaps with the eroded and highly sloped soil health criteria. The CRP program has been successful in mitigating erosion and improving soil health by enrolling vulnerable land in these categories. In this area, perennial grasses may prove to be of interest as an energy crop as they have the potential to meet conservation and energy goals simultaneously. Bioenergy production could aid in meeting the fiscal goals of the CRP program. However, differences between energy prices and CRP rental rates and the tradeoffs between revenue, conservation, and energy goals need to be evaluated at the farm scale.

As shown in Fig. 1b, approximately half of the state's farmland consists of pastureland and rangeland, a land-use category found primarily in the western half of the state. Approximately 68% of this area has also been shown to be highly sloped (Fig. 1a). It may be feasible to include rotation between pasture and energy crop production using perennial grasses and/or short-rotation woody crops on these lands. This would enable reuse of the manure from livestock by the energy crops and thus improve crop productivity while mitigating environmental impacts from livestock production. It would also provide ranchers with an alternative income stream from energy crop production and hence be of use in revitalizing rural communities. By growing energy crops in riparian rangeland, some of the environmentally riskiest practices (e.g., allowing cattle to graze at the edge of water bodies) could be avoided. However, the economic benefits of changing land use under these circumstances need to be further evaluated.

As concerns about energy and water use in agriculture and impacts from climate change become increasingly important, the tradeoff between current land uses and agricultural practices and new landscape designs may be relevant. For example, a possible scenario may arise where the continued use of energy and water in irrigating crops becomes unsustainable. In such a case, it may become prudent to redesign the landscape to grow perennial grasses and/or short-rotation woody crops for energy purposes where irrigation is unsustainable and to maintain food production in productive land that can support it. The tradeoff between energy and environmental costs on one hand and new landscape designs on the other would become more apparent and would need to be further explored.

This study highlights the limitations and benefits in landscape management of using multiple criteria to define marginal land. One limitation of this approach is the use of satellite imagery and databases with different resolutions to classify marginal land. The STATSGO database has a mapunit with an area of 617 ha (1544 acres) as the smallest unit. While the mapunit may be classified as eroded or poorly drained, determining the spatial location of the eroded or poorly drained land within the mapunit is not possible using this database. Finer-resolution databases are needed to verify this information at the field scale, but these databases (e.g., the USDA's SSURGO database) are not as complete at larger scales and hence cannot be used for analysis at the state or regional scale. Additionally, the USDA database for land use has a resolution scale of 56 m, which is significantly less than the resolution required to evaluate the placement of buffer strips 10 to 50 m in width. Further, the use of satellite imagery itself to classify land is problematic as land may be only temporarily fallow, may have been recently cleared, or may be being used in nontraditional ways, which can lead to errors in land classification. Better integration of the different datasets and field-scale verification of the results presented here are necessary to improve the classification and quantification of marginal land and in developing strategies to integrate bioenergy crops into the landscape.

In addition, social and cultural considerations, which have not been evaluated in this study, will need to be taken into consideration when determining what constitutes marginal land in other countries. Marginal lands often provide key subsistence functions for the rural poor through much of the world and are most often farmed by women. Land considered marginal in the United States can be the primary source of livelihood in rural developing countries (Rossi and Lambrou, 2008). Communities and lower-income groups often depend on these lands to meet food, fuel, and medicinal needs. In parts of Africa, marginal lands may be in use by pastoralists and indigenous communities and may also have spiritual connections. Thus, the definition of what constitutes marginal land would need to be further broadened to incorporate social and cultural values.

In summary, this research provides a framework for classifying land as marginal on the basis of land use, soil health, and environmental criteria. Our results suggest that proper management and introduction of bioenergy crops on marginal land could meet energy, environmental, and economic goals; however, the tradeoffs need to be evaluated at the farm-scale. Uncertainties present in the classification of marginal land could be the result of database limitations, and further verification (e.g., quantification of eroded, frequently flooded land) at the field-scale is necessary.

