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Potential Environmental Impacts of Increased Reliance on Corn-Based Bioenergy

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Abstract This paper integrates economic and physical models to assess: a) how increases in agricultural commodity prices, driven by ethanol production and other factors, affect land use and cropping systems in the US Midwest, and b) how the changes in land use and cropping systems in turn affect environmental quality in the region. The empirical framework includes a set of econometric models that predict land conversion, crop choices, and crop rotations at the parcel level based on commodity prices, land quality, climate conditions, and other physical characteristics at the sites. The predictions are then combined with site-specific environmental production functions to determine the effect of rising commodity prices on nitrate runoff and leaching, soil water and wind erosion, and carbon sequestration. Results suggest that increasing commodity prices will result in widespread conversions of non-cropland to cropland. Fifty percent of the region's pasture and range land will be converted to cropland with $6 corn. Rising commodity prices will also result in dramatic changes in crop mix and rotation systems in the Midwest. With $6 corn, the total acreage of corn will increase by 23% and 40% in the Corn Belt and Lake States, respectively; the acreage of continuous corn will increase considerably in both regions as well. These changes in land use and crop mix will have a large impact on agricultural pollution. Approaches to mitigating the environmental impacts are discussed.

Keywords Bio energy · Ethanol · Corn prices · Crop choice · Environmental quality

JEL Classification Q28 · Q42 · Q48

Greater emphasis on energy security, in conjunction with the upward trend in oil prices, has generated significant growth in ethanol production and increased corn acreage in the United

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States. Crude oil prices, which averaged less than $20 per barrel in the 1990s, remain at roughly four times that price (close to $80 per barrel in mid-2010) even after dropping from the peak reached in 2008 ($140 per barrel). Additionally, the Energy Policy Act of 2005 mandated that renewable fuel use in gasoline reach 7.5 billion gallons by 2012, and the Energy Independence and Security Act (EISA) of 2007 increased the mandate for renewable fuels to 36 billion gallons by 2022, including 15 billion gallons of ethanol made from grains, primarily corn. The resulting large and rapid expansion of US ethanol production has significantly increased the demand for corn, contributing to sharp increases in commodity prices (Almirall et al. 2010). The amount of corn planted in 2007, 94 million acres, was the highest since World War II, and it yielded a record crop of 13.2 billion bushels (Martin 2007). Because corn is one of the most water and chemical-intensive crops, increasing corn production has generated growing concern about its potential environmental effects (Secchi and Babcock 2007; Zilberman and Rajagopal 2007).

There are a variety of alternative ways in which energy prices, biofuels, commodity prices, agriculture, and land use can evolve in the mid- and long- term future. One possible scenario, more likely in the short- to mid-term, is that the upward pressure on corn and commodity prices continues and that other corn-using sectors adjust to higher corn prices. In the absence of policy changes, this option could lead to substantially higher corn prices than we have seen historically, and hence possibly to higher commodity and food prices (Tyner 2007). Given that production of biofuels removes land from its main alternative uses, including food production and environmental preservation, this scenario could lead to conversions of grassland and forests to energy crops, increased soil erosion, and more chemical and fertilizer application (Rajagopal et al. 2007).

Alternative scenarios, perhaps more likely in the mid- to long-run, envision more optimistic outcomes from the transition to second generation biofuels produced from cellulosic matter, such as switchgrass, miscanthus, poplar trees, corn stover, and other plant materials containing cellulose (Tyner 2007). The use of cellulosic biomass is expected to result in higher energy production and more carbon sequestration compared to starch and sugar based biofuels (Tilman et al. 2006; Sheehan et al. 2003; Farrell et al. 2006). Large-scale production of these crops to generate energy could change the agricultural landscape, as well as the sources, levels, and variability of farm income. In some of the more sanguine outlooks for second-generation biofuels, the agricultural industry itself could be transformed by vertical and horizontal integration as firms seek to minimize risk and take advantage of opportunities to coordinate production of related commodities (Rajagopal et al. 2007). In these scenarios, a smooth transition from first- to second-generation biofuels requires technical innovation, agricultural productivity growth, and an integration of environmental and energy policy. These policy changes might include incentives for development of cellulosic conversion technologies, such as two-part subsidies based on energy security and climate change considerations, and alternative fuel standards (Tyner 2007; Rajagopal et al. 2007).

This paper focuses on the environmental implications of the first, short- to mid-term scenario. Specifically, the objectives of this paper are twofold. First, we examine how increases in commodity prices driven by ethanol mandates will affect land use, including changes in crop mix and conversions of non-cropland to crop production in the US Midwest. Second, we analyze how the changes in land use will affect nitrate runoffs and percolation, soil erosion, and carbon sequestration in the region. Additionally, we evaluate to what extent the negative environmental impacts of increased corn production could be mitigated by alternative conservation practices, such as lower nitrogen application rates or conservation compliance measures such as prohibiting conversions of highly erodible land to crop production. The study region includes the Corn Belt (Ohio, Illinois, Indiana, Iowa, Missouri) and the Lake

States (Michigan, Wisconsin, Minnesota), which accounted for 32% of the nation's cropland and 62% of the nation's corn acreage in 2007 (USDA 2009a,b).[1]

To achieve the objectives of this paper, we integrate economic and physical models. The economic models consist of two parcel-level models; one model predicts major land use (cropland vs. noncropland), and the other predicts crop choice and crop rotation on cropland. The explanatory variables of these models include expected commodity prices, production costs, land quality, weather conditions, and other control variables. The models cover a large geographic region, yet are based on parcel-level data and hence capture the site-specific characteristics and spatial variability needed to accurately assess the environmental effects of land use changes driven by increased biofuel production.

The economic models are integrated with a set of physical models to evaluate the impacts of land use changes, driven by increased ethanol production, on nitrate runoff, nitrate percolation, soil water erosion, soil wind erosion, and carbon sequestration at the parcel level. The spatial distribution of environmental impacts, as well as land use changes, is displayed using GIS maps. The parcel-level effects are also aggregated to the regional level for policy analysis.

Previous studies of the potential environmental impacts of biofuels have focused on whether they create net carbon benefits, given the significant amount of fossil energy expended in their production (Pimentel and Patzek 2005; Farrell et al. 2006). However, other environmental impacts, such as agricultural runoff, have not received the same attention. The only exception, to our knowledge, is Secchi and Babcock (2007), who model CRP enrollment in Iowa for different corn prices. Our approach is to use several crop choice models to examine the environmental impacts of increased demand for corn. We also focus on a larger area, which encompasses the majority of corn production in the US.

Our results suggest that increases in corn prices will result in widespread conversions of non-cropland to cropland, as well as substantial increases in continuous corn rotation acreage. These changes in land use will lead to significant increases in nitrate water pollution, soil erosion and loss of soil carbon. These environmental impacts could be mitigated, to some extent, by implementing conservation practices or land use policies, such as lower nitrogen application rates, a ban on converting highly erodible land to crop production, or incentives for farmers to switch from continuous corn to corn-soybean rotations.

This paper is organized as follows. The next section presents the economic models for predicting land use choices under alternative prices and policy scenarios. This is followed by a description of the physical models that we use to estimate the environmental impacts of land use changes. Next, we integrate the economic and physical models to evaluate the impact of increased ethanol production on land use and agricultural nonpoint pollution. The results and policy implications are discussed in the last section.

1 Economic Models

In this section, we first describe the conceptual framework for estimating the land use choice models and then discuss the data and estimation methods. Estimation results are presented at the end of this section.

[1] Our focus on this region is appropriate for the short- to mid-term analysis conducted here. Potential mid- to long-term transitions to cellulose-based biofuels could lead to significant land use changes in other regions of the country, such as the southern US in the case of switchgrass (Schneider and McCarl 2003; De La Torre Ugarte et al. 2007; Dicks et al. 2009). These changes would impact commodity price ratios in ways not considered in this paper.

