Impact of Environmental Values on the Breakeven Price of Switchgrass

Deepayan Debnath^{a*}, Arthur L. Stoecker^b, and Francis M. Epplin^c

^a Food and Agricultural Policy Research Institute, University of Missouri-Columbia, 101 Park De Ville Dr., Suite E, Columbia MO 65203, USA

^b Department of Agricultural Economics, Oklahoma State University, 316 Ag Hall, Stillwater, OK 74078, USA

^c Department of Agricultural Economics, Oklahoma State University, 416 Ag Hall, Stillwater, OK 74078, USA

ABSTRACT

This study estimates the farm-gate breakeven price of switchgrass relative to wheat in Oklahoma, USA. The breakeven price of switchgrass is determined for two situations: when external consequences are ignored and when the environmental costs of changes in soil erosion, fertilizer (nitrogen and phosphorous) runoff, and soil organic carbon (SOC) are considered. Results suggest that if indirect land use changes are ignored, the farm-gate breakeven price of switchgrass when only the internal costs are considered is 69% to 144% greater (depending on land quality) than if the value of selected external consequences are considered. The potential environmental benefits are greater if highly erodible land is switched from annual cropping to switchgrass.

Key words: Agricultural runoff, farm-gate breakeven price, soil organic carbon (SOC), switchgrass

* Corresponding author. Tel.: +1 405 334 6550. E-mail addresses: debnathd@missouri.edu (D. Debnath), art.stoecker@okstate.edu (A.L. Stoecker), f.epplin@okstate.edu (F.M. Epplin).

1. Introduction

With concern over environmental degradation there has been interest in finding alternative sources of energy across the globe. Part of this interest has focused on renewable bioenergy, which is expected to have fewer negative environmental consequences than hydrocarbon fuels. Among the many potential dedicated energy crops, switchgrass has considerable promise due to its ability to grow on many different types of soil under diverse climatic conditions. Switchgrass is a perennial native grass of North America, where it naturally occurs over an area between 20° N to 55° N and 65° W to 98° W. Switchgrass is a drought and flood tolerant perennial lignocellulosic crop that can produce substantial biomass yields with relatively little chemical fertilizer. As roots expand into the deep subsoil for nutrients and water, switchgrass can deposit organic matter within the soil profile resulting in increasing the soil organic matter. It also provides cover to the soil from the erosive force of wind and rain that reduces erosion relative to continuous cropping with annual crops. There are additional environmental benefits derived from reducing nitrogen and phosphorous runoff [1]. Since 1991 switchgrass production has received special attention in USA when the US Department of Energy declared switchgrass as a model herbaceous energy crop [2].

Switchgrass has been evaluated as a potential biomass crop in several countries. Monti et al. [3] did an economic feasibility study of switchgrass production under several scenarios in Italy and found that the relative yield of switchgrass would have to be increased to enable it to compete for land with maize and alfalfa. However, they did not consider the positive environmental benefits derived from the switchgrass production. Smeets, Lewandowski and Faaij [4] found that switchgrass was a promising bioenergy crop for the European Union mainly because of yield, low production costs, and improved environmental outcomes relative to

conventional crops. Samson and Omielan [5] concluded that in Canada switchgrass has significant potential to be a feedstock for the cellulosic ethanol industry and could be a major contributor in reducing Canadian CO₂ emissions. Dam et al. [6] analyzed the environmental impacts of large-scale biomass production from soybeans and switchgrass in Argentina. They found that switchgrass accumulated more carbon than soybeans and resulted in lower soil loss. They concluded that greatest potential environmental benefits could be achieved by producing switchgrass on abandoned cropland. Ichizen et al. [7] and Ma et al. [8] showed that switchgrass is effective in preventing soil erosion in one of the most arid region of the Loess Plateau in China. The projected potential for switchgrass feedstock production raises several research questions. First, what net price for switchgrass would be required to bid land from its current use to switchgrass production? Second, what are the expected changes in soil erosion, fertilizer (nitrogen and phosphorous) runoff, and soil organic carbon (SOC) from converting crop land into switchgrass production, and what is the expected economic consequence of these changes? In this research study, we estimate selected environmental benefits derived from the conversion of land used to produce winter wheat for grain to the production of switchgrass biomass for biorefinery feedstock.

The USA Environmental Protection Agency (EPA) using the Forestry and Agriculture Optimization Model (FASOM) predicted that by 2022, it would be economically feasible to produce 3.4×10^9 m³ of biofuel from switchgrass biomass feedstock [9]. The FASOM model also projected that most of the switchgrass feedstock would be grown in Oklahoma replacing wheat and hay production. Therefore, based on EPA's finding we consider Oklahoma as our study region.

Several studies have estimated the production costs of switchgrass biomass. Mooney et al. [10] determined the breakeven price of switchgrass for four different locations in Tennessee. They found that the farm-gate breakeven price of switchgrass based on 10-year production contracts was 46 \$ Mg⁻¹ for an average yield of 17.7 Mg ha⁻¹ and 69 \$ Mg⁻¹ for an average yield of 8.5 Mg ha⁻¹. Khanna et al. [11] estimated the Illinois farm-gate breakeven price of switchgrass to be 98 \$ Mg⁻¹ with average yields of 9.42 Mg ha⁻¹. Epplin et al. [12] found that under a land-lease contract in Oklahoma, the estimated cost of switchgrass production was 41 \$ Mg⁻¹ under an assumed eight-month harvest window. The cost increased to 58 \$ Mg⁻¹ when the harvest window was restricted to two months per year. In Tennessee, based on farmer bids, the cost of producing switchgrass ranged from 40 \$ Mg⁻¹ to 60 \$ Mg⁻¹ assuming that an average yield of 15.70 Mg ha⁻¹ could be obtained. McLaughlin and Kszos [13] estimated USA farm-gate prices of switchgrass of 30 \$ Mg⁻¹, and 44 \$ Mg⁻¹ for average yields of 11.4 Mg ha⁻¹, and 9.4 Mg ha⁻¹, respectively. These studies did not consider the environmental consequences of producing switchgrass relative to existing land use and also did not place any monetary value on those consequences while estimating the farm-gate breakeven price of switchgrass.

Nelson et al. [14] discussed the environmental consequences of converting conventional crop land to switchgrass. They used the Soil and Water Assessment Tool (SWAT) watershed-scale water quality model [15-17] to determine the environmental outcomes of switchgrass production. They simulated switchgrass yields and other commodity crop yields and estimated the farm-gate breakeven price of switchgrass. Graham et al. [18] used the Environmental Policy Integrated Climate (EPIC) field-scale environmental model [19, 20] to predict switchgrass and other alternative crop yields and their associated environmental outcomes. They determined the farm-gate breakeven price of switchgrass by comparing it to the production of other alternative

crops. Both of these studies found that switchgrass production reduced soil erosion and nutrient loss compared to annual crops. King et al. [21] also found that switchgrass production reduced soil erosion and nutrient loss. However, these studies did not attach any monetary value to the environmental benefits derived from converting to switchgrass production while estimating the farm-gate breakeven price of switchgrass. Production practices budgeted to estimate in the recognition that the environmental consequences of biomass production from a dedicated energy crop such as switchgrass would be locally specific to the region surrounding the biorefinery constructed to process the feedstock. In addition, the environmental consequences would differ depending on the quality of the land used for producing the biomass and on the current use of the land.

