Received: 3 May 2021 | Accepted: 28 May 2021
DOI: 10.1111/gcbb.12877

INVITED RESEARCH REVIEW

GCB-BIOENERGY Open Access
BIOPRODUCTS FOR A SUSTAINABLE BIOECONOMY
WILEY

Redefining marginal land for bioenergy crop production

Madhu Khanna[1,2] | **Luoye Chen**[1,2] | **Bruno Basso**[3,4,5] | **Ximing Cai**[1,6] | **John L. Field**[7,8,9] | **Kaiyu Guan**[1,10,11] | **Chongya Jiang**[1,10,11] | **Tyler J. Lark**[12,13] | **Tom L. Richard**[9,14] | **Seth A. Spawn-Lee**[12,13,15] | **Pan Yang**[1,6] | **Katherine Y. Zipp**[16]

[1]Center for Advanced Bioenergy and Bioproducts Innovation (CABBI), University of Illinois at Urbana-Champaign, Urbana, IL, USA
[2]Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign, Urbana, IL, USA
[3]Department of Earth and Environmental Sciences, Michigan State University, East Lansing, MI, USA
[4]W.K. Kellogg Biological Station, Michigan State University, East Lansing, MI, USA
[5]Great Lakes Bioenergy Research Center (GLBRC), Michigan State University, East Lansing, MI, USA
[6]Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, USA
[7]Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO, USA
[8]Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN, USA
[9]Center for Bioenergy Innovation (CBI), Oak Ridge National Laboratory, Oak Ridge, TN, USA
[10]Agroecosystem Sustainability Center, Institute for Sustainability, Energy, and Environment, University of Illinois at Urbana Champaign, Urbana, IL, USA
[11]Department of Nature Resources & Environmental Sciences, University of Illinois at Urbana-Champaign, Urbana, IL, USA
[12]Great Lakes Bioenergy Research Center (GLBRC), University of Wisconsin-Madison, Madison, WI, USA
[13]Center for Sustainability and the Global Environment (SAGE), University of Wisconsin-Madison, WI, USA
[14]Department of Agricultural and Biological Engineering, Pennsylvania State University, University Park, PA, USA
[15]Department of Geography, University of Wisconsin-Madison, WI, USA
[16]Department of Agricultural Economics, Sociology, and Education, Pennsylvania State University, University Park, PA, USA

Correspondence
Madhu Khanna, Center for Advanced Bioenergy and Bioproducts Innovation (CABBI), University of Illinois at Urbana-Champaign, Urbana, IL, USA.
Email: khanna1@illinois.edu

Funding information
Office of Science, Grant/Award Number: DE-AC05-00OR22725, DE-SC0018409 and DE-SC0018420; National Institute of Food and Agriculture, Grant/Award Number: 1014400, 2017-67019-26327 and PEN04631

Abstract
Marginal land has received wide attention for its potential to produce bioenergy feedstocks while minimizing diversion of productive agricultural land from food crop production. However, there has been no consensus in the literature on how to define or identify land that is marginal for food crops and beneficial for bioenergy crops. Studies have used different definitions to quantify the amount of such land available; these have largely been based on assumed biophysical thresholds for soil quality and productivity that are unchanging over space and time. We discuss the limitations of these definitions and the rationale for considering economic returns and environmental outcomes in classifying land as marginal. We then propose the concept of "socially" marginal which is defined as land that is earning close to zero returns *after* accounting for the monetized costs of environmental externalities generated. We discuss a broad set of criteria for classifying land as socially marginal for food crops and suitable for bioenergy crops; with these criteria, this classification depends on spatially varying and time-varying factors, such as climate and market conditions and

policy incentives. While there are challenges related to identifying this marginal land, satellite and other large-scale datasets increasingly enable such analysis at a fine spatial resolution. We also discuss reasons why landowners might choose not to convert bioenergy-suitable land to bioenergy crops, and thus the need for policy incentives to support conversion of land that is socially beneficial for bioenergy crop production.

KEYWORDS

bioenergy, biofuels, economically marginal, ecosystem services, land quality, marginal land, returns to land, socially marginal

1 | INTRODUCTION

Marginal land has received wide attention for its potential to produce bioenergy feedstocks—which here we specifically define as cellulosic biomass for producing advanced biofuels and bioenergy—while minimizing diversion of cropland from food crop production, which here we define as annual row crops such as maize and soybean. Publications began connecting marginal lands and bioenergy in 2001 and their number has been growing since then (see the review in Richards et al., 2014). However, there has been no consensus in the literature on the definition of land that is marginal for food crops and suitable for bioenergy crops, and studies have used different assumptions to identify and quantify the amount of such land available (Richards et al., 2014).

The notion of marginal land as applied to bioenergy crops has frequently been considered synonymous with low quality, less productive, or degraded land (Tilman et al. 2006) with reduced value for conventional food crop production. While the term "marginal" is now often seen as having negative connotations for land quality, the term originates from a more narrow definition of land at the economic margin of production which has "potential returns that at best breakeven with the costs of production," that is, earning close to zero net returns under given price, cost, and other conditions (Peterson & Galbraith, 1932). However, Richards et al. (2014) found that among recent studies that explicitly or implicitly defined marginality of land, over half focused on biophysical properties of land, such as slope, soil pH, soil salinization, and drainage that affect crop productivity, and where those effects are expected to be different for food and bioenergy crops. Other studies have identified marginal land based on observed current or historical land use, such as land abandoned from agriculture (Campbell et al. 2008; Stoof et al., 2015) or environmentally sensitive land retired from crop production (Emery et al., 2017; Gelfand et al., 2013; Zhang & Cai, 2011). These lands can, by definition, be put to other uses without affecting food crop production.

However, to determine the desirable locations for bioenergy crops, we propose that in addition to considering the biophysical quality or economic marginality of using the land for food crops (i.e., earning a market return from food crop production that is frequently close to zero), we should also consider environmental externalities of conventional food crop production as well as the potential for energy crops to achieve more positive ecosystem services in the form of improved soil, habitat, water and air quality, and the climate system. Food crop production can generate multiple ecosystem dis-services with magnitudes varying over time and space, and combining them to determine a net impact can be challenging. We propose using non-market monetary values of these ecosystem services to weight and combine these multiple externalities and assess the social costs of food crop production. We put forth the concept of "socially marginal land for food crops" as a normative definition of marginal land which combines the concept of economic returns to the land under food crop production (based on market prices) with the monetized value of the environmental impacts of crop production on that land to determine net social benefits of the land. Land that results in a zero net social return with food crop production should be considered socially marginal land for food crops. Similarly, the economic returns to bioenergy crops can be combined with their monetized ecosystem services to estimate net social benefits, and thus the land that is socially beneficial or socially marginal for bioenergy crops. By defining marginal lands in this way, there is an expanded opportunity to design bioenergy cropping systems and broader agricultural landscapes to maximize social benefits and enhance system sustainability.

Converting land that is socially marginal for food crops could support biomass production while limiting adverse impacts on food crop production, minimizing opportunity costs of bioenergy crop production, and improving ecosystem services. This builds on the notion of economically marginal land for food crops provided by Peterson and Galbraith (1932) and reiterated in the context of bioenergy crops in Richards et al. (2014). However, the concept of socially marginal land goes beyond prior definitions of economic marginality and includes additional considerations such as the value of the environmental damages due to food crop production on that land, as well as the positive ecosystem services of bioenergy crops.

In this concept paper, we review the definitions used in the existing literature to quantify marginal land and explore the extent to which these measures support achieving net social benefits in land use decision-making. We present a case for preferring social marginality over other definitions of marginal land based on biophysical characteristics, prior land use transitions, or economic marginality alone. Defining a land parcel as marginal based on both its economic returns and environmental outcomes requires consideration of crop prices, production costs, and environmental services as affected by economic conditions, land use histories, soil and climate factors, and non-markets valuations, all of which can vary spatially and over time. We also explore how certain conventional marginal land definitions can fail to properly account for the ecosystem service value of current land uses, for example, land that was abandoned from crop production and has since reverted to native grasses or secondary forests with high ecosystem service value. We discuss the challenges in incorporating these considerations into marginal land quantification based on readily available observational data.

Furthermore, we discuss the factors likely to affect the conversion of socially marginal land to bioenergy crops. For any particular land parcel, the combination of suitability for bioenergy crops, crop productivity, market prices, financial incentives, and other amenities from the land will determine the incentives to convert it to bioenergy crops. On the other hand, at high biomass prices and with other policy incentives for biomass production, landowners may decide to convert even productive annual cropland to perennial energy crops if it increases the returns to land while being unwilling to convert previously abandoned marginal land if the environmental amenities and other perceived benefits of that land in a natural state are valued very highly (Barham et al., 2016). We conclude with a discussion of directions for future research.

2 | EXISTING DEFINITIONS OF MARGINAL LAND

Definitions of marginal land vary across different studies in the existing literature, as summarized in Table 1. These definitions can be classified into three categories based on (i) biophysical suitability of land for food crop production (ii) historical and current land use, and (iii) economic marginality. These definitions of marginal land are not necessarily mutually exclusive, and a single study may rely on more than one type of definition.

2.1 | Biophysical suitability for food crop production

Studies in this category attempt to identify lands that have limited long-term productivity for food crop production. Such marginal lands can be mapped using three general approaches: (a) applying suitability thresholds to biophysical grids, (b) mapping derived productivity indices, or (c) identifying areas of degraded land quality. Studies using the first approach identify thresholds in climate conditions and specific land biophysical properties (e.g., slope, soil pH, soil salinization, drainage, etc.) that affect food crop production, and apply them to maps of the corresponding property to identify areas of suitability. Estimates based on this approach are sensitive to the data and assumptions underlying the chosen thresholds and the maps to which they are applied.

The second approach integrates multiple biophysical characteristics of the land into an overall composite land productivity index. As an example, Cai et al. (2011) applied a fuzzy-logic rule to classify land productivity into low, marginal, and regular categories based on climate, slope, and soil properties. More recently, Yang et al. (2020) used machine learning to estimate yields of major crops and then applied a productivity-based threshold to estimate marginal land availability, incorporating uncertainty due to model assumptions and data availability. Other studies have used satellite data to identify cropland with low and unstable productivity for growing food crops as an opportunity to produce energy crops with potentially lower land costs (Basso & Antle, 2020; Basso et al., 2019; Emery et al., 2017; Gu & Wylie, 2017).

The third approach considers soil fertility loss and degradation due to intensive agricultural practices or contamination as potential sources of marginal land. This land may be unsuitable for food crop production because of low yields, but may still have value for energy crop production (Shortall, 2013). Specific types of degradation may include topsoil loss from erosion, groundwater contamination, or overexploitation of local water resources (Gibbs & Salmon, 2015; Gopalakrishnan et al., 2011; Niblick & Landis, 2016; Tang et al., 2018).

2.2 | Historical and current land use

Studies have considered land with a particular land use history or with a specific current-day use to be marginal. Such land use categories include land that has been abandoned from agriculture, idle/fallow land, and cropland that has been put into conservation easements such as the Conservation Reserve Program (CRP). These types of land could possibly be converted to perennial energy crops with relatively low

TABLE 1 Summary of representative studies identifying marginal land

Type of marginal land	Criteria/variable	Typical references	Key comments
Biophysical characteristics for food crops	Soil quality	Gelfand et al. (2013), Kang et al. (2013), Gopalakrishnan et al. (2011)	• Soil property variables including physical factors (slope, temperature, moisture, etc.) and chemical factors (PH, salinization, etc.) • Soil properties not suitable for growing food crops • Specific thresholds of soil property variables based on empirical and theoretical knowledge
	Land productivity	Cai et al. (2011), Yang et al. (2020)	• Based on an overall land productivity index generated from soil biophysical factors • Land productivity indices estimated based on fuzzy-logic rules or crop yield potentials • Low-productive cropland and high-productive non-cropland are usually identified as marginal lands
	Degraded land	Gopalakrishnan et al. (2011), Niblick and Landis (2016)	• Eroded agricultural land • Area with contaminated groundwater • Brownfield sites
Land use	Abandoned land	Field et al. (2008), Hoogwijk et al (2003)	• Historical abandoned agricultural land • Future potential abandoned agricultural land because of food surplus
	Idle land		• Idle or fallow land • Land enrolled in Conservation Reserve Program
	Buffer zones	Varvel et al. (2008), Gopalakrishnan et al. (2011)	• Buffer zones along rivers and roadways
	Convertible non-crop land		• Woodland (shrubland, sparse forest land), grassland, and barren land • Pastureland, forest, and nature reserve lands are not included
Economically Marginality	Break-even price	Kang et al. (2013)	• Breakeven production level of corn grain is less than 5 Mg Ha^{-1}
		Richards et al. (2014), Stoof et al. (2015)	• Potential returns at best break even with the cost of production
Suitability of bioenergy crops	Land rent	Swinton et al. (2011)	• Profits of energy crops are higher than those of food crops
	Energy crop yield	Jiang et al. (2019), Feng et al. (2017), Varvel et al. (2008), Liu et al. (2012), Aust et al. (2014)	• Empirically or theoretically estimated land suitability index for energy crop production • Model simulated energy crop yields

environmental impacts, and, as these land use category names infer, without directly displacing food crops (Chen, Blanc-Betes, et al., 2021; Chen, Debnath, et al., 2021; Field et al., 2008). Vegetated buffer zones along roads and rivers have also been considered suitable for the cultivation of perennial energy crops due to positive ecosystem services, including preventing soil erosion and pollutant runoff (Gopalakrishnan et al., 2011). Other non-cropland land use categories such as pasture and rangeland, forest, and nature reserves are typically not considered suitable for energy crops, since they have high cultural or regulating ecosystem service values and/or protected status, with often a combination of these benefits (Gopalakrishnan et al., 2011; Varvel et al., 2008; Zhuang et al., 2011).