1.1 Modeling Framework

Within our simple framework, a farmer makes land use decisions to maximize his utility. Land use decisions include whether to allocate a parcel to crop production or non-crop activities and, if a parcel is allocated to crop production, which crop to grow. Suppose a farmer can choose among N crops, with $i = 1, 2, \ldots, N$ indicating the crop choices and $i = 0$ indicating non-cropping activity. Let $u_{ij}(\boldsymbol{X_{ij}})$ be the utility from land use i on parcel j, where $\boldsymbol{X_{ij}}$ is a vector of variables affecting the expected profit and risk of growing crop i on parcel j, including expected output and input prices, land characteristics, weather conditions, government commodity program provisions, and land uses in previous years (reflecting crop rotation restrictions). Because individual farmers' preferences and farming skills are unknown to the researcher, $u_{ij}(\boldsymbol{X_{ij}})$ can be considered a random variable and be written as

$$u_{ij}(\boldsymbol{X_{ij}}) = \boldsymbol{X'_{ij}\beta_i} + \varepsilon_{ij}, \quad i = 0, 1, 2, \ldots, N. \tag{1}$$

where ε_{ij} is a random error term. If the residuals ε_{ij} are assumed to be independently and identically distributed with the extreme value distribution, then the probability that the farmer will choose land use i at parcel j is given by a multinomial logit model (Maddala 1983):

$$P_{ij} = \frac{e^{\boldsymbol{X'_{ij}\beta}_i}}{\sum_{k=1}^{N} e^{\boldsymbol{X'_{kj}\beta_k}}}, \quad i = 1, \ldots, N. \tag{2}$$

For estimation purposes, it is convenient to rewrite the probability as follows:

$$P_{0j} = P_j(noncrop) = \frac{e^{\boldsymbol{X'_{0j}\beta_i}}}{\sum_{k=1}^{N} e^{\boldsymbol{X'_{kj}\beta_k}}}, \quad i = 1, \ldots, N \tag{3}$$

$$P_{ij} = P_j(i|crop) \cdot P_j(crop) = \frac{e^{\boldsymbol{X'_{ij}\beta_i}}}{\sum_{k=1}^{N} e^{\boldsymbol{X'_{kj}\beta_k}}} \cdot \frac{\sum_{k=1}^{N} e^{\boldsymbol{X'_{kj}\beta_k}}}{\sum_{k=1}^{N} e^{\boldsymbol{X'_{kj}\beta_k}}}, \quad i = 1, \ldots, N. \tag{4}$$

This decomposition is convenient as it means that we can separately study the major land use decision (crop vs. noncrop) and the crop choice decision (which crop to grow, conditional on the parcel being allocated to crop production). The major land use decision can be estimated as a standard logit model and the crop choice decision can be estimated as a multinomial logit model.

The multinomial logit model has been widely used in economic analysis, including the study of the choice of transportation modes, occupations, asset portfolios, and the number of automobiles demanded. In agriculture, it has been used to model farmers' land allocation decisions (Lichtenberg 1989; Wu and Segerson 1995; Hardie and Parks 1997; Plantinga et al. 1999), the choice of irrigation technologies (Caswell and Zilberman 1985), and the choice of alternative crop management practices (Wu and Babcock 1998).

Alternatively, one can model the major land use decisions and crop choices as a two-stage nested logit; in the first stage, a farmer must decide whether or not to allocate a parcel to crop production, and in the second stage, he must choose which crop to grow if he decides to allocate the parcel to crop production. The main advantage of a nested logit approach in this case is that there is a clear nesting structure, which would allow a tractable generalization of the multinomial model. The main disadvantages are the added complexity in conducting simulations and the computational cost given the relatively large size of our data set. Furthermore, the degenerate nature of the nesting structure in our case (the noncrop branch of the choice tree has no further options and no choice-specific attributes, e.g. no expected price for noncrop land) implies that our model is not well-suited for nested logit estimation.

2 Data and Variable Construction

Because of the substantial differences in weather conditions and cropping systems among the two regions (the Corn Belt and Lake States), separate models are estimated for each region. The estimation requires a substantial amount of data, which must be integrated from multiple sources. These data include a) the land use choice at each NRI site, b) farmers' expected output and input prices, c) government commodity program provisions, and d) site characteristics at each NRI point (soil properties, topographic features, climate conditions). In this subsection, we describe the data sources and construction of the variables used in model estimation.

Time-series data on land use choice at each NRI site were derived from the 1982, 1987, 1992, and 1997 Natural Resources Inventories (NRI). NRI is the most comprehensive resource data ever collected in the United States. The inventories are conducted by the USDA Natural Resources Conservation Service to determine the status, condition, and trend of the nation's soil, water, and related resources. Information on nearly 200 attributes was collected at more than 800,000 sites across the continental United States. Our study region includes 356,019 NRI sites, of which 292,895 (82%) are in cropland (both cultivated and non-cultivated), 63,093 (18%) in pastureland, and 31 (0.009%) in rangeland. Each NRI site was assigned a weight called the xfactor to indicate the acreage it represents. For example, the sum of xfactors at all NRI sites planted to corn gives an estimate of corn acreage in the region. The sampling design ensures that inferences at the national, regional, state, and sub-state levels can be made in a statistically reliable manner.

Each NRI contains crop choice information for 4 years (the current year plus the previous 3 years). Thus, we have crop choice information for 16 years at each NRI site. Pooling these time-series and cross-sectional data results in hundreds of thousands of observations for the crop choice model in each region. For computational feasibility, we randomly selected 20% of the observations for the estimation of the crop choice models.

Several approaches have been used to estimate farmers' expected prices. Gardner (1976) and Just and Rausser (1981) argued for the use of futures prices in acreage response analysis on rational expectations grounds as well as for forecast accuracy. Chavas and Holt (1990) used adaptive expectations and the lagged market price to model farmers' expected prices. Chavas et al. (1983) examined the role of futures prices, lagged market prices, and support prices in acreage response analysis. They found that since futures prices and lagged market prices are highly correlated and reflect similar market information, use of both in supply equations may lead to multicollinearity, while deleting one of the two makes little empirical difference. Shumway (1983) defined the expected price as the higher of the current weighted support price and a geometric lagged function of market prices in the previous 7 years. Wu and Segerson (1995) specified expected prices for program crops as the higher of the current target price and a linear function of previous years' market prices. The number of years lagged is determined using a partial autocorrelation coefficient method.

Based on these studies, the expected prices for corn and wheat were specified as the higher of the weighted target price and the average futures price during the planting season for each crop. The weighted target price is calculated by multiplying the target price by the portion of the base permitted for planting (i.e., 1-Acreage Reduction Program (ARP) rate). The ARP rates and target prices for corn and wheat were taken from Green (1990) and other US Department of Agriculture publications. The average futures price for corn and wheat during their planting seasons were estimated as the averages of the first and second Thursday closing prices in March at the Chicago Board of Trade (CBT) for corn and wheat. Soybean is a non-program crop. Expected prices for soybeans were specified as the average futures prices in its planting season, which was estimated as the average of the first and second Thursday closing prices in March on the CBT for November soybeans. Hay is a multi-year, non-program crop. Market prices lagged 1 year are used as farmers' expected prices for hay. State-level, annual average market price for hay was taken from Agricultural Statistics (U.S Department of Agriculture). Input prices used in the model include the indexes of prices paid by farmers for seeds, agricultural chemicals, and wage rates. All prices are normalized by the current year index of prices paid by farmers for production, interest, taxes, and wage rates (U.S. Department of Agriculture 1999).

