Maintaining Environmental Quality while Expanding Energy Biomass Production: Policy Simulations from Michigan, USA

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1- Introduction

Recent research has shown that the lowest-cost sources of expanded energy biomass production in the United States are likely to be residues from annual grain crops, such as corn and wheat (Egbendewe-Mondzozo et al., 2011; Khanna et al., 2011; National Research Council, 2011). Yet expanding annual crop production results in increased greenhouse gas emissions (GHG) and water quality degradation compared to perennial bioenergy crops (McCarl et al., 2010; Love and Nejadhashemi, 2011; Robertson et al., 2011). The environmental benefits provided by perennial bioenergy crops are related to the fact that they require little or no tillage before planting, use a fraction of the fertilizer required by most annual field crops, maintain or increase soil carbon, and require scant pesticide use. However, at low biomass prices, dedicated perennial bioenergy crops tend to be less profitable than annual cereal crops whose grain yields revenues are supplemented by the harvest and sale of their residues as biomass.

The ecosystem services (ES) from perennial bioenergy crops production come as joint products with the biomass crops. Since the perennial bioenergy crops also yield environmental benefits, the marginal social benefit arising from ecosystem services may be greater than the private benefits derived from biomass cropping. The ES provided by perennial bioenergy crops make their cropping systems more environmentally attractive than the annual ones that currently predominate in the United States. Given the evidence that the minimum breakeven prices for energy biomass production are met only by biomass from annual crop residues that are also associated with damaging impacts for climate and water quality (Egbendewe-Mondzozo et al., 2011; National Research Council, 2011), there is a need to explore policies that could prevent increased environmental degradation from expansion of current farming systems that look to be the main sources of biomass for energy in the near future. Integrated environmental and economic modeling is needed both to analyze how new bioenergy cropping systems would affect patterns of ES provision from agriculture and to evaluate cost-effective policies designed to achieve desirable outcomes.

This study investigates how environmental policies would affect biomass production and environmental impacts from profit-maximizing choices of cropping systems at the sub-regional level. Specifically, the study will a) simulate price-induced increases in sub-regional agricultural biomass supplies and the associated impacts on nitrate (NO_3-N) leaching, nitrous oxide (N_2O-N) emissions, phosphorus loss, soil carbon loss and soil erosion, and b) evaluate the effectiveness and cost of three policy options on environmental quality in the context of biomass supply. Drawing on previous research about biomass supply from the U.S. state of Michigan (Egbendewe-Mondzozo et al., 2011), this research answers two fundamental questions:

1) How will alternative agro-environmental policies affect environmental outcomes from profitable crop production with rising biomass prices?

2) How cost-effective are these policies based on their environmental outcomes and cost of implementation?

In order to address these research questions, we analyze results from a bioeconomic optimization model parameterized for a landscape representing nine counties in southwest Michigan, USA.

The remainder of the paper is organized as follows. First, a theoretical model is developed to show how a profit-oriented representative farmer would respond to environmental policies in the context of joint production of marketed crop products and environmental impacts. Second, an empirical model parameterized for southwest Michigan, USA, is utilized to study environmental impacts of expanded biomass production from traditional crop residues and cellulosic energy crops. Third, the paper analyzes the trade-offs between energy biomass production and environmental sustainability and discusses the cost effectiveness of alternative environmental policies. Finally, the paper summarizes the key results and concludes on the future research opportunities to improve our understanding of bioenergy production and environmental sustainability.

2- Material and methods

2.1- Economic theoretical model of biomass production and environmental quality

Due to the concern that energy biomass production could aggravate environmental impacts of crop production, we frame the producer's decision as being constrained by environmental impacts. Consider a profit-maximizing representative farmer who chooses a set of technology choices x, where each technology choice includes a mix of inputs and production practices. The technologies are used to produce sets of both marketed outputs y and non-marketed environmental impacts e, where $y(x)$ is concave in all x and $e(x)$ is increasing in some, but not all x. Next, let $c(x)$ be a cost function, let p be a vector of exogenously determined product prices, and let t be a technology tax (or subsidy, if negative). Define $E(x)$ as an aggregator function that cumulates each type of environmental impacts in the set $e(x)$, and let E^0 be the reference level of environmental impact from all sources (e.g., prior to energy biomass production) and let q be an environmental impact payment (perhaps resulting from a tradable permit scheme) associated with deviations from E^0.

The technology choice problem facing the representative farmer can be mathematically expressed as a maximization of profit subject to maintaining environmental quality at or below reference level E^0:

$$\operatorname*{Max}_{x}\ py(x) - c(x) - tx + q[E^0 - E(x)] \quad (1)$$

Subject to:

$$E(x) - E^0 \leq M \quad (2)$$

The optimality condition of the Lagrangian function obtained from maximizing (1) subject to (2) is the following:

$$p\,\partial y/\partial x - \partial c/\partial x - t - (q+\mu)\,\partial E/\partial x = 0 \tag{3}$$

where μ is the Lagrange multiplier associated with the environmental impact constraint, which can be interpreted as the unit marginal cost (shadow price) of exceeding the reference level.

Three hypothetical policy scenarios can be analyzed from condition (3), an environmental standard, an environmental impact price and a technology subsidy or tax.

(a) An environmental standard policy that constrains environmental impacts with biomass production to be less than the reference level E^0results from setting $t = 0, q = 0$ and $M = 0$. The optimality condition in (3) simplifies to this:

$$p\,\partial y/\partial x = \partial c/\partial x + \mu\,\partial E/\partial x \tag{4}$$

Condition (4) indicates that at the optimum, the marginal value product must equal the marginal cost of the technology plus the marginal cost of environmental impacts. For a technology for which $\partial E/\partial x > 0$, the marginal cost is increased by $\mu\,\partial E/\partial x$, so the optimal production level of that technology would be less than for a nonpolluting technology. To minimize marginal production cost, the optimizing farmer will choose technologies that have minimal negative environmental impact ($\partial E/\partial x$) if the environmental constraint is binding ($\mu > 0$) or else will choose technologies that do not exceed the environmental reference level E^0, and so have $\mu = 0$.

(b) A carbon price (q) policy where the farmer is rewarded if the total environmental output level $E(x)$ is less than the baseline level E^0 and is penalized otherwise. This case results from setting $t = 0$, while allowing $M \geq 0$. The optimality condition under this policy is given by:

$$p\,\partial y/\partial x = \partial c/\partial x + q\,\partial E/\partial x \tag{5}$$

The condition (5) allows the representative farmer to receive credit in the amount $-q\,\partial E/\partial x$ if the technology choice reduces the total environmental impact ($\partial E/\partial x < 0$). Otherwise, if $\partial E/\partial x > 0$, then the farmer pays $q\,\partial E/\partial x$, the marginal cost of the environmental impact. Equating condition (5) with (4) leads to the following condition:

$$q = \mu \tag{6}$$

which states that where there exists an environmental impact price, the optimality conditions require that the environmental impact price equals the unit marginal cost of environmental impact (the shadow price of the environmental standard policy constraint).

