ECONOMIC COSTS OF SOIL NUTRIENT MINING AND BENEFITS FROM PLANT NUTRIENT RECYCLING: THE CASE OF SWITCHGRASS PRODUCED FOR BIOENERGY FEEDSTOCK

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Abstract

Few attempts have been made to account for the potential costs associated with soil nutrient mining or the potential benefits associated with nutrient remobilization in switchgrass pastures established and managed as a dedicated bioenergy feedstock crop. Continuous soil nutrient mining could result in declining yields and profitability in the long-run and ultimately final exit out of switchgrass production. The objective of this study was to determine the cost associated with nutrient mining and the potential benefits associated with nutrient remobilization associated with one and two-cut switchgrass harvest systems in the southern Great Plain, USA. Data collected from a four-year, two-location agronomic field trial that evaluated two harvest systems, five N rates, and fixed rates of P and K applications were used for analysis. A standard forage analysis was used to determine the concentrations of N, P and K nutrients in the feedstock harvested. Cost of mining (or benefit of recycling) was estimated by comparing two separate economic models. Model 1 follows the conventional economic approach of utilizing yield response to treatments levels of N, P and K. Model 2 follows an approach that accounts for the costs and benefits associated with the N, P and K concentrations removed by the plants at harvest. Results from the convention economic approach indicate that producers should harvest twice per year, lending the system to mine significant quantities of N, P and K. When the benefits and costs associated with total nutrient uptake from plants were accounted, assuming a $110 Mg^{-1}$ for feedstock, the results indicate a producer would be better off harvesting twice (once in the summer and again in the winter), and the non-market economic tradeoff between nutrient mining and long-run soil sustainability was $8.70 Mg^{-1}$.

Keywords: Switchgrass, bioenergy, economic sustainability, cellulosic feedstock, nitrogen, harvest system

1. Introduction

Switchgrass (*Panicum vigatum* L.) has been identified by crop scientists and public policy makers as a leading source of cellulosic feedstock for conversion into bioenergy products in the southern Great Plains—a region in the USA that has a comparative advantage in growing native perennial grasses for conservation programs, wildlife habitat, and livestock enterprises. Published reports (Kazi et al. 2010; Wu, Sperow, and Wang 2010; Haque and Epplin, 2012) indicate that a large-scale biorefinery ($\geq 189 \times 10^6$ L yr^{-1} production capacity) will require between \$100 x 10^6 and \$500 x 10^6 in initial investment capital, depending on the conversion technology utilized (e.g., enzymatic hydrolysis, thermochemical pyrolysis, gasification, etc.). Rational investors would be reluctant to invest in a large-scale biorefinery unless they are certain they can procure a steady, long-term and locally produced supply of feedstock in each year of the expected life of the capital investment in the plant [Haque et al. 2012]. Furthermore, it is important for farmers to have reliable information about the actual fertilizer requirements of the plants in order for them to maintain productive levels of nutrient in their already fragile soil-base in order for them to produce a long-term, economically sustainable and steady supply of feedstock to biorefineries.

Data collected from multi-location, multi-year agronomic field trials in south-central Oklahoma show that significant quantities of nutrients (i.e., N, P and K) in excess of levels supplied via controlled treatments were removed (i.e., mined) from the soil by switchgrass plants that were harvested at the time of plant physiological maturity (prior to plant senescence) in July (Guretzky et al. 2011). Conversely, data from the same trials showed that significant levels of N, P and K nutrients supplied to switchgrass plants were remobilized back to the root zone (and to some extent, back to the soil) of plants harvested in the winter after a hard freeze, after plant senescence. This indicates that if harvest activity can be delayed until after plant senescence, some of the N, P and K will remobilize back into the root system and will minimize the need for their replacement. To date, conventional economic methods commonly used to determine the most economical harvest time and corresponding rates of fertilizer (Lemus et al., 2008; Haque et al., 2009; Boyer et al., 2013) do not consider the potential agronomic problems associated with soil nutrient mining nor the potential benefits associated with nutrient remobilization that are associated with producing switchgrass for bioenergy feedstock.

The objectives of this study were to determine the cost of mining and the potential benefits associated with recycling N, P and K nutrients in one and two-cut switchgrass harvest systems in the southern Great Plains, and to determine the non-market price for which producers would be indifferent between short- and long-run profitability of growing, harvesting and storing switchgrass feedstock on their farms.