Crop yields at individual NRI sites are unavailable for the study region. However, the National Agricultural Statistics Service (NASS)'s county-level, time-series crop data allow us to estimate farmers' expected yields and yield variance in each county. Specifically, following Chavas and Holt (1990), a trend model of $y = \alpha + \beta t + \varepsilon$ was estimated in each county using the NASS data. The resulting predictions were taken as expected yields. The estimated residuals were then used to generate the variances of yields, which are assumed to be constant over time.

To capture the yield differences among NRI sites, physical variables reflecting land quality at individual NRI sites are included as independent variables in the models. NRI provides information on land capability classes and land slope at each NRI site. Slope is a continuous variable measured as a percentage. High quality land is a dummy variable defined as land with a land capability class of 1 or 2. Low-quality land is defined as land with a land capability class above 4. In addition, each NRI sample site is linked to the NRCS's SOILS5 database, providing detailed soil profile information from soil surveys. From the data, average measures of soil properties for top soil layers were calculated. These include average organic matter percentage, clay percentage, soil pH, and permeability. Finally, historical weather data from weather stations across the study region were obtained from the Midwestern Climate Center. The average of the means and variances of maximum and minimum daily temperatures and precipitation during corn, soybean, and wheat growing seasons was estimated for each NRI site using data from the nearest weather station. Because the long-run average of weather conditions changes little over time, farmers' expectations of weather conditions were assumed to be constant and were represented by the averages of the means and variances of temperatures and precipitation during the corn, soybean, and wheat growing seasons from 1975 to 1992.

2.1 Model Estimates and Interpretation

The first step in our analysis is to estimate a logit model of major land use choice (cropland vs. non-cropland). The dependent variable is set equal to one if the parcel is used for crops, and to zero otherwise. The NRI sites located in cropland, rangeland, and pastureland are used in the estimation. The elasticities of the probability of a parcel being allocated to crop production in the two regions are shown in Table 1. The models correctly predict land use choice at 85 and 89% of in-sample sites in the Corn Belt and Lake States, respectively.

The main variables of interest in these models are crop prices. The estimated models exclude the expected price of soybeans because it is highly correlated with the expected price of corn. The elasticities in Table 1 suggest that a 1% increase in the expected price of corn leads, on average, to a 0.06% and 0.14% increase in the probability that a parcel is allocated to cropland in the Corn Belt and Lake States, respectively. A 1% increase in the expected price of wheat causes a 0.06% increase in the probability that a parcel is allocated to cropland in the Corn Belt, and a 0.04% decrease in the Lake States. When the expected price of hay goes up by 1%, the probability that a parcel is used for crop production goes up by

Table 1 Major land use choice models: elasticities of the probability of allocating a parcel to cropland

Variable	Corn Belt	Lake States
Expected price for corn	0.059***	0.142***
Expected price for wheat	0.061***	−0.035***
Expected price for hay	0.032***	0.104***
Expected yield of corn	0.515***	0.062***
Expected variation of corn yield	−0.019***	0.031***
Mean precipitation corn season	−0.126***	0.068***
Std. Deviation precipitation corn season	0.060***	−0.174***
Mean maximum temperature corn season	−0.456***	0.040
Mean precipitation wheat season	0.008***	−0.297***
Std. Deviation precipitation wheat season	−0.048***	0.524***
Slope	−0.071***	−0.010***
Bad land	−0.006***	−0.008***
Good land	0.021***	0.044***
Observations	228,250	93,841
% Correct predictions	85%	89%

*, **, *** Statistical significance at $\alpha = 10\%$, 5%, and 1%. All elasticities are evaluated at the sample means of variables

0.03% in the Corn Belt and by 0.1% in the Lake States. A parcel is more likely to be allocated to crop production in areas where expected yields for corn are high. Also, parcels with high land quality are more likely to be allocated to crop production, while parcels with low land quality and steeper slope are more likely to be allocated to non-crop activities. All these results are consistent with agronomic information. However, the coefficients of the weather variables tend to have different signs in the models for the Corn Belt and the Lake States, implying that changes in temperatures and precipitation during the corn growing season tend to have different impacts on crop choices in the two regions. This occurs perhaps because the two regions have different weather conditions. For example, temperature may be high enough for corn production in the Corn Belt. Further increases in temperature during the corn growing season may be unfavorable for crop production. The opposite may be true in the Lake States.

Next, a multinomial logit crop choice model is estimated for each region. The models correctly predict crop choice at 65 and 67% of sample sites in the two regions, respectively. Furthermore, 88% of actual choices in the sample sites in both regions are predicted as the first or second choice by the models. Tables 2 and 3 present the elasticities of the probabilities of choosing alternative crops in the two regions, estimated using the model coefficients and the sample means of the variables.[2] The results of particular interest are the elasticities with respect to the expected commodity prices. As shown in Tables 2 and 3, own-price elasticities

[2] Estimated coefficients are available upon request. To determine the effect of land quality and other dummy variables on the choice of crops, we calculate elasticities with respect to these dummy variables as if they were continuous. Specifically, the following formula is used to calculate the elasticities with respect to these dummy variables:

$$\varepsilon \equiv \frac{\partial P_i}{\partial D}\frac{\bar{D}}{\mathrm{P_i}} = \bar{D}\left(\hat{\beta}_i^D - \sum_{k=1}^{N}\hat{P}_k\hat{\beta}_k^D\right),$$

where $\bar{D}$ is the mean of D in the sample (i.e., the percent of NRI points where $D = 1$), and $\hat{\beta}_i^D$ is the coefficient on D in equation i. It is necessary to calculate these elasticities because the sign of the coefficients on these dummy variables does not indicate how land quality or other dummy variables affect crop choices.

Table 2 The crop choice model for the Corn Belt: elasticities of probabilities to choose alternative crops

Variable	Corn	Soybeans	Wheat	Hay	Other
Price and policy variables					
Expected price for corn	0.246***	0.086	−1.498***	−0.193	−2.723***
Expected price for wheat	0.004	−0.038	0.288***	−0.112	0.137
Expected price for hay	−0.016	0.027	−0.138*	−0.009	0.081
ARP rate for wheat	0.035***	−0.052***	−0.174***	−0.053*	0.115***
Fuel price	−0.431***	−0.107	3.091***	−1.983***	5.400***
Fertilizer price	−0.224	−0.158	−0.975	−0.356	4.883***
Chemical price	−0.883***	0.903***	1.615***	0.082	2.737***
Wage rates	−0.393***	0.333***	−1.497***	−1.128**	3.806***
Seed price	−0.605***	0.485***	1.300***	−0.611	3.192***
Expected yield and yield variation of corn					
Expected yield of corn	0.602***	−0.475***	−2.315***	−1.756***	−1.317***
Expected variation of corn yield	−0.077***	0.192***	−0.388***	−0.037	−0.316***
Land characteristics					
Good land	0.028***	−0.026***	0.025	−0.055**	−0.124***
Bad land	−0.001**	0.001	0.0004	0.002	0.004**
Slope	0.059***	−0.142***	0.183***	0.219***	0.162***
Available water capacity	−0.026	0.127**	−0.125	−0.131	−0.549***
Organic matter	0.013***	−0.022***	−0.084***	0.009	0.064***
Soil pH	0.286***	−0.224***	−0.935***	−0.281	−1.043***
Coarse-textured soil	0.002***	−0.003***	0.003	0.003	0.002
Fine-textured soil	−0.007***	0.012***	0.007***	−0.011**	−0.007**
Weather conditions during corn or wheat growing season					
Mean maximum temperature corn season	−1.972***	2.791***	5.428***	−5.169***	1.674***
Mean precipitation corn season	0.025	0.046	−1.750***	1.417***	−0.351
St. deviation of precipitation corn season	−0.312***	0.331***	2.103***	−1.244***	0.600**
Mean of precipitation wheat season	0.062***	−0.104***	−0.110**	−0.009	0.128***
St. deviation of precipitation wheat season	−0.152***	0.239**	0.241**	0.144	−0.242*