(c) A technology subsidy or tax (t) can be also introduced to encourage better technological choices (like reduced fertilizer usage or no-till practices). In this case, we assume that $q = 0$ and $M \geq 0$, so the optimality condition (3) becomes:

$$p\,\partial y/\partial x = \partial c/\partial x + t \tag{7}$$

That is, if t is a positive tax rate $(t > 0)$, then the farmer will be forced to choose practices that reduce usage of the technology that is taxed. If otherwise t is a technology subsidy ($t < 0$), then the farmer is encouraged to use more of that technology to maximize profit. Equating (7) and (4) gives:

$$t = \mu\,\partial E/\partial x \tag{8}$$

This condition shows that an effective technology tax or subsidy (t) exactly equals the marginal cost of the aggregate environmental impact of choosing technology$x$. Note, however, that taxes/subsidies tend to apply to specific inputs or practices, so in practice, it can be very difficult to design one that meets the optimality condition in (8) for aggregate environmental impacts $E(x)$.

A variety of environmental policy tools are available to encourage the adoption of practices that result in improved environmental outcomes (Hanley et al., 2007). However, a special feature of policy targeted at nonpoint source environmental emissions, such as those from agricultural fields, is that outcomes are costly to monitor. This feature makes largely infeasible the application of "first best" policies that target outcomes. "Second best" policies, such as technology subsidies or input taxes aim to approximate the results of outcome-oriented policies while using approaches that are feasible to monitor, such as input taxes or subsidies (Griffin and Bromley, 1982; Segerson, 1999). We expand on this theme in the empirical section that follows.

2.2- Empirical analysis of biomass production and environmental quality

To empirically evaluate the impact of biomass production on environmental outcomes, we develop a sub-regional bioeconomic model of crop production parameterized for southwestern Michigan, USA[1]. Our study explores scenarios under which farmers would willingly grow new energy biomass crops and collect cellulosic biomass as residues from annual crops. In order to develop a set of input-output parameters for bioeconomic optimization, we use the Environmental Policy Integrated Climate (EPIC) model (Williams et al., 1989). With EPIC, we simulate 82 cropping systems that are defined by crop rotation, tillage, fertilizer rate, and residue removal rate (Egbendewe-Mondzozo et al., 2011). The crop systems simulated include food and forage crops (some of which offer energy biomass as co-products), as well as seven dedicated energy biomass crops: switchgrass (*Panicum virgatum* L.), miscanthus (*Miscanthus x giganteus*), native prairie cool season mix, native prairie warm season mix, grass mixes of five types (switchgrass, big bluestem (*Andropogon gerardii* L.), little bluestem (*Schizachyrium scoparium*

[1] The empirical model, the cropping systems simulated and the map of the sub-region of study can be found in the appendix materials accompanying this paper.

L.), altai wildrye (*Leymus angustus*), indian grass (*Sorghastrum nutans*)) and six types (including lespedeza (*Lespedeza cuneata*) in addition to the first five types), and hybrid poplar (*Populus* spp.). Current annual crops produced include corn (*Zea mays* L.), soybeans (*Glycine max* L. [Merr]), wheat (*Triticum aestivum* L.), alfalfa (*Medicago sativa* L.), corn for silage, and canola (*Brassica napus* L.) grown in various cropping systems. Costs of production are combined with crop yields, prices and environmental outcomes from each of these systems in a bioeconomic optimization model that simulates crop choices by a profit-maximizing representative farmer.

The landscape of the 9 counties (Allegan, Barry, Eaton, Van Buren, Kalamazoo, Calhoun, Cass, St. Joseph and Branch) is divided into 37 sub-watersheds as defined by their 10-digit hydrologic unit codes (HUC) to capture soil and topographic heterogeneity. The watershed basis also facilitates modeling of water borne nutrient loss and soil erosion. Land heterogeneity is factored in by modeling sites with different soil properties and then aggregating these results by individual sub-watersheds and by using Land Capability Classes (LCC), as defined by the Natural Resources Conservation Service, to group land in two quality types. Lands with few limitations for cropland agriculture include LCC 1 to 4 and those with many limitations include LCC 5 to 7. The combination of sub-watersheds with the two land quality levels generates a total of 70 land units on which each cropping system is evaluated. A cropping system is defined according to the sequence of crops is kept in a rotation, the fertilization level, the type of tillage used and whether or not residues are removed. Each of the 82 cropping systems is then simulated and the results are aggregated on each of the 70 land units to obtain both grain and biomass yields and 5 types of environmental outputs (70 x 82 x 5 total output parameters). These environmental impacts include soil carbon loss in form of carbon dioxide (CO_2) due to soil organic matter decomposition, nitrate (NO_3-N) loss, nitrous oxide (N_2O-N) emissions, phosphorus (P) loss and soil erosion.

The final bioeconomic model follows closely our theoretical model framework assuming Leontief production functions and linear cost functions for annual crops and new cellulosic crop production. The basic model that was used to analyze biomass production from cellulosic crops and crop residues (Egbendewe-Mondzozo et al., 2011) is extended to include taxes and subsidies as well as prices for environmental outputs. The inclusion of an environmental impact price will allow the investigation of the impact of carbon price on agricultural production. After calibration following positive mathematical programming methods (Howitt, 1995; Kanellopoulos et al., 2010), the representative farmer's optimization problem, originally created as a linear program, becomes a quadratic programming model with yield and environmental outputs obtained from EPIC and other market prices and cost parameters drawn from USDA (USDA, 2010) and Michigan agricultural extension services (Stein, 2009; 2010). We calibrated the model using average crop prices, input prices and observed land use data from the period 2007-2009. The overall calibration error was 13%.

3- Results and discussion

3.1- Effect of biomass production on baseline environmental outputs

Since there is currently no market for energy biomass in this region, in order to simulate the impact of introducing energy biomass crops, we systematically increase the price of biomass relative to a benchmark set of crop prices from 2007-09. These price simulations allow identification of 1) the relative price at which biomass production becomes profitable, 2) the sequence of cropping systems that will be chosen, and 3) the set of commercial products and associated environmental outcomes that will follow. Specifically, biomass prices are progressively increased from $0 to $70/Mg, while holding other prices constant. The resulting biomass supply, associated environmental outputs, land use implications and the changes in the crop management practices are reported as a function of biomass-to-corn-grain price ratios in Figure 1. Because we increase biomass prices ceteris paribus, results are reported in terms of the biomass:corn grain price ratio, with corn grain representing all non-biomass prices at their 2007-09 means. The corn grain price used is $162.60/Mg (equivalent to $4.13/bushel, the average 2007-09 price).

The first forms of cellulosic biomass to be supplied are grain crop residues in the form of corn stover and wheat straw (Fig.1, upper-left). These enter the solution when the biomass:corn grain price ratios reach 0.15 ($24/dry Mg) and 0.18 ($29/dry Mg), respectively. The quantity supplied does not become sufficient to feed a medium size biorefinery plant (of 630 Gg/year (Graham et al., 2000)) until the price ratio reaches 0.30 ($49/dry Mg). Fig.1 (bottom-right and left panels) shows that most of the crop residues collected originate from corn-soybean rotations. However, as biomass price rises, more land is shifted into a corn-soybean-wheat rotation, which yields biomass residues from both corn stover and wheat straw. The first perennial crop, switchgrass, becomes profitable to produce only when the biomass:corn price ratio exceeds 0.37 ($60/dry Mg). This pattern of biomass production is directly linked to the levels of environmental output in Fig.1, upper-right panel.