2.3 | Economic marginality

Although the concept of marginal land was initially based on economic returns to the land (Peterson & Galbraith, 1932), only a few studies have identified marginal land using a formal economic perspective (Gutierrez & Ponti, 2009; Kang et al., 2013; Richards et al., 2014; Stoof et al., 2015). These studies define marginal land as being unfit for economically viable crop cultivation (Gutierrez & Ponti, 2009; Richards et al., 2014), or at the margins of production where potential returns are at a breakeven point with production costs (Stoof et al., 2015). Kang et al. (2013) introduced a hierarchical framework that classified economically marginal land as a subcategory of land that is simultaneously physically marginal, biologically marginal, and environmentally marginal, with limited productive value for conventional food crops. While these studies note the concept of economic marginality and the dynamic nature of marginal land (i.e., varying over time with changes in crop prices or costs of production), they do not explicitly calculate the economic returns of land use (as Richard et al. 2014) but rather simply use biophysical or land use definitions as proxies of economic marginality. Both Gutierrez and Ponti (2011) and Stoof et al. (2015) use abandoned agricultural cropland (land that was cleared for agriculture in the past but that is not currently producing crops or being used for pasture on farms) as a proxy for economic marginality. Kang et al. (2013) consider economically marginal land in south-western Michigan to be land that produces less than 5 Mg per hectare of corn, but do not consider how changes in prices and costs might affect that threshold.

2.4 | Limitations of existing approaches of defining marginal land

The studies described above address some aspects of marginal land identification, but they do not necessarily identify areas where it is practical and socially beneficial to site bioenergy crops. Estimates of marginal land based on biophysical characteristics or productivity alone disregard the economic factors that affect viability for food or bioenergy crop production at any point of time, as well as the non-economic amenities that land may be providing. Even low-productivity land may be profitable for crop production if crop prices are sufficiently high, and thus economically marginal land is not necessarily a subset of biophysically marginal land as implied by Kang et al. (2013).

Biophysical and crop productivity-based criteria do not consider the environmental implications of land use, and economic profitability in crop production alone does not negate the possibility that the land could be generating significant environmental disservices (see Section 3). The hierarchical framework developed by Kang et al. (2013) recognizes that highly productive land could be environmentally degraded under crop production and should therefore be considered marginal land. However, while biophysical attributes such as slope, erodibility, and soil organic content are important determinants of environmental performance, they are not sufficient determinants of poor environmental outcomes. Non-point pollution, carbon emissions, and other ecosystem outcomes depend on the interaction of those biophysical risk factors with land use history, current management practices, and climate conditions. Using historical and current land use alone as a criterion for identifying marginal land disregards consideration of its environmental services. Land abandoned from crop production may be economically marginal but not socially marginal, if it has since reverted to secondary forest or native grassland.

3 | A CONCEPTUAL FRAMEWORK FOR CLASSIFYING ECONOMICALLY AND SOCIALLY MARGINAL LAND

In Figure 1, we present a simple conceptual framework that merges both economic and environmental perspectives on marginal land identification and optimal land use. The figure illustrates the returns to land under different land uses on the *y*-axis, as a function of the biophysical productivity of the land for food crops on the *x*-axis.

3.1 | Economically marginal land

The average market-based returns to food crop production can be expected to decline as biophysical land productivity declines, as illustrated by the solid orange line with a *y*-intercept at C^P. The slope and intercept of this relationship can vary over time and space, as can the shape of the curve, which could be linear or nonlinear. Point L_4 represents the land productivity where market returns from food crops become zero under average market, climate, and policy conditions (which can also vary over time and space). Land with productivity near or below L_4 is economically marginal for food crops, and any existing cropland with much lower productivity is likely to be abandoned from agriculture and converted to a non-crop use. This land has low opportunity costs (or foregone returns) of conversion to bioenergy production, and thus represents a target land base that both reduces bioenergy production costs and minimizes interference with food production.

Land of intermediate productivity may be more suitable for growing deep-rooted perennial bioenergy crops, as illustrated in Figure 1 with the solid blue line with a *y*-intercept at E^P. This line has a shallower negative slope than the blue food

GCB-BIOENERGY BIOPRODUCTS FOR A SUSTAINABLE BIOECONOMY Open Access

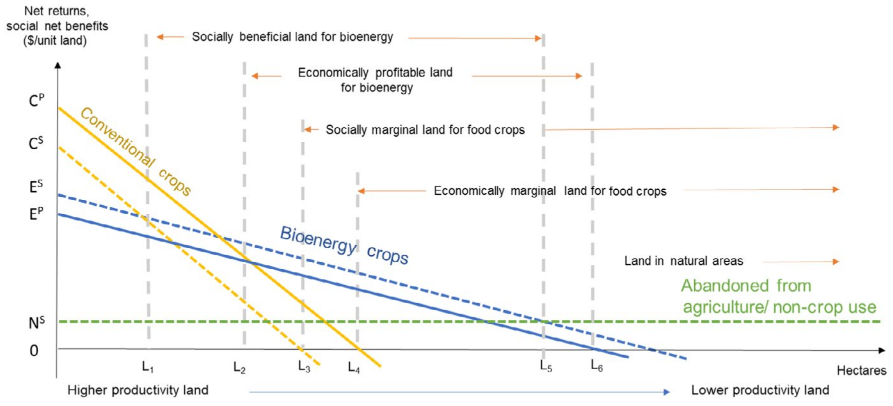

FIGURE 1 Economically and socially beneficial land for bioenergy crops

Note: Figure 1 illustrates the market-based and social returns of harvesting bioenergy crops and conventional crops on land with different soil quality and the range of economically and socially marginal land. The *x*-axis refers to the productivity of land while the *y*-axis refers to the returns per unit of land under food or bioenergy crop production net of the average market returns under non-crop use; for simplicity, this is assumed to be zero in this figure. The solid orange line with *y*-intercept at C^P and the solid blue line with *y*-intercept at E^P refer to the average market-based returns to food and bioenergy crop production relative to non-crop use returns, respectively. The dashed orange line with an intercept of C^S, the dashed blue line with an intercept of E^S, and dashed green line with an intercept of N^S refer to the average total social returns to food, bioenergy crop production as well as native grass/forests relative to average market returns of non-crop use, respectively. Economically profitable land for bioenergy crops is L_6-L_2. Socially beneficial land for bioenergy crops is L_5-L_1. The area L_4-L_2 is not economically marginal land but is profitable to convert to bioenergy crops while L_4-L_1 is not economically marginal but socially beneficial to convert to bioenergy crops.

crop lines since bioenergy crop yields are less sensitive to weather and landscape conditions than annual crops (Wilson et al., 2014) but are still reduced on poorly drained land or areas of extreme soil texture (Boyer et al., 2013; Mooney et al., 2009; Shield et al., 2012). Land to the right of point L_2 would earn greater economic returns under energy crops than food crops. The extent to which this is the case will vary with energy crop species which differ in their tolerance to biophysical and climate conditions, including length of the growing season, precipitation, and frost conditions (Daly et al., 2018). The average market-based returns of using land with productivity to the right of L_6 are lower than those with non-crop uses and, therefore, remains in natural land cover or abandoned. Returns to land of non-crop uses could be positive if the land is being used to provide marketable amenities (such as, hunting or wildlife viewing). We, therefore, define net market returns to crop production and bioenergy crop production as net of the returns to non-crop uses of the land. For ease of graphical representation, we assume the market returns to non-crop uses are zero.

The conceptual diagram in Figure 1 represents a simplification of a more dynamic and complex reality of land use decisions. Although incorporating the profitability or breakeven production threshold sheds some light on identifying marginal land from the economic perspective, it disregards the role of riskiness of crop production on farmers' land use decisions. Weather events such as droughts and floods or other crop stresses can cause dramatic reductions in yield and profitability in some years but not others. These stresses play out differently on different parts of the landscape, in some cases driven by soils or topography such as steep slopes and floodplains, and they also impact different crops in different ways (Martinez-Feria & Basso, 2020a). Farmers that are risk-averse and/or loss-averse would care not only about the average returns to land but also about the variance of those returns and the downside risks of income loss (Anand et al., 2019; Liu & Basso, 2017; Miao & Khanna, 2014). Risk- and loss-averse farmers are likely to be unwilling to produce crops on land that may have net positive returns on average but frequent individual years of negative returns. Thus, the position of point L_4 should depend not only on average returns but also riskiness of those returns. Additionally, it will also depend on access to subsidized crop insurance, disaster relief payments, and other commodity programs that can mitigate risks and make it profitable for low-productivity land to remain in food crop production (Yu et al., 2018).

3.2 | Incorporating a social benefits perspective

The basic model of economically marginal land described above does not consider the environmental externalities generated by producing food or bioenergy crops. Intensive land management for annual food crops can result in ecosystem disservices and other externalities, including greenhouse gas emissions (Carlson et al., 2017), loss of soil fertility (Tiessen et al., 1994), sedimentation of waterways (Knox, 2006), hydrological impacts (Levia et al., 2020), and even human health damages from air or water pollution (Hill et al., 2019). These externalities are multiple in nature and manifest at both the site level (e.g., wildlife habitat reduction) and beyond (e.g., non-point source pollution). Failure to consider these externalities can result in land use decisions that narrowly benefit individual landowners while imposing significant costs on society more broadly. These externalities depend both on the quality of the land and the management practices implemented on the land; the latter, in turn, will depend on the direct incentives or rewards to landowners for implementing environmentally friendly practices (Jack et al., 2008).

With multiple externalities (positive and negative), one way to undertake a full accounting of the "total social returns" of a given land use decision involves tabulating all associated externalities (positive or negative) and applying non-market valuation techniques to monetize them so they can be considered alongside the pure economic market returns. In our conceptual model illustrated in Figure 1, the externalities of food crop production are evaluated in comparison to the case of fallowing or idling that cropland. Production of annual crops can contribute to topsoil erosion and organic matter losses due to tillage disturbance, non-point source pollution due to nutrient and chemical application, and reductions in native biodiversity due to mono-cropping, as discussed in more detail in Section 5. Subtracting the monetized value of these negative externalities from the market-based returns to the food crop production, we obtain the net social returns to cropland, the orange dashed line with a *y*-intercept of C^S. Land near or to the right of point L_3 has total net social returns close to zero, that is, socially marginal land for food crops. The negative environmental externalities of food production outweigh the economic value of that production on lands between L_3 and L_4. Thus, the socially marginal land area is expected to be larger than the economically marginal land area for food crop production.

Compared to fallow or idle land, managed perennial bioenergy crops likely generate several positive environmental externalities (e.g., increased soil carbon, erosion stabilization, etc., discussed further in Section 5). Monetizing these ecosystem services and adding them to the market returns gives the total net social returns to energy crop production, indicated by the dashed blue line with a *y*-intercept of E^S. Accounting for both the positive externalities of energy crop production and the negative externalities of food crop production, all land to the right of L_1 has higher social net benefits under energy crops.

While valuation of environmental externalities expands the amount of relatively high-productivity marginal land suitable for bioenergy crop production, it also reduces the amount of suitable low-productivity land, once the benefits that land can generate under other non-crop uses are considered. Some low-productivity lands might best remain in natural vegetation for biodiversity benefits, or if the soil carbon loss during conversion to bioenergy crops outweighs the greenhouse gas mitigation benefits (Field et al., 2020; Spawn et al., 2019). At some point L_5, the social benefits of leaving land in natural uses (illustrated by the dashed green line with a *y*-intercept of N^S in Figure 1) exceed that of converting it to bioenergy. Therefore, land to the right of point L_5 is socially marginal for bioenergy crops, that is, its social benefits are no longer positive for bioenergy crops (as they were between L_1 and L_5); such land should be allowed to remain in natural land cover. The net social benefits of converting abandoned croplands to bioenergy crops can be highly sensitive to land use history, the length of the abandonment period, and the degree to which the ecosystem service value of the land has recovered (Field et al., 2018; Goldstein et al., 2020; Isbell et al., 2019).

4 | APPROACHES FOR IDENTIFYING ECONOMICALLY MARGINAL AND BIOENERGY-SUITABLE LAND

Identifying economically marginal land at a fine spatial resolution ideally requires information on the operating profits, debt, equity, and other financial data pertaining to current and potential future crop production. These data are not publicly available. While the financial profitability of a land parcel may be related in part to observable phenomena and features such as biophysical, environmental, and market conditions, it also depends on unobserved management practices, expectations about market and climate conditions and policy support that can vary spatially and in association with farmer demographics (Pröbstl-Haider et al., 2016; Skevas et al., 2014, 2016). To this end, there is effectively no way to accurately map economically marginal land, and one must inevitably rely on reasonable but imperfect proxies and assumptions. We discuss some approaches that have used satellite data and computational modeling to identify land that can be classified as economically marginal for food crop production.