2. Theoretical framework

Barber [1984] reported that a balance of sufficient quantities of vital nutrients is required to maintain proper plant growth throughout the growing cycle of the plants. The nutrient balance in the soil is measured by taking the difference between nutrient inflow and outflow [FAO 2004]. A positive balance occurs if nutrient additions (inflow) to the soil are greater than those removed (outflow), and a negative balance occurs if more nutrients are removed the quantity of nutrients added [Gruhn, 2000; Rijpma and Islam 2003; FAO 2004]. Negative balances are directly related to soil nutrient depletion that may lead to soil degradation [Rijpma and Islam 2003; FAO 2004], and soil nutrient depletion is a process by which nutrient are reduced through natural processes, such as soil erosion and leaching, and by human-induced processes, such as continuous nutrient mining through harvested plant biomass without adequate replenishments of nutrients [Drechsel and Gyiele 1999]. Continuous soil nutrient mining affects soil quality adversely and has been shown to reduce crop yields, providing for an unsustainable cropping system over the long term [Hopkins et al. 2001; Tan 2005; Henao and Baanante 2006].

For switchgrass produced for a bioenergy crop, the extent of soil nutrient mining depends heavily on the time of the growing season that it is harvested. If switchgrass is harvested in mid-season (summer harvest) nutrient levels in harvested biomass are relatively high [Guretzky et al. 2011]. On the other hand, if harvest is delayed until after the first hard freeze (after plant senescence), the plants will have recycled some of the nutrients in the plant back to the root zone, providing for a positive nutrient balance for that growing season [Vogel et al. 2002; Mooney et al, 2010;

Guretzky et al. 2011]. Guretzky et al. (2011) reports that the difference between the quantities of N, P and K fertilizer treatments applied to experimental plots and quantities of the same nutrients removed by the plants in a two-cut harvest system was negative, representing nutrient mining. In the same study, a positive difference (reflecting the quantities of nutrients that were remobilized back to the root zone) was found to be the case with the one-cut system.

The conventional economic approach for determining the economically optimal levels of N, P and K nutrients to apply to agricultural crops follow a producer expected profitability optimization framework where yield response to N, P and K nutrient application functions are econometrically estimated using yields actually measured in agronomic experiments from varying quantities of fertilizer treatments (Tembo et al., 2008; Biermacher et al., 2009; and Boyer et al., 2013). Response functions along with expected prices of crop and fertilizers are then used to analytically determine the economically optimal levels of N, P and K. However, this method does not consider the consequences associated with what the plants actually remove from the fixed soil nutrient base.

In this paper, we use the expected profit maximization framework that is commonplace. In addition, we develop a second model that utilizes data representing N, P and K concentrations that were actually removed from the plants at harvest. Using the results from both models, we determine the cost of nutrient mining or benefits from nutrient recycling, depending on the harvest system. Mathematically the cost of nutrient mining can be expressed as follows:

$$C = \mathrm{E}(NR^C) - \mathrm{E}(NR^S), \tag{1}$$

where C refers to the cost of nutrient mining, NR^C is the net return obtained using the conventional economic modeling approach that uses the yields associated with the actual nutrient treatments applied in the agronomic experiment, NR^S is the net return obtained by accounting for the benefits and costs associated with the data representing nutrient concentrations taken from the plants. A positive value of C is defined as the cost of nutrient mining and a negative value for C reflects a benefit associated with nutrient remobilization. At present, the marketplace does not place any value on the cost of excess nutrients that are removed from the soil (or surplus nutrients that are translocated back to the root zone) in excess of the quantities applied by the farmer; that is, farmers tend to consider only those cash costs associated with the quantities of N, P and K that they are actually purchase and applying to their crops.

3. Data

Data were collected in four production seasons (2008-2011) from two agronomic field experiments conducted on established stands of switchgrass (var. 'Alamo'). The first site was near the community of Frederick in Tillman County, OK (34º23´ N, 98º85´ W) and the second located near the community of Burneyville in Love County, OK (33º89´ N, 97º29´ W). The experimental design was a randomized complete block with four replications. The two harvest systems included (1) a single-cut harvest system in the winter after a hard freeze, after plant senescence (WNTR); and (2) a two-cut system that included a summer cut in July at the time of plant maturity, followed by a second cutting of the regrowth in the winter (December) after a hard freeze, after plant senescence (SMWNTR). Each study site and harvest system received 0, 45, 90, 135, 179 and 224 kg ha^{-1} yr^{-1} of N in the form of urea (46-0-0), 67 kg ha^{-1} yr^{-1} of phosphorus in the form of P_2O_5 (0-46-0), and 135 kg ha^{-1} yr^{-1} of potassium in the form of K_2O (0-0-60).

