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Assessing uncertainty in the profitability of prairie biomass production with ecosystem service compensation

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ABSTRACT

Compensation for ecosystem services can encourage the management of agricultural systems for a broad range of benefits beyond crop production. Here we explore how payments for carbon sequestration and phosphorus retention affect the profitability and economic competitiveness of perennial herbaceous biomass. We consider the case of converting marginal land currently in corn and soy production in southern Minnesota, United States, to native diverse prairie grown as a biofuel feedstock. We estimate the resulting changes in soil carbon storage and water quality, and the economic value of both. To test the robustness of our results, we perform Monte Carlo simulations that incorporate variability and uncertainty in our model parameters. Our analyses show that prairie biomass production on marginal lands is 22% likely to be profitable when ecosystem service compensation is included, but only 5% when it is not. This suggests that the two ecosystem services modeled here may alone be insufficient to make prairie biomass production reliably profitable. Furthermore, by using ranges of model parameters rather than point estimates, this study shows that the profitability gap between conventional row crops and prairie is too large to be closed with the two services modeled here across a range of recent economic conditions.

1. Introduction

Ecosystem services are increasingly being recognized for the economic value they provide to society. These services encompass a variety of functions, including biological regulation, habitat and refuge provision, biomass production, and mental health maintenance (Daily et al., 1997). While society benefits from these services, they are rarely directly traded in markets, with the exceptions of biomass (food, feed, and fiber) production and carbon credits. Valuing and creating clear markets for these services allows producers to be compensated for their efforts and society to benefit from increased provisioning of the services. Compensation for these services could therefore provide a means of making ecologically beneficial systems more economically competitive with intensively managed systems, but without traditional markets there is great uncertainty surrounding their value.

We examine this concept in the Midwest United States, where land-use change associated with increased intensity and area of annual row crop production is negatively impacting ecosystem services (Kremen et al., 2007; Metzger et al., 2006; Searchinger et al., 2008), including degraded water quality, decreased soil quality and retention, increased carbon (C) emissions, and loss of biodiversity (Fargione et al., 2009; Gardiner et al., 2010; McLaughlin and Walsh, 1998; Pielke et al., 2002; Polasky et al., 2010). Recent research has suggested a net loss of 530,000 ha of grassland cover to corn and soy in western Corn Belt states between 2006 and 2011 (Wright and Wimberly, 2013), in part driven by increased demand for corn and soy for biofuel production. The negative environmental impacts of corn and soy have prompted interest in perennial biomass sources such as switchgrass (*Panicum virgatum*) and high-diversity prairie biomass for bioenergy production. These have been highlighted as promising lignocellulosic feedstocks because they tend to require lower chemical and fertilizer inputs, and provide higher rates of C sequestration and nutrient retention compared to a corn-soy rotation (Tilman et al., 2006).

Although prairie biomass production has many ecological

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benefits over traditional row cropping, corn and soy remain more profitable on highly productive soils (James et al., 2010; Meehan et al., 2013). Recent studies have therefore focused on using marginal and degraded lands for growing biofuel feedstocks (Gelfand et al., 2013; Tilman et al., 2006). These lands tend to be poorly suited for growing row crops due to increased erosion potential and poor soil fertility, but could be ideal locations to produce prairie biomass as a biofuel feedstock (Gelfand et al., 2013; U. S. Department of Agriculture, 2005; Brandes et al., 2016). Still, although these lands are not ideal for row crop production, they continue to be attractive to farmers for corn and soy production due to recent commodity prices, subsidies, and federal crop insurance programs (Sumner and Zulauf, 2012).

Prior work has examined the competitiveness of switchgrass compared to row crops when the value of ecosystem services of C storage and nitrogen retention are included (Chamberlain and Miller, 2012). In that study, parameter values were based on point estimates, however, and do not provide a probabilistic output that accounts for variability in crop production costs and prices, or uncertainty in ecosystem service valuation. To our knowledge, the potential economic returns, including ecosystem services, of prairie grasslands compared to corn-soy rotations have yet to be quantified in an analysis that incorporates probability distributions for the values of key model parameters.

In this study, we examine the role that payments for ecosystem services can play in making ecologically beneficial systems profitable and competitive. We advance the state of science by examining the uncertainty of the underlying parameters and by providing a probabilistic output for the profitability of potential crops. Our first research objective is to compare the profitability and cost competitiveness of prairie to a corn-soy rotation, both with and without the C storage and phosphorus (P) retention values associated with each land cover. Our second is to quantify the uncertainty in the difference in profitability between prairie and corn-soy rotation on marginal lands.