In a recent study, Jiang et al. (2021) identify economically marginal land as land that is frequently transitioning between crop and non-crop use using high-resolution land use data from the Cropland Data Layer from 2008 to 2016. They consider frequent land use change as an indicator of land that is at the borderline of profitability in crop production and likely to switch easily between crop and non-crop in response to changes in market conditions (i.e., farmers choose to cultivate only in years when they perceive it likely to be profitable). These patterns can be readily observed using remotely sensed imagery supplemented with other gridded data where necessary. This is an imperfect approach to identify economically marginal land because (a) land use change data from satellite images is subject to noisiness and (b) ex-ante assessments of profitability that guide crop planting decisions may differ from

GCB-BIOENERGY BIOPRODUCTS FOR A SUSTAINABLE BIOECONOMY Open Access -WILEY

ex-post realizations of profits given weather, market, and policy conditions. Jiang et al. (2021) use statistical algorithms to distinguish between land use changes that can be inferred as indicators of economic marginality with confidence from those that are in the statistical noise. They find that the area of land that can be confidently classified as economically marginal, and that is in the bioenergy-suitable rainfed region of the US, is substantially smaller than estimates from previous studies using biophysical criteria. Using similar methods based on remote sensing products, Lark et al. (2020) mapped recently transitioned croplands and showed that these areas were characterized by less suitable biophysical conditions such as higher slopes and climate-water deficits as well as lower crop yields. Such findings suggest a level of consistency across marginal land definitions and the land so identified and add further support to such observational approaches to their identification.

Other approaches to identify land that is economically marginal rely on recent advances in the use of precision agricultural tools, including yield monitoring and satellite data, to show spatial heterogeneity in yields and returns to crop production within a field. Basso et al. (2019) used 8 years of high-resolution satellite imagery and other crop data layers to identify subfields in ten Midwestern States that could be classified as having stable low yield, unstable (low yield some years, high others) and stable high yield. These tools can be used to identify areas in a field that have negative profitability under food crop production on a multi-year average, even if they are profitable in a "normal" year (Basso et al., 2019; Maestrini & Basso, 2018; Martinez-Feria & Basso, 2020b).

These approaches indicate opportunities to integrate energy crop production into working agricultural landscapes at sub-field scales, that is, "spatial intensification" (Heaton et al., 2013). Areas within a field that have negative or low profitability under food crop production have potential to be converted to energy crops and increase income from the field (Bonner et al., 2014). Spatially observable data can also be supplemented with economic models to estimate field-level profitability more explicitly. Brandes et al. (2016) estimated the profitability of corn/soy fields across Iowa by combining observable data such as crop yields, commodity price listings, and cash rents gleaned from farmer surveys with estimates of farm-specific production costs from a state-specific cost model. They found that a large portion of these fields were likely unprofitable in the year 2015, and that overall profitability could be increased by replacing low-yielding areas with low-input perennial crops.

Estimates of economically marginal or bioenergy-suitable land are only as good as the data and assumptions upon which they are based. Inference from temporal land use patterns, for example, is sensitive to the methods used for measurement and reporting, and such analyses should proactively address potential sources of bias and causes of spurious change detection (Lark et al., 2017; Lark et al., 2021). Likewise, profitability studies based on county-level crop yields may be improved by emerging remote sensing methods to accurately predict yields at high spatial resolution (Deines et al., 2021). Well-resolved socio-economic data like land value and ownership are sporadically available at the parcel level and could be used to improve profitability assessment if efforts are made to harmonize them over large extents (e.g., Nolte, 2020). These data could also be joined to publicly available data on farm subsidies to directly infer farm-specific economic risk/instability. Further development of scalable economic models like that used by Brandes et al. (2016) will also continue to improve our ability to contextualize proxies in economic terms and fill voids left by unobservable or unavailable data. Collectively, these developments will improve our ability to identify economically marginal land, a necessary precursor for identifying land that is socially marginal for food crops and suitable for bioenergy crops.

We note that not all land that is marginal for food crops is equally suitable for growing bioenergy crops. Liu and Basso (2017) evaluated the amount of land in Michigan that can yield at least 8 tons per hectare of switchgrass. They found that of the productive, low-risk land for switchgrass production in Michigan, about 25% was marginal for food crop production, and that the suitability of such marginal land for switchgrass production tended to be constrained by nitrogen limitations. Feng et al. (2017) classified the suitability of land that was marginal for food crops into five classes (not-, poorly-, moderately-, good-, and highly suitable) for growing switchgrass, miscanthus, and hybrid poplar. They show that 60% of that marginal land (approximately 6 million ha) in the Upper Mississippi River Basin is moderately to highly suitable for growth of switchgrass, miscanthus, and hybrid poplar.

5 | CONSIDERATIONS FOR IDENTIFYING SOCIALLY MARGINAL LAND FOR FOOD CROPS

Identifying socially marginal lands for food crop production starts with the quantification of economic returns as described in the previous section, and then adds in the social costs and benefits of environmental externalities from current and potential future land use. As with economically marginal land, these features can be assessed at any spatial scale/extent and will be different for bioenergy crops than for food crops, as well as for different agronomic practices used for any specific crop. All possible environmental impacts of land use should ideally be considered, though practical considerations and tractability may require the specification of boundary conditions on the environmental externalities to be included. We contend that even partial accounting of environmental externalities (and in some locations, using benefit transfer approaches to monetize their effects) is preferable to ignoring them completely, since that implicitly sets their value at zero.

Below, we use a few well-studied examples to illustrate ways in which these externalities might be quantified and assessed in the service of identifying socially marginal land. These example externalities are selected because they share (a) a good baseline scientific understanding of their impacts under both food and bioenergy crops, (b) a large degree of spatial heterogeneity across agricultural landscapes, and (c) a reasonably well-established basis for quantification and pricing of their non-market impacts. There is also some precedent for considering these externalities among existing bioenergy landscape design and optimization studies (Mishra et al., 2019; Wu et al., 2012; Zhang et al., 2010; Zheng et al., 2018). In most cases, these environmental impacts are difficult to observe or monitor directly, so assessment relies heavily on proxy measurements and statistical or process-based modeling to identify environmental "hotspots" where unfavorable underlying biophysical characteristics (e.g., slope, coarse soil texture, proximity to waterways) lead to disproportionate impact (Saha et al., 2017), and opportunities for changing land use to increase environmental benefits (Cheng et al. 2020; Schulte et al., 2017). In addition to land use choices, environmental performance in these areas is also highly sensitive to crop management decisions (Davis et al., 2013), so observed outcomes reflect the interaction between management practices and land biophysical characteristics.

5.1 | Soil carbon and greenhouse gas emissions

The greenhouse gas impact of conventional crop production is typically dominated by soil-related emissions, specifically changes in soil organic carbon (SOC) storage and soil emissions of nitrous oxide (N_2O). The historic and ongoing clearing of native land covers for crop production has created a substantial soil carbon debt (Sanderman et al., 2017). Cropland soils can be an ongoing moderate source or sink of carbon, depending on when they were first converted to crop production and how they are managed (EPA, 2020). In addition, application of nitrogen (N) fertilizers produces emissions of the potent greenhouse gas N_2O (Crutzen et al., 2008). Seasonal N_2O emissions totals are largely driven by discreet events (e.g., fertilizer additions and precipitation events) and characterized by hotspots of anoxic conditions in fine-textured soils and local topographic depressions (Li et al. 2013). SOC and N_2O outcomes are also highly sensitive to management. Conservation management techniques such as reduced tillage intensity or winter cover cropping can improve SOC trajectories under annual crops (Liu et al., 2020; Minasny et al. 2017; Paustian et al., 2019), whereas careful fertilizer and irrigation management, use of denitrification inhibitors, or application of biochar can help to control N_2O (Akiyama et al., 2009; Borchard et al., 2019; Jin et al., 2019; Liu et al., 2020)

Growing perennial bioenergy crops on lands that were previously row-cropped generally improves SOC accrual (Emery et al., 2017; Martinez-Feria & Basso, 2020b; Qin et al., 2016) and can create a large carbon sink with significant climate change mitigation value (Chen, Debnath, et al., 2021; Tilman et al. 2006). Rates of SOC sequestration depend on site-level specifics (e.g., soil texture, land use history) and duration of time after establishment (Abraha et al., 2019; Chen, Blanc-Betes, et al., 2021). A recent meta-analysis suggests that establishing the perennial energy grasses switchgrass and miscanthus on former cropland results in a median SOC accrual rate of 1.2 Mg C ha^{-1} $year^{-1}$ (25–75th percentile range of 0.4–2.9 Mg C ha^{-1} $year^{-1}$) (Qin et al., 2016). Compared to annual crops, perennial energy crops also make much more efficient use of applied N and have lower relative N requirements, resulting in lower per-area N_2O emissions rates (Pedroso et al., 2014; Tilman et al. 2006; Whitaker et al. 2018).

SOC levels are highly spatially heterogeneous, and time-consuming and costly to measure accurately via soil core collection and combustion-based carbon measurement. As a result, process-based ecosystem models (e.g., ecosys, EPIC, DayCent, SALUS) are often used to simulate SOC trends and N_2O emissions over larger areas or in response to different hypothetical cropping scenarios dynamically over time (Grant et al. 2020; Zhou et al. 2021; Campbell et al. 2018; Dwivedi et al., 2015; Hudiburg et al., 2016). Such models use spatial data on weather/climate, soils, and historic management to drive simulations of carbon, water, nitrogen, and other nutrient cycling in agro-ecosystems (Martinez-Feria & Basso, 2020b). These models can be used to identify socially marginal cropland where SOC levels are significantly depleted such that conversion of land to bioenergy crops would enhance the carbon mitigation services provided by that land. Alternately, more widespread adoption of the conservation management practices described above would reduce the environmental impacts of conventional cropping even in biophysically challenging areas, and thus somewhat reduce the incidence of socially marginal cropland appropriate for bioenergy use.

While the examples above focus on the greenhouse gas sources and sinks within a field to assess broader societal costs and benefits, it may be desirable to consider extending the system boundaries. For both food and bioenergy crops, these could include downstream impacts associated with supply chains, processing, product consumption, and waste disposal, as well as upstream impacts associated with production of fertilizer and other inputs. For the food system, these can result in net greenhouse gas emissions (Crippa et al., 2021), whereas bioenergy crops processed into biofuels are expected to accrue net social benefits including substitution credits relative to fossil fuel emissions and potentially carbon capture and storage (Field et al., 2020).

5.2 | Non-point pollution from crop production

Excess nutrient application for producing food crops is associated with significant pollution of both air (Hill et al., 2019) and water (Basso et al., 2019; Brandes et al., 2018). Thus, the targeted integration of biomass feedstock crops into existing agricultural landscapes is a strategy for reducing nitrogen leaching compared to business-as-usual (Brandes et al., 2018; Davis et al., 2013; Wu et al., 2012). Basso et al. (2019) used 8 years of satellite images to identify areas within corn and soybean fields that would constantly produce low yield (defined as one standard deviation from the mean of the field), and associated high losses of N to the environment via leaching and other processes. They found that nearly 30% of the US Midwest Corn Belt is under-productive with significant losses of N. Such water-pollution hotspots may be suitable for perennial bioenergy crops and can be considered socially marginal for annual crops even if they are profitable for food crop production in some years.

Annual crop production systems are also vulnerable to topsoil erosion due to tillage practices that disrupt soil structure and the network of plant roots and leave fields bare and vulnerable to wind and water forces over the winter months. Erosion risk is a strong function of rainfall intensity and amount, topography, and soil texture and varies spatially and over time. Across the US Corn Belt, topsoil erosion is estimated to reduce crop yields by ~6% causing $2.8 billion in annual economic losses (Thaler et al., 2021). Perennialization of agricultural systems can dramatically reduce erosion losses through the presence of an intact, undisturbed root zone holding soils in place, as well as the retention of protective aboveground biomass over the winter season. The strategic integration of perennial bioenergy grasses into existing agricultural landscapes may offer many of these benefits (Wang et al., 2020). However, energy crop production still involves soil disturbance during initial field preparation, periodic replanting, harvest, and other farm operations, as well as reduced aboveground biomass cover directly following harvest, and thus may offer less benefit than other forms of land protection (e.g., CRP enrollment).

Nitrate leaching and gaseous losses of nitrogen are subject to high levels of spatial and temporal variability, and direct measurement is very expensive and time-consuming. Process-based models such as DNDC, SWAT, and AgroIBIS (Brandes et al., 2018; Ferin et al., 2021; Wu et al., 2012) and various statistical and machine learning approaches (Fezzi et al., 2015; Knoll et al., 2019; Paudel & Crago, 2021) are used to simulate responses to management at watershed and basin scales. Remote sensing can also be used to better constrain aboveground vegetation and processes represented in these models. For examples, high-resolution remote-sensing data have been used to improve the representation of land cover and land use in process-based models of nitrate leaching (Hively et al., 2020), and in empirical models of soil erosion (Phinzi & Ngetar, 2019).

