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The Water Quality Effects of Corn Ethanol vs Switchgrass Based Biofuels in the Midwest

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Abstract: While biofuels may yield renewable fuel benefits, there could be downsides in terms of water quality and other environmental stressors, particularly if corn is relied upon exclusively as the feedstock. In this article, we describe a modeling system that links agricultural land use decisions in the Upper Mississippi River Basin (UMRB) to economic drivers. This modeling system is then used to assess several scenarios to identify the water quality effects of alternative land uses and the impacts of introducing on the landscape alternative feedstocks, such as switchgrass, to support renewable energy goals. Specifically, a scenario that assesses the water quality effects associated with an increase in corn acreage due to higher relative corn prices provides an estimate of the water quality effects that current biofuel policies may have in the UMRB. Since cellulosic alternatives such as switchgrass are not currently technologically feasible, we undertake two additional scenarios to assess the prices needed to induce switchgrass production in the watershed and the associated water quality changes. Switchgrass production has sizable benefits in terms of sediment and phosphorus losses, though targeting does little to improve sediment over the unrestricted location of switchgrass. Nitrate losses are still high, likely because of the high fertilization levels assumed. Our analysis can help evaluate the costs and environmental impacts associated with implementation strategies for the biofuel mandates of the new energy bill.

Unprecedented increases in biofuel production are occurring: the US now produces seven billion gallons of ethanol compared to less than two billion in 2002 (US EIA, 2008). Moreover, the latest energy bill, the Energy Independence and Security Act of 2007 (EISA 2007), mandates 36 billion gallons of ethanol by 2022 with only 15 billion coming from corn. The remaining 21 billion gallons are expected to come from second generation technologies which currently are not commercially viable, such as cellulosic ethanol.

In this article, we use an integrated economic and water quality modeling framework for the Upper Mississippi River Basin (UMRB) to conduct scenario analysis to shed light on potential water quality changes associated with ethanol production. We investigate the water quality changes associated with expanded corn based ethanol or cellulosic ethanol by using a calibrated watershed based water quality model to predict the water quality changes associated with spatially explicit land use changes. While cellulosic ethanol has a much higher net energy balance and it produces less greenhouse gases than corn-based ethanol, it is not currently commercially viable. Thus, assessing the land use and water quality changes associated with the production of ethanol via switchgrass requires the use of scenario analysis. Our modeling framework allows us to estimate the impacts of market forces through price effects and of policies based both on prices and/or environmental characteristics. The modeling system can

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be used to inform a wide range of future policies related to agricultural land use and conservation.

Two overarching questions motivate this research: 1) How much additional nutrients (N and P) are likely to end up in the rivers and streams of the UMRB as a result of the increases in the relative profitability of corn? and (2) How would those nutrient levels differ if switchgrass production in the UMRB became widespread in lieu of total reliance on corn-based ethanol?
We begin the article with a description of land use in the UMRB. Next we describe the key components of the integrated modeling framework; the data, models and assumptions used to generate a baseline are described. The baseline is then compared to several scenarios:

1. Commodity prices as forecast by the futures market and the latest Food and Agricultural Policy Research Institute (FAPRI) long term projections. The two sets of prices differ substantially both in terms of absolute and relative prices;

2. Switchgrass prices high enough to compete with traditional row crop production, and convert a sizable portion of the UMRB's cropland away from row crops, and

3. Switchgrass prices identical to scenario 2, but with production restricted to the most erodible land in the watershed. We then calculate the opportunity cost of producing switchgrass in the targeted areas, and the amount of subsidy necessary to implement the policy.

2. Landuse in the UMRB

We focus our analysis on the UMRB, a largely agricultural watershed that runs from the source of the Mississippi river in Minnesota to Cairo, Illinois. The total drainage area covers portions of seven states, but the main states included in the watershed are five. Nitrogen and phosphorous are the primary agricultural sources of nutrients in the UMRB and evidence suggests that both nitrate and phosphorous loads from the UMRB are linked to the hypoxic zone that occurs annually in the Gulf of Mexico (EPA Science Advisory Board). These nutrients also contribute to poor local water quality problems within many areas of the UMRB. In the most intensive agricultural portions of the Basin, well over 75% of the land is devoted to agricultural uses (USDA, 2000). Table 1 contains a summary of the acreage of key crops in the region. The major agricultural land use categories have remained relatively stable since the end of the 1990s, with the exception of a corn acreage increase in 2007, which is not expected to be maintained in 2008 (USDA NASS, 2008). However, beginning in 2006, there have been large and rapid changes of both absolute and relative prices for both corn and soybeans. Commodity and input prices are the most important drivers of farmers' choices. Therefore, it is very important to use reasonable forecasts to assess future land use changes, and their associated environmental impacts. In our model, farmers can choose between continuous corn, corn and soybean rotations, a corn-corn-soybean rotation and a five year corn alfalfa rotation, besides switchgrass. Farmers choose the most profitable rotation given their land characteristics (yields), their costs of production and the prices of the crops. Thus, the choice of rotation is heavily dependent on relative crop prices and input prices. We focus here on the relative crop price effects, but we are working on an extension that will include effects of input price changes (nitrogen and diesel).

