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Optimal Fertilizer Application and Crop Choice betweenA Perennial Bioenergy Feedstock and an Annual Crop

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Abstract

The objective of this research is to develop a modeling framework to aid in the simulation and empirical analysis of crop choice and optimal fertilizer application rates for bioenergy and conventional crops over lands of varying quality. Lower input use and reduced nutrient runoff are often-cited benefits of bioenergy crop production. Accounting these benefits requires an understanding of the temporal dynamics of fertilizer application, nutrient carryover, and runoff. Fertilizer carryover is the amount of fertilizer applied in previous production periods available for crops in the current growing period. Fertilizer runoff refers to fertilizer that has leached off the field and is no longer available to plants. The optimal available and applied amounts of nitrogen along with the present values of net returns for a pre-determined planning horizon are simulated for switch grass and corn using yield response data.Net returns for both crops increase as carryover rates increase but decrease as runoff rates increase. Switch grass appears to be more profitable than corn only on the most marginal lands where fertilizer runoff exceeds 30%.

Keywords: Dynamic optimization, fertilizer carryover, fertilizer runoff, optimal fertilizer application rates, crop choice, bioenergy

1. Introduction

Increased demand for ethanol has led to rapid expansion of the corn ethanol industry, revealing several challenges to the industry. First, corn ethanol production causes substantial greenhouse gas emissions (Kim and Dale 2005; Liskaet al. 2009; Searchingeret al.2008; Sedjo2007; Wang 2007). Second, increased demand for corn as biofuel feedstock has increased corn prices, which in turn have increased land prices and the downstream costs of food production (Pimentel 1991and 2003; Pimentel and Pimentel1996;Sedjo 2007). These effects have been exacerbated by federal subsidies to the corn ethanol industry that has discouraged ethanol imports into the United States (U.S.), thereby constraining the corn-based ethanol supply to domestic plants and driving more agricultural lands into corn production (Sedjo 2007).Given these challenges, more and more researchers are looking toward nonfood sources for biofuel feedstock. Switch grass (*Panicumvirgatum*), a tall, hardy, perennial grass native to North America that can grow in a variety of soil and climatic conditions, is a promising non-food biofuel feedstock (Rinehart 2006). Once established, switch grass has a productive life of ten to twenty years (Garland et al. 2010). Switch grass also has environmental advantages over corn (*ZeaMaize*). Switch grass has a strong and deep root system which can moderate soil erosion and filter polluting runoff (USDA2006).It also requires less fertilizer than corn (Rinehart 2006).

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Production of ethanol from switch grass also produces fewer greenhouse gas emissions than corn based ethanol production (Samson et al. 2008). However, switch grass is not currently produced as a biomass feedstock on a commercial-scale due to the relatively high costs of converting switch grass to ethanol. Thus, there are currently few opportunities for farmers to produce switch grass as a biofuel feedstock. However, the costs of producing ethanol from switch grass are likely to fall over time given the resources being devoted to improving conversion technologies. For example, the 2008 Farm Bill authorized $1.1 billion of mandatory funds and $1.0 billion of discretionary funds for the development of cellulosic biorefineries (CRS Report for Congress 2008). Once the costs of producing ethanol from switch grass are competitive with those of producing corn-based ethanol, markets for switch grass as a feedstock source for ethanol may emerge. In addition to not directly competing with food production, the production of switch grass as a biofuel feedstock may reduce input use and nutrient runoff compared to corn production. Farmers who have the option of producing dedicated bioenergy crops such as switch grass must decide how to allocate land between long-lived perennials such as switch grass and annual grain crops. The objective of this research is to developa modeling framework to aid in the simulation and empirical analysis of crop production decisions, fertilizer application rates, and net returns for a perennial bioenergy feedstock (switch grass) and an annual crop (corn) over lands of varying quality. An intertemporal theoretical model that maximizes the net returns of fertilizer application given crop choice is developed. Using this model, optimal nitrogen application rates and net returns for the production of switch grass and corn, based on field experiments conducted at the University of Tennessee Research and Education Center in Milan, Tennessee, are simulated over different fertilizer carryover and runoff rates. Fertilizer carryover is the amount of applied fertilizer that is available for crops in subsequent growing seasons (Kennedy et al. 1973), while fertilizer runoff refers to fertilizer that flows or leaches from agricultural lands and is no longer available to crops. The simulation is followed by an analysis of optimal crop choices over land of varying quality between idle land, switch grass, and corn.