We compile enterprise budgets of both corn-soy rotations and prairie biomass feedstocks, and quantify and value ecosystem services associated with prairie replacing a corn-soy rotation on marginal lands in southern Minnesota. Our analysis uses parameter values found in the literature and a spatially-explicit model (Integrated Valuation of Ecosystem Services and Tradeoffs; InVEST). The InVEST suite of models has been used to quantify changes in ecosystem services in a variety of land-use scenarios (Gardiner et al., 2010; Kovacs et al., 2013; Nelson et al., 2009; Polasky et al., 2012). To account for uncertainty in the parameters, we use a stochastic model to estimate the profitability and relative competitiveness of a corn-soy rotation and prairie biomass with and without consideration of C storage and P retention. We also use a Monte Carlo simulation to investigate the key sources of parameter uncertainty in this comparison.

2. Methods

2.1. Study area

The study focused on 81,090 ha of marginal lands in 43 counties in southern Minnesota under corn-soy rotation in 2010 (Fig. S1). Marginal lands were defined using the United States Department of Agriculture's (USDA) National Soil Survey Handbook's Land Capability Classification (Johnson et al., 2012; Meehan et al., 2010), which groups soils on their ability to serve as cropland over time without degradation. Class IV soils were selected for this analysis because they have “very severe limitations that restrict the choice of plants or that require very careful management, or both.” These constraints include a combination of moderate to steep slopes, high to severe susceptibility to erosion, shallow soils, low moisture-holding capacity, low fertility, and moderate to severe salinity or sodium. Class I–III soils were eliminated on the basis of corn and soy being strong economic competitors on these more fertile lands, and Class V soils and above were eliminated on the basis that restrictions such as stoniness, frequent flooding, and very steep slopes would severely restrict the ability of farmers to harvest biomass from them.

2.2. Land use/land cover scenarios

The 2010 USDA Cropland Data Layer was used to create both a baseline 2010 land use/land cover (LULC) map and an alternative biomass production scenario. In preparing the baseline LULC dataset, we aggregated the original 133 land classifications into one of seven broad classifications based on similarity of land cover (Table S1). All land classified as corn or soy was assumed to be in a two-year corn-soy rotation as this is the dominant practice in the domain (Osteen et al., 2012). In the alternative scenario, all of the corn-soy rotation land on class IV soil was converted to prairie.

2.3. Corn, soy, and prairie production costs

To estimate farm-gate production costs, we compiled university Extension enterprise budgets for corn, soy, hay, and diverse-species prairie from Minnesota, Wisconsin, and Iowa from 2008 to 2013 to capture a variety of regionally appropriate production practices. Hay budgets were modified by changing fertilizer and chemical practices to match the prairie production methods described by Tilman et al. (2006). Land rents were based on National Agricultural Statistics Service (NASS) county averages for pasture to represent the marginal quality of the targeted land. Production costs and returns for prairie were annualized over 20-years using an interest rate of 6%. Transportation costs and subsidies for crop insurance were not included in this analysis.

2.4. Corn and soy yields and prices

The distribution of corn and soy production revenue was created using 2008–2012 NASS yield and price data. NASS county yield estimates were adjusted to reflect targeting of marginal land by using the non-irrigated crop yields attribute of the spatially-explicit Soil Survey Geographic Database 2.2 (SSURGO) (Soil Survey Staff, 2011; USDA-NASS, 2014). The ratio between the county average SSURGO yields and actual county average NASS yields was used to adjust yields on marginal land, which are available only in SSURGO, to better reflect variation due to variables not included in SSURGO, such as climate. Commodity price data were from monthly Minnesota averages reported by NASS from January 2008 to May 2013 (USDA-NASS, 2014).

2.5. Prairie biomass price and yield

Biomass price was estimated from crude oil prices from January 2008 to May 2013 using the method of Jiang and Swinton (Jiang and Swinton, 2009), which uses an established relationship between the price of gasoline and crude oil, and adjusts for the energy content difference and the value of ethanol as a fuel additive. This value represents the willingness to pay (WTP) of the refinery for biomass exclusive of transportation costs. Though rare, the WTP for biomass can fall to zero if oil prices are low enough. While producers would likely seek other markets under these circumstances, it was included in simulations to represent the risk of participation in a developing market. A distribution of likely biomass yields was obtained from a survey of studies in and near southern Minnesota (Table S2). We assumed no yield for the first year, half yield for the second year, and full yields from the third through the last year of the stand (McLaughlin and Kszos, 2005).

