Development of Sustainable Landscape Designs for Improved Biomass Production in the U.S. Corn Belt

A Thesis

Presented in Partial Fulfillment of the Requirements for the

Degree of Master of Science

with a

Major in Environmental Science

in the

College of Graduate Studies

University of Idaho

by

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May 2015

Authorization to Submit Thesis

This thesis of Ian J. Bonner, submitted for the degree of Master of Science with a Major in Environmental Science and titled "***Development of Sustainable Landscape Designs for Improved Biomass Production in the U.S. Corn Belt***," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

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Abstract

Demand for renewable and sustainable energy options has resulted in a significant commitment by the US Government to research pathways for fuel production from biomass. The research presented in this thesis describes one potential pathway to increase the amount of biomass available for biofuel production by integrating dedicated energy crops into agricultural fields. In the first chapter an innovative landscape design method based on subfield placement of an energy crop into row crop fields in central Iowa is used to reduce financial loss for farmers, increase and diversify biomass production, and improve soil resources. The second chapter explores how subfield management decisions may be made using high fidelity data and modeling to balance concerns of primary crop production and economics. This work provides critical forward looking support to agricultural land managers and stakeholders in the biomass and bioenergy industry for pathways to improving land stewardship and energy security.

Acknowledgements

This work was made possible by the Biofuels and Renewable Energies Department and Employee Education Program of the Idaho National Laboratory. I thank my manager, Christopher Wright, for his encouragement and support in the pursual of this degree and research. I owe thanks to all of my colleagues who were instrumental in the completion of the research, analyses, and manuscript preparation, including but not limited to: Dave Muth and Gabe McNunn of AgSolver Inc., Kara Cafferty and Jacob Jacobson of INL, and Doug Karlen and Mark Tomer of USDA ARS. Finally, I thank my Major Professor, Max Dakins, for her support, enthusiasm, and patience along our many trips through the weeds. The work presented in this thesis is a synthesis of many great minds; it was my pleasure and honor to be a part of this important research.

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Introduction

Transportation fuels account for 67% of petroleum use in the United States (US), or about 8.5 million barrels of oil per day. This massive consumption of non-renewable fuel has led to increased attention on more sustainable and renewable sources of fuel that also reduce our dependency on foreign oil. To address this, the US Congress passed the Renewable Fuels Standard (RFS) as part of the Energy Independence and Security Act (EISA) of 2007 (U.S. Congress, 2007). The RFS requires 136.3 billion liters (L; 36 billion gal) of biofuels to be used within the US by 2022. While ethanol production from grain-based starch (e.g., corn, wheat, or sorghum grain) is a large industry in the US, producing 54.3 billion L (14.3 billion gal) of ethanol in 2014 (RFA, n.d.), controversy over expanding the use of food crops for energy has led to a RFS goal contribution limit of 56.8 billion L (15 billion gal) for this category of biofuel. The RFS instead adds to the renewable fuel portfolio through the use of non-conventional feedstocks to produce the remaining 79.5 billion L of biofuels (21 billion gal). Of this remainder, 60.6 billion L (16 billion gal) are to be produced from lignocellulosic sources (e.g., agricultural and forest residues and dedicated energy crops). Using a conventional conversion rate of 252 L of ethanol per metric ton of biomass (Humbird et al., 2011), over 242 million metric tonnes (Mg) of biomass would need to be collected and processed annually.

With such an ambitious goal in place, researchers began exploring how much feedstock is sustainably available for bioenergy use within the US. Of major interest were agricultural residues, as they are a presently underutilized source of biomass, harvestable with existing feed and forage equipment, and available at potentially low costs. The Idaho National Laboratory (INL) developed the Landscape Environmental Assessment Framework (LEAF) to estimate the amount of various agricultural residues that could be collected from across the US without negatively impacting soil resources (Muth & Bryden, 2013). The first implementation of LEAF used a series of well-vetted

United States Department of Agriculture (USDA) Natural Resource Conservation Service (NRCS) models to estimate quantitative soil erosion and qualitative soil organic carbon changes resulting from the removal of biomass from agricultural fields. Early analyses by Muth et al. (2013) used LEAF to quantify the amount of biomass that would be sustainably available from agricultural residues across the US without exceeding soil erosion limits or depleting soil organic carbon. This information was then used to inform resource availability for the 2011 Billion Ton Update (BTU) (Perlack & Stokes, 2011); a key piece of literature published by the US Department of Energy (DOE) Bioenergy Technologies Office (BETO) quantifying where resources exist and at what price.

The data made available by the BTU has been the standard source of feedstock availability and future projections for modeling the costs of biofuel production in a mature "billion-ton" biofuel economy. While the BTU has provided critical forward-looking analytical estimates for researchers, industry, and government programmatic goals, the coarse-resolution of its analyses have certain limitations. One notable criticism of the BTU is the omission of practicality and cost of retrieving resources from the site of production and delivering them to a conversion facility. The added cost of feedstock logistics (all of the operations occurring between the farm and refinery, such as storage, handling, and transportation) can quickly add an economic burden to the processing of agricultural residues into biofuels (Hess et al., 2007). Ongoing research at INL has been working to understand the costs associated with retrieving resources that may be isolated or operationally problematic to collect for industrial scale bioenergy production. One key variable in operating cost effective logistics systems is biomass availability, or how much biomass is produced within a given draw area of the end user (Hess et al., 2009). In areas where agricultural land use is dominant, large amounts of residue may be produced, but may not be sustainably collected without putting soil resources at risk (Karlen et al., 2011). Understanding the balance between resource availability and sustainability is paramount for responsible production of biofuels from biomass

(Wilhelm et al., 2010). Only with an understanding of the relationship between soil health, residue collection, and land management practices can informed recommendations be made as to how changes in management can improve biomass availability, sustainability, and economic viability for both biomass producers and end users.

Adoption of conservation practices that protect soil resources is one method of enabling sustainable removal of agricultural residues. Bonner et al. (2014b) demonstrated through LEAF analyses that application of a cover crop or vegetative barriers can increase the amount of sustainably available corn stover (the residual material remaining in the field after grain harvest) in the top five corn producing US states by nearly threefold. This type of management approach capitalizes on the strengths of a conservation practice to overcome the pitfalls of stover removal. When agricultural residues are collected the soil's surface cover is reduced, making it more vulnerable to the erosive forces of wind and water. However, if an erosion-limiting practice such as a winter cover crop is established, the soil's surface is protected by live growth during the vulnerable parts of the year when a field is idle. This added resilience then allows biomass such as corn stover to be collected, or collected in greater quantities, without jeopardizing soil health. Pratt et al. (2014) investigated this potential increase in corn stover availability on the economic return for farmers, discovering that the additional revenue from stover collection can be sufficient to offset the establishment costs of the cover crop. This finding is particularly important as it demonstrates a practical and economically favorable means of increasing biomass availability and sustainability.

The manuscripts included in this thesis utilize LEAF to explore another potential pathway for increasing biomass availability while protecting soil resources and improving the economic return for growers. Both chapters focus on corn-producing lands and the collection of corn stover as the primary agroecosystem and feedstock of interest. Corn stover has been identified as a pioneer feedstock for the emerging lignocellulosic ethanol industry, as demonstrated by the development of three commercial biorefineries in the US Midwest in 2014 and 2015, each using more than 272,000 Mg (300,000 dry tons) of corn stover per year to produce nearly 227 million L (60 million gallons) of ethanol in total.

The first chapter, Opportunities for Energy Crop Production Based on Subfield Scale Distribution of Profitability, explores the potential opportunity for dedicated energy crops to be placed within corn-producing fields in such a way that farm level economic performance is increased, environmental impacts are reduced, and the amount of biomass produced is diversified and increased (Bonner et al., 2014a). This type of management approach utilizes the conservation benefits of perennial crops to improve the sustainability of biomass production, but uses subfield management of profitability to enable the conversion of lands for alternative uses. This work directly impacts concerns of land-use sustainability in the intensely managed agricultural system of the US Corn Belt. The research presented describes the opportunity that may exist should a demand for dedicated energy crops emerge and markets develop. In addition, the co-production of dedicated energy crops with agricultural residue diversifies the feedstock production and density within a given area, enabling a more cost effective logistics system, multiple end users, or feedstock blending, as suggested by INL's 2017 Design Case as a means to further reduce delivered feedstock price and supply risk (Kenney, 2013).

The second chapter, Development of Integrated Bioenergy Landscapes Using Precision-Conservation and Multi-Criteria Decision Analysis Techniques , focuses on the methods by which the subfield decisions conceptualized in Chapter 1 could be developed and customized into actionable management zones. Profitability of corn production based on actual harvesting data for a field in northern Iowa is used in conjunction with modeled metrics for soil health to identify areas of the field that would benefit most from conversion to a dedicated energy crop. The multi-criteria decision analysis method used provides a flexible means to balance the tradeoffs between primary crop production, economic return, and the sustainability of land management. In addition, the work valorizes environmental improvements by applying direct and indirect costs to three major sustainability criteria: soil erosion, nitrate leaching, and soil organic carbon. When the financial savings from environmental improvements are combined with the estimated cost of establishing and maintaining a dedicated energy crop, the economic gap between present practices and a sustainable bioenergy landscape is narrowed.