2. Methods and Materials

2.1. Theoretical Model

Dynamic optimization of fertilizer management has been examined by a number of studies (Heady and Dillon 1961; Fuller 1965; Anderson 1967; Kennedy et al. 1973; Dillon 1977; Kennedy 1981; Taylor 1983; Lanzer and Paris 1981; Kennedy 1986; Watkins et al. 1998; Thomas 2003; Lambert et al.2007). Among these studies, Kennedy (1986) presented the most direct method of deriving an optimal decision rule where the profit maximizing amount of applied fertilizer occurs when the present value of the current crop and input savings from future fertilizer applications obtained from the marginal unit of fertilizer equals the expected fertilizer price in subsequent periods. This rule was derived by Kennedy et al. (1973), who introduced a dynamic programming approach to determine fertilizer application, carryover, and crop rotation in discrete time periods. This research focuses on fertilizer nitrogen because information on corn-nitrogen and switch grass-nitrogen response yields can be easily obtained. However, the model is completely generalizable to other inputs (e.g. phosphorous or potassium) or combinations of inputs. This study refers to nitrogen as mineral N, which is composed of Ammonium N (NH_4) and inorganic N (NO_3). Ammonium is convertible either by volatilization or through nitrification into NO_3 that is stable in the soil or soluble in water (Santhi 2001). At the same time, organic nitrogen in crop residues or soil can be decomposed into NO_3through mineralization process. Although NO_3 is water soluble and likely to leach into groundwater, previous studies find that numerical estimates of nitrogen carryover rates range between 0.16 to 2.51 (Fuller, 1965), 0.16 to 0.5 (Thomas, 2003), and 0.001 to 0.003 (Watkins et al. 1998). Assumptions for the theoretical model are as follows: 1) the total land area is fixed; 2) land can be used to produce switch grass or corn, or left idle; 3) prices are exogenous;4) homogeneous inputs such as fertilizer and labor are used to produce switch grass and corn;5) farmers maximize profit over a time horizon; and 6) a land allocated to switch grass production remains in switch grass production for the stand life of the crop (10 years). The farmer's objective is to maximize net returns with respect to the quantity of fertilizer applied for producing switch grass and corn and the allocation of land to these crops, subject to the amount of farmland available and nonnegative input quantities. To account for the perennial nature of switch grass, a time dimension is added, starting from period1 to a finite period *T*, the stand life for switch grass.

Thus, farmers allocate each unit of land to the crop that generates the greatest discounted net returns from period 1 to *T*. Discounted net returns are:

$$\pi = MAX \left\{ \begin{array}{l} \pi_g = \sum_{t=1}^{T} \rho^{t-1}(\rho P_{gt} Y_{gt} - r_t I_{gt}^{*} - \rho H_{gt} - C_{gt}) \\ \pi_c = \sum_{t=1}^{T} \rho^{t-1}(\rho P_{ct} Y_{ct} - r_t I_{ct}^{*} - \rho H_{ct} - C_{ct}) \\ \pi_i = 0 \end{array} \right\} \quad (1)$$

where π is the present value of the farmer's net returns over the ten year planning horizon for an unit of land; π_g, π_c, and π_i are the present values of the aggregate net returnsinperiods1 to *T* for an unit of land planted to switch grass, corn or left idle, respectively; $I_{gt}^{*}(I_{ct}^{*})$is the optimal quantity (in pounds) of fertilizer applied to each unit of switch grass (corn) in period *t*; $Y_{gt}(Y_{ct})$ is per unityield of switch grass (corn) in period *t*; $H_{gt}(H_{ct})$are per-unit fixed harvest costs for switch grass(corn) in period *t*; $C_{gt}(C_{ct})$ are per-unit establishment and maintenance costs in period *t* for switch grass (Corn); $P_{gt}(P_{ct})$ is the price of switch grass(corn) in period *t*; and r_t is the price of the fertilizer in period *t*. The farmer will produce switch grass on this unit of land from period 1 to *T* if the maximized present value of aggregate net returns for switch grass from period 1 to *T* is positive and higher than that for corn. Alternatively, the farmer will produce corn from period 1 to *T* if the maximized present value of aggregate net returns for corn is positive and higher than that for switch grass. Otherwise, the farmer will leave the land idle. The available farmland is assumed to vary in terms of nutrient carryover capacity and runoff rates, raising the possibility that the farmer's land will not be allocated entirely to the production of one crop or another. The producer's problem of maximizing the present value of aggregate net returns for the production of either crop on a particular land quality (as measured by nutrient carryover capacity and runoff rate) from period 1 to *T* is:

$$\underset{I_t}{MAX}\ p = \sum_{t=1}^{T} \rho^{t-1} [\rho\ P_t Y_t - r_t I_t - \rho\ H_t - C_t] + \rho^{T} F(X_{T+1}) \quad (2)$$

$$s.t.\ I_t, X_t \geq 0\ \forall\ t$$

$$X_{t+1} = \theta\,(1-\phi)(X_t + I_t)\ with\ X_0 = a\ \forall\ t$$

$$F(X_{T+1}) = 0$$

Where I_t is the quantity of fertilizer applied in period *t*(the control variable); X_t is the amount of fertilizer available for crop production at the beginning of period *t*(the state variable); ϕ is the fertilizer runoff rate(a proportion,$0 \leq \phi < 1$)of existing and applied fertilizer that runs off in any one period; θ is the proportion ($0 \leq \theta < 1$) of fertilizer that carries over in soil from one period to the next, such that the amount of fertilizer available for crop production at the beginning of period $t+1$is equal to the sum of the amount of fertilizer available at the beginning of period *t* (X_t) and the fertilizer applied (I_t)in period *t* less the amount of runoff $[(X_t+I_t)\phi]$in period *t* multiplied by the carryover rate, or $[X_t+I_t-(X_t+I_t)\phi]\theta$; ϱ denotes the discount rate; and the terminal condition $F(X_{T+1}) = 0$reflects the assumption that there is no value associated with fertilizer carryover beyond period *T*. A quadratic yield response function with respect to the amount of fertilizer available in the soil for growing crops was used to characterize switch grass and corn yield response to fertilizer (Y_t):

$$Y_t = \beta_0 + \beta_1 (1-\phi)\,(X_t + I_t) + \beta_2 (1-\phi)^2 (X_t + I_t)^2 \quad (3)$$

whereβ_0, β_1, and$\beta_2$are yield response parameters with $\beta_1 > 0$ and $\beta_2 < 0$. Quadratic functions can be interpreted as second-order approximations of any response function for the economic analysis. Interior solutions to input levels result when $f' > 0$ and $f'' < 0$, which provides closed-form analytical solutions to the optimization problem (Hurley et al. 2005, Lambert et al. 2006).