Production of biomass from annual grain crop residues results in increased environmental impacts. Relative to the baseline where only food and forage crops are produced, annual crop residues biomass production is associated with increased greenhouse gas emissions (nitrous oxide and soil carbon loss), soil erosion and nitrate loss (Fig.1, upper-right). The increase in the biomass production from crop residues is associated with a shift in cropping systems toward those under conventional (chisel) tillage. Interestingly, fertilizer prices and crop yield response are such that high fertilization rates rarely enter the solution, as shown in Fig.1 (bottom-right). Environmental impacts only begin to decline with the introduction and expansion of switchgrass, a perennial biomass crop, beginning at a price ratio of 0.37($60/dry Mg).

3.2- Effect of constraining environmental impacts

The increased environmental impacts of intensified annual crop production with harvested biomass residues have prompted scientists' concerns about environmental risks from reliance upon annual crops for energy needs (Graham et al., 2000; Robertson et al., 2011). In search of means to mitigate these environmental impacts, we first identify the minimum cost cropping system changes required to prevent environmental impacts from exceeding their baseline levels prior to biomass production. This scenario does not represent a feasible policy, because it relies on the ability to monitor all environmental outcomes at no cost. However, it does identify the minimum possible cost of not exceeding the baseline environmental impacts, providing a benchmark for the environmental policies tested subsequently. The implicit minimum marginal environmental cost that is given by the shadow prices of the constraints to maintain the environmental quality status quo is shown in the upper-right corner of Fig.2 (labeled "marginal abatement cost").

The environmental constraints result in a changed supply curve for biomass (Fig.2, upper-left). Comparing the biomass supply curves in Fig.1 and Fig.2 shows that, when the model is forced to use cropping systems that maintain environmental quality at baseline levels, most of the biomass supply comes from no-till systems, which limit soil erosion and carbon loss as well as all the potential nutrient runoff associated with soil erosion (Fig.2, bottom-left and right panels). Fig.2 (upper - right panel) illustrates the implicit unit marginal environmental costs to meet the environmental constraints as biomass price rises. Maintaining the level of environmental outputs with increasing biomass prices becomes constraining when the model starts to produce biomass from annual crop residues. This pattern is consistent with Fig.1 (upper -right), where producing biomass from annual crop residues triggers increased environmental outputs. Greenhouse gas (GHG) emissions (CO_2 and N_2O-N) have by far the highest implied marginal environmental cost. The GHG constraint forces the model to select crops that are less intensive in N_2O-N and CO_2 emissions, reducing potential earnings at a marginal cost of $0 to $0.05/kg ($0 to $50/Mg) of carbon-equivalent. Constraints on other fertilizer-related environmental outputs (like nitrate and phosphorus loss) have zero or low shadow prices. As biomass production from switchgrass becomes profitable at a biomass:corn price ratios above 0.40, the levels of environmental impacts decline and become increasingly less constraining.

To evaluate the impact of potential environmental policies, we simulated three policy scenarios. These include i) a carbon-equivalent GHG price to reduce greenhouse gases (CO_2 and NO_2-N) emissions , ii) a tax applied to chemical fertilizers, and iii) a subsidy on land cropped with no tillage. All three policies aim to reduce CO_2 emissions, soil erosion and nutrient runoffs. The last two involve negligible monitoring costs. For the first, we assume that the cost of monitoring carbon fluxes could be kept low by tying payments to quantities of harvested biomass.

3.3- Impact of a carbon price on biomass production and environmental outcomes

Many simulation models have shown that a carbon price can reduce GHG emissions from agriculture (McCarl and Schneider, 2001; McCarl et al., 2010). In the presence of a cap-and-trade program that sets a market price for carbon, emission permits can be sold to allow emission or sequestration of GHG in agriculture. To simulate the impact of a carbon price on environmental outputs under an increasing biomass supply, we construct a net GHG flux variable that sums the greenhouse gases emitted or sequestered (CO_2 and N_2O-N) in carbon-equivalent (CE) units for each cropping system simulated from EPIC. We then introduce into the model an activity that permits the representative farmer to purchase permits if the net GHG emission level exceeds the baseline reference level (when no biomass is produced), or to sell permits otherwise. Carbon prices in the range of $0 to $500/ Mg CE have been studied in the literature (McCarl and Schneider, 2001). Our study considers carbon prices in the range of $0 to $200/Mg CE. As expected from the theoretical model section and the environmentally constrained model results, we find that a carbon price of $50/ Mg CE maintains GHG emissions at or below the baseline reference level of no biomass production. The model results for a $50/Mg CE price are presented in Fig.3.

The introduction of a $50/Mg carbon price reduces the quantity of annual crop residue in favor of biomass from perennial switchgrass and grass mixes as shown in Fig.3, upper-left. Production practice changes include elimination of tillage and reduced fertilizer use compared to the baseline (Fig. 3, bottom-right). However, at this carbon price, sufficient biomass to supply a medium sized biorefinery can be supplied only above a biomass:corn price ratio of 0.39 ($63/dry Mg). All environmental outcomes have significantly improved versus the baseline levels of no biomass production as shown in Fig.3 (upper - right). Relative to the baseline of no biomass production environmental impact levels, soil erosion, nitrate (NO_3-N) loss, nitrous oxide emissions (N_2O-N), phosphorus loss, soil carbon loss, and GHG emissions decrease on average by 1.3%, 1.2%, 1.2%, 1.0%, 1.5% and 2.1% respectively. While perennial crops begin production at slightly lower prices ($58/ dry Mg instead of $60/Mg) than in the case with no environmental policy (Fig.1, upper-left), annual crop residue biomass enters at much higher prices ($33/ dry Mg instead of $24/dry Mg) and in much lower quantities.

3.4- Impact of a fertilizer tax on biomass supply and environmental outcomes

In the absence of a carbon market or a low-cost monitoring of fertilizer use, a fertilizer tax is one kind of second best environmental policy option to reduce GHG emissions and nutrient runoff. We simulated several fertilizer tax rates to analyze the impact of such a tax policy on the biomass supply and associated environmental outcomes. The additional effect of a tax rate above 100% is negligible, so we only present the results pertaining to a 100% tax on fertilizer in Fig.4.

The fertilizer tax triggers a shift in cropping systems that sharply curtails wheat and gradually reduces much of the tillage practices. As shown in Fig.4 (upper-left) all the biomass from crop residues comes from corn stover, albeit at similar prices to the case without environmental policy. Most of the biomass from crop residues comes from corn-soybean and alfalfa-corn rotations that are less intensive in fertilizer than corn-soybean-wheat systems. Although fertilizer use is less than in the case without environmental policy, other environmental impacts associated with tillage practices are higher than in the baseline with no biomass production (Fig. 4, upper-right and bottom-right). As in the case without environmental policy, at high biomass prices significant crop land is dedicated to produce biomass from cellulosic crops (switchgrass), which use little fertilizer.

3.5- Impact of a no-till subsidy on biomass production and environmental outcomes

Another easily monitored second best policy is a subsidy on the area that is not tilled (under no-till management). Soil management with no tillage would be expected to reduce soil erosion and also mitigate soil carbon loss and nutrient runoffs. We evaluated several no-till subsidy levels. As values above \$50/ ha have virtually no added effect on environmental impacts, we report only the \$50/ha no-till subsidy in Fig.5.