The objective of the research presented in this thesis is to demonstrate potentially actionable pathways to sustainable land management for agriculture and biofuels through analytical assessment. The work presented is not a roadmap to success, but instead is a critical toolset for understanding the complexity of land management and developing communicable opportunities and pathways that may be adopted, customized, and deployed by land managers and stakeholders in the biomass and bioenergy industries. The results of this work demonstrate significant opportunity for improving the environmental and economic sustainability of biomass production and the development of reliable systems for food, feed, fiber, and fuel production.

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Chapter 1. *Opportunities for Energy Crop Production Based on Subfield Scale Distribution of Profitability*

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Published Open Access in: Energies, 2014, 7, 6509-6526; doi: 10.3390/en7106509

1.1. Abstract

Incorporation of dedicated herbaceous energy crops into row crop landscapes is a promising means to supply an expanding biofuel industry while benefiting soil and water quality and increasing biodiversity. Despite these positive traits, energy crops remain largely unaccepted due to concerns over their practicality and cost of implementation. This paper presents a case study for Hardin County, Iowa, to demonstrate how subfield decision making can be used to target candidate areas for conversion to energy crop production. Estimates of variability in row crop production at a subfield level are used to model the economic performance of corn (*Zea mays* L.) grain and the environmental impacts of corn stover collection using the Landscape Environmental Analysis Framework (LEAF). The strategy used in the case study integrates switchgrass (*Panicum virgatum* L.) into subfield landscape positions where corn grain is modeled to return a net economic loss. Results show that switchgrass integration has the potential to increase sustainable biomass production from 48% to 99% (depending on the rigor of conservation practices applied to corn stover collection), while also improving field level profitability of corn. Candidate land area is highly sensitive to grain price (0.18 to 0.26 $\$\cdot kg^{-1}$) and dependent on the acceptable subfield net loss for corn production (ranging from 0 to −1000 $\$\cdot ha^{-1}$) and the ability of switchgrass production to meet or exceed this return. This work presents the case that switchgrass may be economically

incorporated into row crop landscapes when management decisions are applied at a subfield scale within field areas modeled to have a negative net profit with current management practices.

1.2. Introduction

While national assessments have identified sufficient biomass resources to meet long term energy goals [1], much of these resources are inaccessible due to economic constraints [2–4]. Some of this is due in part to stranded resources or resources that are remote or isolated due to economies of scale, transportation, and acquisition costs. Strategies to capture these resources exist, like the uniform-format supply system design, but that strategy requires large investments into new infrastructure [5]. The appearance of first generation lignocellulosic conversion plants in highly productive areas of the U.S. Midwest demonstrates the capability to acquire resources at a competitive price in today's market, but future markets will require improvements in sustainability, productivity, and profitability to meet the mandated production of the Energy Independence and Security Act of 2007 (EISA) [6]. Proactive solutions must be developed to address the economic and environmental constraints that limit the amount of agricultural residues (primarily corn (Zea mays L.) stover) currently available for energy use [4,7,8]. Incorporation of high yielding dedicated energy crops into agricultural lands to supplement the current supply of agricultural residues is a promising option, but one that must first overcome concerns of negatively impacting food and fiber supplies, practical limitations, and economic viability [9–12].

Switchgrass (*Panicum virgatum* L.), a perennial herbaceous species, is a promising candidate for integration into America's Corn Belt for biomass production because of its potential for high yields and positive environmental impacts. Under proper management, switchgrass yields of 10 to 15 Mg·ha−1 are reported when appropriate varieties are chosen [13–15]. The increased productivity per areal unit of switchgrass can reduce the draw radius required to supply a biorefinery or satellite processing location, decreasing land use requirements and allowing greater efficiency and productivity of a growing bioenergy system [16]. Additionally, the flexible harvest window and perennial nature of switchgrass results in positive benefits to soil health [17,18], water quality [19], and ecosystem services [20,21]. Despite these positive traits, adoption of switchgrass into agricultural lands has been limited due to a lack of mainstream acceptance as a bioenergy feedstock and uncertain risk of production [9,22,23].

Agricultural land management decisions are complex in nature, varied by site specific conditions, land tenure, policy, perception, and farm-scale economic constraints [24–26]. However, adoption of herbaceous energy crops into agricultural lands dominated by high-value row crops will depend largely on the crop's ability to generate comparable income [26,27]. This view implies that energy crops must be more profitable than row crops to merit a land use change. While this is indeed a logical approach, it is necessary to first consider the scale at which the comparison is being made. Rather than proposing conversion of whole land units to energy crops, we propose that subfield decisions can be used to identify candidate areas where economic competition may favor energy crops.

Subfield decision making has been greatly enabled in recent years due to the development of precision agriculture and remote sensing technologies. Nutrient management is a key example of this; using spatial grain yield monitoring and soils data, variable rate nutrient application plans are developed to better manage the heterogeneity of a field's productivity and economics [28]. With access to similar high fidelity data, precision conservation techniques have become increasingly more common in the agricultural research community. Using remote sensing techniques Daughtry et al. [29] have investigated the variation in corn stover residue cover within fields to better inform tillage intensity and soil management practices. Tomer et al. [30] have utilized LiDAR (Light Detection and Ranging) data together with soil survey and field specific land use information to develop a precision watershed management framework to identify those areas where conservation practices could improve soil health and protect water quality. Similar to nutrient management, Muth et al. [31] have combined yield monitoring data with subfield soil and surface conditions to demonstrate the necessity for managing sustainable corn stover collection on a subfield basis. Abodeely et al. [32] continued the work of Muth et al. to suggest integration of switchgrass based on protecting sensitive portions of the field from erosion and nutrient loss. Our research expands upon these precision conservation techniques to identify the areas of fields where energy crops may be more economically competitive compared to row crops and explores the potential increase to county level biomass production.

This work utilizes Natural Resources Conservation Service (NRCS) SSURGO (Soil Survey Geographic Database) soil map units [33] to distribute grain production across each field in Hardin County, Iowa and determine subfield profit during the period of 2007 to 2012. Using estimated yields of corn stover and switchgrass, the Landscape Environmental Assessment Framework (LEAF) [34] is used to show how the quantity of sustainably available biomass increases as non-profiting areas are removed from row crop production and converted to switchgrass. The objective of this work is to demonstrate the potential opportunity for switchgrass to enter row crop landscapes when management decisions are based on subfield profitability. The results of this work investigate if precision conservation principals used to incorporate energy crop production on less profitable portions of row crop lands can be an economically viable pathway for increasing bioenergy feedstock supplies.

1.3. Methods

1.3.1. Study Area

This analysis uses Hardin County, Iowa as the area of interest. This county includes areas that boast corn yields that are amongst the greatest found in rain fed areas of the Corn Belt; county-wide average annual grain yields were 10.9 ± 0.5 (mean ± 95% confidence interval (CI)) $Mg \cdot ha^{-1}$ from 2001 to 2013, and 43% to 56% of county's 147,600 ha area was used for corn production each year [35]. Field delineations are developed beginning with publicly released (pre-2008) USDA-Farm (United States Department of Agriculture) Service Agency Common Land Unit boundary data, with all farm-level and county-level attributions removed. Field boundaries were edited using 2009 National Agricultural Imagery Program [36] to minimize the number of field polygons with mixed land cover, resulting in a total of 4659 unique parcels. Only fields that were used to produce corn between 2007 and 2012 are used in this analysis (4234 total). The field-specific information on crop rotations was determined by overlaying yearly crop-cover data for 2007–2012, obtained from the USDA National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) [37], with the field boundaries. A six-year sequence of majority crop cover was determined for each field, but flagged if the majority cover was less than 75% of the field's area. These sequences were classified into groups: i.e., a corn-soybean (*Glycine max* (L.) Merr.) (CS) rotation indicated a sequence of either "CSCSCS" or "SCSCSC" across the six year period, a "continuous corn" (CC) rotation was assigned to those fields under corn production all six years (i.e., "CCCCCC"), and "continuous corn with soybean" (CCS) was assigned to fields in which consecutive years of corn occurred at least once, and soybean was the only other crop observed (i.e., "CSCCSC"). These were the dominant rotations and comprised 87% of the cropland in Hardin County, with the remaining cropland occupied by three minor classes. In situations where additional crops were grown in rotation, a "conservation rotation" was denoted if the third crop was a perennial (i.e., alfalfa), or an "extended rotation" was denoted if the additional crop was an annual (i.e., wheat or oats). Finally, a "mixed agriculture" was designated where the CDL information indicated a rotation that did not fit into the above classes, or if majority cover was difficult to discriminate (i.e., small fields or fields in contour-strip rotations). It is recognized that field boundaries may have changed over the study duration and that the simplification of crop rotations introduces error; however, those fields falling in the three largest classes were indicated to have at least 75% cover of the majority crop all six years, and therefore, any affects caused by these assumptions are believed to be minimal for the purpose of this research. Subfield spatial units are created by intersecting the field boundaries with the NRCS SSURGO [33] soil polygons for the county, resulting in a total of 72,045 subfield areas (Figure 1). The subfield units are used as the base unit of analysis for distributing variability across each of the fields in the county.