The recent rises in prices have made forecasting long term equilibrium prices very complex. The latest FAPRI long term projections for the year 2018 forecast corn prices of \$153.54 per metric ton (/mt) (\$3.9/bushel) and soybean prices of \$385.81/mt (\$10.5/bushel) (FAPRI 2008). On the other hand, at the Chicago Board of Trade (CBOT) futures contracts for the Fall of 2010—the latest crop year for which both corn and soybean futures are available—are currently trading at \$259.04/mt for corn (\$6.58/bushel) and \$540.13/mt for soybean (\$14.7/bushel) (CBOT settlement June 19). The FAPRI predictions for 2010 are \$152.36/mt (\$3.87/bushel) for corn and \$361.56/mt (\$9.84/bushel) for soybeans (FAPRI, 2008). Thus, actual future market prices are diverging greatly from modeled forecasts.

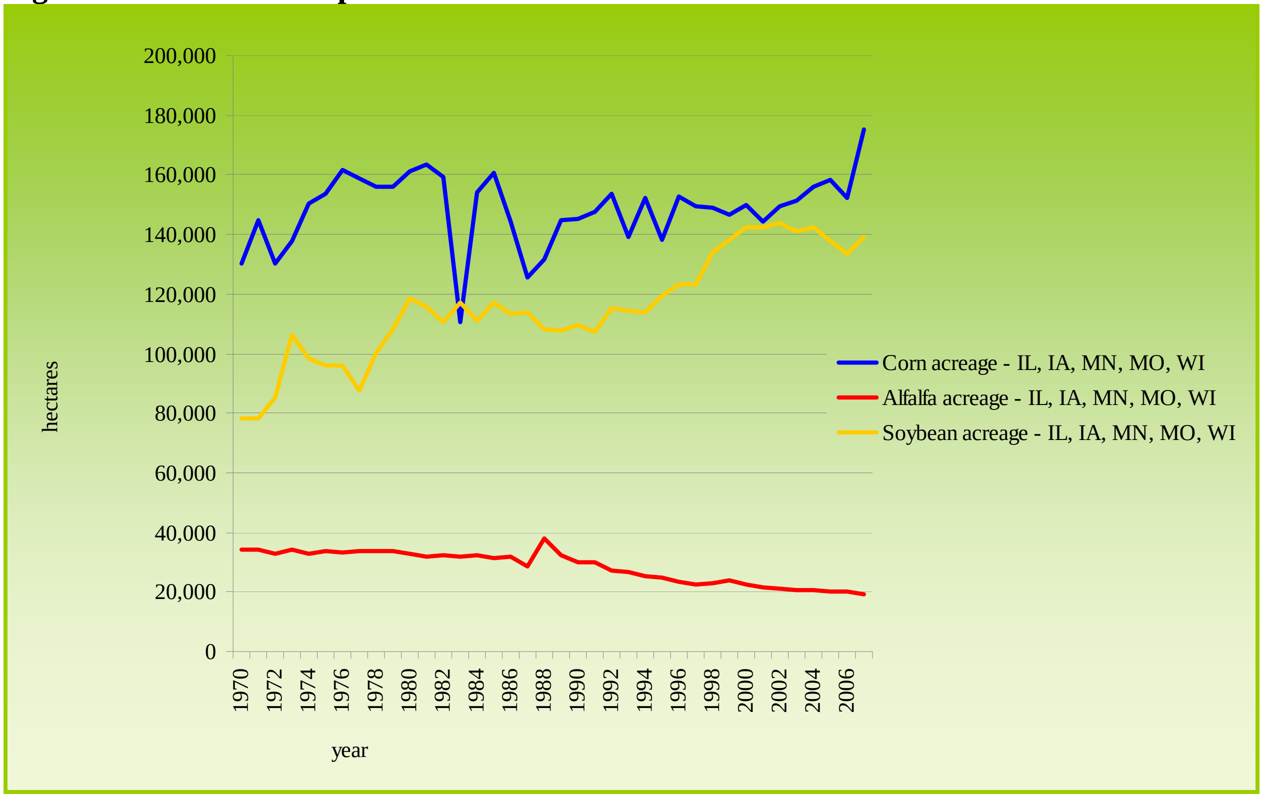
Table 1 – Land use changes in the Upper Mississippi River Basin (km^2)