The no-till subsidy drives all crop production to zero tillage (Fig.5 bottom - right). Biomass from crop residues (wheat straw and corn stover) are seen at lower biomass prices than in case without environmental policy ($22 dry Mg instead of $24/dry Mg). Switchgrass enters the solution at a level similar to the case without environmental policy, at a biomass:corn grain price ratio of 0.37 ($60/dry Mg). Environmental impacts levels are initially lower than the baseline of no biomass production levels, but exceed them at higher levels of annual crop residue removal (Fig.5, upper-right). The land use implications of the no-till subsidy environmental policy (Fig.5, bottom-left) are similar to the case with no environmental policy (Fig.1, bottom - left). The crop residues for biomass are mainly supplied through corn and soybean rotations and at medium and higher biomass prices wheat straw is supplied from corn-soybean-wheat systems.

3.6- Evaluating the environmental policy costs of achieving environmental sustainability

We evaluate the results of these three policy scenarios by their effectiveness at not exceeding the environmental impacts from the baseline case with no biomass production and doing so in a cost-effective manner. The environmental results show that only one of the policies systematically maintained environmental impacts at or below the baseline: the carbon price of $50/Mg. The no-till subsidy of $50/ha is effective only at relatively low biomass prices, while the fertilizer tax of 100% does not suppress environmental impacts at all.

In terms of cost effectiveness, even though our model cannot capture all the costs and the benefits that pertain to these policies (e.g. value of cleaner water and cleaner air, welfare change in displacing specific crops), we can calculate the direct costs in terms of the total GHG permits sold, total fertilizer tax revenue collected or the total subsidy paid by the environmental regulatory agency. Finally, we can also estimate the change in the farm net income levels implied by these policies. These results are presented in Fig.6 and Fig.7.

From the representative farmer's standpoint, the $50/ha no-till subsidy is the most profitable policy scenario, followed by the carbon price policy. The fertilizer tax policy reduces income in addition to being environmentally ineffective (Fig.6). On the expenditure side (Fig.7), the fertilizer tax policy will cost the farmer significantly more and it is the most costly policy overall, followed by the no-till subsidy, which entails government expenditures. The carbon price is clearly the most effective of the policies reviewed by both environmental effectiveness and cost criteria.

4. Conclusions

This paper uses a bioeconomic optimization model to study the impact of environmental policies on biomass production and environmental outcomes from agriculture at sub-regional level. First, a theoretical framework is developed to derive optimality conditions for a profit-maximizing farmer's choice of crop(s) and technology in the presence of an environmental quality constraint. Second, an empirical optimization model parameterized for southwest Michigan is used to simulate the impact of a set of environmental policy alternatives. we simulated three environmental policy scenarios under which a) a $50/Mg CE price is put on carbon, b) a 100% tax is placed on fertilizer and c) a $50/ha subsidy is put on no-till soil management practices.

The three policy scenarios indicate that only the carbon price of $50/Mg could reliably meet the policy goal of maintaining environmental quality at or below baseline levels as biomass price rises. Not only is this policy the most effective, it also costs less than the no-till subsidy or the fertilizer tax policy. The fertilizer tax policy is both the least effective and the most costly.

This analysis demonstrates that rising prices for biomass are likely to lead to aggravated environmental impacts from intensified production of annual cereal crop residues. Certain environmental policy tools can prevent worsened impacts on soil, water and climate. However, other policy tools may be ineffective. A fertilizer tax and a subsidy for non-tilled land both prove to have limited or no effect on the environmental impacts evaluated. A carbon price is demonstrated to be highly effective at maintaining soil, water and climate quality. However, such a price may be difficult to enforce without simplified guidelines to curtail the cost of monitoring diffuse greenhouse gas emissions and carbon sequestration. Future research should explicitly model the effectiveness of a low-cost proxy for unobservable fluxes in greenhouse gasses. Another valuable extension would be to model agricultural and environmental outcomes in the presence of commodity prices that are simultaneously determined with rising biomass prices.

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References

Egbendewe-Mondzozo, A., Swinton, S.M., Izaurralde, R.C., Manowitz, D.H., Xuesong, Z., 2011. Biomass supply from alternative cellulosic crops and crop residues: a spatially explicit bioeconomic modeling approach. Biomass and Bioenergy 35, 4636-4647.

Graham, R., English, B., Noon, C., 2000. A geographical information system-based modeling system for evaluating the cost of delivered energy crop and feedstock. Biomass and Bioenergy 18, 309-329.

Griffin, R., Bromley, D.W., 1982. Agricultural run off as a nonpoint externality. American Journal of Agricultural Economics 64, 547-552.

Hanley, N., Shogren, F.J., White, B., 2007. Environmental Economics in Theory and Practice, second ed. Palgrave Macmillan, New York.

Howitt, R., 1995. Positive mathematical programming. American Journal of Agricultural Economics 77, 329-342.

Kanellopoulos, A., Berentsen, P., Heckelei, T., Ittersum, M., Lansink, A., 2010. Assessing the forecasting performance of a generic bio-economic farm model calibrated with two different PMP variants. Journal of Agricultural Economics 61, 274–294.

Khanna, M., Chen, X., Huang, H., Onal, H., 2011. Supply of cellulosic biofuel feedstocks and regional production patterns. American Journal of Agricultural Economics 93, 473-480.

Love, B.J., Nejadhashemi, P.A., 2011. Water quality impact assessment of large-scale biofuel crops expansion in agriculture regions of Michigan. Bioenergy and Biomass 35, 2200-2216.

McCarl, B.A., Maung, T., Szulczyk, K.R., 2010. Could bioenergy be used to harvest the greenhouse: an economic investigation of bioenergy and climate change, in: Khanna, M., Scheffran, J., Zilberman, D. (Eds.), Handbook of Bioenergy Economics and Policy. Springer, New York, pp. 195-218.

McCarl, B.A., Schneider, A., 2001. Greenhouse gas mitigation in U.S. agriculture and forestry. Science 294, 2481-2482.

National Research Council, 2011. Renewable fuel standard: potential economic and environmental effects of U.S. biofuel policy, Washington, DC.

Robertson, P.G., Hamilton, S.K., Del Grosso, J.S., Parton, W.J., 2011. The biogeochemistry of bioenergy landscapes: carbon, nitrogen and water considerations. Ecological Applications 21, 1055–1067.

Segerson, K., 1999. Flexible incentives: a unifying framework for policy analysis, in: Casey, F., Schmitz, A., Swinton, S.M., Zilberman, D. (Eds.), Flexible Incentives for the Adoption of Environmental Technologies in Agriculture. Kluwer Academic Publishers, Massachusetts, pp. 79-95.

Stein, D., 2009. 2009 crop budget. Michigan State University, East Lansing, (Accessed on May 19), https://www.msu.edu/~steind/

Stein, D., 2010. Machine work rate for Michigan 2009-10. Michigan State University, East Lansing, (Accessed on May 10), https://www.msu.edu/~steind/

USDA, 2010. National Agricultural Statistics. Field crops prices. Department of Agriculture, Washington, DC, (Accessed on May 10). http://www.nass.usda.gov/Data_and_Statistics/

Williams, J.R., Jones, C.A., Kiniry, J.R., Spanel, D.A., 1989. The EPIC crop growth model. Transactions of ASAE 32, 497-511.