While croplands with high rates of nutrient loss or erosion may be good candidates for bioenergy feedstock production, these issues can also be mitigated through adoption of best management practices in existing cropping systems. The N_2O-reducing conservation measures discussed in the previous section also serve to reduce nitrogen losses via leaching and volatilization pathways. Similarly, cover cropping, tillage intensity reduction, contour tilling, and the use of riparian buffers and perennial strips can help to control erosion losses and sedimentation issues (Rickson, 2014; Volk et al., 2010). The costs and effectiveness of these conservation practices relative to those of bioenergy crop production need to be considered in determining the net social benefits of alternative land uses.

5.3 | Biodiversity

Expansion of annual cropland contributes to the fragmentation and/or loss of perennial vegetation and can thus lead to species decline (Lark et al., 2020; Rosenberg et al., 2019). Such losses can be mitigated to a certain extent through conservation management practices such as winter cover cropping or no-till management that leaves significant residue cover in place (VanBeek et al., 2014; Wilcoxen et al., 2018). Alternately, conversion of cropland to perennial crops can improve habitat for various species of ecological, economic, or aesthetic interest including pollinators and game species (Rupp & Ribic, 2019). Perennial bioenergy grasses have been shown to support greater diversity of insects and birds than corn cultivation, with switchgrass monocultures performing more similarly to native prairie grass mixtures than to corn monocultures (Werling et al., 2014). In highly cultivated landscapes, these lands may be particularly important as the only remaining habitat patches in which species can seek refuge (Haddad et al., 2015). We note, however, that natural grassland and forests may provide better habitat and ecosystem services than bioenergy crops. Similarly, the biodiversity implications of CRP conversion to bioenergy crops are less clear (Haan & Landis, 2019a, 2019b; Rupp & Ribic, 2019). Further study is needed to identify bioenergy crop species mixes and management regimes that maintain or enhance habitat quality compared to cropland and CRP land (Chen, Debnath, et al., 2021; Dale & Polasky, 2007; Garbach et al. 2014; Zhang et al., 2007).

Assessing the habitat and biodiversity value of both present and potential future land cover is particularly challenging given the range of species and their requirements and their compounding complexity when considered as ecological assemblages. Unlike the previous examples, habitat quality and biodiversity are less reliably modeled at the relatively fine scales required by marginality assessment. Instead, these phenomena often still require field assessment which can be labor-intensive and subject to inconsistency in methods used. For example, the North American Breeding Bird Survey (BBS), a long-term monitoring of abundance and species of birds at fine resolution across a large spatial extent, requires months of field assessment that involves roadsides surveys conducted by thousands of high-skilled bird observers each year (Sauer et al. 2017). To address this challenge, it may be possible to identify “indicator” or “umbrella” species representative of the requirements of the ecological community as a whole, greatly reducing the number of species that need to be assessed (Roberge & Angelstam, 2004). However, these approaches are inherently subjective and may overlook the needs of less abundant but important species. Recent studies suggest that remotely sensed indices of vegetation texture and phenology might serve as additional reliable proxies for habitat complexity, habitat quality, and/or biodiversity (Farwell et al., 2021; Silveira et al., 2021).

5.4 | Within-field socially marginal land

By strategically combining production of perennial crops with annual crops within a field in areas that are less productive and environmentally sensitive, it may be possible to enhance ecosystem services. Studies show that perennial crops can trap the run-off from other areas in the field (Basso, 2021; Dimitriou et al. 2018; Englund et al., 2020; Kreig et al., 2019; Schulte et al., 2006; Zhou et al., 2014). Integrating shrub willows on underproductive land in the corn belt and growing switchgrass in the space in-between rows of trees in the southern US can improve the overall sustainability of the landscape (Dimitriou et al. 2018; Englund et al., 2020). These studies show that with an integrated cropping system that combines bioenergy crops with food crops at a landscape scale, the bioenergy crop can intercept the nitrate applied to the upgradient portion of land and grow without direct fertilizer application. Although there is no clear evidence in the literature about the net economic and environmental benefits of wider implementation of these designs, experimental studies at few locations, such as in Iowa, Illinois and the coastal plain of North Carolina, show that heterogeneity in the soils, topography, and land use history of real-world agricultural landscapes provides an opportunity to strategically integrate energy crops in ways that further decrease nitrogen losses (Brandes et al., 2018) and N_2O emissions (Adler et al. 2012; Field et al., 2018). For instance, Brandes et al. (2018) show that a substantial reduction in nitrogen leaching can be achieved through the targeted replacement of annual crops such as corn and soybean with switchgrass on portions of fields in Iowa that are consistently underperforming in terms of corn/soybean yields as well as overall profitability.

5.5 | Non-market methods for quantifying social returns to land

There is a large literature assessing the monetized value of the ecosystem services/disservices from agricultural production (Chen, Debnath, et al., 2021; Dale & Polasky, 2007; Garbach et al., 2014; Zhang et al., 2007). While a formal review of the approaches and challenges in assessing such non-market values is beyond this paper's scope, below we present some examples for select externalities and how they might be applied to determine the net social benefits of food crops and energy crops.

A widely applied approach to valuing the greenhouse gas mitigation impacts of crop production is by using the social cost of carbon (SCC), the change in the discounted value of economic damages (loss in welfare) from an additional unit of carbon dioxide equivalent (CO_2-equivalent) emissions (IWG, 2021; Nordhaus, 2017). There is considerable consensus that \$51 per metric ton of CO_2 equivalent (Mg^{-1} CO_2-eq) is a reasonable estimate of SCC with the 3% social discount rate and \$76 Mg^{-1} CO_2-eq at 2.5% discount rate (Havranek et al., 2015; IWG, 2021; Khanna et al., 2017). Applying a \$51 Mg^{-1} CO_2-eq SCC value to the Qin et al. (2016) median SOC accrual rate from perennial energy grass production on former cropland (1.2 Mg C ha^{-1} $year^{-1}$) implies an additional social return of \$224 ha^{-1}, a substantial amount that could easily affect the choice of crop to grow. Chen, Blanc-Betes, et al. (2021) apply these estimates to systematically quantify the net monetary value of greenhouse gas savings (including soil carbon change) due to the conversion of CRP land to energy crops across the eastern US.

Similar to the SCC, the concept of social cost of nitrogen (SCN) has been developed and applied in the assessment of externalities from nitrate leaching and other forms of N loss. Despite the similarity in concept, estimating the SCN is more challenging since the impacts of nitrogen are highly spatially heterogeneous (Keeler et al., 2016). In the absence of spatially heterogeneous N leakage data and the environmental damages due to it, studies such as Sobota et al. (2015) propose a simple unit value transfer method by compiling the damage costs associated with nitrogen application (air/climate, freshwater, drinking water, and coastal-zone-related damages) based on information obtained from existing studies (Compton et al., 2011; Van Grinsven et al., 2013). The SCN estimated by Sobota et al. (2015) ranges from \$5.5 to 16.9 kg^{-1} N applied. Using these SCC and SCN values, Chen, Debnath, et al. (2021) quantified the net social costs and benefits of producing biofuels from food crops and energy crops by monetizing the change in greenhouse gas emissions and N-leakage.

The non-market value of other ecosystem dis-services due to crop production, such as soil erosion, biodiversity loss, and pesticide damage has also been estimated by studies (Adhikari & Nadella, 2011; Bartkowski et al., 2015; Florax, 2005; Plaas et al., 2019 and many others). While a thorough review of this literature is beyond the scope of this paper, analysts, policy developers, and other decision-makers can use a portfolio of such non-market values to assess the social net returns of crop production depending on their objectives. We do, however, note the need for caution in simply adding up a series of independent value estimates for different ecosystem services, which might result in a biased estimate due to the potential substitute or complementary nature of the relationship between these services and dis-services (Hoehn & Loomis, 1993). Additionally, we also note that there is a need to distinguish between ecosystem end-products (such as, drinking water, vegetation types, and wildlife species) and intermediate ecosystem services (such as, purification of water, dispersal of seeds, and maintenance of habitats for plants and animals) to avoid the problem of double-counting (Brown et al., 2007; Kroeger & Casey, 2007). Finally, the lack of formal markets and measurement uncertainties for most ecosystem services, as well as the varying objectives of policy developers and other decision-makers, requires strong stakeholder engagement and careful design including consideration of qualitative measures and weighting factors, to develop meaningful multi-objective assessments (Marchand et al., 2014; Ostrom, 1990; Parish et al., 2012).

6 | INCENTIVES FOR CONVERTING LAND TO BIOENERGY CROP PRODUCTION

The incentives for converting land to energy crop production will depend on the market returns to bioenergy crop production (defined as the revenue from biomass net of the costs of production) and the riskiness of those returns relative to those with the existing use of that land, which could be crop or non-crop use. They will also depend on farmer characteristics and behavioral preferences of landowners. We now discuss the factors likely to affect the conversion of land marginal for food crops to bioenergy crops and reasons that this conversion need not be limited to marginal land only.

6.1 | Incentives for converting marginal land to bioenergy crops

Even when land is socially and economically marginal for food crops and suitable for energy crop production, farmers may be unwilling to convert it. Breakeven analyses of various bioenergy crops shed light on the direct costs and opportunity costs of producing these crops and the incentives for farmers to convert various types of land to energy crops (Jain et al., 2010; Khanna et al., 2008; Mooney et al., 2009). Although the land to the right of L_4 in Figure 1 has positive economic returns from bioenergy crop production that are higher than those from food crops, landowners may be reluctant to convert the land to energy crops for various non-economic or behavioral reasons, including socio-cultural and aesthetic factors. Promoting conversion of socially marginal lands to bioenergy crops will thus likely depend on additional policy incentives to further encourage shifts in land use.

Some studies show that the supply of marginal land for bioenergy crops is generally lower than the availability estimated through conventional marginal land assessments. These discrepancies are due to landowners' preferences, their belief that this land is not "in play" for production, high amenity values on marginal lands, high conversion costs, and inertia (Barham et al., 2016; Eaton et al., 2018, 2019). Two studies found that landowners are only willing to rent or supply land for bioenergy-crop production on 21% of available marginal land in the Northern Great Lakes Region, even when rental rates are twice as high as current rates (Swinton et al., 2017), and 27% of marginal lands in Lower Southern Michigan at typical rental rates (Skevas et al., 2016). Chen, Blanc-Betes, et al. (2021) show that converting CRP land to energy crops would require relatively high biomass prices if landowners were required to forego some or all of the relatively high rental payment for this land provided by the government.

Various farmer characteristics that have consistently been associated with a higher propensity to grow bioenergy crops include lower age, higher education levels, prior knowledge of bioenergy crops, use of alternative fuels, lower risk aversion, and less present-biasedness (Jiang et al., 2018; Khanna et al., 2017; Lynes et al., 2016; Mattia et al., 2018; Mooney et al., 2015; Qualls et al., 2012; Skevas et al., 2018; Swinton et al., 2017). Off-farm income has been shown to increase the willingness to supply bioenergy crops (Jensen et al., 2007; Qualls et al., 2012; Smith et al., 2018). Farm characteristics such as larger farms, higher percentage of farm leased, higher percentage of land in CRP, more marginal land, land already in a perennial land use such as hay, and the distance to bioenergy pellet facilities also contribute to a greater probability of bioenergy crop production (Jiang et al., 2018, 2019; Lynes et al., 2016). For a comprehensive meta-analysis of the farmer characteristics that influence willingness to produce bioenergy crops, see Galik (2015).

6.2 | Incentives for converting cropland to energy crops

There is no regulatory or other "firewall" preventing landowners from converting land that is not socially marginal for food crop production to bioenergy crops if the market conditions make it profitable to do so. Figure 1 shows that in some cases, it may be appropriate to expect conversion of some productive cropland to bioenergy crop production. The area L_4-L_2 is not economically marginal land for food crops but is nonetheless profitable to convert to bioenergy crops, while L_4-L_1 is not economically marginal but socially beneficial to convert to bioenergy crops. Land with unstable food crop yields, relatively low returns, and high risks may be more profitable under bioenergy crop production if food crop prices are low and biomass prices are high. For instance, energy crop production on some portion of the cropland can diversify risks for a landowner. Miao and Khanna (2014) show that the risks and returns to land under food crop production and miscanthus production are negatively correlated and this can create incentives to grow energy crops on cropland. Anand et al. (2019) show that considerations of risk aversion and loss aversion among farmers affect the type of land (and its location) that might be converted to miscanthus vs. switchgrass, since these crops differ in the spatial pattern of the riskiness of their returns to land relative to corn and soybeans.

However, it is also worth noting that landowner willingness to convert this type of non-marginal cropland to energy crops may require biomass prices that are significantly higher than the breakeven price to offset not only the opportunity costs of the existing land but also other costs such as learning risks, price risks as relevant bioenergy markets evolve, yield and price uncertainty, and the costs of reversing the land conversion decision (Fewell et al., 2011; Li & Zipp, 2019; Song et al., 2011). Studies show that farmers may also be reluctant to convert cropland from annual to perennial crops due to lack of availability of equipment, uncertainties about future markets, and their own risk and time preferences (Eaton et al., 2018, 2019; Fewell et al., 2011; Khanna et al., 2017). There is mixed evidence on the impact of net farm income on incentives to grow energy crops, with Jensen et al. (2007) reporting a lower willingness to supply bioenergy crops for farmers with higher net farm income per hectare under the current land use due to the higher opportunity cost of converting land out of its current use, and Smith et al. (2018) reporting a smaller amount of acreage supplied with lower total farm income due to the higher aversion to risk and severe liquidity constraints. Khanna et al. (2017) show that landowners with crop insurance for food crops are less likely to convert cropland to energy crops. The provision of subsidized crop insurance for food crops and no crop insurance for energy crops will increase the riskiness of producing energy crops.