	Corn area	Soybean area	Alfalfa area	CRP area	Switchgrass area
Baseline	119783	84618	22592	17344	0
FAPRI prices					
Without CRP	128281	99953	25623	0	0
With CRP	120371	95094	22572	17344	0
CBOT prices					
Without CRP	193612	36749	24204	0	0
With CRP	184402	33400	21014	17344	0
FAPRI prices					
With max net returns switchgrass	107264	83460	21099	17344	26952
With targeted switchgrass	110081	91618	15758	17344	23988
CBOT prices					
With max net returns switchgrass	170264	25642	19564	17344	24073
With targeted switchgrass	173102	31365	13912	17344	23988

Forecasting the price of feedstocks for cellulosic ethanol production is even more challenging, given that the technology is not commercially viable and the logistics and storage aspects of such a production systems are in their infancy. A recent study assumes costs ranging from \$90 to \$200 per ton (Toman et al., 2008). However, even though this is a very recent report, it assumes oil prices much lower than the current ones, as it is based on the 2006 Annual Energy Outlook projections.

The uncertainty in predicting absolute and relative prices of agricultural commodities and oil and natural gas translates into uncertainty in predicting farmers' choice of crop choice and rotations, and their consequent environmental impacts. A higher relative corn price means shifts into higher levels of corn production (as witnessed in 2007, when farmers, in response to high corn prices relative to soybeans, increased corn acreage by over 14% compared to the average acreage in the previous five years) (see Figure 1).

Figure 1 – Historical cropland levels in the five states of the UMRB



USDA NASS. 2008. Agricultural Statistics Data Base. URL: http://www.nass.usda.gov/Data_and_Statistics/Quick_Stats/

Another complicating factor is the fact that—particularly in the northern part of the UMRB—corn has been grown in rotation with alfalfa to be used for hay production. Because of transportation and storage costs due to hay's bulkiness, markets for hay tend to be local (Diersen, 2008). Therefore, demand for hay is highly inelastic for production levels higher than the levels that can be supported by the local livestock industry. Thus, price forecasts for hay at a national level, such as the one provided by FAPRI, have large margins of error when used to determine land use choices at a fine geographical scale. Indeed, the latest FAPRI Outlook states that "Hay markets are more fragmented than markets for most other agricultural commodities, so trends in national average prices may not be reflected at the local level" (FAPRI, 2008, p.110). For example, according to our analysis, if alfalfa prices in the UMRB were $128.55/metric ton ($116.62/ton) as forecast in FAPRI's long term projections for the year 2018, and the other crop prices followed FAPRI's projections, the alfalfa acreage would almost quadruple in the UMRB.

This suggests that the FAPRI forecast is likely overestimating the price of alfalfa in the watershed. Given that since the 1970s the alfalfa acreage in the five states of the watershed has been slowly declining (Figure 1), a more realistic alternative is to solve for the price of alfalfa that keeps the acreage constant. Thus, for both the FAPRI and CBOT prices we found the price of alfalfa the corresponded to an acreage close to the historical one and used that price.

The reasons behind these large changes in prices are currently the subject of intense debate which we do not attempt to resolve here, but most analysts point to rising energy prices, a low dollar, rising food demand from historically low income countries, trade policies in some parts of the world, and, most relevant for our discussion, ethanol policy which has raised the returns to corn production relative to other crops. Higher relative corn prices will alter crop planting decisions. In particular, the most likely expansion of corn production is likely to occur by shifting from corn-soybean, which is the historically dominant cropping rotation in the corn belt, to more use of continuous corn or corn-corn-soybean rotations.

In short, the combination of ethanol policy and subsidies with changing world conditions has lead to historically high crop prices. Farmers respond to prices by changing their cropping patterns, and this has the potential to reduce water quality in the region. Here we link two forecasted prices – which diverge in the predicted amount of land planted on corn - to changes to land use and cropping patterns in the Upper Mississippi River Basin and follow the impact of those land use changes onto their impacts on water quality. If degradation of water quality is occurring, as suggested by Simpson et al. (2008), it may be appropriate for government to consider implementation of policies that counteract these effects by supporting conservation actions that can offset this degradation (such as implementation of buffers, restoration of wetlands, or the elimination of fall fertilizer applications). Alternatively, it may be appropriate to re-configure the subsidies for ethanol production to favor an alternative feed stock, such as the perennial switchgrass.