The primary objective of this study is to determine the site-specific farm-gate breakeven price of switchgrass for two situations: (1) when external consequences are ignored and (2) when the environment costs of changes in soil erosion, fertilizer (nitrogen and phosphorous) runoff, and SOC are considered. To achieve the objective it is necessary to estimate the expected yield of switchgrass and grain-only wheat and the expected differences in nitrogen loss, phosphorous loss, soil loss, and changes in SOC for alternative soil classes over a multi-county area.

The landowners' decision regarding shifting into a long-term investment such as switchgrass by replacing an existing annual crop depends on the relative expected returns. Since no formal market exists for switchgrass biomass, the opportunity cost of producing switchgrass is estimated from the returns of the best alternative crop, which is wheat in the study region.

This study is divided into three sections: (1) the EPIC model, which was used to simulate the expected yield of switchgrass and wheat along with the environmental outcomes including (a) total soil loss (Mg ha^{-1}), (b) nitrogen loss (kg ha^{-1}), (c) phosphorous loss (kg ha^{-1}), and (d)

changes in SOC (kg ha^{-1}); (2) an economic model, which was used to estimate the farm-gate breakeven price of switchgrass when external consequences are ignored, and (3) the farm-gate breakeven price of switchgrass, which was estimated as a function of the environmental costs of soil erosion, fertilizer (nitrogen and phosphorous) runoff, and SOC depletion.

2. Materials and Methods

This study examined switchgrass production in counties surrounding a hypothetical potential biorefinery located near Okemah in Okfuskee County, Oklahoma. The site was chosen because it is located near the geographical center of three of the biorefinery locations (Lincoln, Hughes, and Muskogee counties) identified by the US-EPA [9]. This potential biorefinery is assumed to have an annual switchgrass feedstock requirement of 700,000 Mg. Debnath [22] previously determined the location and land classes where land would optimally be leased. Farm-gate breakeven prices were determined for each of these counties and land classes (Figure 1).

Data were obtained from several sources. Historical weather information was obtained from National Oceanographic Atmospheric Association (NOAA) [23] and Mesonet [24]. The quality of proposed land with land capability classifications of I, II, and III in each county was determined from the USDA-NRCS Land Survey Geographic (SSURGO) database [25]. Land classes greater than III have very severe limitations for crop production. Hence, the study was limited to land capability classes I-III (land class I, II, and III). The land capability classification is a system of grouping soils primarily on the basis of their capability to produce common cultivated crops and pasture plants without deteriorating over a long period of time. A land capability class within each county may include several soil series and types. Soils are classified into series based on morphology and other characteristics such as color, texture, structure, and mineral composition. Land classified as Class I in one region may not be nearly as productive as

Class I land in another region. Universal Soil Loss Equation (USLE) related attributes for each land class of each county was obtained from the USDA-NRCS [26] report. Production costs of switchgrass were obtained from Turhollow and Epplin [27] showed in table 1, while cost of grain-only wheat production was taken from the Oklahoma State University, enterprise budget database [28]. The price of wheat was obtained from the Food and Agricultural Policy Research Institute baseline model [29]. Environmental outcomes were valued based on previously published literature.

2.1. *EPIC model validation and simulation*

Switchgrass was assumed to be seeded with a no-till drill at a planting rate of 5.6 kg ha⁻¹, established, but not harvested, in year one. From year two onwards it was assumed to be fertilized with 78 kg of nitrogen ha⁻¹ y⁻¹. It was assumed that one condition of the land contract is that the land owner would be responsible for the cost of any phosphorus and potassium fertilizer and lime necessary for adequate pH, and adequate soil levels of phosphorus and potassium prior to switchgrass establishment [30]. The switchgrass plants are assumed to be cut at a height of about 15 cm. Plant material between the soil surface and 15 cm is assumed to be retained to maintain healthy stands. The mowed switchgrass biomass was assumed to be harvested (baled) once in October in each year. Production practices budgeted to estimate the cost of switchgrass establishment, maintenance, and harvest were based on a no-till establishment system [27]. Table 1 includes estimates of switchgrass production and harvest costs.

According to EPIC v. 0509 users guide “*MUSLE, MUSS, and MUST usually give similar results and are appropriate for estimating sediment yield from small watersheds up to about 250 km². The USLE is an erosion equation that is useful in studies like assessing the effect of erosion on productivity. RUSLE is preferred for steep slopes > 20%.*” [31]. The area of our

study region (65,382 ha) is 2.6 times the size of a small watershed of 25,000 ha (250 km²) suggested in the EPIC users guide, and the highest slope in our study region is 4% (Table 5). Therefore, instead of MUSLE (Modified-USLE) or RUSLE (Revised-USLE) which are used either for small watersheds or for the slopes greater than 20% [31], we choose USLE equation while establishing the EPIC simulation for the environmental outcomes.

The expected yields and the selected environmental outcomes for wheat and switchgrass production were simulated using the EPIC model. For wheat, only the grain was removed. Wheat residue was assumed to be returned to the soil surface. The EPIC crop yield estimates were calibrated and validated prior to executing the scenarios. The switchgrass and wheat yields were validated against results obtained from experimental field trial data [32, 33] shown in table 2, while the EPIC simulated soil loss for both switchgrass and wheat production were validated against the soil loss estimated using the USLE equation [22] shown in table 3. However, in the absence of any field trail SOC accumulation information, calibration of SOC could not be performed.

After the yields and the soil loss for both no-till wheat and switchgrass production are calibrated and validated, the calibrated models were used to simulate wheat and switchgrass yields and environmental outcomes based on 50 years of daily weather information. Each year's data was considered as a state of nature. The EPIC switchgrass simulation was performed under the assumption that crop land was converted from wheat to switchgrass and replanted every tenth year. Ten different 50 year random weather scenarios were generated based on a unique random number generator seed used in the EPIC control table. Each of these random weather scenarios was used to simulate a 50-year yield distribution along with the selected environmental outcomes for each county and each land class. The expected switchgrass and wheat yields and

environmental outcomes were then based on the results of the ten 50 year simulations (using random weather) for each crop.

2.2 *Economic model*

Site-specific enterprise budgets based on the detailed field operations for both crops were prepared for each county for each of three land capability classes [27, 28]. The foregone profit from the best alternative use, wheat production, was considered as the opportunity cost of the land for each land class (I, II, and III) and for each county. However, in this study while estimating the farm-gate breakeven price of switchgrass land was valued at a rate in excess of the revenue lost from not producing wheat. This is based on the assumption that a landowner would require an incentive to convert cropland from an annual crop to the perennial switchgrass [34]. Therefore, land value is the opportunity costs of the land derived from the forgone wheat production plus the extrapolated USDA [35] cropland rental rate¹. Since the switchgrass and wheat production costs were not inflated, a real rate of interest was used as the discount rate with the assumption that all prices will change as per the general inflation rate [36]. In the USA, the average real rate of interest over the last 15 years was 4% [37]. Therefore, a discount rate of 4% was used.