7 | CONCLUSION

The notion of using marginal land for bioenergy crop production to avoid conflict with food crop production has generated a large literature on definitions of marginal land and a wide range of estimates of the amount of marginal land available. Differences in these definitions and the assumptions underlying them make it difficult to compare these estimates with each other. We propose a new conceptual framework wherein socially marginal land is defined as land earning a low return (close to zero) after accounting for its negative environmental impacts in its current use. This definition is likely to encompass land that is biophysically poor and land that is currently idle/fallow (economically marginal land for food crops), as well as land that is in crop production but losing soil organic matter, suffering from erosion or high nutrient run-off, or foregoing significant habitat value (socially marginal land for food crops). A strong case can be made that strategically converting such lands to perennial biomass crops would yield climate and environmental benefits while minimizing diversion of land from food crops. However, the thresholds for biophysical productivity or specific land covers that should be classified as marginal will be determined by climate conditions, market conditions, policy incentives, or disincentives for retiring environmentally sensitive cropland and other amenities the land provides. As a result, the biophysical and economic thresholds for defining marginal land will vary spatially and over time.

While marginal lands suitable for bioenergy crops offer the potential for growing bioenergy crops without diverting land from food crops and of enhancing ecosystem services on the land, we note that not all land that is suitable for conversion to bioenergy crops may be made available by landowners to do so. Future research is needed to understand the drivers of the incentives by landowners to convert this land to bioenergy crops, which may depend on various factors such as the yields of these crops, biomass prices, technology for converting these crops to bioenergy, and market demand for bioenergy. A key component of these incentives is the yield of bioenergy crops on low-quality marginal land relative to highly productive cropland and the changes in the yields of these crops as they become older. Future research that improves our understanding of the yield performance of bioenergy crops on marginal lands will enable better quantification of the economic potential for converting marginal lands for bioenergy crops. Future research also needs to develop strategies for breeding bioenergy crops to demonstrate higher economic and environmental performance on marginal lands.

While the framework developed here is largely conceptual, expanding the definition of marginal land to consider environmental impacts and net social benefits may both expand the land area appropriate for bioenergy crop production and enhance the sustainability of agricultural landscapes. Such landscapes, designed to optimize the net social benefits of food crops, bioenergy crops, and natural ecosystems, can deliver greater value to society, but will also require an expanded set of incentives for non-market attributes as well as uncertainties and risks. Future research and interdisciplinary collaborations are needed to operationalize this framework and determine the amount of socially marginal land that is available for conversion to bioenergy crops, and the market and policy incentives needed to incentivize this conversion.

ACKNOWLEDGEMENTS

This work was funded by the DOE Center for Advanced Bioenergy and Bioproducts Innovation (US Department of Energy, Office of Science, Office of Biological and Environmental Research under Award Number DE-SC0018420) to M.K., L.C., X.C., K.G., C.J., and P.Y.; the Great Lakes Bioenergy Research Center (award number DE-SC0018409) to B.B., T.J.L., and S.A.S.; the Center for Bioenergy Innovation, a US Department of Energy Research Center supported by the Office of Biological and Environmental Research in the DOE Office of Science (award number DE-AC05-00OR22725) to J.L.F and T.L.R. J.L.F acknowledges partial support from US Department of Agriculture National Institute of Food and Agriculture USDA/NIFA grant# 2017-67019-26327. T.L.R. acknowledges partial support from US Department of Agriculture National Institute of Food and Agriculture USDA/NIFA grant# 2020-68012-31824. K.Y.Z acknowledges support from the USDA National Institute of Food and Agriculture and Multistate Hatch Appropriations under Project # PEN04631 and Accession #1014400. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the US Department of Energy.

This manuscript has been authored in part by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE). The US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

ORCID

Madhu Khanna https://orcid.org/0000-0003-4994-4451
Luoye Chen https://orcid.org/0000-0002-2514-8162
Bruno Basso https://orcid.org/0000-0003-2090-4616
John L. Field https://orcid.org/0000-0003-4451-8947
Tyler J. Lark https://orcid.org/0000-0002-4583-6878
Tom L. Richard https://orcid.org/0000-0002-0833-4844
Seth A. Spawn-Lee https://orcid.org/0000-0001-8821-5345
Katherine Y. Zipp https://orcid.org/0000-0002-7206-5159

REFERENCES

Abraha, M., Gelfand, I., Hamilton, S. K., Chen, J., & Robertson, G. P. (2019). Carbon debt of field-scale conservation reserve program grasslands converted to annual and perennial bioenergy crops. *Environmental Research Letters*, *14*, 24019. https://doi.org/10.1088/1748-9326/aafc10

Adhikari, B., & Nadella, K. (2011). Ecological economics of soil erosion: A review of the current state of knowledge. *Annals of the New York Academy of Sciences*, *1219*, 134–152. https://doi.org/10.1111/j.1749-6632.2010.05910.x.

Adler, P. R., Del Grosso, S. J., Inman, D., Jenkins, R. E., Spatari, S., & Zhang, Y. (2012). Mitigation opportunities for life-cycle greenhouse gas emissions during feedstock production across heterogeneous landscapes. In *Managing agricultural greenhouse gases* (pp. 203–219). Elsevier. https://linkinghub.elsevier.com/retrieve/pii/B9780123868978000127

Akiyama, H., Yan, X., & Yagi, K. (2009). Evaluation of effectiveness of enhanced-efficiency fertilizers as mitigation options for N_2O and NO emissions from agricultural soils: Meta-analysis. *Global Change Biology*, *16*, 1837–1846. https://doi.org/10.1111/j.1365-2486.2009.02031.x

Anand, M., Miao, R., & Khanna, M. (2019). Adopting bioenergy crops: Does farmers‘ attitude toward loss matter? *Agricultural Economics*, *50*, 435–450. https://doi.org/10.1111/agec.12501

Aust, C., Schweier, J., Brodbeck, F., Sauter, U. H., Becker, G., & Schnitzler, J-P. (2014). Land availability and potential biomass production with poplar and willow short rotation coppices in Germany. *GCB Bioenergy*, *6*(5), 521–533. https://doi.org/10.1111/gcbb.12083

Barham, B. L., Mooney, D. F., & Swinton, S. M. (2016). Inconvenient truths about landowner (un) willingness to grow dedicated bioenergy crops. *Agricultural & Applied Economics Association*, *31*, 1–8.

Bartkowski, B., Lienhoop, N., & Hansjürgens, B. (2015). Capturing the complexity of biodiversity: A critical review of economic valuation studies of biological diversity. *Ecological Economics*, *113*, 1–14. https://linkinghub.elsevier.com/retrieve/pii/S0921800915000701

Basso, B. (2021). Precision conservation for a changing climate. *Nature Food*, *2*, 322–323. http://www.nature.com/articles/s43016-021-00283-z

Basso, B., & Antle, J. (2020). Digital agriculture to design sustainable agricultural systems. *Nature Sustainability*, *3*, 254–256.

Bruno, B., Guanyuan, S., Jinshui, Z., & Philip, R. G. (2019). Yield stability analysis reveals sources of large-scale nitrogen loss from the US Midwest. *Scientific Reports*, *9*(1), 1–9. https://doi.org/10.1038/s41598-019-42271-1

Bonner, I. J., Cafferty, K. G., Muth, D. J., Tomer, M. D., James, D. E., Porter, S. A., & Karlen, D. L. (2014). Opportunities for energy crop production based on subfield scale distribution of profitability. *Energies*, *7*, 6509–6526.

Borchard, N., Schirrmann, M., Cayuela, M. L., Kammann, C., Wrage-Mönnig, N., Estavillo, J. M., Fuertes-Mendizábal, T., Sigua, G., Spokas, K., Ippolito, J. A., & Novak, J. (2019). Biochar, soil and land-use interactions that reduce nitrate leaching and N_2O emissions: A meta-analysis. *Science of the Total Environment*, *651*, 2354–2364. https://doi.org/10.1016/j.scitotenv.2018.10.060

Boyer, C. N., Roberts, R. K., English, B. C., Tyler, D. D., Larson, J. A., & Mooney, D. F. (2013). Effects of soil type and landscape on yield and profit maximizing nitrogen rates for switchgrass production. *Biomass and Bioenergy*, *48*, 33–42.

Brandes, E., McNunn, G. S., Schulte, L. A., Bonner, I. J., Muth, D. J., Babcock, B. A., Sharma, B., & Heaton, E. A. (2016). Subfield profitability analysis reveals an economic case for cropland diversification. *Environmental Research Letters*, *11*, 14009. https://doi.org/10.1088/1748-9326/11/1/014009

Brandes, E., McNunn, G. S., Schulte, L. A., Muth, D. J., VanLoocke, A., & Heaton, E. A. (2018). Targeted subfield switchgrass integration could improve the farm economy, water quality, and bioenergy feedstock production. *GCB Bioenergy*, *10*, 199–212. https://doi.org/10.1111/gcbb.12481

Brown, T. C., Bergstrom, J. C., & Loomis, J. B. (2007). Defining, valuing, and providing ecosystem goods and services. *Natural Resources Journal*, *47*, 329–376.

Cai, X., Zhang, X., & Wang, D. (2011). Land availability for biofuel production. *Environmental Science & Technology*, *45*, 334–339.

Campbell, E., Field, J. L., & Paustian, K. (2008). The global potential of bioenergy on abandoned agriculture lands (ed. D. Reicosky). *Environmental Science*, *2*, 97–123. https://doi.org/10.19103/AS.2017.0033.21

Campbell, E. E., Field, J. L., & Paustian, K. (2018). Modelling soil organic matter dynamics as a soil health indicator. In D. Reicosky (Ed.), *Managing soil health for sustainable agriculture: Volume 2: Monitoring and management* (pp. 97–123). Burleigh Dodds Science Publishing.

Carlson, K. M., Gerber, J. S., Mueller, N. D., Herrero, M., MacDonald, G. K., Brauman, K. A., Havlik, P., O'Connell, C. S., Johnson, J. A., Saatchi, S., & West, P. C. (2017). Greenhouse gas emissions intensity of global croplands. *Nature Climate Change*, *7*, 63–68.

Chen, L., Blanc-Betes, E., Hudiburg, T. W., Hellerstein, D., Wallander, S., DeLucia, E. H., & Khanna, M. (2021). Assessing the returns to land and greenhouse gas savings from producing energy crops on conservation reserve program land. *Environmental Science and Technology of Food Industry*, *55*, 1301–1309. https://pubs.acs.org/doi/10.1021/acs.est.0c06133

Chen, L., Debnath, D., Zhong, J., Ferin, K., VanLoocke, A., & Khanna, M. (2021). The economic and environmental costs and benefits of the renewable fuel standard. *Environmental Research Letters*, *16*. https://iopscience.iop.org/article/10.1088/1748-9326/abd7af

Cheng, F. Y., Van Meter, K. J., Byrnes, D. K., & Basu, N. B. (2020). Maximizing US nitrate removal through wetland protection and restoration. *Nature*, *588*(7839), 625–630. https://doi.org/10.1038/s41586-020-03042-5

Compton, J. E., Harrison, J. A., Dennis, R. L., Greaver, T. L., Hill, B. H., Jordan, S. J., Walker, H., & Campbell, H. V. (2011). Ecosystem services altered by human changes in the nitrogen cycle: a new perspective for US decision making. *Ecology Letters*, *14*, 804–815. https://doi.org/10.1111/j.1461-0248.2011.01631.x

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F. N., & Leip, A. (2021). Food systems are responsible for a third of global anthropogenic GHG emissions. *Ecology Letters*, *2*, 198–209. http://www.nature.com/articles/s43016-021-00225-9

Crutzen, P. J., Mosier, A. R., Smith, K. A., & Winiwarter, W. (2008). N_2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. *Atmospheric Chemistry and Physics*, *8*, 389–395.

Dale, V. H., & Polasky, S. (2007). Measures of the effects of agricultural practices on ecosystem services. *Ecological Economics*, *64*, 286–296.