The crop choice and fertilizer application model can be solved using a dynamic programming approach (Kennedy 1986). The objective function applies Bellman's (1957) recursive equation:

$$V_t\{X_t\} = \underset{I_t}{Max}\{\rho\, P_t\, Y_t - r_t I_t - \rho\, H_t - C_t + \rho\, V_{t+1}[\theta(1-\phi)(X_t + I_t)]\} \quad (4)$$

Subject to: $I_t \geq 0 \,\forall\, t$

$X_{t+1} = \theta(1-\phi)(X_t + I_t)$ *with* X_0 *given*

$V_{T+1}\{\theta(1-\phi)(X_T + I_T)\}=0$

where V_t is the present value of net returns in period *t*. Taking the first order conditions (FOCs) of the objective function(4) with respect to the control variable I_t:

$$\frac{\partial V_t}{\partial I_t} = \rho\, P_t[\beta_1(1-\phi)+2\beta_2(1-\phi)^2(X_t + I_t)] - r_t + \rho\,(dV_{t+1}/dX_{t+1})\,\theta(1-\phi) = 0 \qquad (5)$$

Rearranging(5) yields:

$$\rho\,(dV_{t+1}/dX_{t+1})\,\theta(1-\phi) = r_t - \rho\, P_t[\beta_1(1-\phi)+2\beta_2(1-\phi)^2(X_t + I_t)] \qquad (6)$$

Differentiating (4) with respect to the state variable X_t yields:

$$dV_t/dX_t = \rho\, P_t[\beta_1(1-\phi) + 2\beta_2\,(1-\phi)^2(X_t + I_t)] + \rho\,(dV_{t+1}/dX_{t+1})\,\theta(1-\phi) \qquad (7)$$

Substituting $\rho\,(dV_{t+1}/dX_{t+1})\,\theta(1-\phi) = r_t - \rho\, P_t[\beta_1(1-\phi) - 2\beta_2(1-\phi)^2(X_t + I_t)]$ into (7):

$dV_t/dX_t = r_t$(8) Equation (8)means that the net benefit from an additional unit of fertilizer carried over from period *t*-1 to period *t*equals the price of fertilizer in period *t*. Therefore,

$dV_{t+1}/dX_{t+1} = r_{t+1}$(9)

Substituting (9) back into (5) yields:

$$\rho\, P_t[\beta_1(1-\phi)+2\beta_2(1-\phi)^2(X_t + I_t)] - r_t + \rho\, r_{t+1}\,\theta(1-\phi) = 0 \qquad (10)$$

Rearranging (10) yields the optimal condition for fertilizer application over a multiperiod planning horizon:

$$\rho\, P_t[\beta_1(1-\phi)+2\beta_2(1-\phi)^2(X_t + I_t)] = r_t - \rho\, r_{t+1}\,\theta(1-\phi) \qquad (11)$$

Equation (11) states that the present value of the marginal value product of fertilizer evaluated at $X_t + I_t^*$ equals the price of fertilizer at period *t* less the present value of cost savings associated with a reduction of $\theta(1-\phi)$units of applied fertilizer in period *t*+1because of soil carryover capacity. Solving equation (11) for $X_t + I_t$ yields the analytical solution for optimal amount of fertilizer available in the soil before runoff occurs in period *t* or $(X_t + I_t)^*$:

$$(X_t + I_t)^* = \frac{r_t - \rho r_{t+1}\theta(1-\phi) - \rho P_t \beta_1(1-\phi)}{2\beta_2 \rho P_t (1-\phi)^2} \quad (12)$$

The optimal amount of fertilizer available in the soil after in-period runoff in period *t* is then:

$$(1-\phi)(X_t + I_t)^* = \frac{r_t - \rho r_{t+1}\theta(1-\phi) - \rho P_t \beta_1(1-\phi)}{2\beta_2 \rho P_t (1-\phi)} \quad (13)$$

These conditions can be used to simulate the effects of prices and land quality on optimal fertilizer rates and crop choice decisions.

2.2. Parameters and Data

The model was parameterized using estimates from field experiments conducted at the University of Tennessee Research and Education Center at Milan, Tennessee and crop budgets developed by University of Tennessee Extension (UT Extension). Switch grass yield response parameters estimated by Mooney et al. (2010) were used to simulate switch grass response to nitrogen. The predominant land type for switch grass production in the experiments was characterized as moderately well drained level upland. Switch grass yield response estimates were:

$$Y_{gt} = 3.163 + 0.032\bar{A} + 0.035\, I_{gt} - 0.00013\, I_{gt}^2 \quad (15)$$

$$\text{Standard Error} \quad (0.337) \quad (0.004) \quad (0.007) \quad (0.00003)$$