The net present value derived from wheat production in each county for each soil type from the profit maximizing landowners' perspective is estimated using the following equation:

$$E(NPVP_{c,s}^w) = \sum_{i=1}^n \left(\frac{p_i^w E(Y_{i,c,s}^w) - VC_{i,c,s}^w}{(1+r)^i} \right) \quad (1)$$

¹ USDA cropland rental rate is extrapolated using the following equation:

$\omega_{ij} = \mu_{ij} (\sum_j X_{ij} \chi_i / \sum_j \mu_{ij} X_{ij})$, ω_{ij} is the rental cost of a hectare of land in county i and land class j ; μ_{ij} is the potential wheat yield in county i and land class j as reported in the SSURGO data base, and; X_{ij} is the available hectares of land in county i and land class j ; χ_i is the USDA reported cropland rental rate for the county i

207 where $E(NPVP_{c,s}^w)$ is the expected private profit maximizing landowners' net present value
 208 derived from wheat production w for county c and land class type s ; P_i^w is the price of wheat w in
 209 year i ; $E(Y_{i,c,s}^w)$ is the expected wheat yield w for the i^{th} year and for county c and land class type
 210 s ; $VC_{i,c,s}^w$ is the entire production cost including the establishment costs, fertilizer costs, and
 211 harvesting costs of wheat production w in i^{th} year for county c and land class type s ; and r is the
 212 market discount rate. No value is included in the equation for wheat straw. Wheat produced in
 213 the region does not consistently produce sufficient residue to collect for biomass feedstock. Over
 214 years, plant breeders have bred and selected semi-dwarf hard red winter wheat varieties for grain
 215 production and disease resistance rather than straw production.

216 The net present value derived from switchgrass production in each county for each soil is
 217 estimated using the following equation:

$$218 \quad E(NPVP_{c,s}^g) = \sum_{i=1}^n \left(\frac{BEP_{c,s}^g E(Y_{i,c,s}^g) - E(Y_{i,c,s}^g) HC_{i,c,s}^g - VC_{i,c,s}^g - LC_{c,s}}{(1+r)^i} \right) \quad (2)$$

219 where $E(NPVP_{c,s}^g)$ is the expected private profit maximizing land owners' net present value
 220 derived from switchgrass production g for county c and land class type s ; $BEP_{c,s}^g$ is the private
 221 profit maximizing land owners' farm-gate breakeven price of switchgrass g for county c and land
 222 class type s ; $E(Y_{i,c,s}^g)$ is the expected switchgrass yield g for the i^{th} year and for county c and land
 223 class type s ; $HC_{i,c,s}^g$ is the harvesting costs of switchgrass production g in i^{th} year for county c
 224 and land class type s ; $VC_{i,c,s}^g$ is the fixed production cost including the establishment costs,
 225 fertilizer costs and other costs of switchgrass production g in i^{th} year for county c and land class
 226 type s ; $LC_{c,s}$ is the extrapolated USDA [35] cropland rental rate for county c and land class type
 227 s , to represent additional payment made to incentivize the landowner/farmer to switch from wheat
 228 to the perennial switchgrass.

The landowner/farmer would be indifferent between producing either wheat or switchgrass only when the net present value derived from producing wheat would be identical to the net present value derived from producing switchgrass. Therefore, the farm-gate breakeven price of switchgrass derived from private profit maximizing landowners' perspective is estimated by equating equation 1 and equation 2, and solving for $BEP_{c,s}^g$.

2.3 *Environmental Analysis*

The environmental analysis portion of this study deals with determining the differences in soil erosion, nitrogen and phosphorous runoff, and changes in SOC that would occur from converting traditional wheat production land into switchgrass production. The EPIC model was used to simulate 50-year site-specific distribution of environmental outcomes including nitrogen loss, phosphorous loss, off-site soil erosion, and changes in SOC derived from switchgrass and wheat production for each of the ten different random weather scenarios for each location. Site-specific simulated expected environmental outcomes were then estimated for each of the selected counties and land classes.

Each of the selected environmental variables (soil loss, fertilizer runoff, and SOC) would impose environmental consequences on the surrounding watershed and the atmospheric carbon cycle. The economic consequences of these environmental outcomes can be modeled either in terms of damage cost or abatement cost. The optimal level of abatement occurs where the marginal damage costs equal marginal treatment costs.

Several previous studies have estimated the costs associated with the abatement of agricultural runoff including nitrogen and phosphorous, and the off-site damage costs of soil erosion. Gerlach and DeSimone [38] estimated the abatement costs of nitrogen in Maryland to be 13 \$ kg⁻¹. Zivojinovich [39] estimated nitrogen abatement costs of 55 \$ kg⁻¹ using algal turf

scrubber. Ribaud et al. [40] estimated a US average nitrogen abatement cost using wetland restoration of 6.37 \$ kg⁻¹. Rabotyagov et al. [41] estimated that an abatement cost of 6.67 \$ kg⁻¹ would be required to reduce nitrogen loading by 30% through the reduction in the nitrogen fertilizer application on fields in the upper Mississippi River basin.

Non-point phosphorous abatement costs were estimated by Johansson and Randell [42], Johansson et al. [43], Keplinger et al. [44], and Ancev et al. [45]. Ancev et al. [45] estimated marginal phosphorous abatement costs equivalent with marginal damage costs from phosphorous pollution for the Eucha-Spavinaw watershed in Oklahoma to range from 14.16 \$ kg⁻¹ to 70.17 \$ kg⁻¹. Estimates of off-site damage costs from soil erosion including the non-monetary recreational values have also been produced in several previous studies [46-48].

In this study, the costs of abating nitrogen is assumed to be 6.37 \$ kg⁻¹ based on the Ribaud et al. [40] estimated USA average nitrogen abatement costs; while phosphorus, and off-site soil erosion damage are assumed to be 25.83 \$ kg⁻¹, and 3.15 \$ Mg⁻¹, respectively based on an estimate produced by Ancev et al. [45] for the Eucha-Spavinaw watershed which is located in Oklahoma near the study area, and Ribaud's [47] estimated off-site soil erosion damage costs for the US southern plains (all these values are in 2012 US dollars [49]). According to Bloomberg new energy finance [50], carbon credits have been auctioned for 12 \$ Mg⁻¹ to 15 \$ Mg⁻¹ of CO₂ by the California Air Resources Board. Therefore, the value of sequestering SOC was assumed to be 15 \$ Mg⁻¹ CO₂.