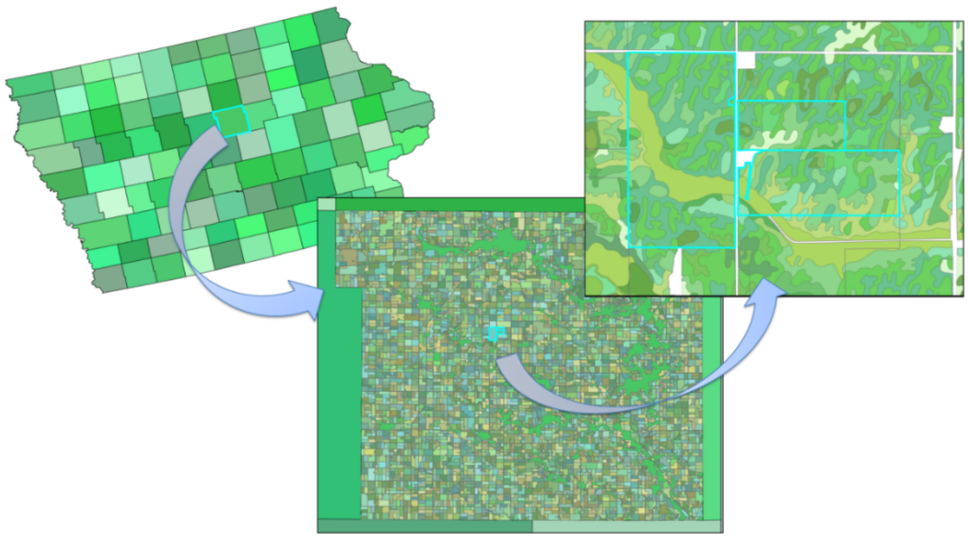

Figure 1. Depiction of the study area including the location of Hardin County within the state of Iowa (**left**); each of the field boundaries within the county (**center**); and subfield soil polygons within each field (**right**).

1.3.2. Establishing Subfield Yields

The Iowa Soil Properties and Interpretations Database (ISPAID) [38] is used to predict corn and switchgrass yields for every field's soil subunits. ISPAID estimates corn yield for each soil map unit based on slope class, parent material, erosion class, drainage class, and subsoil characteristics. In order to correct for annual variability between actual corn yields and the ISPAID predicted corn yields we normalized the predicted yields to the NASS [35] reported county level production statistics for each year from 2007 to 2012 such that the predicted yield matches the actual annual reported values. This is done by first calculating the county level estimated grain production across all soil types in a given year:

$$EY_j = \sum_i a_{ij} \cdot \text{ISPAID}_i \tag{1}$$

where EY_j is the estimated county level yield in year j, a_{ij} is the area of a given soil map unit i in year j producing corn and $ISPAID_i$ is the estimated corn yield for soil i. A correction factor can then be determined for each year:

$$CF_j = \left(NY_j - EY_j\right)/NY_j \tag{2}$$

where CF_j is the annual correction factor for year j and NY_j is the NASS reported county level corn grain yield for year j. By using this technique we are able to maintain realistic county-level production of corn grain, but gain the ability to distribute grain production across the landscape in such a way that variation in subfield conditions are respected, resulting in non-uniform corn production within each field. While we recognize that this method of production distribution will not be accurate for all fields within the county due to a number of reasons (*i.e.*, current and historical land management practices, crop rotations, and a number of site characteristics) the ISPAID results provide this analysis with a defensible high-level approach to depict subfield variability across the county, in the absence of site specific subfield scale data.

Predicted biomass yields of switchgrass are not provided by ISPAID. In lieu of this the predicted corn yield was converted to $Mg \cdot ha^{-1}$ and used as a surrogate value to describe switchgrass production across the landscape. This same method is used by ISPAID to describe the yield of other crops such as alfalfa-bromegrass hay. In the case of switchgrass a 1:1 ratio of corn grain to switchgrass yield results in a mean yield of 13.3 $Mg \cdot ha^{-1}$, minimum yield of 4.6 $Mg \cdot ha^{-1}$, and maximum yield of 15.1 $Mg \cdot ha^{-1}$, agreeing well with reported ranges of switchgrass production in the Midwest [14–16,39,40]. To account for decreased yield during switchgrass establishment [41], the first year in the six year rotation is assumed to yield only 2.3 $Mg \cdot ha^{-1}$ biomass on all soil types, one-half of the soil-based predicted yield on the second year, and the full predicted yield on years three through six. While the final yields and establishment period of switchgrass will vary based on variety, location, and management practices, the assumptions used in this analysis are intended to broadly fit growth performance in the literature. Future works targeting specific varieties or management may improve upon these estimates with appropriate field data.

1.3.3. Profit Calculation

The Iowa State Extension and Outreach Ag Decision Maker Tool is used to estimate the net operating cost for corn production using locally standard practices [42]. Based on the six year crop rotation identified for each field, the Ag Decision Maker template for “Corn following Corn”, or “Corn following Soybeans” is selected. Land prices within the Ag Decision Maker are set at 803 $\$\cdot ha^{-1}$ for Hardin County, identified as the medium quality land prices in the Iowa State University Cash Rental Rates for Iowa Survey [43] for 2013. The Ag Decision Maker is then wrapped in a dynamic library and integrated in LEAF. It is run for corn grain prices from 0.14 to 0.28 $\$\cdot kg^{-1}$ (3.50 to 7.00 $\$\cdot bushel^{-1}$) at 0.02 $\$\cdot kg^{-1}$ increments across a range of yields. The new profit database is then used to assign a profit to each relevant soil map unit in Hardin County based on the adjusted ISPAID yield for each of the corn producing years in the six year rotation, as described in Sections 1.3.1 and 1.3.2. An average profit for corn production over the entire rotation is then determined and used for this analysis.

1.3.4. Sustainable Stover Calculation

Quantities of sustainable corn stover are calculated using the Landscape Environmental Assessment Framework [34]. LEAF utilizes the Revised Universal Soil Loss Equation (2) (RUSLE2) [44], the Wind Erosion Prediction System (WEPS) [45], and Soil Conditioning Index (SCI) [46] to determine the sustainably available quantities of agricultural residues on national, regional, or subfield scales [8,31,47]. RUSLE2 simulates daily changes in soil water and temperature dynamics to estimate the impacts of water erosion processes. WEPS is a process based daily time step model that simulates wind erosion based on soil condition. The SCI value generated through RUSLE2 and WEPS is used to qualitatively describe whether soil organic matter is being increased, decreased, or sustained as a function of biomass input, erosion, and land management. Further details on the function of each of these three major models and their use in LEAF are discussed by Muth, Bryden and Nelson [8].

1.3.4.1. Climate Data

LEAF uses three sources of climate data to meet the needs of each component model. RUSLE2 uses a set of spatially explicit databases managed by NRCS [44]. WEPS utilizes the CLIGEN and WINDGEN submodels to generate daily climate and wind speed and direction, respectively, based on historic data. Both RUSLE2 and WEPS receive location information at the county level based on SSURGO map units.

1.3.4.2. Crop Rotations

Crop rotations from the six year period discussed previously are simplified into three rotations for LEAF; continuous corn, corn-corn-soybean (continuous corn with soybean), and corn-soybean (a combination of any "corn-soybean" and "mixed agriculture" units). Again, the simplification from converting field specific crop rotations from each field to a generalized class of rotation in the county will introduce error to the analysis, but is believed to be minimal. The LEAF determination of sustainably available corn stover by crop rotation is presented both on a whole-rotation basis (where, for example, in a three year rotation with one year of soybean only two of the three years may yield stover, lowering the three year average) or a corn-only basis (where the average quantity of sustainable stover is calculated from only years in corn production). The use of these two forms is noted throughout the Results and Discussion.

1.3.4.3. Land Management and Tillage Practices

Land management practices are built using the series of operations identified for each crop rotation in the Ag Decision Maker Tool described in Section 1.3.3. The tillage management systems represent reduced tillage concepts as defined by Purdue's Conservation Technology Information Center [48], meaning that typical soil surface cover at the time of planting is between 15% and 30%. The modeled tillage configuration consists of a single fall pass with a chisel plow followed by one to two spring passes with a field cultivator and/or tandem disk. Planting and harvesting dates are set to represent standard dates over the six year rotation for Hardin County [49]. The dates and timing of tillage, nutrient applications, and herbicide applications are set using standards relative to the established planting dates.

1.3.4.4. Residue Removal Practices

Four of the five residue removal methods developed by Muth and Bryden [34] are used for each combination of soil type and crop rotation in this study. These include no residue harvest (0% removal), moderate residue harvest (35% removal), moderately high residue harvest (52% removal), and high residue harvest (83% removal). Fractions of standing and laying residue and orientation are generated by the component models using currently available farm machinery.

Total soil erosion loss (wind plus water; $Mg \cdot ha^{-1}$) and SCI values (composite factor as well as the organic matter factor (SCI-OM)) are used to describe the sustainability performance of each residue removal method. Two sets of sustainability criteria as described by Bonner, Muth, Koch and

Karlen [47] are used in this analysis. The first case represents standard NRCS guidelines and is considered sustainable if (1) total erosion is < *T* (where *T* is the tolerable annual soil loss factor as reported for each SSURGO soil map unit in $Mg \cdot ha^{-1} \cdot year^{-1}$) and (2) soil organic matter is not being depleted as indicated by a composite SCI factor >0. The second more rigorous criteria requires that (1) total erosion is <½*T* for each SSURGO unit and (2) the SCI composite factor and SCI-OM sub-factor are both >0 to ensure organic matter is being maintained or increased.

Annual maximum sustainable residue removal for each field and the entire county for each year is calculated by summing the LEAF generated stover mass from the highest of the three removal methods that meets the respective sustainability criteria. This method of calculating total sustainably available stover assumes that collection methods can be managed across a field, such that portions of any given field may require no collection or collection at any of the three harvest rates.