Appendix

Mathematical formulation of the empirical bioeconomic model

Given the EPIC crops and environmental yield parameters plus market prices and biomass transport costs to a central biorefinery located in Kalamazoo, Michigan, the representative farmer will choose which of the 82 cropping systems to grow on each of the 70 land units to maximize net returns. The mathematical expression is the calibrated quadratic program expressed as follows:

$$\operatorname{Max}_{x_{ij}} \sum_{i=1}^{70}\sum_{j=1}^{82}\left[-t_j c_j x_{ij} - \sum_{l=1}^{3} r_l o_{lj} x_{ij} + \sum_{s=1}^{15} p_s(1-\emptyset_s)(\rho_s x_{ij} - \delta_s x_{ij}^2) + \sum_{n=1}^{5} q_n(E_n^o - e_{nj}x_{ij})\right] - \sum_{h=1}^{9} TC_h \qquad Eq.(A.1)$$

Subject to:

$$\sum_{j}^{82} x_{ij} \leq b_i, \forall\, i = 1\ to\ 70, \qquad Eq.(A.2)$$

$$\sum_{i=1}^{70}\sum_{j=1}^{82} e_{nj}x_{ij} - E_n^o \leq M, \forall\, n = 1\ to\ 5, \qquad Eq(A.3)$$

$$\sum_{i}^{70}\sum_{j}^{82} a_{ijh}\, x_{ij} * (\beta + \gamma y_i + \theta z_i) = TC_h, \qquad \forall\, h = 1\ to\ 9, \qquad Eq(A.4)$$

$$\sum_{h}^{9}\sum_{i}^{70}\sum_{j}^{82} a_{ijh}(1-\emptyset_h)\, x_{ij} = \Psi \qquad Eq(A.5)$$

The mathematical sets, variables and parameters used in the model are defined in Table 1.

The objective function (A.1) contains five expressions. The first expression $\left(-\sum_i^{70}\sum_j^{82} t_j c_j x_{ij}\right)$ represents the total variable production costs across all cropping systems and sub-watersheds.

The second expression $\left(-\sum_{i}^{70}\sum_{j}^{82}\sum_{l=1}^{3} r_l o_{lj} x_{ij}\right)$ is the total cost of synthetic fertilizers across systems and sub-watersheds. The third expression $\left(\sum_{i}^{70}\sum_{j}^{82}\sum_{s=1}^{15} p_s(1-\emptyset_s)(\rho_s x_{ij}-\delta_s x_{ij}^2)\right)$ is the total crop sales revenue from all cropping systems and sub-watersheds adjusted for storage losses. The term $(\rho_s x_{ij}-\delta_s x_{ij}^2)$ defines the quadratic output levels obtained by multiplication of the linear calibrated marginal yield expression $(\rho_s-\delta_s x_{ij})$ by the quantity of land x_{ij} allocated to the production of output s. The fourth expression $(\sum_{i}^{70}\sum_{j}^{82}\sum_{n=1}^{5} q_n(E_n^o-e_{nj}x_{ij})$ is the sum of each environmental output cost or subsidy across all cropping systems and sub-watersheds. The last expression $(\sum_{h=1}^{9} TC_h)$ represents the total transport cost of each biomass type to the refinery plant. Equation (A.2) is the expression of the 70 land resource constraints. Equation (A.3) is a set of constraints enabling the creation of limits on permitted environmental output levels, while the last two accounting equations (A.4) and (A.5) are respectively used to calculate transport costs and total biomass quantity. $(\beta+\gamma y_i+\theta z_i)$ is the transport cost of one tonne (Mg) of biomass to the refinery site; with β being the cost of loading and unloading, γ is the cost per kilometer of hauling distance and θ the cost per hour of hauling time. The variables y_i and z_i are respectively the hauling distance and time from a parcel i to the refinery plant site.

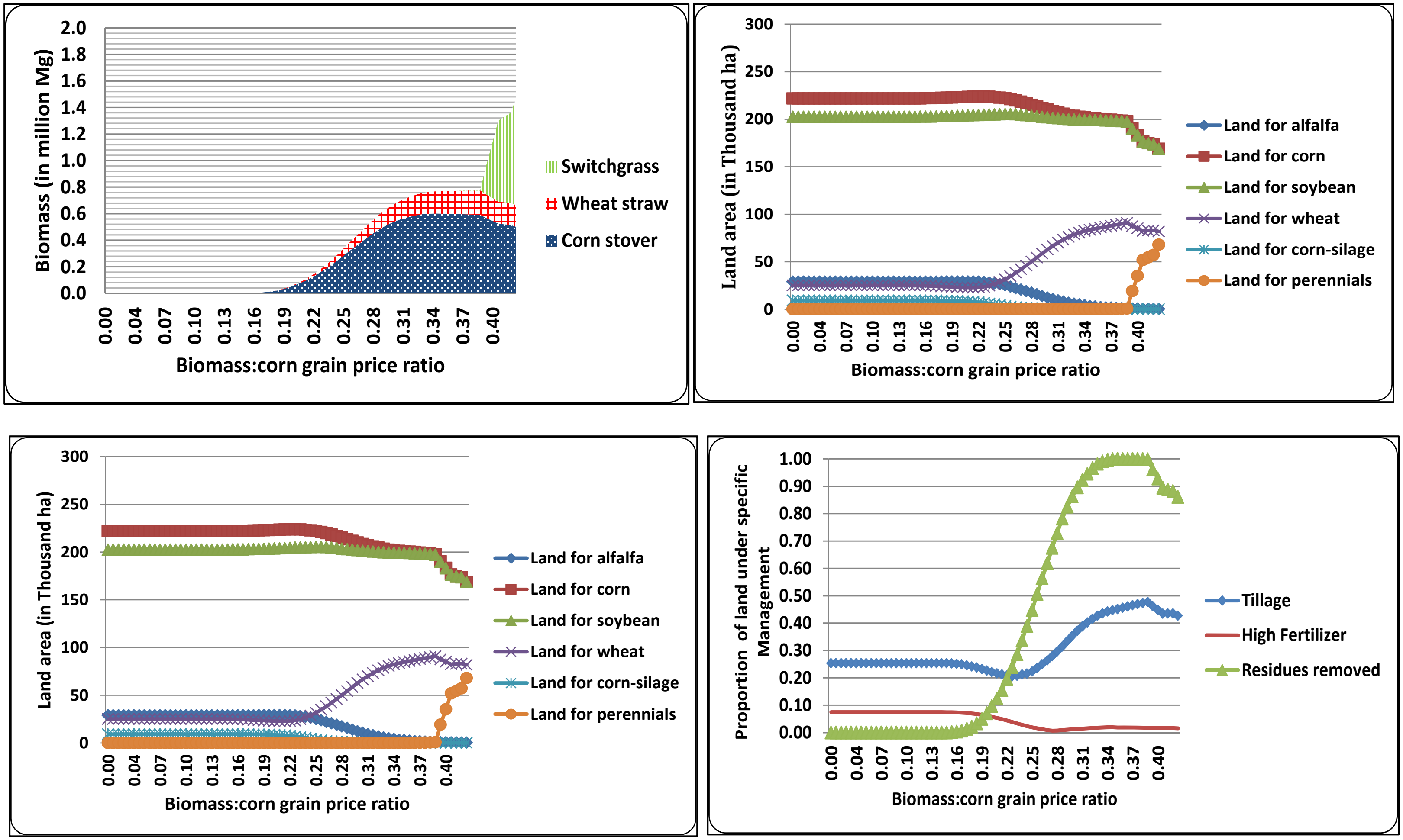

Fig. 1: Biomass quantity and sources (upper-left), percent change of environmental outputs from baseline (upper-right), land use change (bottom-left), and proportion of land under specific management (bottom-right) as *biomass price rises without environmental policy*.