*, **, *** Statistical significance at $\alpha = 10, 5$, and 1%. All elasticities are evaluated at the sample means of variables

Table 3 The crop choice model for the Lake States: elasticities of probabilities to choose alternative crops

	Corn	Soybeans	Wheat	Hay	Other
Price and policy variables					
Expected price for corn	0.725***	−0.821**	−1.567***	0.086	−1.361***
Expected price for wheat	−0.128***	0.209*	0.161	0.292**	0.070
Expected price for hay	−0.014	−0.378***	−0.388**	0.136	0.295***
ARP rate for wheat	0.033***	−0.059*	−0.221***	0.063	−0.049*
Fuel price	−1.144***	1.207**	1.054	−1.616**	3.182***
Fertilizer price	−0.481**	0.763	−0.833	−0.854	1.485***
Chemical price	−1.292***	0.371	0.132	−0.835	3.956***
Wage rate	0.072	0.039	−1.446***	0.334	−0.141
Seed price	−0.469**	1.012**	2.370***	−1.054	0.807
Expected yield and yield variation of corn					
Expected yield of corn	0.126***	2.471***	−1.613***	−1.102***	−1.176***
Expected variation of corn yield	0.057**	0.741***	−0.528***	−0.249***	−0.441***
Land characteristics					
Good land	0.031***	0.047**	0.048	−0.017	−0.125***
Bad land	−0.009**	−0.005	−0.002	−0.003	0.017***
Slope	−0.021***	−0.189***	0.0100	0.087***	0.143***
Available water capacity	−0.057*	0.202**	0.285*	0.207**	−0.118
Organic matter	0.007*	−0.071***	−0.018	−0.043***	0.049**
Soil pH	0.053	−0.077	2.348***	−1.008***	−0.037
Coarse-textured soil	−0.005**	−0.001	0.012	−0.004	0.015***
Fine-textured soil	−0.001	0.005***	0.0100***	−0.006*	0.001
Weather conditions during the corn growing season					
Mean maximum temperature corn season	0.948***	−0.061	−1.081	−1.495***	−1.840***
Mean precipitation corn season	−0.094	−0.654**	−3.545***	0.937***	0.890***
St. deviation of precipitation corn season	0.445***	0.358	1.765***	−0.893**	−1.435***
Mean of precipitation wheat season	0.242***	0.136	1.505***	−0.692***	−0.739***
St. deviation of precipitation wheat season	−0.325***	−0.579**	−2.738***	1.147***	1.277***

*, **, *** Statistical significance at $\alpha = 10$, 5, and 1%. All elasticities are evaluated at the sample means of variables

are positive (with the exception of hay in the Corn Belt), indicating an increase in the expected price for a crop will increase the likelihood that the crop will be planted. However, consistent with previous studies, most price elasticities are inelastic (Wu et al. 2004). Thus, crop choice in the study region is relatively unresponsive to changes in the price variables. This is not surprising, in view of agronomic (rotational) constraints and the relatively few crops grown in the study region.

The elasticities with respect to the climate variables indicate climate changes have different impacts on crop choices in the two regions. For example, although an increase in the average maximum daily temperature during the corn growing season increases the likelihood that corn is planted in the Lake States, it reduces the likelihood that corn is planted in the Corn Belt. Likewise, although an increase in the average precipitation during the corn growing season increases the likelihood that corn is planted in the Corn Belt, it reduces the likelihood that corn is planted in the Lake States. Land quality also affects crop choice. It seems that fine-textured soils are less likely to be planted to corn, while steep land is less likely to be planted to soybeans because it is an erosion-prone crop.

To capture the rotational constraints, dummy variables indicating the crop grown on the site in the previous year are included to reflect the influence of crop rotation on the selection of current year's crop. As shown in the appendix, all the coefficients on these dummy variables are statistically significant. Finally, to capture the differences across the landscape in each region that are not reflected by the independent variables (e.g., cultural practices), we include Major Land Resource Area (MLRA) dummy variables in the models.[3]

3 Environmental Production Functions

Increases in commodity prices, driven by ethanol mandates, have the potential to dramatically change the landscape in the Midwest. These changes will affect nitrate runoff, nitrate percolation, soil water erosion, soil wind erosion, and carbon sequestration in the region. Following Wu et al. (2004) and Wu and Babcock (1999), we use environmental production functions to predict changes in agricultural externalities. The environmental production functions are estimated using a metamodeling approach (Wu and Babcock 1999). Specifically, for a sample of NRI points, the Erosion Productivity Impact Calculator (EPIC) (Sharpley and Williams 1990; Williams et al. 1990) is used to simulate environmental impacts based on crop management practices (crop rotation, tillage, and conservation practices), soil characteristics, and climatic factors at that site. Environmental production functions are then estimated by regressing the simulated environmental data (e.g., measures of nitrate runoff and leaching) on the vector of crop management practices and site characteristics using appropriate models and econometric methods. For example, Wu and Babcock (1999) use a generalized Tobit model to estimate the nitrate-N runoff and percolation production functions to account for heteroskedasticity and censoring problems. The estimated environmental production functions are then used to predict environmental impacts at the full set of NRI points. These functions use the same information as the simulation model, but they eliminate the need to conduct model simulations for all input combinations, since they predict the outcome of such simulations (Wu et al. 2004). Metamodeling is required because it is not feasible to simulate environmental impacts at all sites and for all sets of conditions that arise in a large regional analysis such as performed here. Furthermore, metamodels simplify the analysis of changes

[3] Each MLRA is characterized by particular patterns of soil, climate, water resources, land use and type of farming.

in crop management practices because instead of conducting new simulations, regression coefficients can reveal how changes affect predicted outcomes.

The nitrate runoff and percolation production functions are taken from Wu and Babcock (1999). The methodologies used to develop the erosion and carbon sequestration production functions, similar to those used in this analysis, are described in Lakshminarayan et al. (1996) and Mitchell et al. (1998), respectively. Environmental production functions of the type used here have been applied in Gassman et al. (1998); Wu and Babcock (1999), and Wu et al. (2004).

The site-specific impacts measured at each NRI site are aggregated to the watershed and regional level using the acreage expansion factors provided in the NRI dataset. The watersheds are defined using the 8-digit hydrologic unit code (HUC) developed by the US Geological Survey. HUCs are the smallest geographic unit with which an NRI site can be identified.

4 Potential Environmental Impacts of Ethanol Mandates

The preceding sections describe a set of land use and environmental performance models that collectively form an assessment framework. In this section we apply this framework to evaluate how changes in commodity prices, driven by increased ethanol production, will affect land use and agricultural nonpoint source pollution in the Midwest.

We first establish a baseline for the evaluation. The baseline includes 3 years because environmental impacts of land use depend not only on crop choice, but also on crop rotations. For example, continuous corn uses between 175 and 250% more nitrogen fertilizer than corn following soybeans. Likewise, the corn–corn–soybean rotation and the corn–soybean rotation may also have different environmental impacts. To determine crop rotations at each NRI point in the baseline, we must determine crop choices in three consecutive years at each NRI site. In this study, we use the historical mean of commodity prices between 1982 and 2005 to determine crop rotations and levels of agricultural pollution in the baseline (see Table 4). We chose this time frame to include the earliest year in which NRI data are available (1982) and to extend up to the passage of the Energy Policy Act of 2005. This is the first federal law mandating minimum amounts of ethanol for production of gasoline.