1.3.5. Data Analysis

Spatial data was compiled and managed in ArcGIS 10.1 (Esri; Redlands, CA, USA). Exported data was managed and analyzed in Excel 2010 (Microsoft; Redmond, WA, USA) and JMP 10 (SAS Institute Inc.; Cary, NC, USA).

1.4. Results and Discussion

1.4.1. Production and Sustainably Available Corn Stover

Normalization of the ISPAID corn yield estimate with the NASS county level statistics for Hardin County results in an annual adjustment factor ranging from 0.74 to 0.88 across the six year period, meaning that on average the ISPAID data over-predicts corn grain yield by 19% for Hardin County. The corrected quantity of corn grain production across the six year period results in a county level mean corn stover production of 846,000 $Mg \cdot year^{-1}$ when using a harvest index of 0.5. This translates to a county level six-year mean stover production of 6.8 $Mg \cdot ha^{-1}$ with a range of 2.4 to 11.5 $Mg \cdot ha^{-1}$ (two standard deviations from the mean). Variation in this period average is due to the variability in grain yield captured through the ISPAID prediction as well as crop rotation, where fields with lower frequency of corn production will yield less stover over the six year period when compared to an equal-performing field managed in continuous corn. If estimated stover production is normalized to corn-only years, the mean production for the county shifts upwards to 10.8 Mg·ha^{-1} with 95% of the data points between 8.3 and 12.2 Mg·ha^{-1}.

LEAF analysis results in sustainable corn stover removal rates ranging from 0 to 6.6 Mg ha^{-1} under both conservation scenarios, but the frequency of low- or no-sustainable collection rates increases under the rigorous criteria (particularly in the eastern portion of the county), resulting in a mean sustainable removal rate of 2.3 Mg ha^{-1}, down from 4.5 Mg ha^{-1} under the standard criteria (Figure 2). Six year annual average sustainable stover collection for the county is 372,000 and 217,000 Mg·year^{-1} for the standard and rigorous scenarios, respectively. These values serve as the baselines by which we can understand the impact of switchgrass integration on biomass availability.

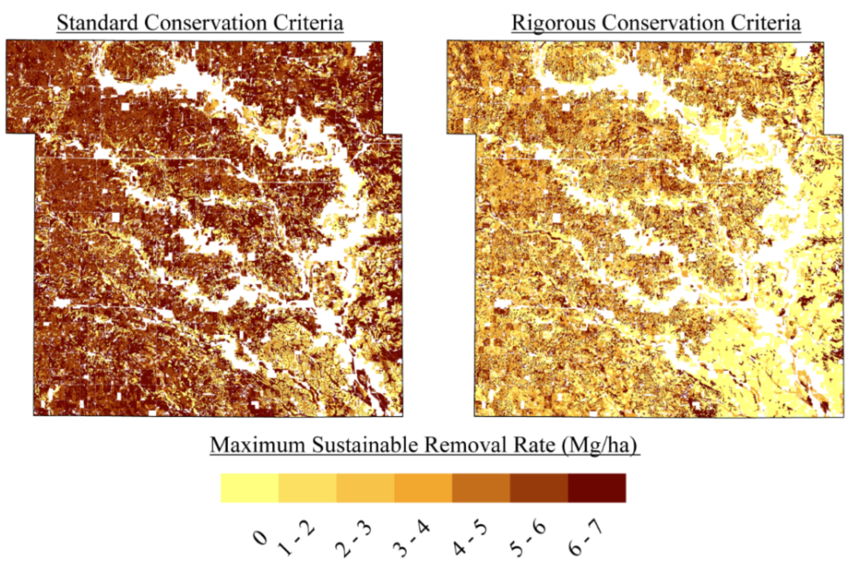

Figure 2. Six year average maximum sustainable corn stover availability resulting from the annually adjusted Iowa Soil Properties and Interpretations Database (ISPAID) data and Landscape Environmental Analysis Framework (LEAF) analysis adhering to crop rotations observed from 2007 to 2012 for Hardin County, Iowa under standard conservation criteria (soil erosion < T and SCI > 0) and rigorous conservation criteria (soil erosion < ½T and SCI and SCI-OM > 0).

1.4.2. Profit

Profitability across the county is extremely sensitive to corn grain price, particularly within the range of current grain prices at the time of this analysis; 0.18 to 0.20 \$·kg^{-1} (Figure 3). Two important large scale trends are seen in this data. First, there are a small number of subfield units, particularly those in lowland areas, that consistently operate at high modeled net losses (<400

$\$\cdot ha^{-1}$) at current grain prices. Second, the far eastern portion of the county is less sensitive to grain price in the range of 0.18 to 0.20 $\$\cdot kg^{-1}$ compared to the remainder of the county that fluctuates between a negative and positive profits as grain price shifts in this range. It is an interesting contrast that the most profitable areas in the county are also those that require the most conservative (or no) corn stover removal. This spatial trend is caused by a transition between two state level Major Land Resource Areas (Central and Eastern Iowa and Minnesota Till Prairies) along the county's eastern edge where soil regions transition from often poorly drained glacial till in the west to more sloping loess-mantled landscapes in the east [50]. At a grain price of 0.18 $\$\cdot kg^{-1}$ only 28% of the county is netting a positive profit from corn production, while at 0.20 $\$\cdot kg^{-1}$ 78% of the county is modeled to operate at a net positive profit. This large change in profitability with a relatively small change in grain price clearly demonstrates the potential risks of corn production and susceptibility to grain prices, even within an area considered to be prime for corn production.

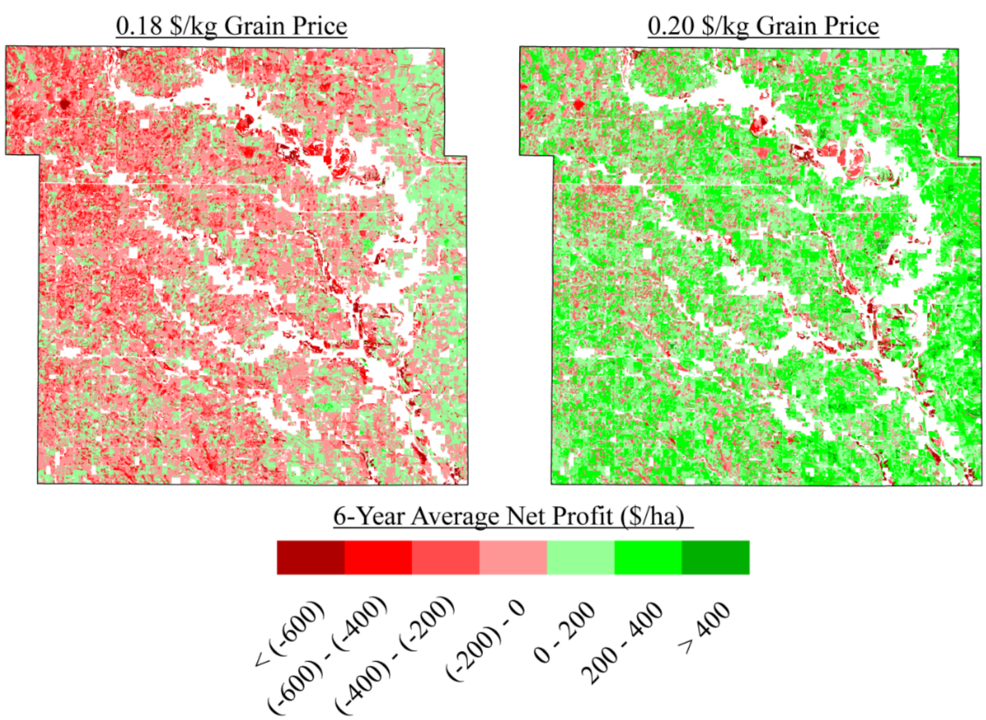

Figure 3. Dependence of six year average corn grain profits in Hardin County, Iowa based on grain prices of 0.18 $\$\cdot kg^{-1}$ (left) and 0.20 $\$\cdot kg^{-1}$ (right) resulting from the annually adjusted ISPAID corn yields and crop budget modeling.

The subfield scale analysis reveals important trends in farm level profitability across the county. At a 0.20 $\$\cdot kg^{-1}$ grain price the field-to-field variability is fairly low, accounting for 27% of the variance in profit for the whole county. Across the six year period the field level average profit is 113 $\$\cdot ha^{-1}$ with a standard deviation of 125 $\$\cdot ha^{-1}$. However, when we investigate within-field variability (the variation caused by different site characteristics within a single field's boundary) the standard deviation of the average net profit increases to 205 $\$\cdot ha^{-1}$ and 59% of the county's variance is contained within this group, indicating that most fields contain small areas that operate at profound net losses; if fact, we see that 85% of the corn producing fields in the county are modeled to have some area operating at a negative net cost. This large variability translates to an average field-level 95% confidence interval of −47 to 273 $\$\cdot ha^{-1}$ mean net profit for the county. If the grain price is dropped to 0.18 $\$\cdot kg^{-1}$, the average 95% confidence interval for mean field level profit becomes −244 to 42 $\$\cdot ha^{-1}$; again stressing the volatility of the area's potential profit to corn prices.