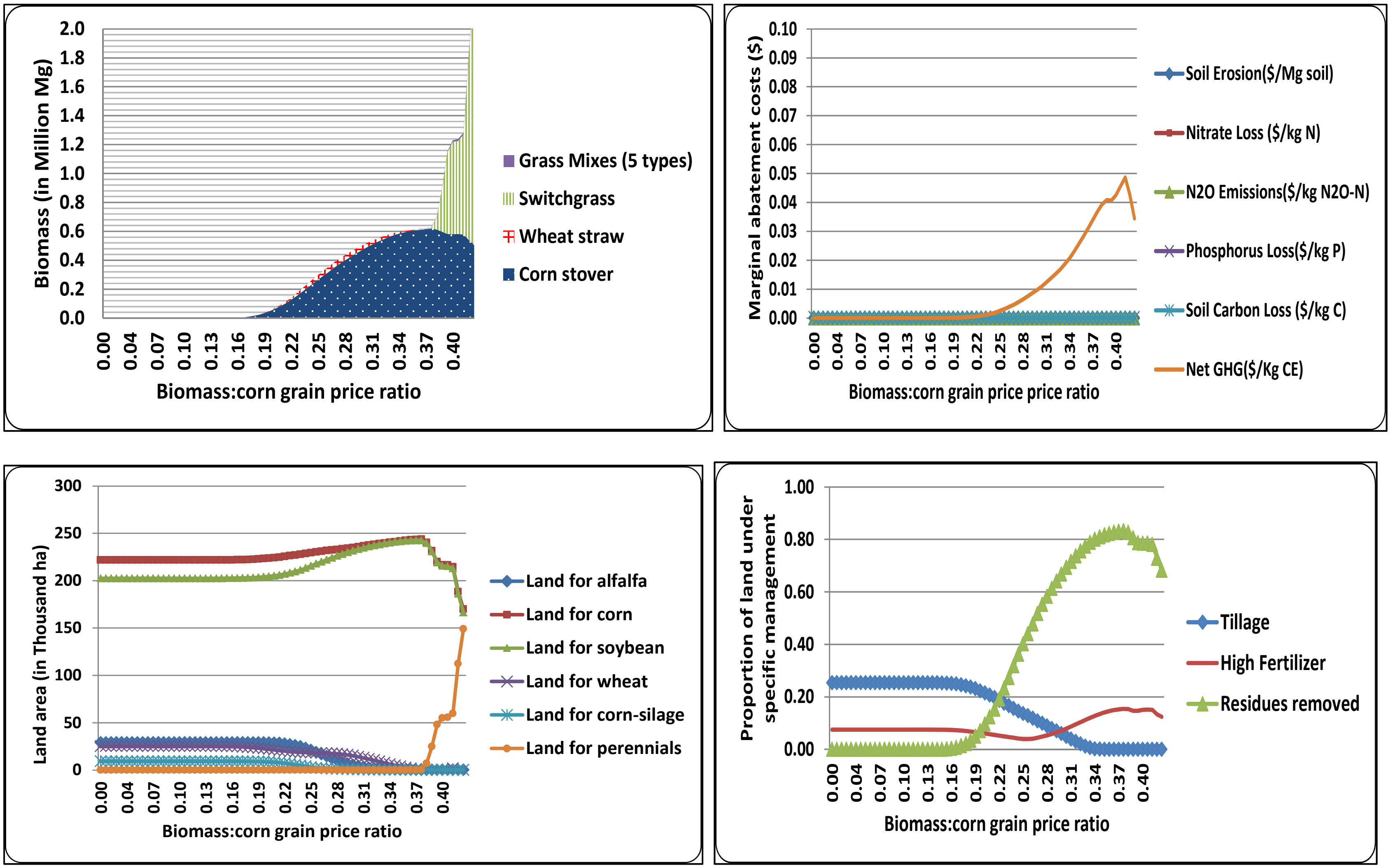

Fig. 2: Biomass supply and sources (upper left), environmental outputs marginal abatement costs (upper right), land use change (bottom left), and proportion of land under specific management (bottom right) as *biomass price rises while environmental outputs are constrained not to exceed the baseline of zero biomass production.*