Land uses and crop rotation at each NRI point in the baseline are established using the following procedure. First, we use the major land use choice model to predict which NRI parcels will be used for crops.[4] Next, for the parcels designated as cropland, we calculate the probabilities of choosing alternative crops in the first baseline year by substituting historical average prices into the crop choice models. Based on the predicted probabilities, we then use a random number generator to determine crop choice at each NRI site in the first baseline year. Once the crop choice in the first year is determined, we determine crop choices in the second year, and then repeat the process for the third year. To adjust for declining yields in continuous corn rotations, we decrease the expected corn yield by 8.4% when the crop planted the previous year was corn.[5] Finally, based on the crop choices in the three baseline years, we determine crop rotation at each NRI site in the baseline. For example, if corn is chosen each year at an NRI site, we have continuous corn at that NRI site. The spatial patterns

[4] Parcels are designated as crop land if the predicted probability that the site will be used for crops is greater than 0.5.

[5] We thank an anonymous referee for pointing this out. The amount of the reduction is based on the average difference in yields between corn-corn and soybean-corn rotations used in Duffy (2010).

of land use acreage and cropping systems generated this way are generally consistent with the historical averages for the period 1982–2005.

The baseline levels of fertilizer and pesticide use are calculated using average application rates for each crop and state (U.S. Department of Agriculture 1998) and predicted baseline acreages.[6] Agricultural pollution is estimated using the environmental production functions. Specifically, by substituting the crop rotations and the corresponding level of nitrogen application at each NRI site into the environmental production functions, we estimate the level of nitrate runoff, nitrate percolation, soil water erosion, soil wind erosion, and carbon sequestration at each NRI site in the baseline. The site-specific measures of environmental impacts are aggregated to the regional levels using the expansion factor to facilitate presentation of the results.

The baseline serves as a benchmark for evaluating the environmental impacts of increased commodity prices. We consider three main scenarios, based on three alternative future prices for corn: a low price of \$4, a medium price of \$6, and a high price of \$8 per bushel, as listed for corn futures on the Chicago Board of Trade (CBT) between January and June 2008. In each of these scenarios we also allow the prices of other crops in our models to change (see Table 4). The corresponding prices for soybeans and wheat are obtained from futures prices (for the same dates) listed on CBT. For hay, we assume that the initial ratio to the price of corn remains constant and use this ratio to predict the corresponding price in each scenario. To be able to isolate the effects of changes in crop prices in the simulations, we keep the input prices constant at baseline levels.

As a robustness test for our simulations, we consider two additional sources of future commodity price projections. The USDA (2010) and the Food and Agricultural Policy Research Institute (FAPRI 2009) forecast prices for corn, wheat, and soybeans until 2019, and FAPRI forecasts prices for hay as well. We compare these projections with the ones we use (from CBT) by comparing the ratios of the predicted prices of wheat, soybean, and hay to that of corn. The range of soybean–corn ratios is consistent with the one we use (2.3–2.7). The range of hay–corn ratios for the USDA and FAPRI projections (34.7–43.1) is somewhat higher than for CBT (31.7–34.3), and their range of wheat-corn ratios (1.3–1.7) is somewhat lower than for the prices we use (1.3–2.2). Therefore, we consider two additional scenarios, which we define as variants of our intermediate price scenario (see Table 4). The fourth scenario (a high hay price scenario) uses a higher hay-corn ratio (43.1) to set the price of hay. The fifth scenario (a low wheat price scenario) uses a lower wheat-corn ratio (1.4) to set the price of wheat.

The land use choices, crop rotations, fertilizer and pesticide application, and the levels of environmental impacts under each of the scenarios are estimated in the same way as in the baseline. Specifically, we first estimate crop choices and crop rotation at each NRI site under each scenario using the crop choice models and then estimate the environmental impacts at each NRI site using the environmental production functions. Finally, we compare the results under each scenario with the baseline to determine the impacts of increased ethanol production and commodity prices.

This approach to analyzing the environmental effects of increased commodity prices driven by ethanol production has certain limitations. For instance, other factors may have contributed to the increases in crop prices. If so, our results cannot pinpoint and reveal how much of the environmental impacts are caused by ethanol production. Nevertheless, this analysis

[6] USDA (1998) provides state-level data on application rates (total lbs/acre) of fertilizers (nitrogen, phosphate, and potash) and pesticides (herbicides and insecticides) for different crops. We aggregate to the regional level using a weighted-average application rate, with weights based on each state's planted acreage of each crop.

Table 4 Crop prices used in simulations

Crop	Baseline		Scenario 1 Low Corn Price	Scenario 2 Medium Corn Price	Scenario 3 High Corn Price	Scenario 4 High Hay–Corn Ratio	Scenario 5 Low Wheat–Corn Ratio
	Corn Belt	Lake States					
Corn	3.13	3.02	4.00	6.00	8.00	6.00	6.00
Soybeans	7.90	7.72	10.97	14.13	20.39	14.13	14.13
Wheat	4.03	4.13	8.76	9.92	13.72	9.92	8.26
Hay	107.57	95.61	137.3	201.00	272.5	254.29	201.00

provides insight into potential impacts of increased reliance on corn-based ethanol which thus far have not entered the debate surrounding biofuels.

The land use and environmental impacts of increased commodity prices are presented in Tables 5 and 6. The tables show the 3-year average of acres of the various crops, non-cropland (range and pasture), total acreage of land in various crop rotations, fertilizer and pesticide application levels, total nitrogen runoff and percolation, total wind and water erosion, and total loss of soil carbon for each of the two regions in the baseline and for the three price scenarios. Baseline differences in the environmental quality measures between regions reflect different total acreage in each region as well as variation in per-acre values of these measures. For instance, mean nitrate runoff and percolation and mean water erosion per acre are higher in the Corn Belt than in the Lake States. The results in Tables 5 and 6 are generally robust to the additional scenarios presented in Table A1.

The simulation results suggest that rising prices would result in widespread conversions of non-cropland to cropland. The land use models predict there are approximately 8 million acres of pasture and range land in the study region. Fifty percent of those lands (approximately 4.2 million acres) will be converted to cropland when corn prices rise to $6.

Rising commodity prices will also result in dramatic changes in crop mix and rotation systems in the Midwest. With $4 corn, the total acreage of corn will increase by 14 and 17% in the Corn Belt and Lake States, respectively. These modeling results are generally consistent with historical data. The average price received for corn from 2007 to 2009 was $3.99 in the US. The corresponding average corn acreage for those 3 years was 16% more than the historical average from 1982–2005. With $6 corn, the total acreage of corn will increase by 23 and 40% in the Corn Belt and Lake States, respectively.[7] The smaller percent increase in the Corn Belt reflects the large corn base in the region (seventy one percent of corn acres in the study region are located in the Corn Belt).

In addition to the changes in crop mix, cropping systems also adjust with rising commodity prices. The acreage of continuous corn increases considerably in both regions with $6 corn, with the largest percentage increase in the Lake States. In the Corn Belt, where corn-soybeans rotations are popular, the acreage of the corn-soybeans rotation increases by 28% with $6 corn. In the Lake States, where the corn-soybean rotation is less popular, this cropping system increases by 11% with $6 corn, but would be switched to continuous corn if the price of corn reached $8.