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References

Bennett, E.M., S.R. Carpenter, and N.F. Caraco. 2001. Human impact on erodable phosphorus and eutrophication: A global perspective. BioScience 51:227–234. doi:10.1641/0006-3568(2001)051[0227:HIOEPA]2.0.CO;2

Borjesson, P., and G. Berndes. 2006. The prospects for willow plantations for wastewater treatment in Sweden. Biomass Bioenergy 30:428–438. doi:10.1016/j.biombioe.2005.11.018

Bradford, S.A., E. Segal, W. Zheng, Q. Wang, and S.R. Hutchins. 2008. Reuse of concentrated animal feeding operation wastewater on agricultural lands. J. Environ. Qual. 37:S97–S115. doi:10.2134/jeq2007.0393

Campbell, J.E., D.B. Lobell, R.C. Genova, and C.B. Field. 2008. The global potential of bioenergy on abandoned agricultural lands. Environ. Sci. Technol. 42:5791–5794. doi:10.1021/es800052w

Corwin, D.L., and S.A. Bradford. 2008. Environmental impacts and sustainability of degraded water reuse. J. Environ. Qual. 37:S1–S7. doi:10.2134/jeq2008.0210

Dale, V.H., K.L. Kline, J. Weins, and J. Fragione. 2010. Biofuels: Implications for land use and biodiversity. Biofuels and Sustainability Reports. Ecological Society of America, Washington, DC. Available at www.esa.org/

biofuelsreports (verified 13 July 2011).

Fischer, G., H. van Velthuizen, M. Shah, and F. Nachtergaele. 2002. Global agro-ecological assessment for agriculture in the 21st century: Methodology and results. International Inst. for Applied Systems Analysis, Laxenburg, Austria.

Gleick, P.H. 2003. Water use. Annu. Rev. Environ. Resour. 28:275–282. doi:10.1146/annurev.energy.28.040202.122849

Gopalakrishnan, G., M.C. Negri, M. Wang, M. Wu, S.W. Snyder, and L. LaFreniere. 2009. Biofuels, land, and water: A systems approach to sustainability. Environ. Sci. Technol. 43:6094–6100. doi:10.1021/es900801u

Hutson, S.S., N.L. Barber, J.F. Kenny, K.S. Linsey, D.S. Lumina, and M.A. Maupin. 2005. Estimated use of water in the United States in 2000. USGS Circ. 1268. Available at http://pubs.usgs.gov/circ/2004/circ1268/ (verified 13 July 2011).

Karlen, D. 2010. A landscape vision for integrating industrial crops into biofuel systems. *In* Association for the Advancement of Industrial Crops 22nd Annu. Meeting, Fort Collins, CO. 18–22 Sept. 2010. AAIC.

Larson, G.A., G. Roloff, and W.E. Larson. 1998. A new approach to marginal agricultural land classification. J. Soil Water Conserv. 43:103–106.

Lovell, S.T., and W.C. Sullivan. 2006. Environmental benefits of conservation buffers in the United States: Evidence, promise, and open questions. Agric. Ecosyst. Environ. 112:249–260. doi:10.1016/j.agee.2005.08.002

Louwagie, G., S.H. Gay, and A. Burrell. 2009. Addressing soil degradation in EU agriculture: Relevant processes, practices, and policies— Report on the project "Sustainable agriculture and soil conservation (SoCo)." JRC Scientific and Technical Reports. Office for Official Publications of the European Communities, Luxembourg.

Matson, P.A., W.J. Parton, A.G. Power, and M.J. Swift. 1997. Agricultural intensification and ecosystem properties. Science 277:504–506. doi:10.1126/science.277.5325.504

McGuire, V.L., M.R. Johnson, R.L. Schieffer, J.S. Stanton, S.K. Sebree, and I.M. Verstraeten. 2003. Water in storage and approaches to ground-water management, High Plains aquifer, 2000. USGS Circ. 1243. Available at http://pubs.usgs.gov/circ/2003/circ1243/ (verified 13 July 2011).

Moulton, R.J., and K.R. Richards. 1990. Costs of sequestering carbon through tree planting and forest management in the United States. General Technical Rep. WO-58. USDA Forest Service, Washington, DC.