Daly, C., Halbleib, M. D., Hannaway, D. B., & Eaton, L. M. (2018). Environmental limitation mapping of potential biomass resources across the conterminous United States. *GCB Bioenergy*, *10*, 717–734. https://doi.org/10.1111/gcbb.12496

Davis, S. C., Boddey, R. M., Alves, B. J. R., Cowie, A. L., George, B. H., Ogle, S. M., Smith, P., van Noordwijk, M., & van Wijk, M. T. (2013). Management swing potential for bioenergy crops. *GCB Bioenergy*, *5*(6), 623–638. https://doi.org/10.1111/gcbb.12042

Deines, J. M., Patel, R., Liang, S.-Z., Dado, W., & Lobell, D. B. (2021). A million kernels of truth: Insights into scalable satellite maize yield mapping and yield gap analysis from an extensive ground dataset in the US Corn Belt. *Remote Sensing of Environment*, *253*, 112174–https://doi.org/10.1016/j.rse.2020.112174

Dimitriou, I., Berndes, G., Englund, O., Brown, M., Busch, G., Dale, V., Devlin, G., English, B., Goss, K., Jackson, S., Kline, K. L., McDonnell, K., McGrath, J., Mola-Yudego, B., Murphy, F., Negri, M. C., Parish, E. S., Ssegane, H., & Tyler, D. (2018). *Lignocellulosic crops in agricultural landscapes: Production systems for biomass and other environmental benefits - examples, incentives, and barriers*. Chalmers tekniska högskola, International Energy Agency (IEA). http://edepot.wur.nl/471044

Dwivedi, P., Wang, W., Hudiburg, T., Jaiswal, D., Parton, W., Long, S., Delucia, E., & Khanna, M. (2015). Cost of abating greenhouse gas emissions with cellulosic ethanol. *Environmental Science and Technology of Food Industry*, *49*, 2512–2522.

Eaton, W. M., Burnham, M., Hinrichs, C. C., Selfa, T., & Yang, S. (2018). How do sociocultural factors shape rural landowner responses to the prospect of perennial bioenergy crops? *Landscape and Urban Planning*, *175*, 195–204.

Eaton, W. M., Burnham, M., Running, K., Hinrichs, C. C., & Selfa, T. (2019). Symbolic meanings, landowner support, and dedicated bioenergy crops in the rural northeastern United States. *Energy Research & Social Science*, *52*, 247–257.

Emery, I., Mueller, S., Qin, Z., & Dunn, J. B. (2017). Evaluating the potential of marginal land for cellulosic feedstock production and carbon sequestration in the United States. *Environmental Science and Technology of Food Industry*, *51*, 733–741.

Englund, O., Dimitriou, I., Dale, V. H., Kline, K. L., Mola-Yudego, B., Murphy, F., English, B., McGrath, J., Busch, G., Negri, M. C., Brown, M., Goss, K., Jackson, S., Parish, E. S., Cacho, J., Zumpf, C., Quinn, J., & Mishra, S. K. (2020). Multifunctional perennial production systems for bioenergy: Performance and progress. *Wiley Interdisciplinary Reviews: Energy and Environment*, *9*, 1–24.

EPA. (2020). *Inventory of U.S. greenhouse gas emissions and sinks: 1990–2005*. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2018

Farwell, L. S., Gudex-Cross, D., Anise, I. E., Bosch, M. J., Olah, A. M., Radeloff, V. C., Razenkova, E., Rogova, N., Silveira, E. M. O., Smith, M. M., & Pidgeon, A. M. (2021). Satellite image texture captures vegetation heterogeneity and explains patterns of bird richness. *Remote Sensing of Environment*, *253*, 112175–https://doi.org/10.1016/j.rse.2020.112175

Feng, Q., Chaubey, I., Engel, B., Cibin, R., Sudheer, K. P., & Volenec, J. (2017). Marginal land suitability for switchgrass, Miscanthus and hybrid poplar in the Upper Mississippi River Basin (UMRB). *Environmental Modelling & Software*, *93*, 356–365. https://doi.org/10.1016/j.envsoft.2017.03.027

Ferin, K. M., Luoye, C., Jia, Z., Sarah, A., Heaton, E. A., Madhu, K., & Andy, V. L. (2021). Water quality effects of economically viable land use change in the Mississippi River Basin under the Renewable fuel standard. *Environmental Science & Technology*, *55*(3), 1566–1575. https://doi.org/10.1021/acs.est.0c04358

Fewell, J., Bergtold, J., & Williams, J. (2011). Farmers' willingness to grow switchgrass as a cellulosic bioenergy crop: A stated choice approach. *Joint Annual Meeting of the Canadian Agricultural Economics Society & Western Agricultural Economics Association*, *30*.

Fezzi, C., Harwood, A. R., Lovett, A. A., & Bateman, I. J. (2015). The environmental impact of climate change adaptation on land use and water quality. *Nature Climate Change*, *5*, 255–260. http://www.nature.com/articles/nclimate2525

Field, C. B., Campbell, J. E., & Lobell, D. B. (2008). Biomass energy: The scale of the potential resource. *Trends in Ecology & Evolution*, *23*, 65–72.

Field, J. L., Evans, S. G., Marx, E., Easter, M., Adler, P. R., Dinh, T., Willson, B., & Paustian, K. (2018). High-resolution techno-ecological modelling of a bioenergy landscape to identify climate mitigation opportunities in cellulosic ethanol production. *Nature Energy*, *3*, 211–219. https://doi.org/10.1038/s41560-018- 0088-1

Field, J. L., Richard, T. L., Smithwick, E. A. H., Cai, H., Laser, M. S., LeBauer, D. S., Long, S. P., Paustian, K., Qin, Z., Sheehan, J. J., Smith, P., Wang, M. Q., & Lynd, L. R. (2020). Robust paths to net greenhouse gas mitigation and negative emissions via advanced biofuels. *Proceedings of the National Academy of Sciences of the United States of America*, *117*, 21968–21977.

Florax, R. J. G. M. (2005). A meta-analysis of the willingness to pay for reductions in pesticide risk exposure. *European Review of Agricultural Economics*, *32*, 441–467. https://academic.oup.com/erae/article-lookup/doi/10.1093/erae/jbi025

Galik, C. S. (2015). Exploring the determinants of emerging bioenergy market participation. *Renewable and Sustainable Energy Reviews*, *47*, 107–116. https://linkinghub.elsevier.com/retrieve/pii/S1364032115001501

Garbach, K., Milder, J. C., Montenegro, M., Karp, D. S., & DeClerck, F. A. J. (2014). Biodiversity and ecosystem services in agroecosystems. *Encyclopedia of Agriculture and Food Systems*, *2*, 21–40.

Gelfand, I., Sahajpal, R., Zhang, X., Izaurralde, R. C., Gross, K. L., & Robertson, G. P. (2013). Sustainable bioenergy production from marginal lands in the US Midwest. *Nature*, *493*, 514–517. https://doi.org/10.1038/nature11811

Gibbs, H. K., & Salmon, J. M. (2015). Mapping the world's degraded lands. *Applied Geography*, *57*, 12–21. https://doi.org/10.1016/j.apgeog.2014.11.024

Goldstein, A., Turner, W. R., Spawn, S. A., Anderson-Teixeira, K. J., Cook-Patton, S., Fargione, J., Gibbs, H. K., Griscom, B., Hewson, J. H., Howard, J. F., Ledezma, J. C., Page, S., Koh, L. P., Rockström, J., Sanderman, J., & Hole, D. G. (2020). Protecting irrecoverable carbon in Earth's ecosystems. *Nature Climate Change*, *10*, 287–295.

Gopalakrishnan, G., Cristina Negri, M., & Snyder, S. W. (2011). A novel framework to classify marginal land for sustainable biomass feedstock production. *Journal of Environmental Quality*, *40*, 1593–1600.

Grant, R. F., Dyck, M., & Puurveen, D. (2020). Nitrogen and phosphorus control carbon sequestration in agricultural ecosystems: modelling carbon, nitrogen, and phosphorus balances at the Breton Plots with ecosys under historical and future climates. *Canadian Journal of Soil Science, 100*, 408–429. https://doi.org/10.1139/cjss-2019-0132.

Gu, Y., & Wylie, B. K. (2017). Mapping marginal croplands suitable for cellulosic feedstock crops in the Great Plains. *United States GCB Bioenergy*, *9*, 836–844.

Gutierrez, A. P., & Ponti, L. (2009). Bioeconomic sustainability of cellulosic biofuel production on marginal lands. *Bulletin of Science, Technology & Society*, *29*, 213–225. http://journals.sagepub.com/doi/10.1177/0270467609333729

Haan, N. L., & Landis, D. A. (2019a). Grassland disturbance increases monarch butterfly oviposition and decreases arthropod predator abundance. *Biological Conservation*, *233*, 185–192.

Haan, N. L., & Landis, D. A. (2019). The importance of shifting disturbance regimes in monarch butterfly decline and recovery. *Frontiers in Ecology and Evolution*, *7*, 191–199. https://doi.org/10.3389/fevo.2019.00191

Haddad, N. M., Brudvig, L. A., Jean, C., Davies, K. F., Andrew, G., Holt, R. D., Lovejoy, T. E., Sexton, J. O., Austin, M. P., Collins, C. D., Cook, W. M., Damschen, E. I., Ewers, R. M., Foster, B. L., Jenkins, C. N., King, A. J., Laurance, W. F., Levey, D. J., Margules, C. R., … Townshend, J. R. (2015). Habitat fragmentation and its lasting impact on Earth's ecosystems. *Science Advances*, *1*(2), e1500052. https://doi.org/10.1126/sciadv.1500052

Havranek, T., Irsova, Z., Janda, K., & Zilberman, D. (2015). Selective reporting and the social cost of carbon. *Energy Economics*, *51*, 394–406. https://linkinghub.elsevier.com/retrieve/pii/S0140988315002327

Heaton, E. A., Schulte, L. A., Berti, M., Langeveld, H., Zegada-Lizarazu, W., Parrish, D., & Monti, A. (2013). Managing a second-generation crop portfolio through sustainable intensification: Examples from the USA and the EU. *Biofuels, Bioproducts and Biorefining*, *7*(6), 702–714. https://doi.org/10.1002/bbb.1429

Hill, J., Goodkind, A., Tessum, C., Thakrar, S., Tilman, D., Polasky, S., Smith, T., Hunt, N., Mullins, K., Clark, M., & Marshall, J. (2019). Air-quality-related health damages of maize. *Nature Sustainability*, *2*, 397–403. https://doi.org/10.1038/s41893-019-0261-y

Hively, W. D., Lee, S., Sadeghi, A. M., McCarty, G. W., Lamb, B. T., Soroka, A., Keppler, J., Yeo, I. Y., & Moglen, G. E. (2020). Estimating the effect of winter cover crops on nitrogen leaching using cost-share enrollment data, satellite remote sensing, and Soil and Water Assessment Tool (SWAT) modeling. *Journal of Soil and Water Conservation*, *75*, 362–375.

Hoehn, J. P., & Loomis, J. B. (1993). Substitution effects in the valuation of multiple environmental programs. *Journal of Environmental Economics and Management*, *25*, 56–75. https://linkinghub.elsevier.com/retrieve/pii/S0095069683710260

Hoogwijk, M., Faaij, A., van den Broek, R., Berndes, G., Gielen, D., & Turkenburg, W. (2003). Exploration of the ranges of the global potential of biomass for energy. *Biomass and Bioenergy*, *25*(2), 119–133. https://doi.org/10.1016/s0961-9534(02)00191-5

Hudiburg, T. W., Wang, W., Khanna, M., Long, S. P., Dwivedi, P., Parton, W. J., Hartman, M., & Delucia, E. H. (2016). Impacts of a 32-billion-gallon bioenergy landscape on land and fossil fuel use in the US. *Nature Energy*, *1*, 1–7.

Interagency Working Group on the Social Cost of Greenhouse Gases. (2021). *Technical support document: Social cost of carbon, methane, and nitrous oxide; Interim estimates under executive order 13990*.

Isbell, F., Tilman, D., Reich, P. B., & Clark, A. T. (2019). Deficits of biodiversity and productivity linger a century after agricultural abandonment. *Nature Ecology & Evolution*, *3*, 1533–1538. https://doi.org/10.1038/s41559-019-1012-1

Jack, B. K., Kousky, C., & Sims, K. R. E. (2008). Designing payments for ecosystem services: Lessons from previous experience with incentive-based mechanisms. *Proceedings of the National Academy of Sciences of the United States of America*, *105*, 9465–9470. https://doi.org/10.1073/pnas.0705503104

Jain, A. K., Khanna, M., Erickson, M., & Huang, H. (2010). An integrated biogeochemical and economic analysis of bioenergy crops in the Midwestern United States. *GCB Bioenergy*, *2*(5), 217–234. https://doi.org/10.1111/j.1757-1707.2010.01041.x

Jensen, K., Clark, C., Ellis, P., English, B., Menard, J., Walsh, M., & Delatorreugrate, D. (2007). Farmer willingness to grow switchgrass for energy production. *Biomass and Bioenergy*, *31*, 773–781. https://doi.org/10.1016/j.biombioe.2007.04.002

Jiang, C., Guan, K., Khanna, M., Chen, L., & Peng, J. (2021). Assessing marginal land availability based on high-resolution land use change information in the Contiguous United States. *Environmental Science & Technology*. https://pubs.acs.org/doi/abs/10.1021/acs.est.1c02236

Jiang, W., Zipp, K. Y., & Jacobson, M. (2018). Economic assessment of landowners‘ willingness to supply energy crops on marginal lands in the northeastern of the United States. *Biomass and Bioenergy*, *113*, 22–30. https://doi.org/10.1016/j.biombioe.2018.03.005

Jiang, W., Zipp, K. Y., Langholtz, M. H., & Jacobson, M. G. (2019). Modeling spatial dependence and economic hotspots in landowners' willingness to supply bioenergy crops in the Northeastern United States. *GCB Bioenergy*, *11*, gcbb.12617. https://onlinelibrary.wiley.com/doi/abs/10.1111/gcbb.12617

Jin, V. L., Schmer, M. R., Stewart, C. E., Mitchell, R. B., Williams, C. O., Wienhold, B. J., Varvel, G. E., Follett, R. F., Kimble, J., & Vogel, K. P. (2019). Management controls the net greenhouse gas outcomes of growing bioenergy feedstocks on marginally productive croplands. *Science Advances*, *5*, eaav9318. https://advances.sciencemag.org/lookup/doi/10.1126/sciadv.aav9318

Kang, S., Post, W., Wang, D., Nichols, J., Bandaru, V., & West, T. (2013). Hierarchical marginal land assessment for land use planning. *Land Use Policy*, *30*, 106–113. https://doi.org/10.1016/j.landusepol.2012.03.002

Keeler, B. L., Gourevitch, J. D., Polasky, S., Isbell, F., Tessum, C. W., Hill, J. D., & Marshall, J. D. (2016). The social costs of nitrogen. *Science Advances*, *2*, 1600219.