3. The Integrated Modeling System

Our modeling system uses the 1997 Natural Resources Inventory (NRI) database. There are over 110,000 NRI "points" in the UMRB, each representing a combination of weather, soil characteristics, crop choices, rotations, and other agro-ecological conditions, thus allowing the model to represent the rich economic and environmental diversity of this spatially diverse, managed ecosystem. The economic model is linked to a watershed-level hydrological model, the Soil and Watershed Assessment Tool (SWAT) based again on the NRI.[4]

The SWAT model (Arnold and Fohrer, 2005; Gassman et al., 2007) is a conceptual, physically based, long-term, continuous watershed scale simulation model that operates on a daily time step. In SWAT, a watershed is divided into multiple subwatersheds, which are further subdivided into Hydrologic Response Units (HRUs) that consist of homogeneous land use, management, and soil characteristics. Streamflow generation, sediment yield, and non-point-source loadings from each HRU are summed and the resulting loads are routed through channels,

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[4] It is important to note that several other studies have integrated economic decision models with environmental process models to evaluate policies within the UMRB; notably Wu et al. (2004), Wu and Tanaka (2005), and Booth and Campbell (2007). For a discussion of similarities and differences in the modeling approaches see EPA, SAB (2007).

ponds, and/or reservoirs to the watershed outlet. Key components of SWAT include hydrology, plant growth, erosion, nutrient transport and transformation, and management practices. Outputs provided by SWAT include streamflow and in-stream loading or concentration estimates of sediment, organic nitrogen, nitrate, organic phosphorous, soluble phosphorus, and pesticides. Previous applications of SWAT for streamflow and/or pollutant loadings have compared favorably with measured data for a variety of watershed scales (Gassman et al., 2007). The UMRB SWAT simulation framework builds on the work of Arnold et al. (2000) and relies on numerous data sources to develop and execute the model. SWAT calibration and validation results for the entire UMRB or subregions are reported in Jha et al. (2006), Jha et al. (2003), Jha et al. (2007), Secchi et al. (2007).

The economic component of the modeling system assumes that farmers/landowners choose the crop and associated crop rotation for their land to maximize their net returns (profits) from farming. Thus, to predict the crop rotation and crop choice for an NRI point, we construct the costs of producing each crop under each rotation that is appropriate to that particular soil type, climate, and other physical characteristics. Of course, the profitability of a particular crop will also depend critically on the price of the commodity. The costs of production budgets are based on Iowa costs of production for 2008 (Duffy and Smith, 2008). We use state-based rates of fertilizer application, based on historical averages calculated by USDA ERS (USDA-ERS. 2007).

4. Scenario Analysis: Future Row Crop Landuse

To undertake policy relevant scenarios, we need to establish the likely cropping patterns and water quality in the UMRB in the absence of a perennial feedstock. As we noted above, this is complicated by the instability of the current price environment. Therefore, we use two price forecasts – the FAPRI ones, which correspond to a land use more closely aligned with the recent past, and the CBOT future prices, which would tilt the balance in favor of corn production. Once these scenarios are established, we can use the integrated modeling system just described to perform counterfactual scenario analysis. That is, we can imagine that positive returns to alternative crops, such as switchgrass, become reality to predict crop location across the region. With that altered cropping pattern, we run the calibrated SWAT model to predict pollutant loadings. Comparison with the row crop only scenarios allow us to indicate the degree to which water quality will be altered, for better or worse, due to the introduction of the new crop. Comparisons between the row crop only scenarios, on the other hand, illustrate the water quality impacts due to the relative increase in corn prices and the consequent increase in corn acreage.

As we noted above, an important agricultural land use in the region is enrollment in the Conservation Reserve Program (CRP), a government funded program that pays farmers to remove land from agricultural production. Over 17,000 km2 in the region were enrolled according to the NRI (Table 1). We assume that the land enrolled in CRP in 1997 remains in the CRP or returns to production. We will mostly focus here on the scenarios in which CRP remains constant in order to construct as much as possible a *ceteris paribus* analysis. Figure 2a illustrates how closely corn acreage would follow historical patterns if the FAPRI forecasts are realized. Most of the watershed was and would remain in corn – soybean rotations. In contrast, if the CBOT prices were to prevail, Iowa and Central Illinois would see tremendous increases in corn acreage, with consequent water quality effects as illustrated by Table 2.