1.4.3. Opportunity for Energy Crops

The variability of within-field profit presents itself as an important potential entry point for energy crops. Candidate areas can be identified by assessing the amount of land within the county losing more than any given $\$\cdot ha^{-1}$ amount. If energy crops can be implemented and managed on a subfield basis, it is reasonable to suggest that the new crop would be competing against the subarea corn profit rather than against the field level average. For example, if an area within a field is producing corn at a net loss of 200 $\$\cdot ha^{-1}$, implementation of an energy crop in that area would be economically justifiable if it can successfully operate at a minimum of −200 $\$\cdot ha^{-1}$. Smith, Schulman, Current and Easter [26] concluded from a survey of landowners in southern Minnesota that 72% of growers were willing to produce perennial grasses if net profits exceeded current profit from row crops while 45% of growers were willing if net incomes were only equal. Bergtold, Fewell and Williams [9] also found that over 60% of surveyed farmers in Kansas were willing to produce annual energy crops and nearly 50% were willing to produce perennial crops if their production added value beyond the next best available practice. While both of these works identify economic competition on a field level annual net return, participant responses clearly indicate that growers perceive the adoption of energy crops on a subfield basis (*i.e.*, preferentially targeting poorly drained or higher sloped soils where row crop performance is poor) [26]. These responses support the case of establishing the objective function of energy crop integration through subfield profitability.

The availability of areas at different net losses can thus be used to identify candidate areas within Hardin County that may be available for conversion to switchgrass should agronomic practices and biomass market prices allow switchgrass to meet or exceed the profit occurring for corn. It is important to remember that this work only presents the opportunity for subfield scale integration of energy crops, and does not imply the actual production costs of switchgrass are equal to or greater than any given net loss for corn grain production. Because of this, the following results should be interpreted as a potential outcome of switchgrass integration into row crop landscapes if the economics are indeed locally favorable. Continued research is exploring the production costs of switchgrass and the interaction with feedstock markets to determine the impact of this type of management decision framework on agricultural planning and the bioenergy industry.

As discussed previously, the area operating at a range of net losses is heavily influenced by grain price (Figure 4). Interestingly, at grain prices $\leq$ 0.16 $\$\cdot kg^{-1}$, none of the land within the county is calculated to net a positive profit from corn production. The large change in profitability between 0.18 and 0.20 $\$\cdot kg^{-1}$ corn is clearly shown by the change in slope between a 0 $\$\cdot ha^{-1}$ net profit and a 400 $\$\cdot ha^{-1}$ net loss. For example, at a 0.18 $\$\cdot kg^{-1}$ grain price, nearly 17,000 ha (14% of the corn producing land) are estimated to operate at a net profit of ≤ -300 $\$\cdot ha^{-1}$, though at a 0.20 $\$\cdot kg^{-1}$ grain price less than 4000 ha (3% of land) are modeled to operate at or below the same net profit point. Following this approach, estimates of the potential area available to switchgrass conversion (assuming it can compete against the net losses estimated for row crop production) enables analysis of past, present, and future corn markets. As a conservative approach, the analysis conducted for this discussion assumes a corn price of 0.20 $\$\cdot kg^{-1}$ for further exploration of the changes in subfield, field, and county level performance.

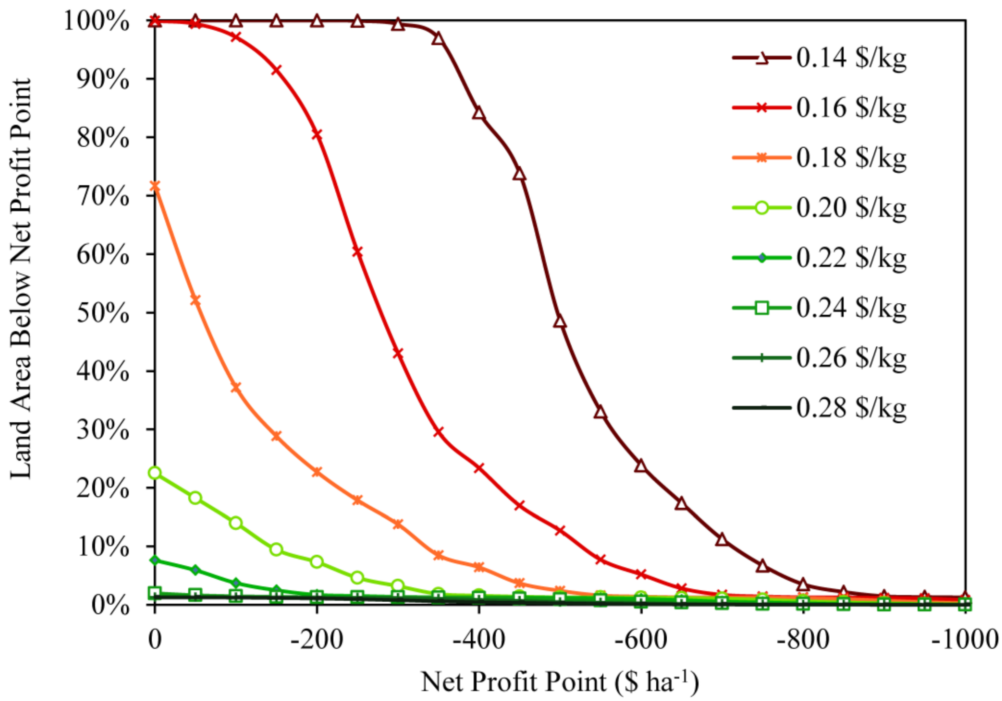

Figure 4. Area within Hardin County, Iowa operating at or below a range of six year average net losses based on varied corn grain price.

1.4.4. Impact on County-Level Production and Field-Level Profit

The quantity of candidate areas for conversion to switchgrass at a 0.20 $\$\cdot kg^{-1}$ grain price ranges from 800 ha (1% of the total corn producing area in the county) at a net profit decision point of −800 $\$\cdot ha^{-1}$ to 27,600 ha (22% of the total area) at a 0 $\$\cdot ha^{-1}$ net profit decision point (Figure 4; Table 1). As these areas are replaced with switchgrass the average county level annual availability of sustainable biomass (the ISPAID based switchgrass yield estimate plus the sustainable stover production calculated by LEAF) rises to 550,000 $Mg\cdot year^{-1}$ under the most generous decision point (0 $\$\cdot ha^{-1}$ net operating cost) and standard conservation criteria; a 180,000 $Mg\cdot year^{-1}$ increasing from the baseline. The rate of biomass increase per unit land change ranges from 3.4 to 6.5 $Mg\cdot ha^{-1}$ under the standard conservation criteria and 4.2 to 7.8 $Mg\cdot ha^{-1}$ under the rigorous conservation criteria (Figure 5).

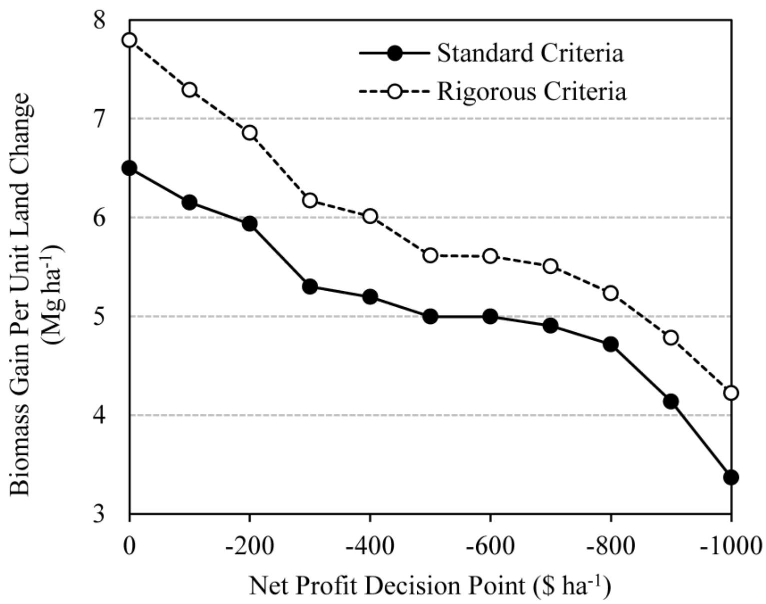

Figure 5. Increase in annual county level sustainable biomass production relative to the area converted as switchgrass is implemented into Hardin County, Iowa at a range of net profit decision points for the standard conservation criteria (soil erosion < *T* and SCI > 0) and rigorous conservation criteria (soil erosion < ½*T* and SCI and SCI-OM > 0).

Although both cases show increasing rates of biomass addition per unit land change at low decision points, very little land is actually being converted and thusly county level impacts are minimal (<4% increase to total biomass availability) and the rates begin to stabilize between the −700 and −500 $\$\cdot ha^{-1}$ decision points. Once the decision point is increased above −500 $\$\cdot ha^{-1}$, the rate of biomass gain begins to rise once more. As a result of these increased rates and increased occurrence of land areas operating at less negative decision points we see county level biomass availability increase rapidly (Figure 6). In the standard conservation scenario biomass availability is increased by 28% at the −100·$ ha^{-1} decision point, requiring 14% of the corn producing area to be converted to switchgrass and resulting in 31% of the county's total biomass availability to come from switchgrass. At this same point under the rigorous conservation criteria total biomass availability rises by 58% (43% of which is switchgrass) while the same 14% of the land area is converted (Table 1). These estimates are, of course, directly dependent on the assumed yield of switchgrass relative to ISPAID predicted corn yield. If this relationship were to differ, the quantity of switchgrass produced should be adjusted proportionally. For example, using the rigorous conservation criteria at the −100 $\$\cdot ha^{-1}$ decision point, if switchgrass yields were 25% lower than corn yields the total biomass availability would drop to 305,000 $Mg\cdot year^{-1}$ (an 11% decrease) comprised of 37% switchgrass (down from 43%). Alternatively, if switchgrass yields were 25% higher than corn yields, total biomass availability would rise to 379,000 Mg·year^{-1} (an 11% increase) with a distribution of 51% stover and 49% switchgrass.