Where A represents an Angstrom Index, which proxies growing conditions and includes information about precipitation and temperature (Mooney et al. 2010).The switch grass yield response function is evaluated at the mean of the index (64.75). Three years (2006-2008) of corn yield data was used to estimate corn yield response to nitrogen from field experiments conducted at the University of Tennessee Research and Education Centers at Milan and Highland Rim, Tennessee. The predominant land type for corn production in the experiments was also characterized as moderately well drained level upland. Corn yield response estimates to nitrogen were (UT Extension):

$$Y_{ct} = 52.903 + 0.902 I_{ct} - 0.002 I_{ct}^2 \quad (16)$$

$$\text{Standard Error} \quad (14.999) \quad (0.323) \quad (0.001)$$

The yield-nitrogen response estimates are used in the optimization model. However, there is a difference between the yield response nitrogen estimates and the yield response function implied by the dynamic model. The former means yield as a function of the amount of applied nitrogen while the latter is yield as a function of the amount of nitrogen available in the soil. Due to the lack of information on carryover and runoff rates, the yield-nitrogen response estimates were substituted for the yield response parameters in the dynamic program. Using output from the Soil and Water Assessment Tool (SWAT),a biophysical simulation model (Santhi 2001) calibrated for a Tennessee watershed (Zhou et al. 2011), average soil nitrogen carryover rates were estimated to be 0.05year^{-1} for corn and 0.07year^{-1} for switch grass over ten years of simulation and the entire farm land (Table1). Carryover rates were calculated by dividing the simulated amount of nitrogen available in the soil in the next period by the amount of nitrogen available plus the amount of nitrogen applied less the simulated nitrogen runoff in the current period (Table 1). Given the likelihood that these rates could vary, a range of soil carryover rates from 0.0 to 0.1 was used in the simulation for a sensitivity analysis. Runoff rates for nitrogen were calculated by dividing the amount of nitrogen runoff by the amount of available and applied nitrogen (Table 1). The simulated runoff rates were 0.12 for corn and 0.11 for switch grass. In a sensitivity analysis, a broader range of runoff rates (0.10 to 0.36) was used for this analysis to more fully explore the crop choice decision. Given values of 0.00, 0.02, 0.04, 0.06, 0.08, and 0.10 for the carryover rate and values of 0.10, 0.20, 0.30, 0.32, 0.34, and 0.36 for the runoff rate, the optimal amount of nitrogen available in the soil, the optimal applied amount of nitrogen, and present values of maximized net returns over a ten-year period were calculated for switch grass and corn using the analytical solutions (equations 12 and 13). Other parameters for the optimization model were obtained from switch grass (UT Extension 2008) and field crop budgets (UT Extension2010) produced by UT Extension (Table 2). Detailed items for the establishment, maintenance, and harvesting budgets in Table 2 are provided in Tables 3 and 4. Because the maintenance and harvesting budget for corn is provided only for yields of 7531 and 9414 kg ha^{-1}, budgets for other estimated corn yields were interpolated between the 7531 and 9414kg ha^{-1}yield numbers. To be consistent, input prices from the 2010 corn budget (UT Extension 2010) were used as parameters for both switch grass and corn. A ten year time horizon was evaluated to compare cumulative net returns for switch grass and corn. For switch grass, revenues for the first two years were assumed to be zero because harvest costs are typically assumed to exceed the value of switch grass yields during the first two years of switch grass production (Garland et al. 2010). The expected net returns were based on the analytical solutions of the optimization model for fertilizer application.

3. Results and Discussion

The optimal amount of nitrogen available in the soil, the optimal applied amount of fertilizer nitrogen, and the present values of maximized net returns over varying carryover and runoff rates(for both switch grass and corn) are provided in Tables 5, 6, and 7, respectively. The optimal amount of nitrogen available in the soil is constant for years one through nine because the analytical solution for the optimal available amount of nitrogen is the same for each year. The optimal amount of nitrogen available in the soil is different for the last year because no value is placed on nitrogen in the soil beyond the ten year horizon. Thus, the optimal amount of nitrogen available in the soil for the last period is independent of the carryover rate (Table 5). The optimal amount of nitrogen available in the soil in years one through nine increases as soil carryover capacity increases. The optimal applied amount of nitrogen is constant for years two through nine but different for the first and last years because the initial amount of nitrogen in the soil is assumed to be 105 kg ha^{-1} and no value is placed on nitrogen in the soil beyond the ten year planning horizon (Table 6). The optimal applied amount of nitrogen in years one through nine increases as soil carryover capacity increases. The present values of maximized net returns over a ten-year period given the optimal amount of nitrogen available in the soil over varying runoff and carryover rates for switch grass and corn are presented in Table 7.The present values of total net returns for corn and switch grass increase as the soil carryover capacity increases and decrease as the runoff rate increases. To determine whether land of a particular quality (i.e. carryover and runoff rate combination) would be allocated to switch grass or corn, the present values of total net returns for corn were subtracted from those of switch grass. As shown in Table 7, the switching point for crop choice from corn to switch grass occurs where the runoff rate is around 0.3with nutrient carryover capacities ranging from 0.0to 0.1.Thus, at the assumed prices and costs and estimated yield response to nitrogen, switch grass appears to be more profitable than corn only on the most marginal lands where fertilizer runoff exceeds30% of the available nutrients. More specifically, switch grass becomes more profitable than corn when the runoff rate reaches: (1) 0.32 if the carryover rate is between 0.00 and 0.02; (2) 0.34 if the carryover rate is between 0.04 and 0.08; and (3) 0.36 if the carryover rate is 0.10 (Table 7).Either switch grass or corn, or both, generated positive discounted net returns for each of the land qualities. Thus, no land would be left idle. Aggregate runoff amounts of nitrogen from switch grass and corn planting were calculated, respectively, according to equations 12 and 13 (Table 8). The aggregate runoff amounts from switch grass planting are approximately half of those from corn at each carryover and runoff level. This implies that switch grass planting substantially reduces the amount of nutrient runoff.