Figure 2a. Location of corn area—no switchgrass scenarios

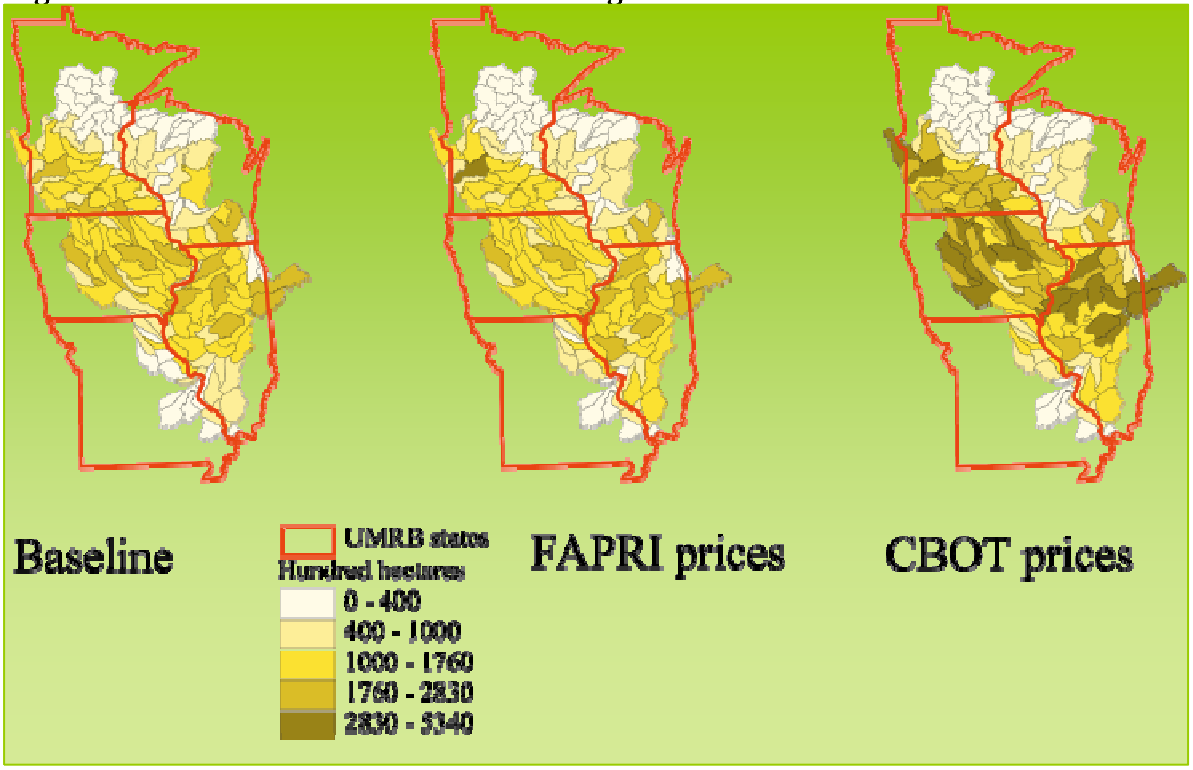


Figure 2b. Location of switchgrass area

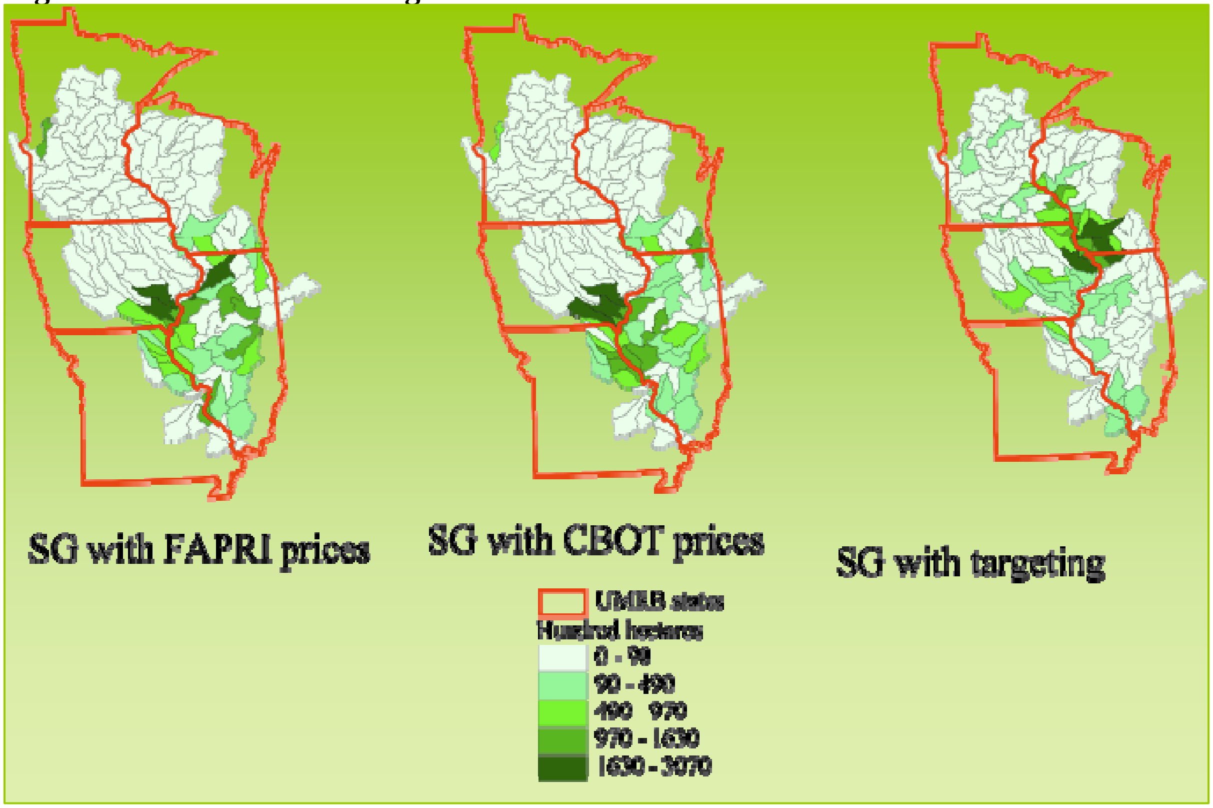


Table 2. SWAT results

	Avg Sediment Out Metric tons	Avg NO3 Out Kgs	Avg P Out Kgs
Baseline	23974833	329371667	25044750
FAPRI prices – No switchgrass	25412208	357808336	24912167
FAPRI prices – With switchgrass	22320875	363887503	22320708
FAPRI prices – With targeted switchgrass	21824958	411370837	22758375
CBOT prices – No switchgrass	24541375	346083335	27238500
CBOT prices – With switchgrass	20482083	353125001	24503250
CBOT prices – With targeted switchgrass	20263542	401183335	25009000

5. Scenario Analysis: Switchgrass

In addition to understanding the effect that higher corn prices could have on water quality in the region, it is also of interest to understand how water quality might change if an alternative feedstock were economically viable in the region.

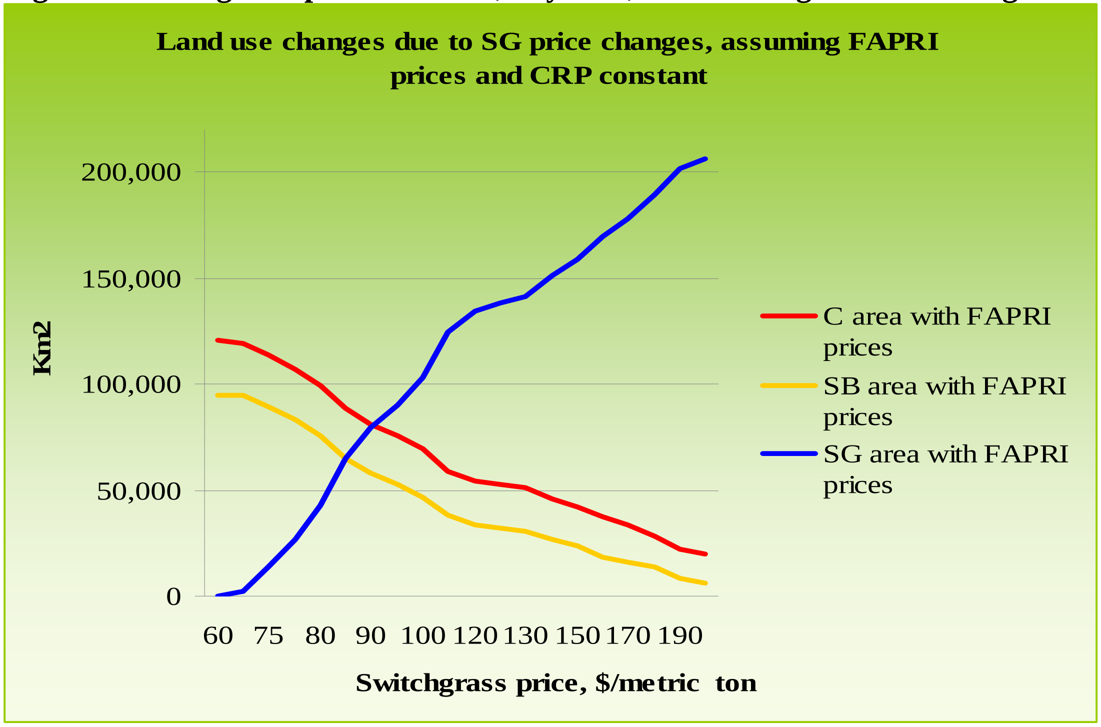
Switchgrass has been extensively evaluated as a biofuel crop throughout the US. Optimal fertilizer application rates have also been extensively investigated. Vogel et al. (2002) consider a wide range of nitrogen application rates and find that the optimal rate is 120 kg N ha^{-1}. There is consensus in the literature that higher rates of fertilization are needed in colder climate with a shorter growing season. McLaughlin and Adams Kszos (2005) and a recent extension publication (Barnhart et al., 2007) suggests higher rates would be optimal, at 157 kg N ha^{-1}. For our modeling purposes, we construct switchgrass net returns building upon Iowa State University's switchgrass budget cost assumptions (Duffy). The ISU budgets assume a fertilizer rate application of 112 kg ha^{-1}, but given the recent findings that higher rates may be optimal, we approximate a yield response function and identify optimal