The net present value derived from wheat production in each county for each soil type when considering the selected environmental variables is:

$$E(NPVS_{c,s}^w) = \sum_{i=1}^n \left(\frac{p_i^w E(Y_{i,c,s}^w) - VC_{i,c,s}^w - \alpha N_{i,c,s}^w - \beta P_{i,c,s}^w - \lambda SL_{i,c,s}^w}{(1+r)^i} \right) \quad (3)$$

where $E(NPVS_{c,s}^w)$ is the expected net present value derived from wheat production w for county c and land class type s ; the additional terms $N_{i,c,s}^w$ and $P_{i,c,s}^w$ are the quantity of nitrogen and phosphorous runoff in kg ha^{-1} derived from wheat production for the i^{th} year and for county c and land class type s ; $SL_{i,c,s}^w$ is the quantity of soil loss in Mg ha^{-1} derived from wheat production for the i^{th} year and for county c and land class type s ; α, β are the abatement costs of nitrogen and phosphorous runoff respectively; and λ is the damage costs associated with the soil loss.

The net present value derived from switchgrass production in each county for each soil type when considering the selected environmental variables is:

$$E(NPVS_{c,s}^g) = \sum_{i=1}^n \left(\frac{BES_{c,s}^g E(Y_{i,c,s}^g) + \delta C_{i,c,s}^g - E(Y_{i,c,s}^g) HC_{i,c,s}^g - VC_{i,c,s}^g - LC_{c,s} - \alpha N_{i,c,s}^g - \beta P_{i,c,s}^g - \lambda SL_{i,c,s}^g}{(1+r)^i} \right) \quad (4)$$

where $E(NPVS_{c,s}^g)$ is the net present value derived from switchgrass production g for county c and land class type s ; $BES_{c,s}^g$ is the farm-gate breakeven price of switchgrass g for county c and land class type s including selected environmental values; $C_{i,c,s}^g$ is the net change in the quantity of SOC (Mg ha^{-1}) derived from switching to switchgrass production g from wheat production for the i^{th} year and for county c and land class type s ; $N_{i,c,s}^w, P_{i,c,s}^w$ and $SL_{i,c,s}^g$ are the quantity of nitrogen and phosphorous runoff in kg ha^{-1} and the quantity of soil loss in Mg ha^{-1} derived from switchgrass production g for the i^{th} year and for county c and land class type s ; δ is the carbon credit ($\$ \text{Mg}^{-1}$) producers' received for sequestering carbon by producing switchgrass; and other variables are as previously defined. Equating equation 3 and equation 4, and solving for $BES_{c,s}^g$ the site-specific farm-gate breakeven price of switchgrass was estimated for the internal costs plus selected external environmental consequences.

2.4 Sensitivity Analysis

Further, the sensitivity of the farm-gate breakeven price of switchgrass obtained under both scenarios (with and without considering the consequences of the selected environmental

outcomes) was examined. We analyzed three different scenarios to determine the robustness of our finding. These are: (a) doubled the rate of interest: a key parameter in estimating the NPVs'; (b) doubled the price of wheat: crucial in determining the opportunity cost of the land for each land class (I, II, and III); and (c) doubled the land rental rate: played significant role in incentivizing the landowner/farmer to move land from wheat to the perennial switchgrass production.

3. Results

The EPIC model predicts that there will be a significant reduction in nitrogen loss, phosphorous loss, and soil loss if no-till wheat production is replaced by switchgrass production. The site-specific reduction in estimated nitrogen loss ranges from $23.51 \text{ kg}^{-1} \text{ ha}^{-1} \text{ y}^{-1}$ on land class I in Hughes County to $68.54 \text{ kg}^{-1} \text{ ha}^{-1} \text{ y}^{-1}$ on land class III in Hughes County. The estimated reduction in soil loss ranges from $0.40 \text{ Mg}^{-1} \text{ ha}^{-1} \text{ y}^{-1}$ on land class II in Lincoln County to $2.71 \text{ Mg}^{-1} \text{ ha}^{-1} \text{ y}^{-1}$ on land class III in Hughes County. The estimated reduction in phosphorous loss ranges from $0.02 \text{ kg}^{-1} \text{ ha}^{-1} \text{ y}^{-1}$ on land class II in Latimer County to $1.89 \text{ kg}^{-1} \text{ ha}^{-1} \text{ y}^{-1}$ on land class III in McIntosh County. These are the net changes estimated from replacing no-till wheat production with switchgrass production (Table 4). The potential environmental benefits from converting land from no-till grain only wheat to switchgrass is greater on land more prone to erosion (land class III in this study region).

The production of switchgrass can also sequester SOC. In an average year the site-specific net increase in SOC derived from replacing no-till wheat with switchgrass ranges from $122.10 \text{ kg ha}^{-1}$ on land class III in Hughes County to $531.41 \text{ kg ha}^{-1}$ also in Hughes County on land class I (Table 4). However, the SOC accumulation is greater on land class I compared to land class II and III, due to increased plant biomass. In the absence of data required to calibrate

the EPIC model to observed SOC changes in response to regional conditions, these results completely rely on default EPIC values for simulating SOC values which are not consistent with the findings reported by Follett et al. [51]. They argue that essentially the SOC accumulation for switchgrass production remains in the same range regardless of the difference in the biomass yield. Another study done by Mondzozo et al. [52] showed that in the presence of carbon price switchgrass was favored over crop residue as an alternative feedstocks. Irrespective of the relationship between the biomass yield and SOC accumulation both study showed that the SOC accumulation has significantly increased with switchgrass production. However, whether SOC accumulation remain the same across different biomass yield or not does not change the finding of our study.

The average reductions in soil, nitrogen, and phosphorous losses estimated from switchgrass production on land class I are lower as compared to the estimated reductions for land classes II and III (Figure 2). The greatest environmental benefits occurred for land class III (with a slope gradient of 4%) in Hughes, McIntosh, and Pittsburg counties, which resulted from replacing no-till wheat production with switchgrass production (Table 4). On the other hand, switchgrass produced on land class I sequesters more carbon than that produced on land class II and class III (Figure 2). Therefore, converting land class III from no-till wheat to switchgrass production is associated with greater reduction in runoff and thus more beneficial to society compared to converting class I, and class II land.

The site-specific farm-gate breakeven price of switchgrass derived from the profit maximizing private landowner's (internal returns and cost) perspective ranges from 37 \$ Mg⁻¹ (Pottawatomie County land class I) to 66 \$ Mg⁻¹ (Johnston County land class I) (Table 5). Switchgrass produced on land class III of each county has a higher farm-gate breakeven price

compare to the switchgrass produced on land class I and land class II, due to lower yields. However, when the selected environmental consequences are valued and considered (on-farm plus environmental benefits) the breakeven price declines and ranges from 11 \$ Mg⁻¹ (Hughes County land class III) to 39 \$ Mg⁻¹ (Johnston County land class I). The average farm-gate breakeven price of switchgrass derived from the private landowners' perspective increases as the average yields decrease from good quality soil to lower quality soil. However, when selected environmental outcomes are valued then the average farm-gate switchgrass breakeven price decreases from good quality soil to lower quality soil. The selected environmental benefits derived from converting no-till wheat to switchgrass production on lower quality soil offsets the revenue loss due to lower yields on the lower quality soil.