4. Conclusion

This paper presented a theoretical model for the dynamic optimization of fertilizer application with carryover and runoff and crop choice among switch grass, corn, and idle land. Runoff rate was included in the dynamic optimization model. Subsequently, crop choice was determined at different runoff rates. Given optimal fertilizer application rate, optimal crop choice was determined using the present values of net returns for switch grass and corn over different fertilizer carryover and runoff rates. The analysis suggests that switch grass would be more profitable than corn only on the most marginal lands, in this case, those with fertilizer runoff rates exceeding 30%. These results are clearly dependent on the assumptions underlying the theoretical model and the values used to parameterize the model. The switching point for crop choice from corn to switch grass is determined by factors including concavity of net benefit curves, the yield response functions, prices, fertilizer cost, and establishment, maintenance, and harvesting costs. For example, a change in the price of switch grass or corn could alter the result as could a technological change that lowered the establishment, maintenance, and harvesting costs for switch grass. Also, switch grass planting reduces nitrogen runoff amount by approximately 50% than corn. In addition, some limitations to the analysis suggest caution in interpreting the results. For example, the yield response function in the production decision model is a function of the available amount of fertilizer obtained by the amount of fertilizer left in the soil plus the amount applied subtracted by the amount of runoff. However, the yield response estimates applied in the application for West Tennessee are yield functions of the applied amount of nitrogen for both switch grass and corn. Empirical research on estimating dynamic yield response with carryover could provide more realistic yield response functions for both switch grass and corn. The inclusion of the runoff rate in the dynamic optimization and programming approach provides opportunities for future analyses. For example, the model could be extended to consider the environmental implications of fertilizer runoff and the effect of fertilizer application and crop choice decisions on a broader social welfare measure.

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6. References

Anderson, J.R.1967. Economic interpretation of fertilizer response data.Rev Marketing Agr Econ 35: 43-57.

Bellman, R.E. 1957. Dynamic programming. Princeton University Press, Princeton, New Jersey.

De La Torre Ugarte, D.G.,M.E.Walsh, H.Shapouri, and S.P.Slinsky.2003.The economicimpacts of bioenergy crop production on U.S. agriculture.Agricultural EconomicReport Number 816.Department of Agriculture, Office of the Chief Economist, Office of Energy Policy and New Uses.

Dillon, J.L.1977.The analysis of response in crop and livestock production, 2nd edition, PergamonPress, Oxford.

Fuller, W.A. 1965.Stochastic fertilizer production functions for continuous corn.J. Farm Econ 47:105-119.

Garland, C.D., G.E.Bates, C.D.Clark, D.A.Dalton, D.C.Gerloff, J.J.Goddard, K.J.L.Howard, P.D. Keyser, M.A.Newman, D.R.Perrin, L.E.Steckel, F.Stribling, D.D.Tyler, M.D. Wilcox, and J.B.Wills. 2010. Growing and harvesting switchgrass for switchgrass for ethanol production in Tennessee, University of Tennessee Extension.

Heady, E.O. andJ.L.Dillon.1961.Agricultural production functions, Iowa State University Press, Ames.

Hurley, T.M., K.Oishi, and G.L.Malzer.2005.Estimating the potential value of variable rate nitrogen applications: acomparison of spatial econometric and geostatisticalmodels.J Agr Resource Econ 30:231-249.

Kennedy, J.O.S., I.F.Whan, R.Jackson, and J. L. Dillon. 1973. Optimal fertilizer carryover and crop recycling policies for a tropical grain crop.Australian J Agr Econ17:104-113.

Kennedy, J.O.S. 1981.An alternativemethod for deriving optimal fertilizer rates: comment and extension. RevMarketingAgr Econ49:203–209.

Kennedy, J.O.S. 1986. Rules for optimal fertilizer carryover: an alternative explanation. Rev Marketing Agr Econ 54:3-10.

Kim, S. andB.E.Dale.2005.Environmental aspects of ethanol derived from no-tilled corn grain: nonrenewable energy consumption and greenhouse gas emissions. Biomass and Bioenergy 28:475-489.

Lambert, D.M., J.Lowenberg-Deboer, andG.L.Malzer.2006.Economic analysis of spatial-temporal patterns in corn and soybean response to nitrogen and phosphorus.Agron J98:43-54.

Lambert, D.M., J.Lowenberg-Deboer, and G.Malzer.2007. Managing phosphorous soil dynamics over space and time.Agr Econ 37:43-53.

Liska, A.J., H.S.Yang, V.R.Bremer, T.J.Klopfenstein, D.T.Walters, G.E.Erickson, andK.G.Cassman. 2009. Improvements in Life Cycle Energy Efficiency and Greenhouse Gas Emissions of Corn-Ethanol.J Ind Econ 13:58-74.

Mooney, D.F., R.K. Roland, B.C.English, J.A.Larson, and D.D.Tyler.2010.Is switchgrassyield response to nitrogen fertilizer dynamic? implications for profitability and sustainability at the farm level. Southern Agricultural Economics Association Annual Meeting, Orlando, Florida, February 6-9.

Park, S.C., R.T.Woodward, A.Stoecker, andJ.A.Hattey.2010.Optimal nitrogen applications: astochastic dynamic model of irrigated corn in the southern high plains. Agricultural & Applied Economics Association's Annual Meeting, Denver, Colorado, July 25-27.

Pimentel, D. 1991. Ethanol fuels: energy security, economics, and the environment.J Agr Environ Ethic 4:1-13.

Pimentel, D. 2003. Ethanol fuels: energy balance, economics, and environmental impacts are negative. Nat Resour Econ 12:127-134.