Table 1. Impacts of switchgrass integration at a range of profit decision points on: County level sustainable biomass availability, biomass distribution and land change, and field level profit impacts. Biomass availability values modeled for the rigorous conservation criteria (soil erosion < ½*T* and SCI and SCI-OM > 0) using a grain price of 0.20 \$·kg^{-1}. Land change and profit analyses are applicable to both stover removal scenarios.

County Level Statistics	**Net Profit Decision Point (\$·ha^{-1})**						
	0	**−100**	**−200**	**−300**	**−400**	**−600**	**None**
Corn Stover Availability, Mg·year^{-1}	182,000	193,000	206,000	213,000	217,000	217,000	217,000
Switchgrass Availability, Mg·year^{-1}	250,000	149,000	73,000	29,000	12,000	9,000	0
Total Biomass Availability, Mg·year^{-1}	432,000	342,000	278,000	241,000	228,000	226,000	217,000
Mass Fraction Corn Stover	42%	57%	74%	88%	95%	96%	100%
Mass Fraction Switchgrass	58%	43%	26%	12%	5%	4%	0%
Annual Biomass Increase [a]	99%	58%	28%	11%	5%	4%	-
Land Conversion	22%	14%	7%	3%	2%	1%	-
Fields Affected	85%	74%	57%	30%	16%	15%	-
Mean Field Level Area Change [b]	25%	18%	12%	10%	10%	9%	-
Mean Field Level Profit, \$·ha^{-1} [c]	198	174	151	134	127	125	113
Field Level Profit Std.Dev, \$·ha^{-1}	92	127	157	175	183	185	205
Profit Variance Between Fields	49%	39%	36%	37%	38%	38%	41%
Profit Variance Within Fields	51%	61%	64%	63%	62%	62%	59%
Reduction in Total Profit Variance	78%	65%	50%	36%	28%	25%	-

[a] Biomass increase relative to sustainable corn stover availability when no landscape integration is considered; [b] Mean change in area of only the fields affected by landscape integration at each respective decision point; [c] All profit calculations are relative to the remaining row crop area of all fields as switchgrass is incorporated.

These results can help us form an understanding of how an integrated landscape can be achieved using the principals of subfield management and what the impacts may be on production practices. Using the −200 $·ha^{-1} decision point as an example, only 7% of the corn producing lands (9000 ha) are considered for conversion to switchgrass, but a 28% increase in biomass availability is modeled using the rigorous conservation criteria (Table 1). In this case, 57% of the corn producing fields would be participating in landscape integration. Of these fields 21% would have area conversions <3.75%; 50% of the fields would have area conversions <8.75%; and over 80% of the fields would have area conversions <21.75%. As we move the decision point upward to −100 $·ha^{-1} the number of fields participating climbs to 74% (again, accounting for 14% of the corn producing lands) and the distribution of area conversion begins to stretch outward, where now only 37% of the fields would have an area conversion <8.75%, and the mean area change climbs from 12% to 18%. Implementation of a proper decision point will certainly be dependent on balancing the financial rewards of land conversion with acceptable loss of row crop production. With this point in mind, we can explore the behavior of profitability as a means to describe potential economic benefit to producers.

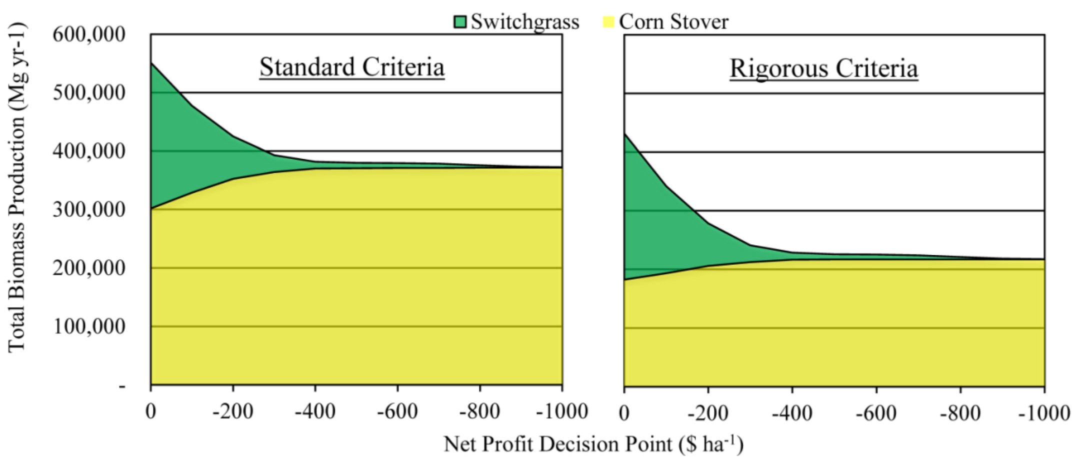

Figure 6. Sustainable county level biomass availability as switchgrass is incorporated at a range of net profit decision points for the standard conservation criteria (soil erosion < *T* and SCI > 0) and rigorous conservation criteria (soil erosion < ½*T* and SCI and SCI-OM > 0) using a grain price of 0.20 $·kg^{-1}.

As landscape integration is applied across the county the within-field proportion of the county's profit variance decreases slightly to 51% at a decision point of 0 $·ha^{-1} (down from 59% when no energy crops are implemented), but more importantly the total variance of the remaining row crop area is decreased by 78% (Table 1). The downward trend in total profit variance translates to a greater mean field profit for corn and decreased standard deviation for the remaining corn area in each field; up to a 76% increase in mean profit and 57% decrease in standard deviation of profit at the 0 $\$\cdot ha^{-1}$ decision point (Table 1). As a result, the level of uncertainty in row crop production decreases from 113 ± 160 $\$\cdot ha^{-1}$ (mean ± average 95% confidence interval of the mean) when no integration is implemented to 127 ± 142 $\$\cdot ha^{-1}$ at a decision point of −400 $\$\cdot ha^{-1}$ and to 198 ± 84 $\$\cdot ha^{-1}$ at a decision point of 0 $\$\cdot ha^{-1}$; a 48% improvement. While it is important to remember that actual field practices and crop budgets must be utilized to guide specific management decisions, the data presented here shows promise of positive benefits to the grower's row crop economics and biomass availability while conserving soil resources.

1.5. Conclusions

This study demonstrates a key economic opportunity for integration of energy crops into row crop landscapes. Within Hardin County, Iowa we have shown that up to 85% of the corn producing fields have areas operating at modeled negative net profits under current grain prices. By converting these areas to energy crop production, field level profitability is improved while the county's annual biomass availability is nearly doubled when using rigorous conservation criteria. These estimates can be used to guide further identification of candidate areas for conversion to energy crops based on site specific performance and management practices. Large scale assessments can be performed using the analysis techniques presented, allowing valuable field and subfield variability to be retained for better assessment of potential impacts to grower economics and the bioenergy industry. Future efforts should be focused on refining our understanding of the dynamics of subfield economics, exploring the subfield impacts on production logistics and metrics of sustainability, and gauge industry level impacts across diversely managed lands.

1.6. Acknowledgments

The authors thank Emily Heaton and Elke Brandes of Iowa State University for their expert guidance on switchgrass production. We also thank Maxine Dakins of the University of Idaho for her guidance in statistical analysis.

This work is supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, Bioenergy Technologies Office, under DOE Idaho Operations Office Contract DE-AC07-05ID14517. Accordingly, the U.S. Government retains a nonexclusive,

1.7. References

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Chapter 2. *Development of Integrated Bioenergy Landscapes Using Precision-Conservation and Multi-Criteria Decision Analysis Techniques*

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Submitted for Publication in January, 2015; Currently Under Review

2.1. Abstract

Development of a productive advanced biofuels economy requires a robust suite of lignocellulosic feedstocks, including both agricultural residues and dedicated energy crops. Where and how energy crops will be produced is controversial, however, due to economic and practical constraints. This research utilizes precision-conservation and multi-criteria decision analysis techniques to model the integration of switchgrass (*Panicum virgatum* L.), a perennial bioenergy crop, into a corn (*Zea mays* L.) producing field in Iowa, USA. The impacts of landscape integration are quantified in terms of productivity, economics, and environmental performance. Management areas identified using a multi-objective optimization method are modeled using the Landscape Environmental Assessment Framework (LEAF) to calculate biomass availability and impacts to soil health, while the Water Quality Index for Agricultural Lands (WQIag) is used to assess the risk to surface water quality. The results show that subfield management zones optimized to reduce economic losses and maximize environmental performance are capable of improving the annual rate of soil organic carbon gain by 69%, reducing annual soil erosion by 63%, and increasing sustainable biomass availability by 35%. Environmental improvements are valued at 158 US$ ha^{-1} (64 US$ ac^{-1}), making the integrated landscape design an effective loss mitigation strategy compared to conventional corn production only when feedstock prices are > 107 US$ Mg^{-1} (97 US$ t^{-1}). The results of this work demonstrate that integrated landscapes can be a tenable means to improve the overall production of a field, improve the profitability of row crop farming, and preserve or improve water and soil resources.