The results in Tables 5 and 6 indicate that the conversions of non-cropland to cropland and the changes in crop mix and rotational systems have a significant impact on fertilizer and pesticide use, agricultural runoff, and environmental quality. With $6 corn, fertilizer use will increase by 18 and 18.7%, and pesticide use by 23.1 and 27.5% in the Corn Belt and Lake States, respectively. Nitrogen leaching will increase in both regions, although by a larger proportion in the Corn Belt. Wind erosion increases by roughly 50% in both regions. Nitrogen runoff will also increase significantly in the Corn Belt. In the Lake States nitrogen runoff decreases because the impact of switching from cropping systems involving corn–soybean rotations to continuous corn, which is less prone to runoff than corn–soybeans rotations, dominates the effect of increased conversion to cropland. Loss of soil organic carbon increases in the Lake States, but there is no significant change in the Corn Belt. Finally, there is practically no change in water erosion in the Corn Belt, and only a small increase in the Lake States. These results suggest that, with some exceptions in particular regions, changes in land

[7] Assuming that all the additional corn is used to produce ethanol, and using a corn-to-ethanol conversion rate of 2.7 gallons/bushel (Baker and Zahmser 2006) and an average corn yield for the Corn Belt and Lake States of 165 bushels/acre (NASS 2009), this would roughly translate into an additional production of 4.1 billion gallons of ethanol with a corn price of $4 and 7.8 billion gallons of ethanol with a corn price of $6.

Table 5 The estimated impacts of higher commodity prices on land use and environmental quality in the Corn Belt

Land use/environmental impacts	Baseline	Scenario 1: \$4 corn		Scenario 2: \$6 corn		Scenario 3: \$8 corn	
		Level	% Change	Level	% Change	Level	% Change
Land use (1000 acres)							
Acres of corn	44,042	50,110	13.78	54,358	23.43	58,137	32.00
Acres of soybeans	30,191	34,063	12.83	37,302	23.55	38,869	28.74
Acres of wheat	5,263	4,048	−23.08	2,170	−58.76	1,349	−74.38
Acres of hay	10,412	11,599	11.39	12,329	18.41	12,153	16.71
Acres of non-cropland	6,373	4,647	−27.08	3,742	−41.28	2,528	−60.33
Cropping systems (1000 acres)							
Continuous corn	27,935	32,070	14.80	34,898	24.93	37,764	35.19
Continuous soybeans	11,758	13,544	15.19	15,502	31.84	16,437	39.79
Continuous wheat	1,954	1,534	−21.50	753	−61.48	537	−72.50
Corn–soybeans	30,482	35,162	15.35	39,074	28.19	41,265	35.38
Corn–corn–soybeans	1,302	1,101	−15.41	747	−42.63	558	−57.16
Corn–soybeans–wheat	473	539	13.84	297	−37.22	181	−61.73
Soybeans–soybeans–corn	281	254	−9.68	205	−26.97	194	−30.84
Wheat–soybeans	1,681	1,152	−31.45	432	−74.30	142	−91.56
Corn–corn–alfalfa	10	6	−35.79	0	−100.00	0	−100.00
Environmental quality							
Fertilizer use (1000 s lbs.)	16,807	18,662	11.04	19,833	18.00	20,787	23.68
Pesticide use (1000 s lbs.)	189	214	13.44	232	23.12	246	30.54
Nitrogen runoff (1000 s lbs.)	422,826	481,341	13.84	528,346	24.96	561,213	32.73
Nitrogen percolation (1000 s lbs)	955,399	1,062,605	11.22	1,147,138	20.07	1,216,035	27.28
Loss of soil organic carbon (1000 s metric tons)	1,007,777	1,010,789	0.30	1,007,079	−0.07	1,009,503	0.17
Wind erosion (1000 s tons)	5,929	7,405	24.90	9,036	52.41	10,403	75.45
Water erosion (1000 s tons)	294,463	293,132	−0.45	293,922	−0.18	293,354	−0.38

Table 6 The estimated impacts of higher commodity prices on land use and environmental quality in the Lake States

Land use/environmental impacts	Baseline	Scenario 1: $4 corn		Scenario 2: $6 corn		Scenario 3: $8 corn	
		Level	% Change	Level	% Change	Level	% Change
Land use (1000 acres)							
Acres of corn	18,038	21,101	16.98	25,270	40.09	28,178	56.22
Acres of soybeans	9,028	7,893	−12.57	5,640	−37.53	3,749	−58.48
Acres of wheat	3,341	2,374	−28.93	1,205	−63.94	523	−84.35
Acres of hay	7,110	9,220	29.69	10,362	45.74	12,186	71.41
Acres of non-cropland	1,946	1,184	−39.18	406	−79.13	121	−93.79
Cropping systems (1000 acres)							
Continuous corn	14,311	16,999	18.78	21,307	48.88	25,012	74.77
Continuous soybeans	4,849	3,598	−25.79	1,816	−62.55	788	−83.75
Continuous wheat	2,150	1,578	−26.59	807	−62.45	331	−84.60
Corn–soybeans	6,055	6,938	14.59	6,740	11.31	5,361	−11.45
Corn–corn–soybeans	560	547	−2.34	482	−13.80	483	−13.65
Corn–soybeans–wheat	198	279	41.15	230	16.13	105	−46.71
Soybeans–soybeans–corn	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Wheat–soybeans	497	183	−63.23	9	−98.27	0.00	−100.00
Corn–corn–alfalfa	291	203	−30.19	155	−46.94	44	−84.86
Environmental quality							
Fertilizer use (1000 s lbs.)	4,619	5,065	9.66	5,483	18.70	5,780	25.13
Pesticide use (1000 s lbs.)	57	64	13.29	72	27.48	78	38.31
Nitrogen runoff (1000s lbs.)	111,990	109,190	−2.50	99,934	−10.77	92,018	−17.83
Nitrogen percolation (1000 s lbs)	329,028	339,576	3.21	340,763	3.57	342,816	4.20
Loss of soil organic carbon (1000 s metric tons)	303,805	312,854	2.98	326,070	7.33	340,056	11.93
Wind erosion (1000 s tons)	3,273	3,913	19.57	4,949	51.23	5,692	73.92
Water erosion (1000s tons)	42,740	43,095	0.83	43,576	1.96	43,916	2.75

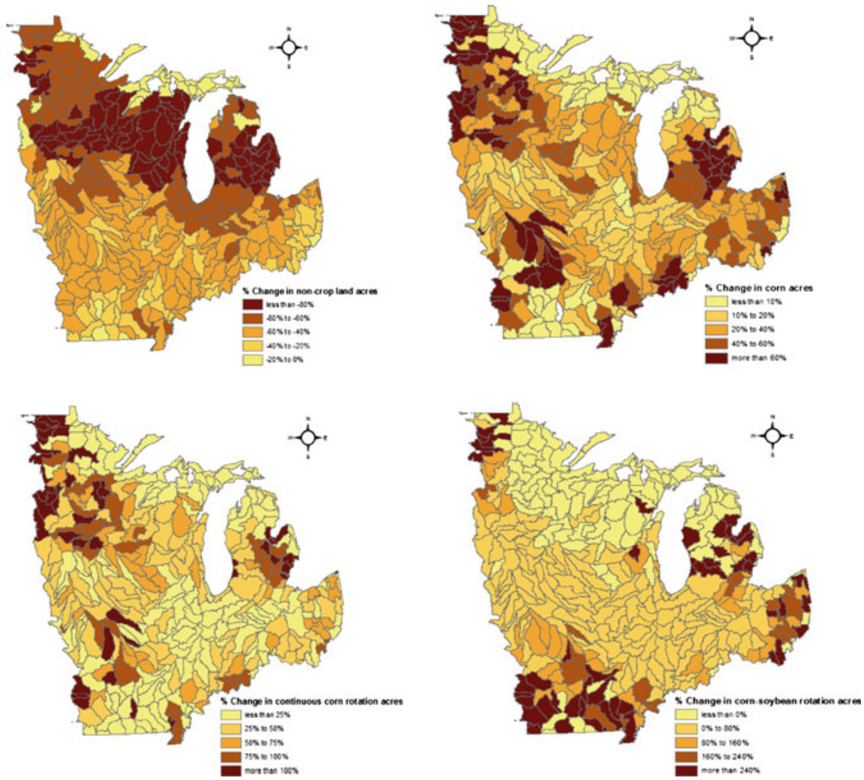

Fig. 1 Changes in land use and cropping systems with $6 corn

use driven by increased commodity prices, as already reflected in futures contracts, will lead to significant increases in nitrate water pollution, soil erosion, and soil organic carbon losses.