Replacing no-till wheat production in Hughes County on land class III resulted in the greatest reduction in runoff and at the same time has the lowest SOC accumulation (Table 5). However, the benefits derived from reducing runoff exceeded the benefits derived from lower accumulation of SOC in Hughes County land class III compared to land class I and land class II of the same county, resulting in the lowest farm-gate breakeven price of switchgrass in Hughes County on land class III. Land class III of Hughes County, McIntosh County land class III and Pittsburg County land class III with a slope gradient of 4% has the highest potential runoff reduction from replacing no-till wheat with switchgrass, and also has the lowest farm-gate breakeven price of switchgrass 11 \$ Mg⁻¹, 13 \$ Mg⁻¹, and 13 \$ Mg⁻¹, respectively (Table 5) if the external costs are considered.

The difference between the farm-gate breakeven prices derived from the internal returns and cost perspective and the on-farm plus selected environmental consequences perspective (Table 5) range from 13 \$ Mg⁻¹ y⁻¹ on land class I in Latimer County to 46 \$ Mg⁻¹ y⁻¹ on land

class III in Pittsburg County. As expected these differences are highest for land class III in Hughes, McIntosh, and Pittsburg counties. When multiplied by the average switchgrass yield of 9 Mg ha⁻¹ y⁻¹, the environmental benefits derived from replacing no-till wheat with switchgrass on these highly erodible lands for land class III in Hughes, McIntosh, and Pittsburg counties would be on average 408 \$ ha⁻¹ y⁻¹.

The potential environmental benefits from converting land from no-till wheat to switchgrass production to produce feedstock for one potential 700,000 Mg y⁻¹ biorefinery can be estimated by multiplying these differences by the average yields per hectare and by the hectares of land converted for each land class and in each county (Table 5). The environmental benefit ranges from 5,652 \$ for 14 ha of McIntosh County land class I cropland to 3.47 \$ x 10⁶ for 6,368 ha of land class III cropland in Hughes County. In an average year, around 26 \$ x 10⁶ of environmental benefits could accrue to society from converting no-till wheat to switchgrass on 65,382 ha to produce feedstock for a single 700,000 Mg y⁻¹ biorefinery. These benefits follow from the assumptions that (a) the change in wheat production will be sufficiently small to not affect the wheat price; and (b) that the reduction of wheat produced in these counties will not provide an incentive for farmers elsewhere to increase land area seeded to wheat. On average, the highest annual environmental benefits were predicted for land class III (Figure 3). Therefore, converting the most erodible land from wheat to the production of switchgrass has the greatest potential environmental benefits. Therefore, any public policies designed to incentivize feedstock production might best serve the interest of society by including land quality considerations.

Results obtained from the sensitivity analysis of the site-specific breakeven price of switchgrass are shown in table 6. It is found that none of the results significantly change when (a) the discount rate is increased from 4% to 8%; (b) when the expected wheat price is doubled;

and (c) when the land rental values are doubled. The farm-gate breakeven price of switchgrass derived from only internal costs is greater than the farm-gate breakeven price of switchgrass derived from on-farm plus environmental benefits.

4. Discussion

This study found that switchgrass production has the potential to reduce nitrogen and phosphorous runoff, reduce soil loss, and increase sequestration of SOC, resulting in environmental benefits as compared to no-till wheat production. The economic differences in the environmental benefits between switchgrass production and no-till wheat production were determined by placing specific monetary values on the environmental benefits. Valuing selected environmental benefits derived from switchgrass production reduces the site-specific farm-gate breakeven price of switchgrass. The difference between the farm-gate breakeven prices of switchgrass derived from considering only the internal returns and cost and from considering on-farm plus selected environmental consequences was estimated to be greatest at 46 \$ Mg⁻¹ y⁻¹ on land class III in Pittsburg County and lowest at 13 \$ Mg⁻¹ y⁻¹ on land class I in Latimer County. Switchgrass production results in relatively greater environmental benefits when it is used to replace wheat grown on the most highly erodible land (land class III). Consideration of differences in environmental consequences and potential benefits to society would be appropriate if public policies are used to incentivize switchgrass production.

Sites with a slope gradient of 4% within the study area (Hughes County land class III, McIntosh County land class III and Pittsburg County land class III) have an average annual estimated environmental benefit of 408 \$ ha⁻¹ for reducing runoff by converting from no-till wheat to switchgrass.

In USA, the government established the Conservation Reserve Program (CRP) in 1985. Under the CRP program, highly erodible land was removed from agricultural production and planted to trees or perennial grasses [53]. Land included in the CRP is required to have an erodibility index equal to or greater than eight [54]. According to the estimated erodibility index, Hughes County land class III, McIntosh County land class III, and Pittsburg County land class III would qualify for inclusion in the CRP. Results show that when environmental benefits are considered the farm-gate breakeven price of switchgrass is lowest in those counties.

As noted, the estimated environmental benefits are contingent on the assumptions that conversion of cropland to switchgrass would not affect the wheat price, and that the reduction of wheat produced in these counties would not provide an incentive for farmers elsewhere to convert idle land or pasture land to wheat. For a single biorefinery, these assumptions are reasonable. However, if several million hectares were converted from cropland to switchgrass, crop prices could be expected to increase, providing an incentive to bring land elsewhere into crop production. As a result of the bulky nature of biomass, the production of dedicated biomass crops and the conversion of biomass to biobased products is likely to be locally focused. The environmental consequences of converting cropland to the production of dedicated energy crops will depend on local conditions. Thus, care should be made to not extrapolate the findings of this study to another region that has different soil and climate conditions and that produces other crops that would be displaced. However, the methods used in this study could be applied to other locations around the world. These findings could contribute to a more comprehensive life cycle analysis of consequences at a local, single biorefinery, level.

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References

- [1] Oklahoma State University, Department of Plant and Soil Science. Switchgrass: Environmental Impacts. 2014. <http://switchgrass.okstate.edu/environmental-impacts/environmental-impacts> [accessed 13.04.2014].
- [2] McLaughlin SB. New switchgrass biofuels research program for the Southeast. Proceedings of the Annual Automobile Technology Development Contractors' Coordination Meeting, Michigan, USA, Nov. 2-5, 1992. p. 111–115.
- [3] Monti A, Fazio S, Lychnaras V, Soldatos P, Ventri G. A full economic analysis of switchgrass under different scenarios in Italy estimated by BEE model. *Biomass and Bioenerg* 2007;(31):177–185.
- [4] Smeets EMW, Lewandowski IM, Faaij APC. The economical and environmental performance of miscanthus and switchgrass production and supply chains in a European setting. *Renew and Sustainable Energy Reviews* 2009;(13):1230–1245.
- [5] Samson RA, Omielan JA. Switchgrass: A potential biomass energy crop for ethanol production. Proceedings of the Thirteenth North American Prairie Conference: spirit of the land, our prairie legacy, Ontario, CA: Aug. 6-9, 1992. p. 253–1258.
- [6] van Dam J, Faaij APC, Petruzzi H, Turkenburg WC. Large-scale bioenergy production from soybeans and switchgrass in Argentina part B: Environmental and socio-economic impacts on a regional level. *Renew and Sustainable Energy Reviews* 2009;(13):1679–1709.
- [7] Ichizen N, Takahashi H, Nishio T, Liu G, Li D, Huang J. Impacts of switchgrass (*Panicum virgatum* L.) planting on soil erosion in the hills of the Loess Plateau in China. *Weed Biology Management* 2005;(5):31–34.