2.6. Carbon storage and valuation

To model changes in C storage associated with conversion of corn-soy rotation to prairie, we reviewed the literature to establish a range of estimates for annual soil C accumulation rates in land that transitioned from agriculture to grassland in Minnesota, Iowa, and South Dakota. We used the distribution of estimates for the social cost of carbon emissions in peer reviewed literature, compiled in a meta-study by Tol (2011), to create a probability distribution to draw from in the Monte Carlo simulation (Table S3). For example, 17% of the reviewed studies estimated the societal cost of 1 Mg C^{-1} emissions to be between $33 and $87, therefore 17% of the trials in the Monte Carlo simulation used a value in this range when estimating the value of the service of annual C storage.

2.7. Phosphorus retention and valuation

To estimate the quantity of phosphorus retention, we used the InVEST model. InVEST combines maps, tabular data describing biophysical processes, and economic valuations to create spatially-explicit predictions of the change in value of ecosystem services resulting from a defined land-use change scenario (Tallis et al., 2011). To calculate changes in P retention, the model first calculates the amount of water runoff for each cell as the difference between water input from precipitation and loss to evaporation. Next, root depth, P loading, and P retention coefficients for each land-cover type were drawn primarily from a previous study in the Minnesota River Valley (Johnson et al., 2012) (Table S4). These biophysical coefficients were used to determine the amount of P export and retention per cell. We then summed P export at the watershed level for the baseline and alternative scenarios.

To place an economic value on phosphorus retention, we used five equally weighted estimates—four based on a WTP study within our study area and one based on an economic impact analysis of P reduction in Wisconsin water bodies. The multiple WTP values are from different methods of analyzing a survey of household WTP for a 40% reduction in P loading in the Minnesota River. Using a method described by Polasky et al. (2010) and also employed by Kovacs et al. (2013), we assumed that a reduction of P loading in waterways throughout the study area would be valued similarly by all households in the study area and that household WTP varied linearly with percent reduction of P loading.

2.8. Profitability, uncertainty, and sensitivity analyses

Profitability analysis was conducted to determine the probability that crops produced on marginal lands are profitable and the probability that one crop is more profitable than another. These analyses were repeated under four scenarios: inclusion of only feedstock (prairie biomass or corn-soy rotation) value, inclusion of feedstock and C storage values, inclusion of feedstock and P retention values, and inclusion of feedstock, C storage, and P retention values.

To address the uncertainty in economic and biophysical parameters, we ran a Monte Carlo simulation using the Oracle Crystal Ball Excel add-in. Monte Carlo is a simple stochastic model that draws on probability distributions to create a number of independent simulations (Morgan et al., 1990), which can be used to determine the likelihood of a particular outcome.

We gathered a range of representative values for each parameter and selected appropriate distributions for the data (Table S5). The Anderson-Darling test was used to select distributions for corn and soy yields and costs, prairie biomass prices, and prairie production costs that best fit the observed values (Table 1). A uniform distribution was selected for corn and soy prices, C storage, and prairie biomass yield because it could not be determined whether any value would be more likely than any other value (Morgan et al., 1990).

Table 1
Descriptive statistics of parameters used in Monte Carlo simulation.

Parameter	Unit	Min	Max	Mean	Distribution
Corn price	$ Mg^{-1}	136.2	300	217	Uniform
Soy price	$ Mg^{-1}	382.7	660.2	519.7	Uniform
Corn yield	Mg ha^{-1}	4.5	10.8	7.7	Beta
Soy yield	Mg ha^{-1}	1.2	2.9	2	Beta
Corn costs	$ ha^{-1}	857	1273.4	1065.2	Weibull
Soy costs	$ ha^{-1}	457.5	707.9	582.7	Weibull
Land rent	$ ha^{-1}	34.7	175.8	91.9	Lognormal
Prairie price	$ Mg^{-1}	0	122.7	40.5	Logistic
Prairie yield	Mg ha^{-1}	3.7	8	5.8	Uniform
Prairie costs	$ ha^{-1}	345.6	725.8	535.7	Lognormal
Carbon price	$ Mg^{-1}	0	771.1	133.1	Custom
Carbon storage	Mg ha^{-1}	0.14	0.95	0.5	Uniform
Phosphorus retention	$ ha^{-1}	24.8	157.6	56.2	Discrete uniform

This study did not assume any correlation between the parameters of the Monte Carlo simulation. While there are likely correlations between some parameters, there was insufficient data to incorporate these into the simulation. As such, uncertainty still remains in the tails of the probability distributions.