2.2. Introduction

The need for renewable biofuels has garnered much attention for dedicated energy crops, yet crop implementation on agricultural lands in a way that protects the environment and the producer's bottom line is not clear. In 2007 the United States passed the Energy Independence and Security Act, mandating 60.5 billion liters of biofuels (ethanol equivalent) to be produced from lignocellulosic materials by 2022 (U.S.Congress n.d.). Achieving this goal will require heavy investment in all of the bioenergy system's component processes, namely feedstock production, handling, processing, and conversion. While significant amounts of research have been aimed at exploring the use of extant agricultural residues such as corn (*Zea mays* L.) stover for ethanol production (Aden and Foust 2009; Hess et al. 2007), additional feedstocks will be necessary. Amongst this feedstock portfolio are dedicated energy crops, plants grown for the sole purpose of producing bioenergy (Perlack and Stokes 2011). While evidence suggests that energy crop production is a sustainable method of increasing biomass production for bioenergy (Heaton et al. 2008; Pohekar and Ramachandran 2004), extensive analysis at the field scale is required to understand practical methods of integrating bioenergy crop production into existing agricultural landscapes and to avoid unintended consequences to the environment or the economics of biomass producers (Dale et al. 2011; Paine et al. 1996; Tilman et al. 2002).

Production of herbaceous energy crops in concert with primary crops, such as corn, that provide residual biomass for bioenergy is likely to yield the greatest near-term benefits due to growing biomass markets and concerns over the sustainability of row crop production. By utilizing the marginal, negative-revenue areas of fields, Bonner et al. (2014a) showed biomass availability within an Iowa county to nearly double depending on the potential profitability of an energy crop when integrated at a subfield level. The opportunity to increase biomass availability and improve environmental stewardship are both salient goals, however, understanding how changes will be executed at the field-level is a critical first step for identifying barriers and influencing adoption. The field of sustainable landscape development has long recognized the importance of balancing socioeconomic concerns with ecological goals when crafting alternative management solutions (Lee et al. 1992). Loomis (2002) constructed a five-point structure to facilitate the evaluation of management options where the merits of an alternative are judged in terms of: (1) physical and biological feasibility, (2) economic efficiency, (3) distribution of equity within and between generations, (4) social and cultural acceptability, and (5) operational practicality. These points can be easily adapted to the core questions facing adoption of energy crops in agricultural landscapes, for example:

1. Is the production of an energy crop in a given area more or less demanding on soil and water resources than current agricultural use?
2. Is the net return or rate of return on energy crop production more favorable than conventional practices?
3. How do near and long-term benefits of energy crop integration compare to those provided by conventional production (social, economic, and environmental)?
4. Will the adoption of energy crops in landscapes typically associated with food production be accepted by the public?
5. How can practical constraints such as plot size, shape, or condition be overcome so that energy crops may be incorporated in agricultural landscapes?

While this logical approach to alternative evaluation is clearly a beneficial exercise, analyzing and interpreting complex and interrelated metrics is a challenge. The development and application of Multi-Criteria Decision Analysis (MCDA) methods for natural resource management can help to address such concerns and questions simultaneously using computational simulations (Belton and Stewart 2002; Huang et al. 2011). In a summary of key considerations regarding MCDA, Belton and Stewart (2002) state that "the process leads to better considered, justifiable, and explainable decisions". For these reasons the application of MCDA techniques to the development and assessment of integrated landscape designs provides critical transparency to analysis logic and outcome. Application of this method does, however, require access to data that faithfully represents current conditions and anticipated effects of alternative choices.

Enabled from advancements in geographic information systems (GIS) and precision-agriculture, precision-conservation techniques are now a well-established means of understanding subfield variability and aiding agricultural management decisions (Delgado and Berry 2008; Tomer et al. 2013). Precision-conservation has been explicitly defined as the application of spatial technologies and temporal knowledge to inform the implementation of conservation practices across natural and agricultural ecosystems to reduce soil erosion and promote soil and water health (Berry et al. 2003). The core principals of precision-conservation lend themselves well to providing the data and conceptual environment necessary for MCDA of integrated landscapes. Furthermore, when precision-conservation plans are coupled with site-specific economics, the lost opportunity cost resulting from displacement of agricultural production with conservation practices can be estimated, better informing land managers about the costs and benefits of alternative land uses (Kitchen et al. 2005; McConnell and Burger 2011; Muth 2014). While most conservation practices do not generate direct annual revenue for the farmer and instead result in off-site and societal benefits, production of perennial energy crops such as switchgrass (*Panicum virgatum* L.) on marginal positions within agricultural fields has the potential to produce large quantities of marketable biomass feedstock while also protecting soil and water resources and enhancing biodiversity (Bonner et al. 2014a; Heaton et al. 2010; Robertson et al. 2010; Werling et al. 2014).

This work expands upon the concept of subfield profit management presented by Muth (2014) by using energy crops as a means to improve environmental performance and return on investment (ROI). MCDA and precision-conservation techniques are used to design and assess the potential for integrated bioenergy landscapes where switchgrass is inserted into a corn producing field on a subfield basis. The method utilizes a multi-objective optimization to simultaneously consider the impacts of management on profitability, productivity, and sustainability given high resolution datasets for a case study field in Northern Iowa. Environmental impacts resulting from alternative management practices are modeled using the Landscape Environmental Assessment Framework (LEAF; Muth and Bryden 2013). The cases presented quantify the potential changes to field performance when switchgrass is considered to be a bioenergy feedstock crop as well as a conservation tool. The results demonstrate clear potential for reducing environmental impacts on primary production lands while increasing sustainable biomass availability. The methods developed for this work are a transparent means of aiding landscape design decisions and are readily adaptable to broader decision making platforms involving multiple stakeholders.

2.3. Materials and Methods

2.3.1. Study Site

A 62 ha (153 ac) continuous corn field in Cerro Gordo County, Iowa, is modeled in this work. The field is delineated into 66,775 individual 9.3 m^2 (100 ft^2) grid-cells, each defined by unique spatial attributes. Soil properties at the site are defined using Natural Resources Conservation Service (NRCS) SSURGO (Soil Survey Geographic Database) soil map units (NRCS, n.d.-d) and LiDAR (Light Detection and Ranging) slopes (Løken 2007). Spatially explicit corn grain yields were recorded across the field during harvests from 2008 to 2010. The averages of these yield measurements are applied to the grid-cells to create a distribution of productivity across the field (Figure 7). Additional information about the soil conditions and management practices associated with the field have been reported by Muth et al. (2012).

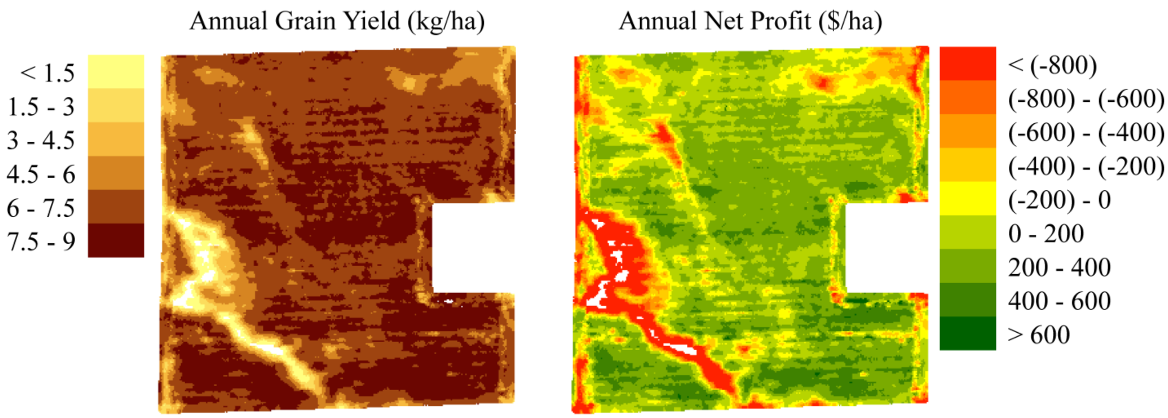

Figure 7. Average corn grain productivity measured during harvests from 2008 to 2010 [left], and profitability based on a uniform input costs across the field [right]

2.3.2. Profitability of Crop Production

Profitability of corn production was calculated using the Iowa State Extension and Outreach Ag Decision Maker Tool (Duffy 2014) with the "Corn following Corn" template and a land rental rate of 754 US$ ha^{-1} (305 US$ ac^{-1}). The Ag Decision maker was wrapped in a dynamic library within LEAF and utilized for a range of average grain yields assuming even input costs across the entire field and a grain price of 0.2 US$ kg^{-1} (5 US$ bu^{-1}). The resulting database of net profits was then related back to each grid-cell based on average measured grain yield, producing a spatially explicit map of net financial return from corn production (Figure 7).

The costs and profit of switchgrass production were calculated using the Iowa State Ag Decision Maker crop budget for switchgrass (Cook and Beyea 2000), updated with costs from Iowa State's 2014 Custom Rate Survey (Dosskey et al. 2005). Land rent was assumed to be equal to that used for corn production.

2.3.3. Impacts to Soil Health

Soil health is modeled using the Landscape Environmental Assessment Framework as described by Muth and Bryden (2013) for conventional corn production and switchgrass production. The LEAF toolset has been used at national, regional, and subfield scales to assess biomass resource availability and sustainability of management practices (Bonner et al. 2014b; Muth et al. 2012, 2013). LEAF utilizes the Revised Universal Soil Loss Equation (2) (RUSLE2) (NRCS, n.d.-b), the Wind Erosion Prediction System (WEPS) (NRCS 2010), the Soil Conditioning

Index (SCI) (NRCS n.d.-c), and the DNDC biogeochemistry model (UNH n.d.). The quantitative outputs from LEAF used here include annual soil erosion from wind and water (Mg ha^{-1} yr^{-1}), annual change in soil organic carbon (SOC; kg ha^{-1} yr^{-1}), and annual loss of nitrogen through nitrate leaching (NO_3; kg ha^{-1} yr^{-1}). Applying alternative management practices, the entire field is modeled at the grid-cell level multiple times to build a library of field responses. This response database is then used to evaluate integrated landscape designs where management decisions are made at the subfield level.