nitrogen application rate by using rates of 100, 120, 140 and 157 kg N ha^{-1} to compute yield and net returns from growing switchgrass throughout the UMRB. The optimal rates were determined by running the SWAT model at the rates mentioned above, finding the corresponding profit levels and choosing the highest possible profit level. Thus, our model is dependent on the SWAT model crop growth response function to nitrogen. We realize this crop growth may not be adequately representative of yield response functions. That is why we are working closely with agronomists and monitoring the published literature to make sure our assumptions are reasonable. Our annual costs of production for switchgrass are $34.6 per metric ton, constructed for a target yield of 15.38 tons ha^{-1}. It is important to note that these costs include only variable costs and only apply to land that is already cropped. Land of lesser quality and with lower rental rates may have lower opportunity costs than cropland. Note also that we are assuming the farmer would not incur any storage/transportation to storage costs. Because currently there are no substantial markets for switchgrass for ethanol production, the structure of such markets is largely a matter of speculation. The imputation of some of the costs related to processing could substantially alter net returns for farmers. Since we have assumed here that the processors would cover storage and transportation costs, our estimates could be considered to be on the low end of the spectrum. These costs may appear low compared to the switchgrass prices that we are using in the analysis. However, what needs to be considered are the opportunity costs – that is the returns from the production of alternative crops, in our case corn and soybeans. High prices in traditional row crop production mean that alternative crops will have to have relatively high prices to be grown.