Following the Monte Carlo simulation, a sensitivity analysis was run to determine which parameters contributed most to the variance in the scenarios. Contribution to variance and rank correlation values were collected for each parameter using features within the Crystal Ball software.

3. Results and discussion

The profitability analysis found that corn-soy rotation is nearly always profitable (Fig. 1), consistent with this land being used for this purpose. On this same land, prairie grown as a biofuel feedstock with no payment for the two ecosystem services modeled here is rarely profitable. Without ecosystem service compensation, the most likely outcome of producing prairie biomass is a loss of $273 ha^{-1} yr^{-1}. With ecosystem service compensation, the likelihood of profitability of prairie biomass production increases. A change from a corn-soy rotation on marginal lands to prairie increases ecosystem services across the landscape. Compared to the corn-soy rotation scenario, the prairie scenario increases C storage by an average of 0.5 Mg ha^{-1} yr^{-1} and reduces P export by 0.61 kg ha^{-1} yr^{-1}. The value of C storage ranges from $0 to $771 ha^{-1} yr^{-1}, with an average of $73 ha^{-1} yr^{-1}. The value of the reduced P export ranges from $25 to $158 ha^{-1} yr^{-1} with an average of $56 ha^{-1} yr^{-1}. These two services represent an average annual value of $129 ha^{-1} yr^{-1}, however, this is typically insufficient for prairie biomass to achieve breakeven profitability.

Comparison of profitability between corn-soy rotation and prairie shows that regardless of the inclusion of C storage and P retention, prairie is unlikely to be more profitable (Fig. 2). When ecosystem services are excluded, it is highly unlikely that farmers will profit from converting corn-soy rotation to prairie; including the ecosystem services of C storage and P retention increases the likelihood only marginally. With the value of both services included, the most likely outcome of switching from a corn-soy rotation is a net loss of $587 ha^{-1} yr^{-1} (Table S6).

Sensitivity analysis shows that the greatest factor affecting differences in profitability is corn price (Fig. 3), which is consistent with the findings of James et al. (2010). When predicting

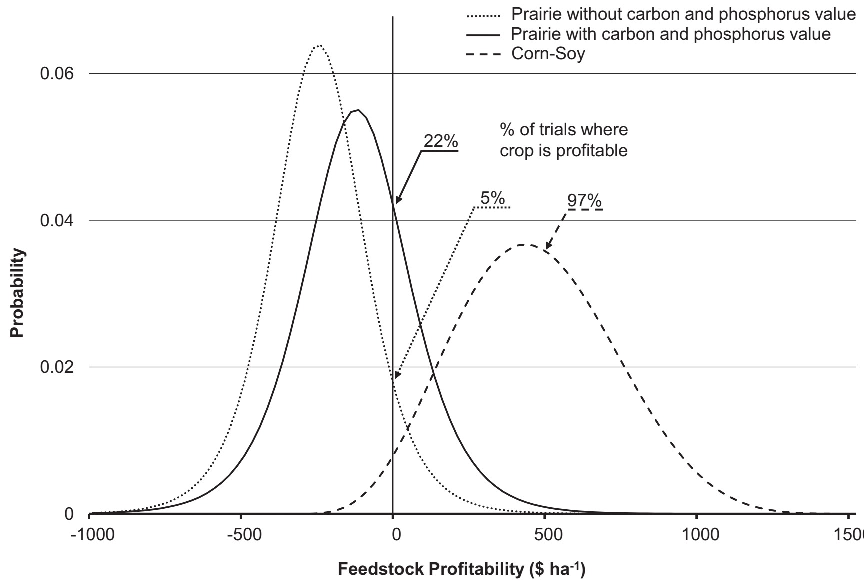

Fig. 1. Probability distributions for feedstock profitability for both corn-soy rotation and prairie biomass with and without the ecosystem services of C storage and P retention. The area under the curve past the break even point ($0) represents the probability of exceeding the profitability threshold. Corn-soy rotation has the greatest uncertainty in its distribution due to large, uniform distributions of two key parameters: corn price and soy price.