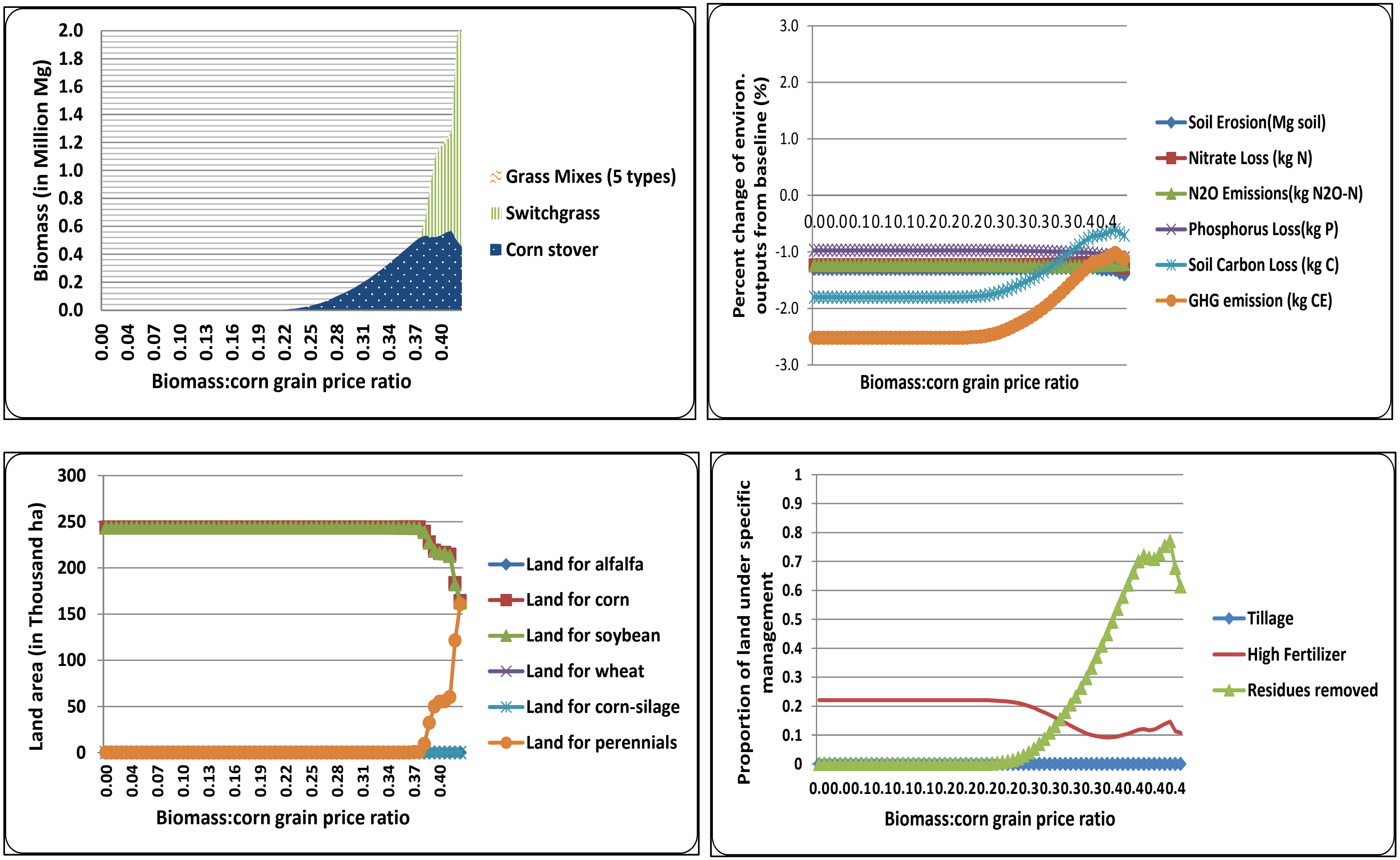

Fig. 3: Biomass quantity and sources (upper left), percent change of environmental outputs from baseline (upper right), land use change (bottom left), and proportion of land under specific managements (bottom right) as *biomass price rises with carbon priced at $50/Mg*.

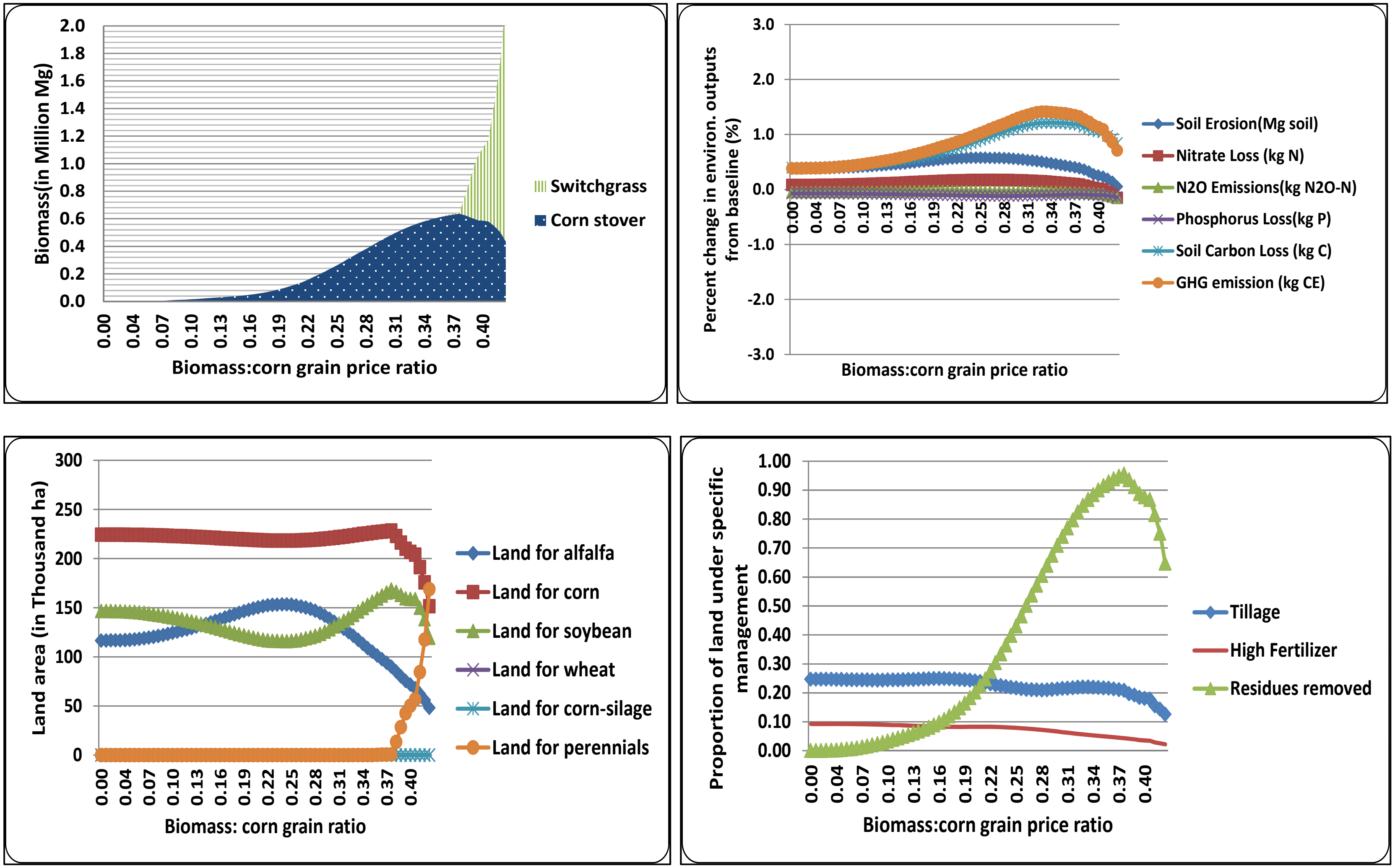

Fig. 4: Biomass quantity and sources (upper-left), percent change of environmental outputs from baseline (upper-right), land use change (bottom-left), and proportion of land under specific managements (bottom-right) as *biomass price rises when a fertilizer tax of 100% is applied.*