- [8] Ma Y, An Y, Shui J, Sun Z. Adaptability evaluation of switchgrass (*Panicum virgatum* L.) cultivars on the Loess Plateau of China. *Plant Science* 2011;(181):638–643.
- [9] US Environmental Protection Agency. Renewable Fuel Standard Program (RFS2) regulatory impact analysis. 2012. <http://nepis.epa.gov/Adobe/PDF/P1006DXP.PDF> [accessed 03.03.2012].
- [10] Mooney DF, Roberts RK, English BC, Tyler DD, Larson JA. Yield and breakeven price of ‘Alamo’ switchgrass for biofuels in Tennessee. *Agron J* 2009;(101):1234–1242.
- [11] Khanna M, Dhungana B, Brown JC. Costs of producing miscanthus and switchgrass for bioenergy in Illinois. *Biomass and Bioenerg* 2008;(32):482–93.
- [12] Epplin FM, Clark CD, Roberts RK, Hwang S. Challenges to the development of a dedicated energy crop. *Amer J Agr Econ* 2007;(89):1296–1302.
- [13] McLaughlin SB, Kszos LA. Development of switchgrass (*panicum virgatum*) as a bioenergy feedstock in the United States. *Biomass and Bioenerg* 2005;(28):515–535.
- [14] Nelson RG, Ascough II JC, Langemeier MR. Environmental and Economic Analysis of Switchgrass Production for Water Quality Improvement in Northeast Kansas. *J Environ Manage* 2006;(79):336–347.
- [15] Arnold JG, Moriasi DN, Gassman PW, Abbaspour KC, White MJ, Srinivasan R, Santhi C, Harmel RD, Griensven van A, Van Liew NW, Kannan N, Jha MK. SWAT: Model use, calibration, and validation. *T ASABE*. 2012;55(4):1491–1508.
- [16] Gassman PW, Reyes MR, Green CH, and Arnold JG. The Soil and Water Assessment Tool: historical development, applications, and future research directions. *T ASABE* 2007;50(4): 1211–1250.

484 [17] Williams JR, Arnold JG, Kiniry JR, Gassman PW, Green CH. History of model
 485 development at Temple, Texas. *Hydrolog Sci J* 2008;53(5): 948–960. Doi:
 486 10.1623/hysj.53.5.948.

487 [18] Graham RL, Downing M, Walsh ME. A framework to assess regional environmental
 488 impacts of dedicated energy crop production. *Environ Manage* 1996;(20):475–485.

489 [19] Williams JR, Jones CA, Dyke PT. A modeling approach to determining the relationship
 490 between erosion and soil productivity. *T ASAE* 1984;(27):129–144.

491 [20] Williams JR. The erosion productivity impact calculator (EPIC) model: a case history. *Phil*
 492 *Trans R Soc Lond*. 1990;(329): 421–428.

493 [21] King JE, Hannifan JM, Nelson RG. An assessment of the feasibility of electric power
 494 derived from biomass and waste feedstock. Report No. KRD-9513. Kansas Electric Utility
 495 Research Program and Kansas Corporation Commission, Topeka, KS. 1998. p. 280.

496 [22] Debnath D. Three Essays: Reservoir Management; Switchgrass Land Leasing; and its
 497 Environmental Impact. Ph.D. Dissertation, Department of Agricultural Economics,
 498 Oklahoma State University, Stillwater, OK. 2012.

499 [23] National Oceanographic Atmospheric Administration, National Climatic Data Center,
 500 National Climatic Data Center. Daily weather data for Oklahoma 1961-1994.
 501 <http://gis.ncdc.noaa.gov/map/cdo/> [accessed 02.03.2012].

502 [24] Mesonet Oklahoma. Oklahoma Climatological Survey: Daily weather data. 2011.
 503 http://www.mesonet.org/index.php/weather/category/past_data_files [accessed
 504 02.02.2012].

505 [25] US Department of Agriculture. Soil Service Geographic (SSURGO) Database for
 506 Oklahoma, 2011. <http://soils.usda.gov/survey/geography/ssurgo/> [accessed 08.15.2011].

507 [26] US Department of Agriculture. NRCS Part 630 Hydrology National Engineering
508 Handbook. Chapter 7. Hydrologic Soil Group, 2007.
509 <http://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=17757.wba>
510 [accessed 10.24.2012].

511 [27] Turhollow AF, Epplin FM. Estimating region specific costs to produce and deliver
512 switchgrass. Chapter 8 pp. 187-204 in Switchgrass: A valuable biomass crop for energy.
513 ed. Andrea Monti, New York: Springer Publishing Co. 2012.

514 [28] Oklahoma State University. Agricultural economics agricultural budget software. Dryland
515 wheat enterprise-grain only. Stillwater, OK. 2012.

516 [29] Food and Agricultural Policy Research Institute (FAPRI) Staff. 2010 U.S. and world
517 agricultural outlook. Ames, IA: FAPRI at Iowa State University; 2010. P. 435, FAPRI Staff
518 Report 07-fs1.

519 [30] Haque M, Epplin FM, Taliaferro CM. Nitrogen and harvest frequency effect on yield and
520 cost for four perennial grasses. Agron J 2009;(101):1463–1469.

521 [31] Williams JR, Wang E, Meinardus A, Siemers M, Atwood JD. EPIC Users guide v. 0509.
522 Temple, TX. 2006. <http://epicapex.tamu.edu/files/2013/02/epic0509usermanualupdated.pdf>
523 [accessed 16.10.2011]

524 [32] Fuentes RG, Taliaferro CM. Biomass yields stability of switchgrass cultivars. Trends in
525 new crops and new uses. J. Janick and A. Whipkey, eds. Alexandria, VA: ASHS Press.
526 2002. p. 276–82.

527 [33] Oklahoma State University. OSU small grains variety performance tests. Department of
528 Plant and Soil Science, Stillwater, OK. 2012. [http://wheat.okstate.edu/variety-testing/grain-](http://wheat.okstate.edu/variety-testing/grain-yield)
529 [yield](http://wheat.okstate.edu/variety-testing/grain-yield) [accessed 03.02.2012]

- [34] Fewell J, Bergtold J, Williams J. Farmer's willingness to grow switchgrass as a cellulosic bioenergy crop: A stated choice approach." Paper presented at the joint annual meeting of the Canadian Agricultural Economics Society and Western Agricultural Economics Association, Banff, Alberta, Canada, June 29-July 1, 2011.
- [35] US Department of Agriculture. National Agricultural Statistics Service (NASS) land values and cash rents, 2011. <http://quickstats.nass.usda.gov/results/63D3252C-0498-3E63-99DD-20935377B67D> [accessed 02.14. 2012].
- [36] Campbell HF, Brown RPC. Benefit-cost analysis financial and economic appraisal using spreadsheet. Melbourne, Australia: Cambridge University Press, 2009.
- [37] World Bank. Real Rate of Interest (%). International Monetary Fund, International Financial Statistics and data files using World Bank data on the GDP deflator. <http://data.worldbank.org/indicator/FR.INR.RINR> [accessed 10.04.2012].
- [38] Gerlach SB, DeSimone C. Refinement of nitrogen removal from municipal wastewater treatment plants. Maryland Department of the Environment. 2005.
- [39] Zivojnovich MJ. Algae based water treatment systems cost-effective nutrient population control and for point and nonpoint source applications. HydroMentia, Inc. Ocala, Florida, 2010. http://www.alachuacounty.us/Depts/EPD/WaterResources/SantaFeRiverSprings/110216_Algae%20Turf%20Scrubbers.pdf [accessed 03.05.2012].
- [40] Ribaud M, Delgado J, Hansen LR, Livingston M, Mosheim R, Williamson . Nitrogen in agricultural systems: Implication for conservation policy. RR -127. USDA, Economic Research Service, September 2011.