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

Khanna, M., Louviere, J., & Yang, X. (2017). Motivations to grow energy crops: The role of crop and contract attributes. *Agricultural Economics*, *48*, 263–277. https://doi.org/10.1111/agec.12332

Knoll, L., Breuer, L., & Bach, M. (2019). Large scale prediction of groundwater nitrate concentrations from spatial data using machine learning. *Science of the Total Environment*, *668*, 1317–1327. https://linkinghub.elsevier.com/retrieve/pii/S004896971931023X

Knox, J. C. (2006). Floodplain sedimentation in the Upper Mississippi Valley: Natural versus human accelerated. *Geomorphology*, *79*, 286–310.

Kreig, J. A. F., Ssegane, H., Chaubey, I., Negri, M. C., & Jager, H. I. (2019). Designing bioenergy landscapes to protect water quality. *Biomass and Bioenergy*, *128*, 105327. https://doi.org/10.1016/j.biombioe.2019.105327

Kroeger, T., & Casey, F. (2007). An assessment of market-based approaches to providing ecosystem services on agricultural lands. *Ecological Economics*, *64*, 321–332. https://linkinghub.elsevier.com/retrieve/pii/S0921800907004156

Lark, T. J., Mueller, R. M., Johnson, D. M., & Gibbs, H. K. (2017). Measuring land-use and land-cover change using the U.S. department of agriculture's cropland data layer: Cautions and recommendations. *International Journal of Applied Earth Observation and Geoinformation*, *62*, 224–235. https://doi.org/10.1016/j.jag.2017.06.007

Lark, T. J., Spawn, S. A., Bougie, M., & Gibbs, H. K. (2020). Cropland expansion in the United States produces marginal yields at high costs to wildlife. *Nature Communications*, *11*(1), 1–11. https://doi.org/10.1038/s41467-020-18045-z

Lark, T. J., Schelly, I. H., & Gibbs, H. K. (2021). Accuracy, Bias, and Improvements in Mapping Crops and Cropland across the United States Using the USDA Cropland Data Layer. *Remote Sensing.*, *13*, 968. https://doi.org/10.3390/rs13050968.

Levia, D. F., Creed, I. F., Hannah, D. M., Nanko, K., Boyer, E. W., Carlyle-Moses, D. E., van de Giesen, N., Grasso, D., Guswa, A. J., Hudson, J. E., Hudson, S. A., Iida, S., Jackson, R. B., Katul, G. G., Kumagai, T., Llorens, P., Ribeiro, F. L., Pataki, D. E., Peters, C. A., … Bruen, M. (2020). Homogenization of the terrestrial water cycle. *Nature Geoscience*, *13*(10), 656–658. https://doi.org/10.1038/s41561-020-0641-y

Li, X., & Zipp, K. Y. (2019). Dynamics and uncertainty in land use conversion for perennial energy crop production: Exploring effects of payments for ecosystem services policies. *Agricultural and Resource Economics Review*, *48*(02), 328–358. https://doi.org/10.1017/age.2019.3

Li, Y., Fu, X., Liu, X., Shen, J., Luo, Q., Xiao, R., Li, Y., Tong, C., & Wu, J. (2013). Spatial variability and distribution of N_2O emissions from a tea field during the dry season in subtropical central China. *Geoderma*, *193–194*, 1–12. https://doi.org/10.1016/j.geoderma.2012.10.008

Liu, L., & Basso, B. (2017). Spatial evaluation of switchgrass productivity under historical and future climate scenarios in Michigan. *GCB Bioenergy*, *9*(8), 1320–1332. https://doi.org/10.1111/gcbb.12417

Liu, X., Kwon, H., Northrup, D., & Wang, M. (2020). Shifting agricultural practices to produce sustainable, low carbon intensity feedstocks for biofuel production. *Environmental Research Letters*, *15*(8), 084014. https://doi.org/10.1088/1748-9326/ab794e

Liu, W., Yan, J., Li, J, & Sang, T. (2012). Yield potential of Miscanthus energy crops in the Loess Plateau of China. *GCB Bioenergy*, *4*(5), 545–554. https://doi.org/10.1111/j.1757-1707.2011.01157.x

Lynes, M. K., Bergtold, J. S., Williams, J. R., & Fewell, J. E. (2016). Willingness of Kansas farm managers to produce alternative cellulosic biofuel feedstocks: An analysis of adoption and initial acreage allocation. *Energy Economics*, *59*, 336–348. https://doi.org/10.1016/j.eneco.2016.08.005

Maestrini, B., & Basso, B. (2018). Predicting spatial patterns of within-field crop yield variability. *Field Crops Research*, *219*, 106–112. https://doi.org/10.1016/j.fcr.2018.01.028

Marchand, F., Debruyne, L., Triste, L., Gerrard, C., Padel, S., & Lauwers, L. (2014). Key characteristics for tool choice in indicator-based sustainability assessment at farm level. *Ecology and Society*, *19*(3), 46–56. https://doi.org/10.5751/ES-06876-190346

Martinez-Feria, R. A., & Basso, B. (2020a). Unstable crop yields reveal opportunities for site-specific adaptations to climate variability. *Scientific Reports*, *10*(1), 2885–2895. https://doi.org/10.1038/s41598-020-59494-2

Martinez-Feria, R., & Basso, B. (2020b). Predicting soil carbon changes in switchgrass grown on marginal lands under climate change and adaptation strategies. *GCB Bioenergy*, *12*(9), 742–755. https://doi.org/10.1111/gcbb.12726

Mattia, C. M., Lovell, S. T., & Davis, A. (2018). Identifying barriers and motivators for adoption of multifunctional perennial cropping systems by landowners in the Upper Sangamon River Watershed, Illinois. *Agroforestry Systems*, *92*(5), 1155–1169. https://doi.org/10.1007/s10457-016-0053-6

Miao, R., & Khanna, M. (2014). Are bioenergy crops riskier than corn? *Implications for Biomass Price Choices*, *29*, 1–6.

Minasny, B., Malone, B. P., McBratney, A. B., Angers, D. A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z.-S., Cheng, K., Das, B. S., Field, D. J., Gimona, A., Hedley, C. B., Hong, S. Y., Mandal, B., Marchant, B. P., Martin, M., McConkey, B. G., Mulder, V. L., … Winowiecki, L. (2017). Soil carbon 4 per mille. *Geoderma*, *292*, 59–86. https://linkinghub.elsevier.com/retrieve/pii/S0016706117300095

Mishra, S. K., Negri, M. C., Kozak, J., Cacho, J. F., Quinn, J., Secchi, S., & Ssegane, H. (2019). Valuation of ecosystem services in alternative bioenergy landscape scenarios. *GCB Bioenergy*, *11*(6), 748–762. https://doi.org/10.1111/gcbb.12602

Mooney, D. F., Barham, B. L., & Lian, C. (2015). Inelastic and fragmented farm supply response for second-generation bioenergy feedstocks: Ex Ante survey evidence from Wisconsin. *Applied Economic Perspectives and Policy*, *37*, 287–310.

Mooney, D. F., Roberts, R. K., English, B. C., Tyler, D. D., & Larson, J. A. (2009). Yield and breakeven price of 'alamo' switchgrass for biofuels in Tennessee. *Agronomy Journal*, *101*(5), 1234–1242. https://doi.org/10.2134/agronj2009.0090

Niblick, B., & Landis, A. E. (2016). Assessing renewable energy potential on United States marginal and contaminated sites. *Renewable and Sustainable Energy Reviews*, *60*, 489–497. https://doi.org/10.1016/j.rser.2015.12.045

Nolte, C. (2020). High-resolution land value maps reveal underestimation of conservation costs in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, *117*(47), 29577–29583. https://doi.org/10.1073/pnas.2012865117

Nordhaus, W. D. (2017). Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences of the United States of America*, *114*, 1518–1523. https://doi.org/10.1073/pnas.1609244114

Ostrom, E. (1990). *Governing the commons: The evolution of institutions for collective action*. Cambridge University Press.

Parish, E. S., Hilliard, M. R., Baskaran, L. M., Dale, V. H., Griffiths, N. A., Mulholland, P. J., Sorokine, A., Thomas, N. A., Downing, M. E., & Middleton, R. S. (2012). Multimetric spatial optimization of switchgrass plantings across a watershed. *Biofuels, Bioproducts and Biorefining*, *6*, 58–72.

Paudel, J., & Crago, C. L. (2021). Environmental externalities from agriculture: evidence from water quality in the United States. *American Journal of Agricultural Economics*, *103*(1), 185–210. https://doi.org/10.1111/ajae.12130

Paustian, K., Larson, E., Kent, J., Marx, E., & Swan, A. (2019). Soil C sequestration as a biological negative emission Strategy. *Frontiers in Climate*, *1*. https://www.frontiersin.org/article/10.3389/fclim.2019.00008/full

Pedroso, G. M., van Kessel, C., Six, J., Putnam, D. H., & Linquist, B. A. (2014). Productivity, ^{15}N dynamics and water use efficiency in low- and high-input switchgrass systems. *GCB Bioenergy*, *6*, 704–716. https://doi.org/10.1111/gcbb.12104

Peterson, G. M., & Galbraith, J. K. (1932). The concept of marginal land. *Journal of Farm Economics*, *14*, 295. https://doi.org/10.2307/1230112

Phinzi, K., & Ngetar, N. S. (2019). The assessment of water-borne erosion at catchment level using GIS-based RUSLE and remote sensing: A review. *International Soil and Water Conservation Research*, *7*, 27–46. https://doi.org/10.1016/j.iswcr.2018.12.002

Plaas, E., Meyer-Wolfarth, F., Banse, M., Bengtsson, J., Bergmann, H., Faber, J., Potthoff, M., Runge, T., Schrader, S., & Taylor, A. (2019). Towards valuation of biodiversity in agricultural soils: A case for earthworms. *Ecological Economics*, *159*, 291–300. https://doi.org/10.1016/j.ecolecon.2019.02.003

Pröbstl-Haider, U., Mostegl, N. M., Kelemen-Finan, J., Haider, W., Formayer, H., Kantelhardt, J., Moser, T., Kapfer, M., & Trenholm, R. (2016). Farmers' preferences for future agricultural land use under the consideration of climate change. *Environmental Management*, *58*, 446–464.

Qin, Z., Dunn, J. B., Kwon, H., Mueller, S., & Wander, M. M. (2016). Soil carbon sequestration and land use change associated with biofuel production: empirical evidence. *GCB Bioenergy*, *8*(1), 66–80. https://doi.org/10.1111/gcbb.12237

Qualls, D. J., Jensen, K. L., Clark, C. D., English, B. C., Larson, J. A., & Yen, S. T. (2012). Analysis of factors affecting willingness to produce switchgrass in the southeastern United States. *Biomass and Bioenergy*, *39*, 159–167.

Richards, B. K., Stoof, C. R., Cary, I. J., & Woodbury, P. B. (2014). Reporting on marginal lands for bioenergy feedstock production: A modest proposal. *BioEnergy Research*, *7*(3), 1060–1062. https://doi.org/10.1007/s12155-014-9408-x

Rickson, R. J. (2014). Can control of soil erosion mitigate water pollution by sediments? *Science of the Total Environment*, *468–469*, 1187–1197. https://doi.org/10.1016/j.scitotenv.2013.05.057

Roberge, J.-M., & Angelstam, P. (2004). Usefulness of the umbrella species concept as a conservation tool. *Conservation Biology*, *18*(1), 76–85. https://doi.org/10.1111/j.1523-1739.2004.00450.x

Rosenberg, K. V., Dokter, A. M., Blancher, P. J., Sauer, J. R., Smith, A. C., Smith, P. A., Stanton, J. C., Panjabi, A., Helft, L., Parr, M., & Marra, P. P. (2019). Decline of the North American avifauna. *Science*, *366*(6461), 120–124. https://doi.org/10.1126/science.aaw1313

Rupp, S. P., & Ribic, C. A. (2019). Second-generation feedstocks from dedictaed energy crops. In C. E. Moorman, S. M. Grodsky, & S. Rupp (Eds.), *Renewable energy and wildlife conservation* (p. 64). JHU Press.