Mueller, L., U. Schindler, W. Mirschel, T.G. Shepherd, B.C. Ball, K. Helming, J. Rogasik, F. Eulenstein, and H. Wiggering. 2010. Assessing the productivity function of soils: A review. Agron. Sustain. Dev. 30:601–614. doi:10.1051/agro/2009057

Murray, W.G., D.G. Harris, G.A. Miller, and N.S. Thompson. 1983. Farm appraisal and valuation. 6th ed. Iowa State Univ. Press, Ames.

National Cooperative Highway Research Program (NCHRP). 2005. Integrated roadside vegetation management: A synthesis of highway practice. NCHRP Synthesis 341. Available at http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_syn_341.pdf (verified 13 July 2011).

Nebraska Department of Environmental Quality (NDEQ). 2007. Quality-assessed agrichemical contaminant database for Nebraska ground water. Available at http://dnrdata.dnr.ne.gov/clearinghouse/ (verified 13 July 2011).

Nebraska Department of Environmental Quality (NDEQ). 2008. Interpretative maps and data for Nebraska 2008. Available at http://deqims.deq.state.ne.us/DEQ/ (verified 13 July 2011).

Perlack, R.D., L.L. Wright, A.F. Turhollow, R.L. Graham, B.J. Stokes, and D.C. Erbach. 2005. Biomass as feedstock for a bioenergy and bioproducts industry: The technical feasibility of a billion-ton annual supply. Technical Rep. A357634. Oak Ridge National Laboratory, Oak Ridge, TN.

Peterson, G.M., and J.K. Galbraith. 1932. The concept of marginal land. J. Farm Econ. 14:295–310. doi:10.2307/1230112

Pimm, S.L., and P. Raven. 2000. Biodiversity: Extinction by numbers. Nature 423:528–529.

Postel, S.L. 1992. Last oasis: Facing water scarcity. Norton, New York.

Rossi, A., and Y. Lambrou. 2008. Gender and equity issues in liquid biofuels production: Minimising the risks to maximise the opportunities. FAO, Rome.

Royal Society. 2008. Sustainable biofuels: Prospects and challenges. Royal Society, London. Available at http://royalsociety.org/Sustainable-biofuels-prospects-and-challenges/ (verified 13 July 2011).

Schmer, M. R., K.P. Vogel, R.B. Mitchell, and R.K. Perrin. 2008. Net energy of cellulosic ethanol from switchgrass. Proc. Natl. Acad. Sci. USA 105(2):464–469. doi:10.1073/pnas.0704767105

Tilman, D., K.G. Cassman, P.A. Matson, R. Naylor, and S. Polasky. 2002. Agricultural sustainability and intensive production practices. Nature 418:671–677. doi:10.1038/nature01014

Tilman, D., J. Hill, and C. Lehman. 2006. Carbon-negative biofuels from low-input high diversity grassland biomass. Science 314:1598–1600. doi:10.1126/science.1133306

Turner, R.E., N.N. Rabalais, and D. Justic. 2008. Gulf of Mexico hypoxia: Alternate states and a legacy. Environ. Sci. Technol. 42:2323–2327. doi:10.1021/es071617k

UN-Energy. 2007. Sustainable bioenergy: A framework for decision makers. United Nations, New York. Available at http://www.fao.org/docrep/010/a1094e/a1094e00.htm (verified 13 July 2011).

USDA. 2002. The census of agriculture. Available at http://www.agcensus.usda.gov/Publications/2002/index.asp (verified 20 July 2011).

USDA. 2007. Cropland data layer, US 2007. Available at http://datagateway.nrcs.usda.gov/ (verified 20 July 2011).

USDA–NRCS. 1991. State Soil Geographic (STATSGO) Data Base. USDA–NRCS Publ. 1492. Available at http://soildatamart.nrcs.usda.gov/ (verified 13 July 2011).

USEPA. 2002. Impaired waters dataset 2002. Available at http://www.epa.gov/waters/data/downloads.html.

USGS. 2002. Probability of nitrate contamination of recently recharged ground waters in the conterminous United States 2002, Available at http://water.usgs.gov/GIS/metadata/usgswrd/XML/gwrisk.xml (verified 13 July 2011).