551 [41] Rabotyagov S, Campbell T, Jha M, Gassman PW, Arnold J, Kurkalova L, Secchi S, Feng
552 H, Kling CL. Least-cost control of agricultural nutrient contributions to the gulf of Mexico
553 hypoxic zone. *Ecol Appl* 2010;(20):1542-1555.

554 [41] Johansson RC, Randall J. Watershed abatement costs for agricultural phosphorous. *Water*
555 *Resour Res* 2003;(4):3.1-3.8.

556 [43] Johansson RC, Gowda PH, Mulla DJ, Dalzell BJ. Metamodelling phosphorous best
557 management practices for policy use: a frontier approach. *Agri Econ* 2004;(30):63-74.

558 [44] Keplinger KO, Houser JB, Tanter AM, Hauck LM, Beran L. Cost and affordability of
559 phosphorous removal at small wastewater treatment plants. *Small Flow Quart* 2005;(5):36-
560 50.

561 [45] Ancev T, Stoecker AL, Storm DE, White MJ. The economics of efficient phosphorous
562 abatement in a watershed.” *J Agr and Resource Econ* 2006;(31):529-548.

563 [46] Pimentel D, Harvey C, Resosudarmo P, Sinclair K, Kurz D, McNair M, Crist S, Shpritz L,
564 Fitton L, Saffouri R. and Blair R. Environmental and economic costs of soil erosion and
565 conservation benefits.” *Science, New Series* 1995;(267):1117-1123.

566 [47] Ribaud M. Reducing soil erosion: offsite benefits. USDA, Economic Research Service.
567 *Agricultural Economic Report No. 561*. 1986.

568 [48] Hauszar P, Piper S. Estimating the off-site costs of wind erosion in New Mexico. *J Soil*
569 *Water Conserv* 1986;(41):414-416.

570 [49] U.S. Bureau of Labor Statistics. CPI inflation calculator, 2012.
571 http://www.bls.gov/data/inflation_calculator.htm [accessed 09.12.2012].

- 572 [50] Lynn D. California carbon allowances sold out at \$10.09 in auction. 2012.
573 [http://www.bloomberg.com/news/2012-11-19/california-carbon-allowances-sold- for-10-](http://www.bloomberg.com/news/2012-11-19/california-carbon-allowances-sold-for-10-09-in-first-auction.html)
574 [09-in-first-auction.html](http://www.bloomberg.com/news/2012-11-19/california-carbon-allowances-sold-for-10-09-in-first-auction.html) [accessed 11.02.2012].
- 575 [51] Follett RF, Vogel KP, Varvel GE, Mitchell RB, Kimble J. Soil carbon sequestration by
576 switchgrass and no-till maize grown for bioenergy. *Bioenerg Res* 2012;(5):866–875.
- 577 [52] Mondzozo AE, Swinton SM, Izaurrealde RC, Manowitz DH, Zhang X. Maintaining
578 environmental quality while expanding biomass production: Sub-regional U.S. policy
579 simulations. *Energy Pol* 2013;(57):518–531.
- 580 [53] Mapemba LD, Epplin FM, Taliaferro CM, Huhnke RL. Biorefinery feedstock production
581 on conservation reserve program land. *Rev Agr Econ* 2007;(29):227–246.
- 582 [54] US Department of Agriculture, Farm Service Agency Fact Sheet. 2013.
583 http://www.fsa.usda.gov/Internet/FSA_File/crpfactsheet0213.pdf [accessed 03.02.2012].

1 Table 1. Estimated annual production and harvesting costs of switchgrass.

Item	Unit	Quantity	Price unit	Costs
			\$	\$ ha ⁻¹
Establishment costs	ha	1.00		394.45
Land rental	ha	1.00	variable	variable
Establishment costs, amortized for 10 years at 6.5%	\$		0.065	variable
Nitrogen	kg	78.00	1.23	95.94
Annual Maintenance costs	\$	1.00		9.63
Mowing	ha	1.00		30.97
Raking	ha	1.00		18.89
Baling, 681 kg dry biomass rectangular bale	kg	variable	28.89	variable
Total costs	\$			variable

3 Table 2. Comparison between measured and simulated no-till wheat and switchgrass yields

	Wheat		Switchgrass	
	Measured yields	Simulated yields	Measured yields	Simulated yields
Mean (Mg ha ⁻¹)	2.70	2.65	14.68	14.41
St. Dev.	0.96	0.70	4.29	4.16
Maximum (Mg ha ⁻¹)	4.71	4.18	23.10	21.81
Minimum (Mg ha ⁻¹)	1.35	1.59	7.28	7.57

4

5 Table 3. Comparison between estimated and simulated soil loss derived from no-till wheat and
 6 switchgrass production.

	Wheat		Switchgrass	
	USLE* estimated soil loss	EPIC simulated soil loss	USLE* estimated soil loss	EPIC simulated soil loss
Mean (Mg ha ⁻¹)	1.99	1.77	0.20	0.14
St. Dev.	1.62	1.23	0.16	0.10
Maximum (Mg ha ⁻¹)	7.46	5.81	0.75	0.51
Minimum (Mg ha ⁻¹)	0.42	0.40	0.04	0.02

7 *USLE: Universal Soil Loss Equation

8

Table 4. Site-specific soil loss, nitrogen loss, phosphorous loss reduction and accumulation of soil organic carbon (SOC) derived from replacing no-till wheat production with switchgrass production.