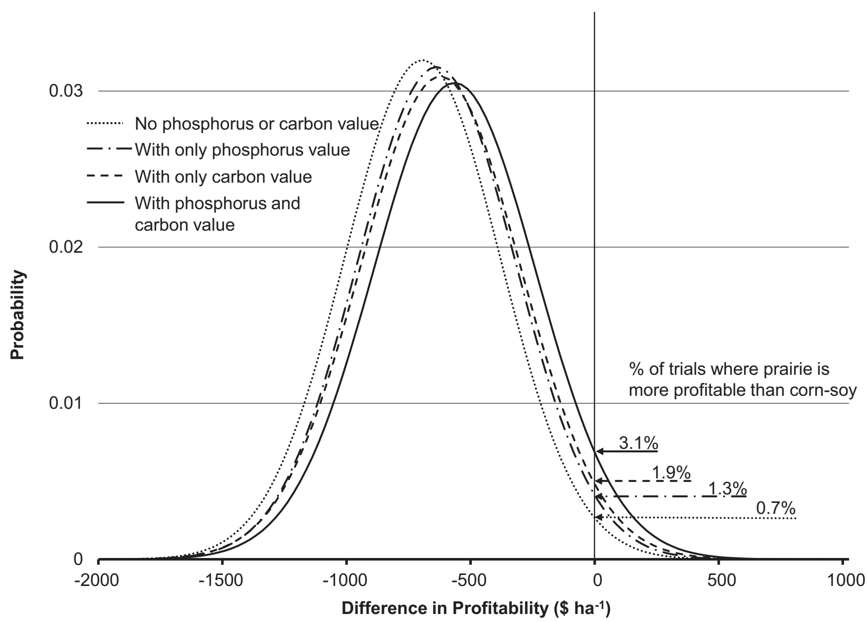

Fig. 2. Probability distributions for the difference in profitability between corn-soy rotation and prairie biomass. Phosphorus and carbon values refer to compensation for the ecosystem services of P retention and C storage, respectively. The area under the curve past the break even point ($0) represents the fraction of trials where prairie is more profitable than corn-soy rotation.

difference in profitability while including ecosystem services, 36% of the variance in the model run can be attributed to the variability in corn prices, while variation in the C price, C storage, and P retention parameters account for only 4%, 2%, and 1% of the total variation, respectively (Table S7). Some of the recent dramatic changes in corn and soy prices can be attributed to policies that increase ethanol demand (Gecan et al., 2009). While quantifying ecosystem service values is vital for understanding benefits to society, the price of corn is a more significant factor in the profitability of prairie vs. corn-soy rotation. Given this, it is important to note that the years used in this study to estimate corn price were some of the highest on record. This trend of record commodity prices has reversed recently, and therefore corn and soy profitability, and their relative competitiveness over prairie, may become less certain, especially on marginal lands. The recent decline in oil prices, which affects the value of prairie biomass for biofuel, adds additional uncertainty.

Although our analysis shows that prairie biomass is unlikely to be an economically competitive biofuel feedstock under recent conditions and commodity prices, further valuation of additional ecosystem services provided by prairie could increase its competitiveness with corn, as could higher prices for prairie biomass. Prairie ecosystems provide a number of public benefits that are not internalized, including N and other nutrient retention, wildlife habitat, biodiversity, aesthetics, and recreation (Asbjornsen et al., 2013). We focus only on C sequestration and P retention due to limitations of data and valuation methodologies; however, if farmers growing prairie biomass as an energy feedstock are