Saha, D., Rau, B. M., Kaye, J. P., Montes, F., Adler, P. R., & Kemanian, A. R. (2017). Landscape control of nitrous oxide emissions during the transition from conservation reserve program to perennial grasses for bioenergy. *GCB Bioenergy*, *9*(4), 783–795. https://doi.org/10.1111/gcbb.12395

Sanderman, J., Hengl, T., & Fiske, G. J. (2017). Soil carbon debt of 12,000 years of human land use. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(36), 9575–9580. https://doi.org/10.1073/pnas.1706103114

Sauer, J. R., Pardieck, K. L., Ziolkowski, D. J., Smith, A. C., Hudson, M.-A.- R., Rodriguez, V., Berlanga, H., Niven, D. K., & Link, W. A. (2017). The first 50 years of the North American Breeding Bird Survey. *The Condor*, *119*(3), 576–593. https://doi.org/10.1650/CONDOR-17-83.1

Schulte, L. A., Liebman, M., Asbjornsen, H., & Crow, T. R. (2006). Agroecosystem restoration through strategic integration of perennials. *Journal of Soil and Water Conservation*, *61*, 165–169.

Schulte, L. A., Niemi, J., Helmers, M. J., Liebman, M., Arbuckle, J. G., James, D. E., Kolka, R. K., O'Neal, M. E., Tomer, M. D., Tyndall, J. C., Asbjornsen, H., Drobney, P., Neal, J., Van Ryswyk, G., & Witte, C. (2017). Prairie strips improve biodiversity and the delivery of multiple ecosystem services from corn–soybean croplands. *Proceedings of the National Academy of Sciences of the United States of America*, *114*, 11247–11252. https://doi.org/10.1073/pnas.1620229114

Shield, I. F., Barraclough, T. J. P., Riche, A. B., & Yates, N. E. (2012). The yield response of the energy crops switchgrass and reed canary grass to fertiliser applications when grown on a low productivity sandy soil. *Biomass and Bioenergy*, *42*, 86–96. https://doi.org/10.1016/j.biombioe.2012.03.017

Shortall, O. K. (2013). "Marginal land" for energy crops: Exploring definitions and embedded assumptions. *Energy Policy*, *62*, 19–27. https://doi.org/10.1016/j.enpol.2013.07.048

Silveira, E. M. O., Radeloff, V. C., Martinuzzi, S., Martínez Pastur, G. J., Rivera, L. O., Politi, N., Lizarraga, L., Farwell, L. S., Elsen, P. R., & Pidgeon, A. M. (2021). Spatio-temporal remotely sensed indices identify hotspots of biodiversity conservation concern. *Remote Sensing of Environment*, *258*, 112368. https://linkinghub.elsevier.com/retrieve/pii/S0034425721000869

Skevas, T., Hayden, N. J., Swinton, S. M., & Lupi, F. (2016). Landowner willingness to supply marginal land for bioenergy production. *Land Use Policy*, *50*, 507–517.

Skevas, T., Skevas, I., & Swinton, S. M. (2018). Does spatial dependence affect the intention to make land available for bioenergy crops? *Journal of Agricultural Economics*, *69*, 393–412. https://doi.org/10.1111/1477-9552.12233

Skevas, T., Swinton, S. M., & Hayden, N. J. (2014). What type of landowner would supply marginal land for energy crops? *Biomass and Bioenergy*, *67*, 252–259. https://doi.org/10.1016/j.biombioe.2014.05.011

Smith, D. J., Current, D., Schulman, C., & Easter, K. W. (2018). Willingness to produce perennial bioenergy crops: A contingent supply approach. *Biomass and Bioenergy*, *117*, 161–172. https://doi.org/10.1016/j.biombioe.2018.06.018

Sobota, D. J., Compton, J. E., McCrackin, M. L., & Singh, S. (2015). Cost of reactive nitrogen release from human activities to the environment in the United States. *Environmental Research Letters*, *10*, 25006.

Song, F., Zhao, J., & Swinton, S. M. (2011). Switching to perennial energy crops under uncertainty and costly reversibility. *American Journal of Agricultural Economics*, *93*, 764–779. https://doi.org/10.1093/ajae/aar018

Spawn, S. A., Lark, T. J., & Gibbs, H. K. (2019). Carbon emissions from cropland expansion in the United States. *Environmental Research Letters*, *14*(4), 045009. https://doi.org/10.1088/1748-9326/ab0399

Stoof, C. R., Richards, B. K., Woodbury, P. B., Fabio, E. S., Brumbach, A. R., Cherney, J., Das, S., Geohring, L., Hansen, J., Hornesky, J., Mayton, H., Mason, C., Ruestow, G., Smart, L. B., Volk, T. A., & Steenhuis, T. S. (2015). Untapped potential: Opportunities and challenges for sustainable bioenergy production from marginal lands in the Northeast USA. *BioEnergy Research*, *8*(2), 482–501. https://doi.org/10.1007/s12155-014-9515-8

Swinton, S. M., Babcock, B. A., James, L. K., & Varaprasad, B. (2011). Higher US crop prices trigger little area expansion so marginal land for biofuel crops is limited. *Energy Policy*, *39*(9), 5254–5258. https://doi.org/10.1016/j.enpol.2011.05.039

Swinton, S. M., Tanner, S., Barham, B. L., Mooney, D. F., & Skevas, T. (2017). How willing are landowners to supply land for bioenergy crops in the Northern Great Lakes Region? *GCB Bioenergy*, *9*, 414–428. https://doi.org/10.1111/gcbb.12336

Tang, C., Yang, X., Chen, X., Ameen, A., & Xie, G. (2018). Sorghum biomass and quality and soil nitrogen balance response to nitrogen rate on semiarid marginal land. *Field Crops Research*, *215*, 12–22. https://doi.org/10.1016/j.fcr.2017.09.031

Thaler, E. A., Larsen, I. J., & Yu, Q. (2021). The extent of soil loss across the US Corn Belt. *Proceedings of the National Academy of Sciences of the United States of America*, *118*, e1922375118. https://doi.org/10.1073/pnas.1922375118

Tiessen, H., Cuevas, E., & Chacon, P. (1994). The role of soil organic matter in sustaining soil fertility. *Nature*, *371*, 783–785. https://doi.org/10.1038/371783a0

Tilman, D., Hill, J., & Lehman, C. (2006). Carbon-negative biofuels from low-input high-diversity grassland biomass. *Science*, *314*(5805), 1598–1600. https://doi.org/10.1126/science.1133306

Van Grinsven, H. J. M., Holland, M., Jacobsen, B. H., Klimont, Z., Sutton, M. A., & Jaap Willems, W. (2013). Costs and benefits of nitrogen for Europe and implications for mitigation. *Environmental Science and Technology of Food Industry*, *47*, 3571–3579. https://pubs.acs.org/doi/10.1021/es303804g

VanBeek, K. R., Brawn, J. D., & Ward, M. P. (2014). Does no-till soybean farming provide any benefits for birds? *Agriculture, Ecosystems & Environment*, *185*, 59–64. https://doi.org/10.1016/j.agee.2013.12.007

Varvel, G. E., Vogel, K. P., Mitchell, R. B., Follett, R. F., & Kimble, J. M. (2008). Comparison of corn and switchgrass on marginal soils for bioenergy. *Biomass and Bioenergy*, *32*, 18–21.

Volk, M., Möller, M., & Wurbs, D. (2010). A pragmatic approach for soil erosion risk assessment within policy hierarchies. *Land Use Policy*, *27*, 997–1009. https://linkinghub.elsevier.com/retrieve/pii/S0264837709002142

Wang, E., Cruse, R. M., Sharma-Acharya, B., Herzmann, D. E., Gelder, B. K., James, D. E., Flanagan, D. C., Blanco-Canqui, H., Mitchell, R. B., & Laird, D. A. (2020). Strategic switchgrass (*Panicum virgatum*) production within row cropping systems: Regional-scale assessment of soil erosion loss and water runoff impacts. *GCB Bioenergy*, *12*, 955–967. https://onlinelibrary.wiley.com/doi/10.1111/gcbb.12749

Werling, B. P., Dickson, T. L., Isaacs, R., Gaines, H., Gratton, C., Gross, K. L., Liere, H., Malmstrom, C. M., Meehan, T. D., Ruan, L., Robertson, B. A., Robertson, G. P., Schmidt, T. M., Schrotenboer, A. C., Teal, T. K., Wilson, J. K., & Landis, D. A. (2014). Perennial grasslands enhance biodiversity and multiple ecosystem services in bioenergy landscapes. *Proceedings of the National Academy of Sciences of the United States of America*, *111*, 1652–1657. https://doi.org/10.1073/pnas.1309492111

Whitaker, J., Field, J. L., Bernacchi, C. J., Cerri, C. E. P., Ceulemans, R., Davies, C. A., DeLucia, E. H., Donnison, I. S., McCalmont, J. P., Paustian, K., Rowe, R. L., Smith, P., Thornley, P., & McNamara, N. P. (2018). Consensus, uncertainties and challenges for perennial bioenergy crops and land use. *GCB Bioenergy*, *10*, 150–164.

Wilcoxen, C. A., Walk, J. W., & Ward, M. P. (2018). Use of cover crop fields by migratory and resident birds. *Agriculture, Ecosystems & Environment*, *252*, 42–50. https://linkinghub.elsevier.com/retrieve/pii/S0167880917304462

Wilson, D. M., Heaton, E. A., Schulte, L. A., Gunther, T. P., Shea, M. E., Hall, R. B., Headlee, W. L., Moore, K. J., & Boersma, N. N. (2014). Establishment and short-term productivity of annual and perennial bioenergy crops across a landscape gradient. *BioEnergy Research*, *7*(3), 885–898. https://doi.org/10.1007/s12155-014-9409-9

Wu, Y., Liu, S., & Li, Z. (2012). Identifying potential areas for biofuel production and evaluating the environmental effects: a case study of the James River Basin in the Midwestern

United States. *GCB Bioenergy*, *4*(6), 875–888. https://doi.org/10.1111/j.1757-1707.2012.01164.x

Yang, P., Zhao, Q., & Cai, X. (2020). Machine learning based estimation of land productivity in the contiguous US using biophysical predictors. *Environmental Research Letters*, *15*(7), 074013. https://doi.org/10.1088/1748-9326/ab865f

Yu, J., Smith, A., & Sumner, D. A. (2018). Effects of crop insurance premium subsidies on crop acreage. *American Journal of Agricultural Economics*, *100*(1), 91–114. https://doi.org/10.1093/ajae/aax058

Zhang, W., Ricketts, T. H., Kremen, C., Carney, K., & Swinton, S. M. (2007). Ecosystem services and dis-services to agriculture. *Ecological Economics*, *64*, 253–260. https://doi.org/10.1016/j.ecolecon.2007.02.024

Zhang, X., & Cai, X. (2011). Climate change impacts on global agricultural land availability. *Environmental Research Letters*, *6*, 014014. https://doi.org/10.1088/1748-9326/6/1/014014

Zhang, X., Izaurralde, R. C., Manowitz, D., West, T. O., Post, W. M., Thomson, A. M., Bandaru, V. P., Nichols, J., & Williams, J. R. (2010). An integrative modeling framework to evaluate the productivity and sustainability of biofuel crop production systems. *GCB Bioenergy*, *2*(5), 258–277. https://doi.org/10.1111/j.1757-1707.2010.01046.x

Zheng, F., Tao, R., Maier, H. R., See, L., Savic, D., Zhang, T., Chen, Q., Assumpção, T. H., Yang, P., Heidari, B., Rieckermann, J., Minsker, B., Bi, W., Cai, X., Solomatine, D., & Popescu, I. (2018). Crowdsourcing methods for data collection in geophysics: State of the art, issues, and future directions. *Reviews of Geophysics*, *56*, 698–740. https://doi.org/10.1029/2018RG000616

Zhou, X., Helmers, M. J., Asbjornsen, H., Kolka, R., Tomer, M. D., & Cruse, R. M. (2014). Nutrient removal by prairie filter strips in agricultural landscapes. *Journal of Soil and Water Conservation*, *69*, 54–64. https://doi.org/10.2489/jswc.69.1.54

Zhou, W., Guan, K., Peng, B., Tang, J., Jin, Z., Jiang, C., Roberts, G., & Symon, M. (2021). Quantifying carbon budget, crop yields and their responses to environmental variability using the ecosys model for U.S. Midwestern agroecosystems. *Agricultural and Forest Meteorology.*, *307*, 1–15. https://doi.org/10.1016/j.agrformet.2021.108521

Zhuang, D., Jiang, D., Liu, L., & Huang, Y. (2011). Assessment of bioenergy potential on marginal land in China. *Renewable and Sustainable Energy Reviews*, *15*(2), 1050–1056. https://doi.org/10.1016/j.rser.2010.11.041

How to cite this article: Khanna, M., Chen, L., Basso, B., Cai, X., Field, J. L., Guan, K., Jiang, C., Lark, T. J., Richard, T. L., Spawn-Lee, S. A., Yang, P., & Zipp, K. Y. (2021). Redefining marginal land for bioenergy crop production. *GCB Bioenergy*, 13, 1590–1609. https://doi.org/10.1111/gcbb.12877