County land class (LC)	Slope (%)	Soil loss reduction (Mg ha ⁻¹ y ⁻¹)	Nitrogen loss reduction (kg ha ⁻¹ y ⁻¹)	Phosphorous loss reduction (kg ha ⁻¹ y ⁻¹)	Changes in SOC (kg ha ⁻¹ y ⁻¹)
Creek LC-I	0.5	1.4	43.6	0.8	158.2
Haskell LC-I	1.0	1.3	46.4	0.9	390.9
Hughes LC-I	1.0	0.8	23.5	1.3	531.4
Johnston LC-I	0.5	1.3	38.3	1.0	367.3
Lincoln LC-I	0.5	0.8	33.7	0.7	231.7
McIntosh LC-I	0.5	1.4	41.0	0.4	524.8
Okfuskee LC-I	0.5	1.2	37.8	0.7	156.0
Oklahoma LC-I	0.5	0.4	33.6	0.4	412.3
Okmulgee LC-I	1.0	1.2	31.4	1.2	467.8
Pittsburg LC-I	1.0	1.2	34.0	0.4	419.4
Pottawatomie LC-I	0.5	1.1	33.4	0.9	395.1
Seminole LC-I	0.5	2.0	41.0	1.3	241.2
Wagoner LC-I	1.0	0.8	29.1	0.7	157.8
Coal LC-II	2.0	2.0	39.8	0.9	302.4
Creek LC-II	2.0	1.2	43.6	1.0	151.9
Hughes LC-II	2.0	1.0	36.0	1.3	261.0
Latimer LC-II	1.0	0.5	25.7	0.0	294.5
Lincoln LC-II	0.5	0.4	25.1	0.6	336.6
McIntosh LC-II	2.0	3.0	59.5	1.4	404.8
Okfuskee LC-II	0.5	0.6	25.9	0.1	319.9
Oklahoma LC-II	0.5	0.9	44.4	0.7	309.6
Okmulgee LC-II	2.0	1.7	52.4	1.2	326.4
Pittsburg LC-II	2.0	2.3	47.7	0.7	209.0
Seminole LC-II	0.5	0.9	41.0	1.3	241.2
Creek LC-III	2.5	3.0	52.2	1.4	210.8
Hughes LC-III	4.0	5.5	68.5	1.3	122.1
McIntosh LC-III	4.0	3.4	66.0	1.9	290.2
Muskogee LC-III	2.0	3.3	29.1	0.7	194.2
Okfuskee LC-III	0.5	0.5	25.9	0.1	279.9
Okmulgee LC-III	1.0	1.5	31.1	0.5	432.9
Pittsburg LC-III	4.0	3.7	63.2	1.5	154.1
Seminole LC-III	2.0	1.9	55.2	1.5	135.9
Wagoner LC-III	1.0	1.3	56.2	1.1	137.8

Table 5. Site-specific farm-gate breakeven price of switchgrass with and without valuing the selected environmental consequences, the differences between them, and hectares of land leased of each land class for each county, and the corresponding environmental benefits.

County land class (LC)	Slope (%)	Internal breakeven price (Mg ⁻¹)	Internal & external breakeven price (Mg ⁻¹)	Difference* (Mg ⁻¹)	Land (ha)	Environmental benefits
Creek LC-I	0.5	\$48	\$25	\$23	1,337	\$470,180
Haskell LC-I	1.0	\$53	\$28	\$24	65	\$28,472
Hughes LC-I	1.0	\$49	\$30	\$19	329	\$99,123
Johnston LC-I	0.5	\$66	\$39	\$27	107	\$51,403
Lincoln LC-I	0.5	\$53	\$36	\$18	251	\$75,644
McIntosh LC-I	0.5	\$51	\$24	\$26	14	\$5,652
Okfuskee LC-I	0.5	\$50	\$32	\$18	774	\$252,815
Oklahoma LC-I	0.5	\$54	\$36	\$19	590	\$200,654
Okmulgee LC-I	1.0	\$49	\$27	\$22	544	\$192,701
Pittsburg LC-I	1.0	\$53	\$33	\$20	142	\$49,768
Pottawatomie LC-I	0.5	\$37	\$20	\$17	669	\$211,861
Seminole LC-I	0.5	\$54	\$32	\$22	120	\$44,981
Wagoner LC-I	1.0	\$52	\$34	\$18	773	\$252,212
Coal LC-II	2.0	\$51	\$34	\$16	999	\$275,298
Creek LC-II	2.0	\$51	\$16	\$34	3,647	\$1,422,695
Hughes LC-II	2.0	\$50	\$28	\$23	2,645	\$934,153
Latimer LC-II	1.0	\$50	\$37	\$13	740	\$163,834
Lincoln LC-II	0.5	\$55	\$37	\$18	2,895	\$815,349
McIntosh LC-II	2.0	\$56	\$18	\$38	1,413	\$743,870
Okfuskee LC-II	0.5	\$52	\$38	\$15	1,057	\$253,309
Oklahoma LC-II	0.5	\$56	\$34	\$22	2,882	\$1,070,551
Okmulgee LC-II	2.0	\$52	\$19	\$33	3,003	\$1,467,664
Pittsburg LC-II	2.0	\$55	\$32	\$24	2,774	\$1,065,487
Seminole LC-II	0.5	\$54	\$32	\$22	1,329	\$498,166
Creek LC-III	2.5	\$56	\$12	\$44	3,842	\$1,757,661
Hughes LC-III	4.0	\$56	\$11	\$45	6,348	\$3,472,148
McIntosh LC-III	4.0	\$58	\$13	\$45	552	\$290,040
Muskogee LC-III	2.0	\$54	\$37	\$17	4,623	\$1,181,251
Okfuskee LC-III	0.5	\$53	\$39	\$14	3,154	\$715,647
Okmulgee LC-III	1.0	\$54	\$30	\$24	5,139	\$1,773,843
Pittsburg LC-III	4.0	\$58	\$13	\$46	5,938	\$3,056,363
Seminole LC-III	2.0	\$57	\$26	\$31	2,242	\$898,225
Wagoner LC-III	1.0	\$55	\$26	\$29	4,445	\$2,075,663
Total						\$25,866,681

*Column 3–column 4

18 Table 6. Sensitivity analysis of the site-specific breakeven price Mg^{-1} of switchgrass.

Internal Breakeven Price			
	Land Class I	Land Class II	Land Class III
Discount rates 4%	\$51.47	\$52.96	\$55.76
Discount rate double (8%)	\$53.63	\$55.22	\$57.86
Wheat Price double	\$107.65	\$111.96	\$118.41
Land rent double	\$55.64	\$57.34	\$59.92
Internal and external breakeven price			
Discount rates 4%	\$30.45	\$29.54	\$22.87
Discount rates double (8%)	\$29.91	\$29.03	\$22.40
Wheat Price double	\$88.28	\$86.59	\$85.58
Land rent double	\$34.58	\$33.65	\$27.09
Differences between internal and internal plus external breakeven price			
Discount rates 4%	\$21.03	\$23.41	\$32.89
Discount rates double (8%)	\$23.72	\$26.19	\$35.46
Wheat Price double	\$19.37	\$25.37	\$32.83
Land rent double	\$21.06	\$23.69	\$32.83

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3 Figure 1. Land to be converted to switchgrass to support a hypothetical biorefinery at Okemah,
4 Oklahoma, USA.

5

—○— $\pm$ 1 standard deviation from the average annual reduction in soil loss, nitrogen and phosphorous runoff, and SOC accumulation

6

7

8 Figure 2. Average per year reduction in soil loss, nitrogen loss, phosphorous loss, and SOC
9 accumulation between land class I (LC I), land class II (LC II), and land class III (LC III).

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13 Figure 3. Average annual total environmental benefits derived to society from the establishment
14 of a hypothetical biorefinery requiring 700,000 Mg y⁻¹ of switchgrass feedstock obtained from
15 5,715 ha of land class I; 23,384 ha of land class II; and 36,283 ha of land class III.

16