We illustrate the spatial distribution of key impacts of rising corn prices in Figs. 1 and 2. Figure 1 shows the distribution of the most relevant land use and crop choice changes between the baseline and the intermediate scenario ($6 corn). Percentage reductions in non-cropland acreage are larger in the Lake States, particularly in Wisconsin, southern Minnesota and eastern Michigan, except for some of the northernmost areas, such as the Upper Peninsula. There is also a considerable amount of pasture and rangeland converted to crop production in Missouri and southern Iowa, although the change is small in percentage terms. The smallest conversions of non-cropland, in terms of both acreage and percentage, occur in Ohio, Illinois and Indiana. The largest percent increases in corn acreage occur in Minnesota (except some northeast areas), southern Michigan, south central Iowa, north central Missouri, and eastern Ohio. In terms of total acreage, the largest increases occur in the southern Lake States and the Corn Belt (except southern Missouri). This area also features the largest increases in acreage of continuous corn rotations, although the percentage increases are relatively small in most parts of Illinois, Indiana and Ohio. Finally, with the exception of some areas in Michigan and in northwest Minnesota, increases in corn–soybean rotations are mostly concentrated in the Corn Belt, particularly in Missouri and eastern Ohio (in terms of percentage).

Figure 2 shows the spatial distribution of changes in the environmental quality measures (we have combined wind and water erosion into a single erosion measure). The largest increases in nitrogen runoff (in terms of both percent and amount) take place in the Corn

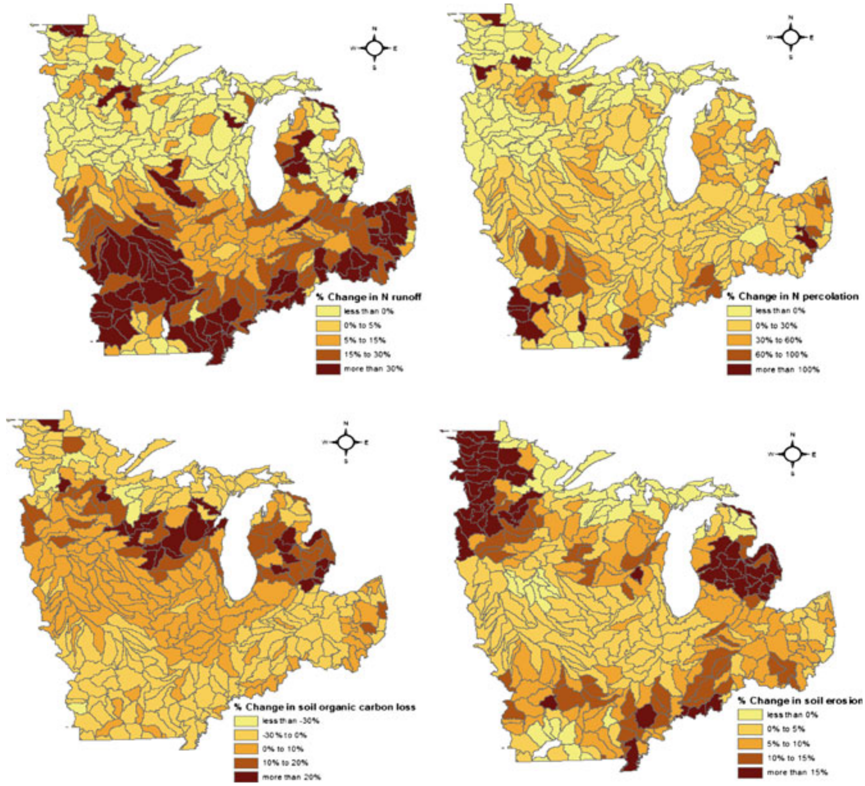

Fig. 2 Changes in selected environmental quality measures with $6 Corn

Belt, particularly in Missouri, southern Indiana, and eastern Ohio. Increases in nitrogen percolation are also larger in the Corn Belt. In addition, parts of central Minnesota and western Michigan also have relatively large increases in nitrogen percolation. Within the Corn Belt, the largest increases in nitrogen percolation are in Missouri, southern Indiana, and Ohio. Soil organic carbon loss is concentrated in the Lake States, particularly in central Minnesota and southern Wisconsin and Michigan. Finally, changes in erosion are mostly small throughout the region (they are dominated by water erosion, which does not change significantly). The largest increases, in terms of both percent and amount, are concentrated in western Minnesota, southern Michigan, central Missouri, southern Illinois and Indiana, and western Ohio.

5 Mitigation Policies

An important question is whether the negative environmental impacts described in Tables 5 and 6 can be mitigated through conservation practices and policies. To address this issue, we conduct some preliminary analysis. Specifically, we analyze the potential impacts of three measures: a) a conservation compliance measure which bans conversion of highly erodible land to crop production, b) a reduction in nitrogen application rates achieved through soil nitrogen testing or a fertilizer use tax, and c) a payment for switching from continuous corn to a corn-soybean rotation. To simulate the impact of the conservation compliance measure, we identify the parcels that are not in cropland in the baseline and have an erodibility index of eight or higher, and we restrict the crop choice models so that no crop is planted on those parcels.[8] We simulate the second policy by reducing nitrogen-application rates by 20%. The reduction in nitrogen application rate could be achieved through soil nitrogen testing or a nitrogen use tax (see, e.g., Wu and Babcock 1998). To simulate the impact of a payment for switching from continuous corn to a corn–soybean rotation, we assume that the policy would cause 10% of (randomly chosen) parcels in continuous corn to switch over to a corn–soybean rotation. We conduct simulations for each of these policies using the procedure described above and a price of corn of $6/bushel, and we compare the outcomes to those of a "no-mitigation" scenario (which corresponds to the $6/bushel results in Tables 5, 6). Our objective here is not to conduct an exhaustive evaluation of policy alternatives, but rather to provide some basic insight into the extent to which the negative environmental impacts from increased ethanol production could be mitigated through reducing nitrogen application rates and some conservation compliance measures.

Table 7 shows the values of the environmental quality measures for the baseline, the no-mitigation scenario, and each of the three policies in both regions (the percentage changes are all relative to the baseline). The results suggest that the conservation compliance measure that bans conversion of highly erodible land could reduce the impact on nitrogen runoff and percolation, as well as on soil wind erosion. Compared to the no-mitigation scenario, nitrogen runoff and percolation and wind erosion increase by less (or decrease by more) if highly erodible land is not converted to cropland. The improvements, however, are relatively small. A reduction in nitrogen application rates could be used to mitigate the impacts on nitrogen runoff and percolation. Reducing nitrogen application leads to smaller increases (or larger decreases) in runoff and percolation than in the no-mitigation scenario. The impact is particularly large for nitrogen percolation levels, where a 20% reduction in nitrogen application would cause percolation to decrease by 10.5 and 17.3% in the Corn Belt and Lake States, respectively, whereas without mitigation it increases by 20 and 3.6%. Payments that cause 10% of parcels in continuous corn to switch to a corn–soybean rotation would reduce nitrogen application levels, since soybean is a less nitrogen-intensive crop. As a result, in the Corn Belt nitrogen runoff and percolation would increase less than in the no-mitigation scenario. In the Lake States, nitrogen percolation would decrease by 21.4% relative to the baseline, whereas without mitigation it increases by 3.6%. There is also a small positive impact on wind erosion levels in both regions.