Pimentel, D. andM.Pimentel.1996. Food, energy and society: Colorado Univ. Press, Boulder, CO, 363 p.

Rinehart, L.2006.Switchgrass as a bioenergy crop.*ATTRA* – National Sustainable Agriculture Information Service, www.attra.ncat.org.

Samson, R., S.Bailey-Stamler, C.Ho Lem. 2008. Optimization of switchgrassmanagement for commercial fuel pellet production, Final Report prepared by REAP-Canada for the Ontario Ministry of Food, Agriculture and Rural Affairs (OMAFRA) under the Alternative Renewable Fuels Fund.

Santhi, C., J.G.Arnold, J.R. Williams, W.A.Dugas, R.Srinivasan, L.M.Hauck. 2001. Validation of the SWAT model on a large river basin with point and nonpoint sources.JAWRA 37:1169-1188.

Sedjo,R.A.2007.From oilfields to energy farms: abrief look at the environmental consequences of biofuels. Resources16-19.

Searchinger, T., R.Heimlich, R.A.Houghton, F.Dong, A.Elobeid, J.Fabiosa, S.Tokgoz, D.Hayes, T,Yu. 2008.Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change.Science 319:1238-1240.

Stubbs, M.2008. Renewable energy programs in the 2008 Farm Bill.CRS Report for Congress, http://ncseonline.org/nle/crsreports/10Sep/RL34130.pdf

Taylor, A.E. andW.R.Mann.1983.Advanced calculus, Third Edition. John Wiley & Sons, Inc.USA, 1983.

Thomas, A.2003.A dynamic model of on-farm integrated nitrogen management.Eur RevAgr Econ30:439-460.

United States Department of Agriculture - Natural Resources Conservation Service.2006.Plant Fact Sheet, PanicumVirgatum (Switchgrass).Plant Materials Program.

University of Tennessee Agricultural Extension.2008.Guideline switchgrassestablishment and annual production budgets over three year planning horizon, available online athttp://economics.ag.utk.edu/extension.html.

University of Tennessee Agricultural Extension.2010. Field crop budgets, available online at http://economics.ag.utk.edu/extension.html.

Wang, M., M. Wu, and H.Huo.2007.Life-cycle energy and greenhouse gasemission impacts of different corn ethanolplant types. Environ Res Letters 2:1-13.

Watkins, K.B., Y.Lu, and W.Huang.1998.Economic and environmental feasibility of variable rate nitrogen fertilizer application with carry-over effects. J Agr Resource Econ 23:401-426.

Zhou, X.2011. Biofuel and water resources.Doctoral Dissertations, University of Tennessee, Knoxville.

Table 1: Carryover and Runoff Rate Calculation Using Parameter Values from SWAT calibrated for a Tennessee Watershed

	Model Parameters	Corn	Switchgrass
[a]**SWAT Simulation Output**			
Final NO_3 in Soil (kgha^{-1})	X_{t+1}	3.92	4.92
Initial NO_3 in Soil (kg ha^{-1})	X_t	61.33	61.33
Nitrogen Fertilizer Applied (kg ha^{-1})	I_t	23.63	20.76
NO_3Leached and Surface Runoff(kg ha^{-1})	$(X_t+I_t)\varphi$	10.55	9.30
Calculated Carryover Rate	$X_{t+1}/[(X_t+I_t)(1-\varphi)]$	0.05	0.07
Calculated Runoff Rate	$[(X_t+I_t)\varphi]/(X_t+I_t)$	0.12	0.11

[a] The SWAT model was simulated for ten years and the numbers in the simulation output are average valueseach year for the entire farm land.

Table 2: Parameters Used in Theoptimization Model for Switchgrass and Corn

Parameters	Representation	Switchgrass	Corn
Initial Amount of Nitrogen in the Soil (kgha^{-1})	X_0	[a]105	[a]105
Nitrogen Price ($kg^{-1})	r_t	[b]1.7	[b]1.7
Output Price ($kg^{-1})	P_t	[c]0.083	[b]$0.142
Discount rate	δ	0.1	0.1
Discount factor	ϱ	0.9	0.9
Quadratic Production Coefficients	β_0	[d]5.235	[b]52.903
	β_1	[d]0.035	[b]0.902
	β_2	[d]0.00013	[b]0.002
Establishment Budget ($ ha^{-1})	C_t	[e]508.3	[e]0.00
Maintenance Budget ($ ha^{-1})		[e]408.0	[e]292.54
Harvesting Budget ($ ha^{-1})	H_t	[e]175.6	

[a]Park et al. (2010)

[b]University of Tennessee Agriculture Extension

[c]De La Torre Ugarte et al.(2003)

[d]Mooney et al. 2010

[e]Guideline Switchgrass Establishment and Annual Production Budgets over Three Year Planning Horizon (2008) and Field Crop Budgets (2010)