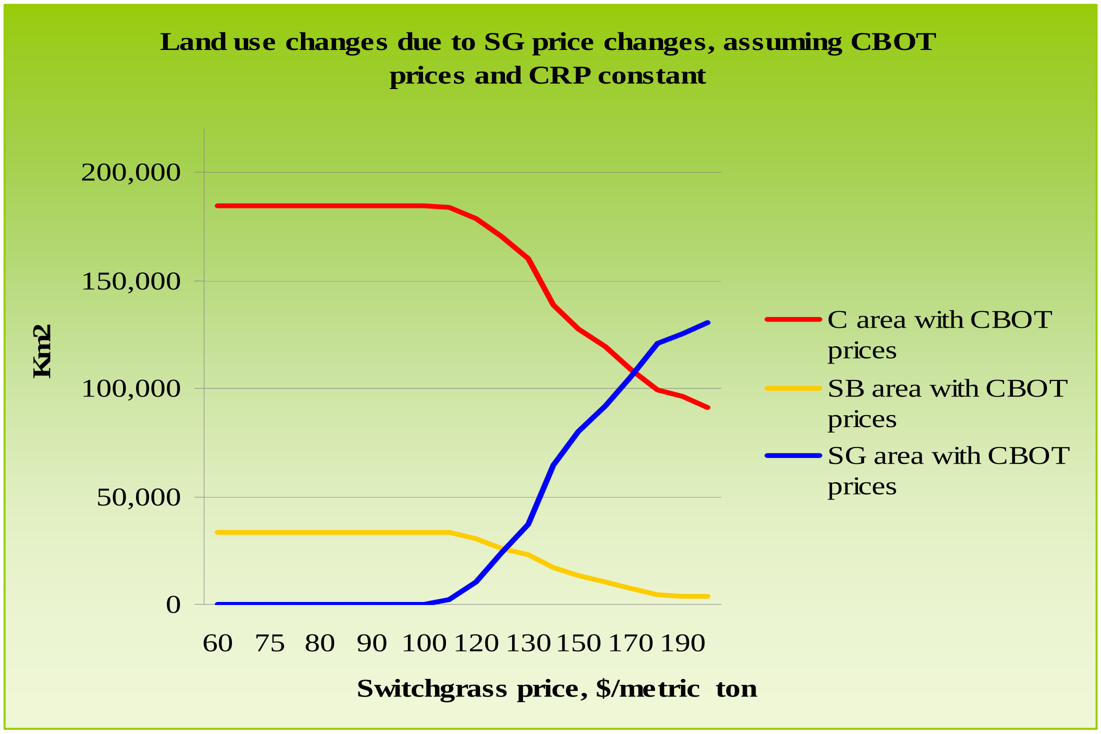
Using the full sets of budgets, we now use the full set of cost information on all crops to generate a switchgrass acreage response curve. As can be seen from Figure 3, the price that makes switchgrass economically competitive with corn and/or soybeans depends very much on the absolute level of row crop prices. Since most of the analysis forecasting cellulosic biomass prices is based on much lower than current oil and commodity prices (Toman et al., 2008; English et al., 2006), we decided to peg the determination of switchgrass' price level to the row crops to obtain around 10% cropland acreage in the watershed being planted in switchgrass. The reason for the – admittedly arbitrary – decision to look at a 10% conversion into switchgrass is that the Upper Mississippi includes some of the best corn producing land in the world. Thus, it is not likely that current cropland will all convert into perennials in the near future. As the following discussion shows, relatively high prices for switchgrass are needed to make the production of this crop more profitable than current row crop production and achieve a 10% land shift. Higher switchgrass prices still would be needed – given the current FAPRI and CBOT projections – to achieve higher switchgrass production in the basin. Note that our analysis could also be used to compute the amount of a subsidy for switchgrass production that would have to be paid to induce varying levels of acreage and production.