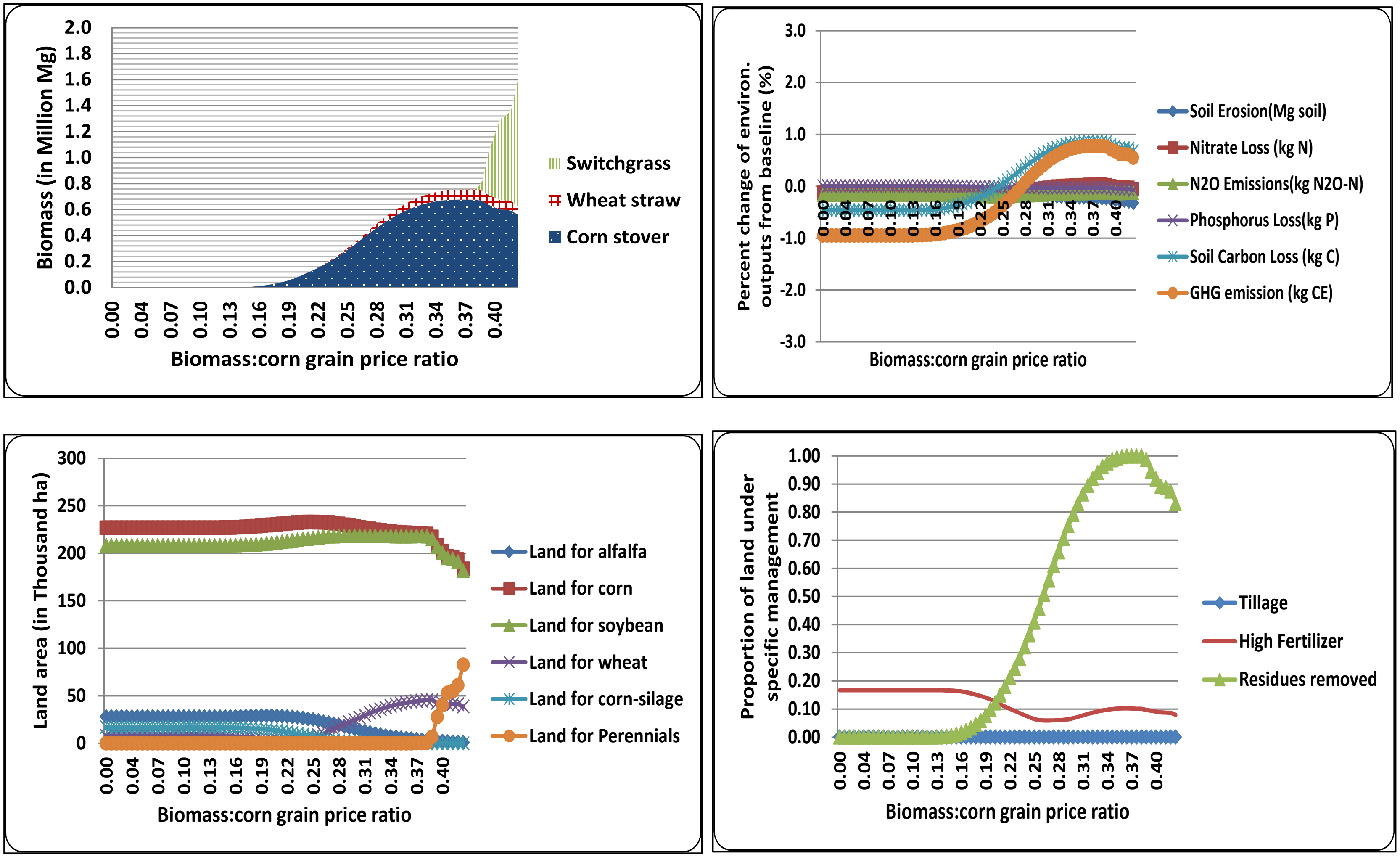

Fig.5: Biomass quantity and sources (upper-left), percent change of environmental outputs from baseline (upper-right), land use change (bottom-left), and proportion of land under specific managements (bottom-right) as *biomass price rises when no-till subsidy of $50/ha is applied.*

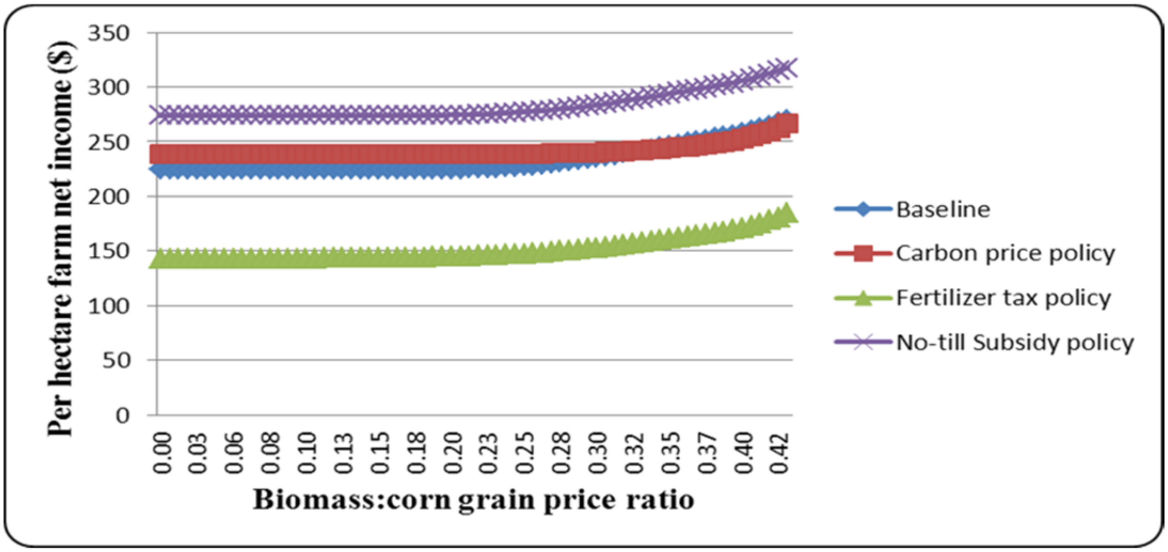

Fig. 6: Farm net income change per hectare for each policy scenario

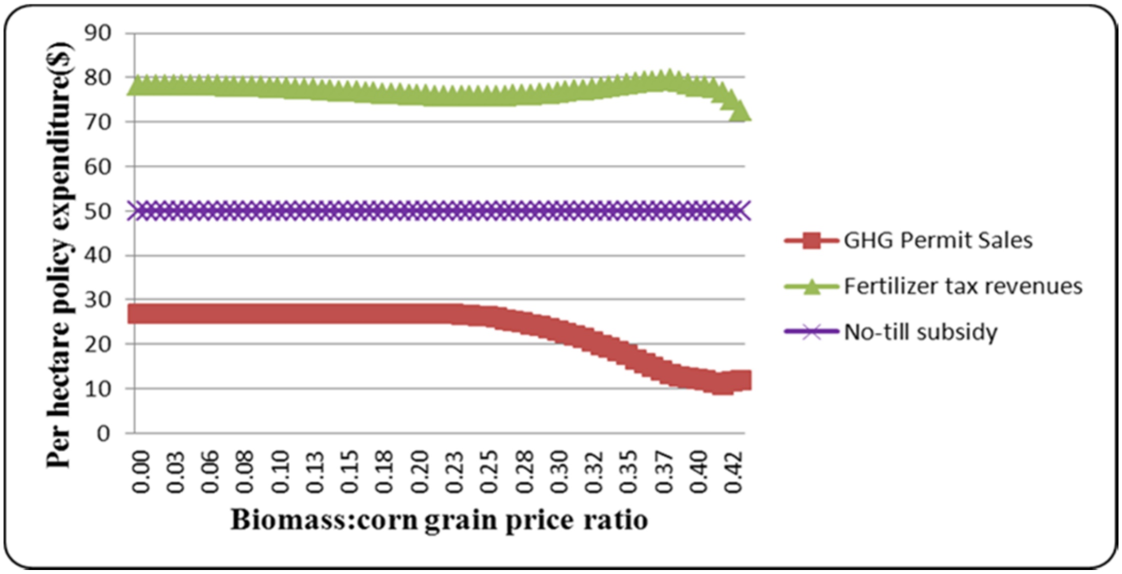

Fig. 7: Expenditure per hectare under each policy scenario. (Note: Zero expenditure assumed for the baseline case.)