Sub-samples of the harvested switchgrass were collected to calculate dry matter yield and nutrient concentration measures for crude protein (CP), P and K. Following drying at 60°C, samples were ground to pass a < 1 mm screen using a Wiley Mill (Thomas Scientific, Swedesboro, NJ). Ground material was analyzed for CP, P and K using the Foss 6500 near infra-red reflectance spectroscopy (NIRS) instrument. The samples were scanned using Foss ISI Scan software and prediction equations developed by the NIRS Forage and Feed Testing Consortium (Hillsboro, WI). The CP concentration mean, standard error of validation, and r^2 for the equation used were: 19.9 g kg^{-1}, 1.3 g kg^{-1} and 0.98, respectively. The P mean, standard error of validation, and r^2 for the equation used were: 1.9 g kg^{-1}, 0.4 g kg^{-1} and 0.73, respectively. The K mean, standard error of validation, and r^2 for the equation used were: 16 g kg^{-1}, 2.8 g kg^{-1} and 0.85, respectively. These equations were then used to predict CP, P, and K for all samples. Concentrations of N removed by the plants were then calculated from CP by dividing each observation of CP by 6.25. Amounts of P and K removed by biomass were converted to P_2O_5 and K_2O kg ha^{-1} equivalents. Comprehensive details regarding the growing conditions and agronomic relationships between feedstock yield response to N, P and K nutrients and concentrations for the alternative harvest systems for each location and year are reported in Guretzky et al. (2011).

4. Economic methods

We assume that a rational farmer wants to know when to manage the timing of harvesting activities (i.e., when to cut, rake, bale and store feedstock) and how best to manage N, P and K nutrients for that system in order to obtain maximum profit on each acre on his farm. Therefore, risk-neutral farmer's objective function can be expressed mathematically as:

$$\max_{H^*,N^*|\bar{P},\bar{K}} E(NR^C) = \max\{\rho_b E[Y(H,N,\bar{P},\bar{K})] - r^N N - r^p \bar{P} - r^k \bar{K} - r^a - r^h - r^b Y(H,N,\bar{P},\bar{K}) - r^x X - FC\},$$

Subject to:

$$Y \geq Y(H,N,\bar{P},\bar{K});$$

$$H \in \{1 = WNTR, 2 = SMWNTR\};$$

$$N,\bar{P},\bar{K},X,FC \geq 0;$$

$$r^N, r^N, r^K, r^a, r^h, r^b, r^x \geq 0 \qquad (2)$$

where E(NR^c) refers to the expected net returns (\$ ha^{-1} yr^{-1}) from conventional economic approach; P_b is the price of switchgrass feedstock (\$ Mg^{-1}); *Y(H,N,P,K)* is feedstock yield (Mg ha^{-1} yr^{-1}) and is a twice differentiable continuous function of the levels nitrogen (*N*) for fixed rates of *P* and *K* fertilizers (kg ha^{-1} yr^{-1}) for a given harvest system *H* (either a winter only system (WNTR) or a summer and winter (SMWNTR) system); r^N, r^P and r^K are the price of *N*, *P* and *K*, respectively; r^a is the custom application rate for applying *N*, *P* and *K* fertilizers (\$ ha^{-1}); r^h is a vector of custom rates for mowing, raking, and staging feedstock (\$ ha^{-1}); r^b is the custom rate for baling switchgrass feedstock (\$ Mg^{-1}); r^x is a vector of prices that corresponds to the vector *X* containing non-fertilizer, non-harvest activity inputs, such as pesticide, pesticide application and interest on operating capital; and *FC* represents fixed cost associated with the annual prorated cost of switchgrass establishment and a land rental rate.