Figure 2b shows that the most profitable locations for growing switchgrass are in the southern part of the watershed, which has the longest growing season. The model could be extended to include other cultivars or species better suited for colder climates, and that would most likely affect the land use and water quality results. The figure also shows how the relative profitability of corn and soybean plays into the location of switchgrass acreage. With higher corn prices, in the CBOT scenario, some of the switchgrass leaves central Illinois, where corn production is more competitive, for southern Iowa and Missouri.

In addition to providing estimates of the water quality impact of switchgrass in the UMRB, the model can be used for policy analysis, for example to assess monetary outlays and water quality impacts of targeting policies. Here we undertake two such scenario simulations for illustrative purposes. Using both sets of prices, we assume that cultivation of switchgrass is restricted to the most erodible land in the watershed. The rationale is that erodible land would benefit the most from a perennial cover. Figure 2a shows that this would shift production to eastern Iowa and western Illinois. The acreage allocated to various crop rotations under the four switchgrass scenarios are provided in Table 1. The opportunity cost of the targeting scenario with FAPRI prices is almost $753 million per year, while the opportunity cost of targeting scenario with CBOT prices is much higher, over $1,319 million.

Figure 3. Acreage Response of Corn, Soybean, and Switchgrass to Switchgrass Prices





The water quality effects of these switchgrass scenarios are presented in Table 2. The model results show that switchgrass production has sizable benefits in terms of sediment losses, though targeting does little to improve sediment over the unrestricted location of switchgrass. This is largely due to the fact that we are measuring changes at the outlet of the watershed, and our targeting mechanism for switchgrass moves production further upstream, so that the impact at the outlet gets diluted by cumulative in-stream processes. The sum of upstream, local water quality impacts is likely higher with targeting, and we are conducting further analysis to ascertain this. The benefits of switchgrass in terms of sediment loads are highest under the CBOT scenario, because switchgrass takes the place of continuous corn more often. The model shows that the high level of fertilization for switchgrass we have assumed would result in worsening of the nitrate loads. This suggests that, since the switchgrass management practices that maximize returns to the farmer are most certainly not low input, incentives would have to be devised to limit fertilization of switchgrass.

The nitrite results are reversed in the case of phosphorus. Since there is no phosphorus fertilization on switchgrass, we would expect the highest losses in the scenario with CBOT prices without switchgrass, which has a lot of continuous corn, and the lowest in the scenario with FAPRI prices without switchgrass, which has the switchgrass and less corn/more beans. As in the case of sediment and nitrates, we would also expect losses to be higher in the targeted scenarios than in those with no targeting, because we are measuring loads at the outlet and targeting moves the switchgrass further up in the watershed.

6. Policy Implications and Conclusions

Simpson et al. (2008) conclude that the increase in corn acreage by about 15% seen from 2006 to 2007 could be expected to increase N loadings to the Gulf of Mexico by about 10% and P loadings by about 5%. Our findings are consistent with this prediction.

A number of important caveats should be noted. First, as discussed above, incomplete data on the location and land cover related to the Conservation Reserve Program have made accurate representation of its location on the landscape impossible. By representing the current CRP land to be in the same location as the land reported in 1997, we may be introducing substantive bias, though in which direction we cannot say. Further limitations include the fact that the model systematically underpredicts corn yields (1997-2006) by an average of 12% and soybeans by over 4%. Additionally, no yield drags for rotations are included in the model as no risk premia that farmers might require to plant a new crop, such as switchgrass, are included in the cost estimates. Moreover, our fertilizer levels for switchgrass are quite high. We are conducting further analysis to investigate the responses of the SWAT model to lower levels of nitrogen fertilizer application in switchgrass. However, our analysis points to the necessity of incorporating responses to economic incentives to environmental assessments. It is not realistic to just assume that farmers will limit themselves to low input production systems if higher input ones are more profitable. Most of the environmental analysis currently available simply assumes low levels of fertilizer application in biomass production systems, and this may not be the optimal behavior for farmers.

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