To summarize, our exploratory analysis suggests that, although there are differences across policies and regions, the mitigation options considered here could be effective in reducing the environmental impacts of higher commodity prices. One important caveat to this analysis is that, although reducing nitrogen application rates is effective in reducing nitrate water pollution, we have not analyzed how the reduction in nitrogen application rates could be achieved. In addition, we have not analyzed the potential costs of each of these policies. For example, it could be costly if landowners have to be paid to switch from continuous corn to a corn–soybean rotation, particularly when corn prices are high relative to soybean prices.

[8] The Natural Resource Conservation Service defines highly erodible land as land which has an erodibility index of eight or more (see http://www.nrcs.usda.gov/Technical/NRI/maps/meta/m5997.html).

Table 7 Effects of mitigation policies on environmental quality measures

	Baseline	No mitigation ($6 Corn)		Reducing N application rate by 20%		Highly erodable land not converted		Switch from continuous corn to corn–soybean rotation	
	Level	Level	% Change	Level	% Change	Level	% Change	Level	% Change
Corn Belt									
Nitrogen runoff (1000s lbs.)	422,826	528,346	24.96	503,861	19.17	513,911	21.54	471,358	11.48
Nitrogen percolation (1000s lbs)	955,399	1,147,138	20.07	854,934	−10.52	1,132,702	18.56	996,603	4.31
Loss of soil organic carbon (1000s metric tons)	1,007,777	1,007,079	−0.07	1,023,160	1.53	1,008,688	0.09	993,623	−1.40
Wind erosion (1000s tons)	5,929	9,036	52.41	9,036	52.40	8,817	48.71	8,908	50.25
Water erosion (1000s tons)	294,463	293,922	−0.18	293,922	−0.18	294,840	0.13	294,109	−0.12
Lake States									
Nitrogen runoff (1000s lbs.)	111,990	99,934	−10.77	93,971	−16.09	98,790	−11.79	82,396	−26.43
Nitrogen percolation (1000s lbs)	329,028	340,763	3.57	272,267	−17.25	338,219	2.79	258,776	−21.35
Loss of soil organic carbon (1000s metric tons)	303,805	326,070	7.33	331,391	9.08	325,969	7.30	317,526	4.52
Wind erosion (1000s tons)	3,273	4,949	51.23	4,949	51.23	4,919	50.31	4,927	50.54
Water erosion (1000s tons)	42,740	43,576	1.96	43,576	1.96	43,620	2.06	43,573	1.95

6 Conclusions

Federal and state legislations mandating minimum amounts of corn-based ethanol will result in increased demand for corn and higher commodity prices. These changes will have impacts on land use and environmental quality. This study presents an empirical modeling framework designed to assess these effects over a large area of the US Midwest (the Corn Belt and Lake States), which produces more than 60% of corn in the US.

The empirical models developed in this study predict land use, crop choices, and crop rotations at the parcel level based on commodity prices, land quality, weather conditions, and other physical characteristics at each parcel. The data on crop rotations, nitrogen application rate, land quality and other physical characteristics are then combined with site-specific environmental production functions to determine the effect of rising commodity prices on nitrate runoff and leaching, soil water and wind erosion, and carbon sequestration at each NRI site. The empirical models are used to explore the extent to which the negative environmental impacts associated with land use changes could be mitigated through conservation practices and government policies.

Our results suggest that increasing commodity prices will result in widespread conversions of non-cropland to cropland. Fifty percent of the region's pasture and range land will be converted to cropland with $6 corn. Rising commodity prices will also result in dramatic changes in crop mix and rotation systems in the Midwest. With $6 corn, the total acreage of corn will increase by 23 and 40% in the Corn Belt and Lake States, respectively; the acreage of continuous corn increases considerably in both regions, with the largest percentage increase in the Lake States.

These changes in land use and cropping systems will have a significant impact on agricultural runoff and environmental quality. Total fertilizer application will increase by almost one fifth in the two regions with $6 corn, and total pesticide application will increase by roughly one fourth. Nitrogen leaching and soil wind erosion also increase in both regions with $6 corn. Nitrogen runoff increases as well in the Corn Belt, and loss of soil organic carbon will increase in the Lake States. These environmental impacts could be mitigated through reduction in nitrogen application rates and implementation of conservation compliance measures such as a ban on converting highly erodible land to crop production or switching crop rotations from continuous corn to corn–soybeans.

Global environmental challenges such as climate change, coupled with energy security concerns, are inspiring many governments, including the United States, to develop policies to encourage biofuel production. These policies have both short-run impacts and long-term repercussions. In this paper, we have evaluated the short- to mid-term effects of increased biofuel production. But in the long-run government policies could lead to development of new generations of biofuel crops. Large-scale production of such crops could dramatically change the agricultural landscape, as well as the sources, levels, and variability of farm income. A careful analysis of alternative mid- to long-term scenarios and the inherent opportunities and pitfalls would be an important topic for future research.

Appendix A

See Table 8.

Table 8 Sensitivity analysis for impacts of higher commodity prices on land use and environmental quality

Land use/environmental impacts	Corn Belt				Lake States			
	Scenario 4: high hay		Scenario 5: low wheat		Scenario 4: high hay		Scenario 5: low wheat	
	Level	% Change	Level	% Change	Level	% Change	Level	% Change
Land use (1000 acres)								
Acres of corn	54,203	23.07	54,191	23.05	25,161	39.50	25,911	43.65
Acres of soybeans	37,650	24.71	37,529	24.31	5,037	−44.21	5,418	−39.99
Acres of wheat	2,036	−61.31	1,962	−62.72	903	−72.98	1,150	−65.58
Acres of hay	12,413	19.22	12,343	18.54	10,432	46.73	9,937	39.76
Acres of non-cropland	3,510	−44.92	4,007	−37.12	234	−87.97	369	−81.03
Cropping systems (1000 acres)								
Continuous corn	34,635	23.99	34,664	24.09	21,408	49.59	21,971	53.52
Continuous soybeans	15,778	34.18	15,670	33.52	1,472	−69.64	1,664	−65.70
Continuous wheat	692	−64.53	651	−66.67	598	−72.18	780	−63.73
Corn–soybeans	39,273	28.84	39,270	28.83	6,413	5.92	6,676	10.26
Corn–corn–soybeans	778	−40.19	739	−43.21	417	−25.48	445	−20.55
Corn–soybeans–wheat	286	−39.56	269	−43.07	171	−13.40	225	13.75
Soybeans–soybeans–corn	203	−27.96	201	−28.39	0	0.00	0	0.00
Wheat–soybeans	399	−76.23	370	−78.02	3	−99.40	3	−99.48
Corn–corn–alfalfa	0	−100.00	0	−100.00	198	−32.04	217	−25.45
Environmental quality								
Fertilizer use (1000s lbs.)	19,832	18.00	19,790	17.75	5,381	16.51	5,534	19.82
Pesticide use (1000s lbs.)	232	23.11	232	22.98	71	26.01	73	29.01
Nitrogen runoff (1000s lbs.)	531,420	25.68	529,911	25.33	95,693	−14.55	99,136	−11.48
Nitrogen percolation (1000s lbs)	1,148,609	20.22	1,146,842	20.04	333,366	1.32	342,768	4.18

Table 8 continued

Land use/environmental impacts	Corn Belt				Lake States			
	Scenario 4: high hay		Scenario 5: low wheat		Scenario 4: high hay		Scenario 5: low wheat	
	Level	% Change	Level	% Change	Level	% Change	Level	% Change
Loss of soil organic carbon (1000 s metric tons)	1,004,908	−0.29	1,005,266	−0.25	327,010	7.64	328,242	8.04
Wind erosion (1000 s tons)	9,093	53.37	9,090	53.31	5,041	54.03	5,089	55.49
Water erosion (1000 s tons)	294,080	−0.13	294,273	−0.06	43,799	2.48	43,528	1.84

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