A similar framework is utilized for the sustainable economic approach (model 2) to determine the most economical harvest system. The primary difference is that the costs and benefits of nutrients (N, P and K) were determined by using the levels of N, P and K that were actually removed from the soil by the switchgrass plants. The concentration levels vary between N rate treatments assigned randomly in the RCBD. In this case, a twice differentiable yield response to nutrients concentrations equation could not be estimated; that is, the yield responded to nutrient concentration levels linearly. Therefore, the objective function for the sustainable economic approach is expressed mathematically as:

$$\max_{H,N^S P^S K^S} E(NR^S) = \max\{\rho_b E[Y(H,N,\bar{P},\bar{K})] - r^N N^S - r^p P^S - r^k K^S - r^a - r^h - r^b Y(H,N,\bar{P},\bar{K}) - r^x X - FC\},$$

Subject to:

$$Y \geq Y(H,N,\bar{P},\bar{K});$$

$$H \in \{1 = WNTR, 2 = SMWNTR\};$$

$$N,\bar{P},\bar{K},X,FC \geq 0;$$

$$r^N, r^N, r^K, r^a, r^h, r^b, r^x \geq 0, \tag{3}$$

where E(NR^s) refers to the expected net return (\$ ha^{-1} yr^{-1}) represented by the sustainable economic approach; N^S, P^S and K^S are the nutrient concentrations levels for N, P and K actually removed from the plants at the time of harvest and for analytical purposes were converted to N, P_2O_5 and K_2O (kg ha^{-1}) equivalents. It is important to note that these data provide insight about how the plants consumed nutrient they had available to them either from the nutrient treatments applied in the study or by surplus sources already available in the soil. Substituting equation (2) and equation (3) in to equation (1) and simplifying yields:

$$C = -r^N N - r^p \bar{P} - r^k \bar{K} - (r^N N^S + r^p P^S + r^k K^S). \tag{4}$$

Full detailed enterprise budgets (AAEA 2000) were developed to determine an estimate for all production cost components in equations (2) and (3), except the cost of owner's labor, management and overhead. These costs were not considered because they tend to differ substantially, depending on farm size and location within the region. The budgets included the prorated annual establishment costs as well as the costs associated with annual stand maintenance and harvesting activities.

Under the conventional economic approach (Eq. 2), only the cost of N, P and K that was purchased from the market and applied on the plots was accounted in the analysis. For the sustainable economic approach (Eq. 3), nutrient cost adjustments were made by calculating the difference between the fertilizer treatments applied and nutrient removal rates. These differences are presented in Table 1.

If the difference is negative, the cost of the nutrients applied to the plots, plus the cost associated with the additional quantity of nutrients removed from the soil by the plants was accounted in the analysis. A positive value indicates the cost of nutrients applied minus the value of the additional quantity of nutrients translocated to the root zone.

Table 1. Levels of N, P and K treatments, removed, and nutrients mined or recycled, and feedstock yield by harvest systems

Nutrient treatment rates (kg ha^{-1} yr^{-1})			Nutrients removed* (kg ha^{-1} yr^{-1})			Nutrients levels mined/recycled** (kg ha^{-1} yr^{-1})			Feedstock yield (Mg ha^{-1})
N	P	K	N	P	K	N	P	K	
WNTR system									
0	67	135	33 (33)§	16 (10)	31 (37)	-33	52	103	10.3 (4.9)
45	67	135	55 (41)	20 (11)	39 (38)	-10	47	95	12.4 (4.8)
90	67	135	68 (50)	25 (13)	44 (47)	21	43	91	14.1 (5.2)
135	67	135	84 (58)	28 (18)	50 (48)	50	39	84	15.0 (6.5)
179	67	135	101 (57)	29 (16)	43 (43)	78	38	92	15.0 (6.5)
224	67	135	105 (60)	30 (17)	48 (48)	119	37	86	14.7 (6.1)
SMWNTR system									
0	67	135	73 (54)	30 (17)	120 (79)	-73	37	15	9.5 (5.5)
45	67	135	106 (65)	41 (20)	170 (91)	-62	26	-36	12.8 (6.5)
90	67	135	154 (77)	56 (27)	236 (120)	-64	11	-102	16.4 (8.1)
135	67	135	185 (86)	61 (32)	256 (135)	-50	7	-121	17.0 (8.5)
179	67	135	220 (107)	71 (37)	309 (163)	-40	-3	-175	20.4 (10.2)
224	67	135	229 (105)	69 (36)	286 (145)	-4	-2	-151	19.3 (9.8)

* Nutrient removal levels are given by a standard forage (NIRS) analysis. These represent levels of nutrients N, P and K (in the form of N, P_2O_5 and K_2O) that were removed from the soil by switchgrass plants.
** Calculated as the difference between nutrient applied and nutrient removal level. A negative value implies the nutrient was mined and a positive value implies the nutrient was remobilized to the root zone of the plant.
*** Numbers in parentheses are standard deviations