Table 3: Establishment, Maintenance, and Harvesting Costs for Switchgrass

	Establishment[a] ($ ha^{-1})	Annual Maintenance[a] ($ ha^{-1})	Annual Harvesting[a] ($ ha^{-1})
Seed Kernels	296.5		
Fertilizer P205		51.4	
Fertilizer K20		87.0	
Triple Tie			25.5
Weed Control Post-Emerge Broadleaf	12.4	12.4	
Weed Control Post-Emerge Grass	19.8	19.8	
Weed Control Post-Emerge Grass	19.8		
Weed Control Fall Burn Glyphosate	19.4		
Weed Control Spring Burn Glyphosate	29.2		
Machinery Repair	19.9		
Machinery Repair Tractor 150 HP		40.7	
Machinery Repair Sprayer		0.3	
Machinery Repair Mower			3.1
Machinery Repair Rake			0.3
Machinery Repair Baler			25.6
Machinery Repair Loader			5.4
Machinery Fuel	26.3		
Machinery Fuel Tractor 150 HP		98.9	
Operating Capital	15.0	23.1	
Machinery Depreciation	21.5		
Machinery Depreciation Tractor 150 HP		41.2	
Machinery Depreciation Sprayer		0.4	
Machinery Depreciation Mower			2.1
Machinery Depreciation Rake			0.6
Machinery Depreciation Baler			27.1
Machinery Depreciation Loader			13.1
Interest Expense	14.0		
Interest Cost Tractor 150 HP		29.3	
Interest Cost Sprayor		0.2	
Interest Cost Mower			1.3
Interest Cost Rake			0.4
Interest Cost Baler			8.1
Interest Cost Loader			5.4
Labor	14.5	3.4	57.6
Total Cost	**508.3**	**408.0**	**175.6**

[a]Guideline Switchgrass Establishment and Annual Production Budegts over Three Year Planning Horizon (2008)

Table 4: Planting, Maintenance, and Harvesting Costs for Corn

	7531 kg ha^{-1} Yield ($/ha^{-1})	9414 kg ha^{-1} Yield ($ ha^{-1})
Seed Kernels	160.6	213.1
Fertilizer P205	64.2	89.9
Fertilizer K20	54.4	76.1
Lime	42.6	42.6
Weed Control Pre-Emerge Bicep	50.3	50.3
Weed Control Post-Emerge Roundup	14.9	14.9
Weed Control Burn Gramoxone	24.3	24.3
Weed Control Burn Surfactant	0.9	0.9
Machinery Repair	41.9	41.9
Machinery Fuel	32.3	32.3
Operating Capital	18.6	23.0
Machinery Depreciation	71.5	71.5
Interest Expense	24.8	24.8
Labor	17.1	17.1
Total Cost	**618.5**	**722.9**

Source: Field Crop Budgets (2010)

Table 5: The Optimal Amount of Nitrogen Available in the Soil in Years 1-10 for Different Carryover and Runoff Rates for Switchgrass and Corn

	Runoff Rate					
	0.10	0.20	0.30	0.32	0.34	0.36
t[a]= 1, 2, 3, 4, 5, 6, 7, 8, 9						
Switchgrass	(kg ha^{-1})					
Carryover Rate[b]						
0.00	108.3	113.5	117.5	118.0	118.3	118.4
0.02	109.3	114.6	118.7	119.3	119.6	119.8
0.04	110.3	115.7	120.0	120.5	120.9	121.2
0.06	111.2	116.8	121.2	121.8	122.3	122.5
0.08	112.2	117.9	122.5	123.1	123.6	123.9
0.10	113.2	119.0	123.7	124.4	124.9	125.3
Corn						
Carryover Rate[b]						
0.00	200.5	214.3	228.3	231.0	233.6	236.1
0.02	201.8	215.7	230.0	232.7	235.4	237.9
0.04	203.1	217.2	231.7	234.4	237.2	239.8
0.06	204.4	218.7	233.3	236.2	239.0	241.6
0.08	205.8	220.2	235.0	237.9	240.7	243.5
0.10	207.1	221.7	236.7	239.7	242.5	245.3
t = 10						
Switchgrass	108.3	113.5	117.5	118.0	118.3	118.4
Corn	200.5	214.3	228.3	231.0	233.6	236.1

[a] The optimal available amount of nitrogen is unchanging for years t=1,…,9.

[b] Carryover rate is irrelevant to the optimal available amount of nitrogen in year 10 given that terminal value of nitrogen in the soil is assumed to be zero.

Table 6: The Optimal Applied Amount of Nitrogen in Years 1-10 for Different Carryover and Runoff Rates for Switchgrass and corn

	Runoff Rate					
	0.10	0.20	0.30	0.32	0.34	0.36
t = 1						
Switchgrass	(kg ha^{-1})					
Carryover Rate[b]						
0.00	3.0	8.2	12.1	12.6	12.9	13.1
0.02	3.9	9.3	13.4	13.9	14.3	14.4
0.04	4.9	10.3	14.6	15.2	15.6	15.8
0.06	5.9	11.4	15.9	16.5	16.9	17.2
0.08	6.8	12.5	17.1	17.7	18.2	18.5
0.10	7.8	13.6	18.4	19.0	19.6	19.9
Corn						
Carryover Rate[b]						
0.00	95.1	108.9	122.9	125.6	128.2	130.7
0.02	96.5	110.4	124.6	127.3	130.0	132.5
0.04	97.8	111.9	126.3	129.1	131.8	134.4
0.06	99.1	113.3	128.0	130.8	133.6	136.2
0.08	100.4	114.8	129.7	132.6	135.4	138.1
0.10	101.7	116.3	131.4	134.3	137.2	139.9
t[a] = 2, 3, 4, 5, 6, 7, 8, 9						
Switchgrass						
Carryover Rate[b]						
0.00	108.3	113.5	117.5	118.0	118.3	118.4
0.02	107.3	112.8	117.1	117.6	118.0	118.3
0.04	106.3	112.0	116.6	117.3	117.8	118.1
0.06	105.2	111.2	116.1	116.9	117.4	117.8
0.08	104.1	110.3	115.6	116.4	117.1	117.6
0.10	103.0	109.5	115.1	115.9	116.7	117.2
Corn						
Carryover Rate[b]						
0.00	200.5	214.3	228.3	231.0	233.6	236.1
0.02	198.2	212.3	226.7	229.5	232.3	234.9
0.04	195.8	210.3	225.2	228.1	230.9	233.6
0.06	193.4	208.2	223.5	226.6	229.5	232.3
0.08	190.9	206.1	221.9	225.0	228.0	231.0
0.10	188.4	203.9	220.2	223.4	226.5	229.6

[a] The optimal applied amount of nitrogen is unchanging for years t=2,…,9.