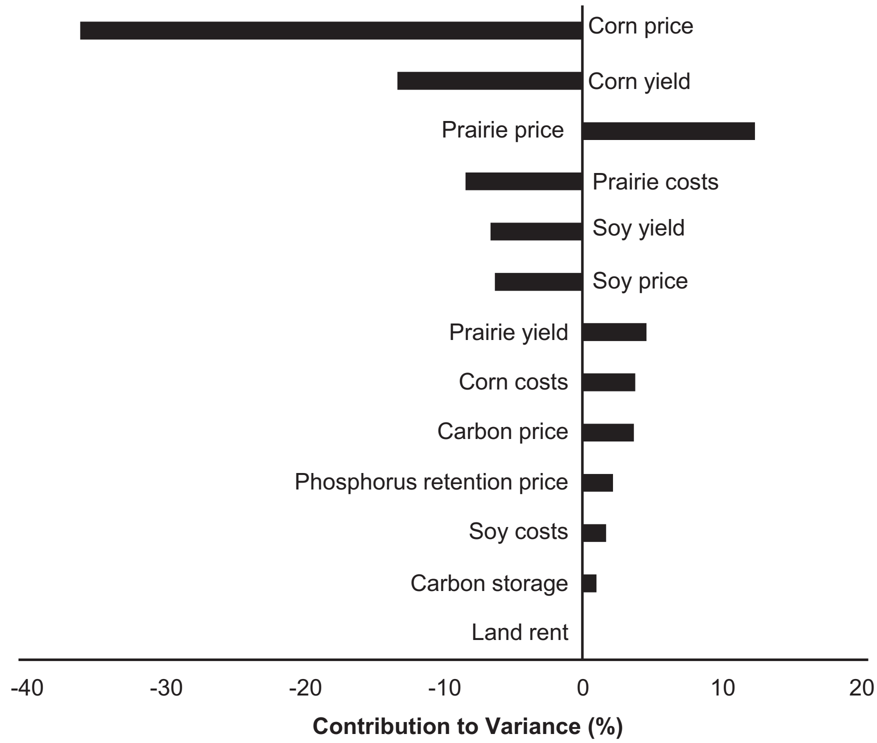

Fig. 3. Sensitivity analysis of the parameters included in the difference in profitability Monte Carlo simulation. Percent contribution to variance represents the fraction of the variance that can be explained by the variability in that parameter. Bars with negative values pull the probability distributions further negative, while bars with positive values pull them further positive. Land rent does not contribute to variance in difference in profitability because, in considering the substitution of prairie for corn-soy rotation, land rent varies between simulations but not between crops.

compensated for the benefits they produce for society as mentioned above, prairie or other perennial feedstocks could become competitive with corn, soy, and other annual crops. For example, N retention can be valued through its avoided impacts on health; diseases such as methaemoglobinaemia (Blue Baby syndrome) are linked to nitrate contamination of water (Ward et al., 2005; Wolfe and Patz, 2002). Additionally, N runoff-induced hypoxic conditions in the Gulf of Mexico affect the food service, tourism, and commercial and recreational fishing sectors (Downing et al., 1999). The increased biodiversity of prairie is difficult to value economically, and some have argued that diversity also has an intrinsic value that cannot be quantified (Ehrenfeld, 1988; Ghilarov, 2000). Recreation value is likewise poorly quantified but can be derived from activities such as hiking, biking, horseback riding, picnicking, and fishing (Klenosky et al., 2004). Although prairie grown as a bioenergy feedstock might not necessarily provide many of these direct recreational opportunities, it would contribute habitat for increased wildlife viewing and hunting, as well as aesthetic appeal (Moir, 1972; Tews et al., 2004).

Payments to incentivize the production of ecosystem services is not without precedent in United States agriculture. The Conservation Reserve Program pays farmers to use vegetative covers to prevent soil erosion and provide habitat. Additionally, government support for cellulosic fuel exists in the United States through the Renewable Fuel Standard. Of the 36 billion gallons of biofuel mandated to be produced in 2022, 16 billion gallons must be cellulosic ethanol (110th Congress, 2007). Even more incentives could be implemented to improve the financial success of growing prairie. For example, federal support in the form of loan guarantees, insurance subsidies, or tax breaks could incentivize the development of a lignocellulosic biomass-based bioenergy industry infrastructure.

Conversely, other factors not considered in this study could further increase the profitability of a corn-soy rotation relative to prairie. For example, any increase in agricultural biomass prices could also benefit corn producers by providing them an additional source of revenue from the harvest of corn stover. Additionally, farmers considering converting their land in corn-soy rotations to prairie may require a premium beyond break even profitability to switch to an unfamiliar practice and to mitigate the financial risk in committing land to a decade of perennial crop production.

Growing prairie biomass for bioenergy has the potential to reduce greenhouse gas emissions from the transportation and electricity sectors, provide additional domestic fuel supply, and contribute important ecosystem services. Our analyses show that in our modeling domain of southern Minnesota, it is challenging for prairie biomass production on marginal land to be competitive with corn-soy rotation production under recent market conditions, even when two important ecosystem service values are considered. Our work also suggests the importance of exploring ecosystem services of agricultural systems beyond greenhouse gas mitigation and water quality improvement, and that further research is needed to provide better estimates of biophysical properties of agricultural lands to improve ecosystem service model predictions.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.ecoser.2016.05.004.

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