5. Results and discussion

The net cost of nutrient mining or net benefits of nutrient recycling, the non-market price adjustment necessary to encourage long-run economic sustainability and the economically sustainable feedstock price by yield and various assumed market prices for feedstock are reported in Table 2. For the base-case price scenario that assumed a feedstock price of \$83 Mg^{-1} and a price of N of \$1.19 kg^{-1}, the expected net return estimated under the conventional economic approach was obtained with the SMWNTR harvest system and was \$388 ha^{-1}. Conversely, the greatest expected net return using the sustainable economic approach was \$392 ha^{-1} and obtained with the one-cut WNTR system. The difference in these two net returns was \$4 ha^{-1} (\$392 - \$388) and reflects the net benefits associated with nutrients that were recycled back to the root zones of the plants harvested in the WNTR system after plant senescence. The benefit of recycling in the two-cut system (SMWNTR) was also accounted, but the costs associated with the nutrients (primarily N and K) that were mined by the plants from the soil with the summer cutting more than exceeded the benefits of recycled nutrients in the winter cut. Further analysis reveals that for the base-case scenario, a producer would actually require \$0.30 less for each metric ton produced on his farm in order to maintain economic sustainability. That is, instead of receiving \$83 Mg^{-1}, he would only require \$82.7 Mg^{-1}.

When a price of \$110 Mg^{-1} of feedstock was assumed in the analysis, the greatest net return using the conventional economic approach was obtained with the two-cut (SMWNTR) system, realizing a net return of \$937 ha^{-1}. The greatest net return found using the sustainable economic approach was the one-cut (WNTR) system, realizing \$806 ha^{-1}. For this feedstock price scenario, our analysis shows that there was a \$131 net cost associated with nutrient mining. In this case, a farmer would need an additional \$8 for each metric ton of feedstock produced in order to encourage her to choose the economically sustainable one-cut (WNTR) system. That is, instead of \$110 Mg^{-1}, she would require \$118.7 Mg^{-1} to compensate her for choosing the more sustainable system (WNTR) that produces 5 Mg ha^{-1} less switchgrass than is produced with the SMWNTR system found using the conventional economic approach. This system had more short-run profit, but is likely unsustainable in the long-run.

The results were most sensitive to the expected price of feedstock and assumptions about the percentage of nutrients that is remobilized back to the root-zone and made available to growing plants in the following year. The results show that the net cost of nutrient mining in the two-cut SMWNTR system increases substantially as the assumptions about the total percentage of the nutrients that is recycled for later use are relaxed and reduced down from the 100% assumed in the base-case.

6. Conclusions

Conventional methods for determining the economical harvest timing and optimal rates of nutrients to apply to a dedicated cellulosic bioenergy feedstock crop do not consider the costs of nutrient mining associated with harvests prior to plant senescence nor the benefits from nutrient recycling with harvests after plant senescence. It is noteworthy to point out that price adjustments necessary to encourage harvest systems that are economically sustainable during the life of the investment into expensive, large-scale biorefineries are not currently valued in the marketplace. Therefore, it is believed that substantial mining of the nutrients in the fixed, already fragile nutrient-base of the soils in the region will be the result, placing additional risk and uncertainty on the economic potential of a large-scale, expensive cellulosic biorefinery.

Table 2. Net cost of nutrient mining or net benefit of nutrient recycling, price adjustment necessary to encourage soil sustainability and the economically sustainable feedstock price by various assumed feedstock prices

Assumed feedstock price (\$ Mg^{-1})	Model 1 Conventional approach			Model 2 Sustainable approach		
	feedstock yield (Mg ha^{-1})	harvest system	net return (\$ ha^{-1})	feedstock yield (Mg ha^{-1})	harvest system	net return (\$ ha^{-1})
55	20.0	SMWNTR	-163	10.3	WNTR	-33
83	20.0	SMWNTR	388	15.0	WNTR	392
110	20.0	SMWNTR	937	15.0	WNTR	806

Net cost of mining/ net benefits of recycling* (\$ ha^{-1})	Price adjustment necessary to encourage sustainability (\$ Mg^{-1})	Economically sustainable feedstock price (\$ Mg^{-1})
130	-12.6	42.4
4	-0.3	82.7
-131	8.7	118.7

* Calculated as the difference in net returns between the sustainable and conventional economic approaches. A negative value implies the net cost of nutrient mining and a positive value implies a net benefit of nutrient recycling

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