Table 6: (Continued from the previous page) The Optimal Applied Amount of Nitrogenin Years 1-10 for Different Carryover and Runoff Rates for Switchgrass and corn

	Runoff Rate					
	0.10	0.20	0.30	0.32	0.34	0.36
t = 10						
Switchgrass	(kg ha^{-1})					
Carryover Rate						
0.00	108.3	113.5	117.5	118.0	118.3	118.4
0.02	106.4	111.7	115.8	116.3	116.7	116.9
0.04	104.4	109.8	114.1	114.7	115.1	115.3
0.06	102.3	107.9	112.4	113.0	113.5	113.7
0.08	100.2	106.0	110.6	111.3	111.8	112.1
0.10	98.1	104.0	108.8	109.5	110.1	110.4
Corn						
Carryover Rate						
0.00	200.5	214.3	228.3	231.0	233.6	236.1
0.02	196.9	210.8	225.1	227.8	230.5	233.0
0.04	193.2	207.3	221.8	224.6	227.3	229.9
0.06	189.5	203.8	218.5	221.3	224.1	226.8
0.08	185.7	200.2	215.1	218.0	220.9	223.6
0.10	181.9	196.5	211.7	214.7	217.6	220.4

Table 7.Present Values of Ten Years of net Returnsfor Switchgrass and Corn over Varying Carryover and Runoff Rates

Present Values of Ten	Runoff Rates					
Years of Net Benefits	0.1	0.2	0.3	0.32	0.34	0.36
	($ ha^{-1})					
Carryover Rate = 0.00						
Switchgrass	1278.7	1155.8	1017.5	988.3	958.5	928.5
Corn	1539.4	1310.0	1044.0	986.2	926.8	866.0
$\prod_g - \prod_c$	-260.8	-154.2	-26.5	**2.1**[a]	31.7	62.5
Carryover Rate = 0.02						
Switchgrass	1294.5	1169.9	1029.5	999.7	969.5	938.8
Corn	1568.6	1336.6	1067.5	1008.9	948.8	887.1
$\prod_g - \prod_c$	-274.1	-166.7	-38.0	**-9.2**[a]	20.7	51.7
Carryover Rate = 0.04						
Switchgrass	1310.5	1184.3	1041.7	1011.4	980.7	949.4
Corn	1598.0	1363.7	1091.4	1032.0	971.1	908.5
$\prod_g - \prod_c$	-287.5	-179.4	-49.6	-20.6	**9.6**[a]	40.9
Carryover Rate = 0.06						
Switchgrass	1326.8	1198.8	1054.2	1023.4	992.0	960.2
Corn	1627.9	1391.0	1115.5	1055.4	993.7	930.3
$\prod_g - \prod_c$	-301.1	-192.1	-61.3	-32.1	**-1.7**[a]	29.9
Carryover Rate = 0.08						
Switchgrass	1343.2	1213.6	1066.8	1035.5	1003.6	971.3
Corn	1658.0	1418.7	1140.0	1079.2	1016.6	952.4
$\prod_g - \prod_c$	-314.8	-205.0	-73.2	-43.7	**-13.0**[a]	18.9
Carryover Rate = 0.10						
Switchgrass	1359.9	1228.7	1079.7	1047.8	1015.4	982.5
Corn	1688.5	1446.7	1164.8	1103.2	1039.9	974.9
$\prod_g - \prod_c$	-328.5	-218.0	-85.1	-55.4	-24.5	**7.7**[a]

[a] Number in bold means the value where switching point occurs.

Table 8: Nitrogen Runoff Amount from Corn V.S. Switchgrassplanting

	Runoff Rate					
	0.10	0.20	0.30	0.32	0.34	0.36
t = 1, 2, 3, 4, 5, 6, 7, 8, 9						
Switchgrass	(kg ha^{-1})					
Carryover Rate						
0.00	10.8	22.7	35.2	37.7	40.2	42.6
0.02	10.9	22.9	35.6	38.2	40.7	43.1
0.04	11.0	23.1	36.0	38.6	41.1	43.6
0.06	11.1	23.4	36.4	39.0	41.6	44.1
0.08	11.2	23.6	36.7	39.4	42.0	44.6
0.10	11.3	23.8	37.1	39.8	42.5	45.1
Corn						
Carryover Rate						
0.00	20.1	42.9	68.5	73.9	79.4	85.0
0.02	20.2	43.1	69.0	74.5	80.0	85.6
0.04	20.3	43.4	69.5	75.0	80.6	86.3
0.06	20.4	43.7	70.0	75.6	81.2	87.0
0.08	20.6	44.0	70.5	76.1	81.9	87.6
0.10	20.7	44.3	71.0	76.7	82.5	88.3
t = 10						
Switchgrass	10.8	22.7	35.2	37.7	40.2	42.6
Corn	20.1	42.9	68.5	73.9	79.4	85.0