2.3.4. Climate Data

Several sources of climate data are used by the component models of LEAF. Climate data for RUSLE2 is obtained from a series of county level databases managed by the NRCS. WEPS utilizes two sub-models, CLIGEN and WINDGEN, to generate daily climate and wind speed and direction, respectively. For this work, DNDC used daily weather data from the National Weather Service (NWS) Cooperative Observer Program (COOP), a national network of volunteers collecting quality controlled weather data (NWS n.d.).

2.3.5. Land Management and Tillage Practices

Land management practices for corn production are built from the operations listed in the "Corn following Corn" template of the Iowa State Ag Decision Maker Tool (Duffy 2014). A "reduced" tillage management plan is used for corn production as defined by Purdue's Conservation Technology Information Center (CTIC n.d.). The modeled tillage configuration consists of a single fall pass and one to two spring passes such that surface cover at the time of planting is between 15% and 30%. The timing of field operations (i.e., tillage, nutrient application, herbicide application, and harvesting) are set based on standard dates for the NRCS crop management zone (NRCS n.d.-a).

Switchgrass management practices including field operations and dates were modeled based on those described in the Iowa State University Extension management guide for switchgrass production (Teel et al. 2003).

2.3.6. Residue Removal Practices

Corn stover harvest using currently available machinery is modeled four separate times corresponding to the four fixed removal rates (0%, 35%, 52%, and 83%) described by Muth and Bryden (2013). The quantity of corn residue produced across the field is estimated from the average measured grain yield and a harvest index of 0.5. The amount of residue removed under each removal rate scenario is then calculated relative to this per-grid-cell starting basis with the soil health impacts being measured based on the residue remaining after collection. The sustainability of residue removal is judged based on the results of total soil erosion and the SCI score for each soil map unit within the field. In order to meet standard NRCS conservation planning criteria, residue removal must result in soil erosion less than the tolerable soil loss factor (*T*; Mg ha^{-1} yr^{-1}) and a positive composite-SCI score. As a means of highlighting areas where residue removal is exceeding these standards, a second, more rigorous criteria is used where total soil erosion must be less than ½ *T* and the composite-SCI and SCI-OM sub-factor both must be positive, indicating an increased likelihood of maintaining and enhancing soil resources.

2.3.7. Risk to Surface Water Quality

The NRCS Water Quality Index for Agricultural Lands (WQIag) (Lal and McKinney 2012) is used to qualitatively describe the risk to surface water quality under the conventional and integrated landscape management scenarios. The use of WQIag is required by all NRCS field offices for evaluating the impact of conservation practices within its National Water Quality Initiative (NWQI) program. The tool utilizes site specific conditions for soil, vegetative cover, and management practices, all of which are utilized within LEAF, to return a score ranging from 1 to 10 where higher numbers represent a reduced risk of negatively impacting surface water quality. WQIag was run for each grid-cell under the four corn stover management scenarios and the switchgrass production scenario.

2.3.8. Multi-Objective Optimization

The method of subfield optimization used in this work requires an initial starting point and direction to orient the selection of areas for conversion to energy crops. Following the landscape integration method of Bonner et al. (2014a), subfield profit is used as the objective function for defining a decision point. To do so, each of the field's individual grid-cells are organized by net profit, beginning with those of the greatest net loss. The areas of the field with the greatest loss are considered first because high-loss areas are the most undesirable. Following this strategy, a greater proportion of the field is identified for alternative land management as the decision point moves upwards from the greatest net loss towards a net zero return. However, this process does not happen in isolation, as other performance metrics are simultaneously impacted as the net profit decision point moves upwards and more switchgrass is considered to replace corn production.

A multi-objective optimization strategy common in MCDA is used to balance the lowest possible net profit decision point with the loss of corn grain production and change in soil erosion, nitrate leaching, and soil organic carbon as each grid-cell is transitioned to switchgrass. More information on this style of optimization is described by Obermiller (1997). Each of the five parameters of interest are plotted by relative land area conversion and fitted to an empirical function. Each of the five parameter functions are then associated with a linear desirability function (Figure 8). For example, because high erosion is undesirable, a negative sloping desirability function is used. Similarly, because high grain production is desirable a positive sloping desirability function is used. The five parameter functions and their corresponding desirability functions are then used simultaneously to maximize desirability and solve for the optimized land conversion rate and associated areas of the field for initial targeting of integrated landscape management zones. All five parameters are weighted equally for this analysis, though any particular parameter could be more heavily weighted to reflect stakeholder values.

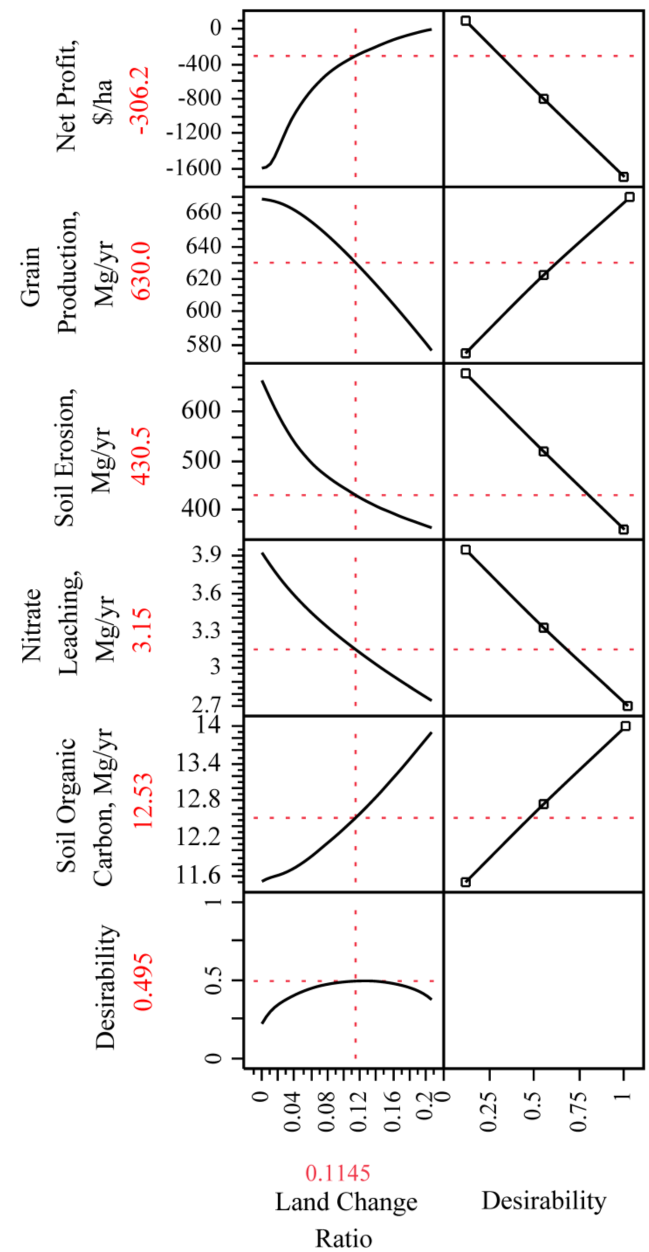

Figure 8. Multi-objective optimization strategy using profit decision point, grain production, soil erosion, nitrate leaching, and soil organic carbon as the metrics of interest to determine the most desirable land conversion rate and associated net profit decision point for initial construction of an integrated landscape design.

2.3.9. Economics of Environmental Performance

In addition to the costs and revenue from grain production, both private and social costs are assigned to the environmental impacts of each management scenario tested. The environmental impacts included LEAF outputs for SOC, total soil erosion, and NO_3 leaching.

One way to assign a meaningful value to changes in SOC is to approximate its cost of replacement, as done by Lal (2014) to evaluate the societal value of soil carbon. Using the estimates of the chemical elements needed to convert biomass C to SOC from Himes (1998), Lal estimated the nutrients to create 10,000 kg (11 t) of SOC from a source of biomass C required 833 kg-N (0.92 t), 200 kg-P (0.22 t) and 143 kg-S (0.16 t). Using these estimates, world fertilizer prices are then converted into \$ kg^{-1} prices for individual nutrients. From this Lal (2014) calculates the nutrient cost of replacement of SOC to be 0.099 US\$ kg^{-1} (0.045 US\$ lb^{-1}). When adjusted for US prices using the Iowa Production Cost Report (USDA, n.d.) and the Argus FMB Sulfur Report (Argus, n.d.), the nutrient replacement cost is increased to 0.126 US\$ kg^{-1} (0.057 US\$ lb^{-1}). This is largely driven by higher costs of nitrogen given by the Iowa Production Cost Report (USDA, n.d.).

The value of nitrate leaching is estimated based on the mitigation costs required to construct a denitrifying bioreactor. Christianson, Tyndall, and Helmers (2013) calculated the comparative average cost effectiveness of nitrogen mitigation from denitrifying bioreactors to be 2.10 ± 0.90 US\$ $kg\text{-}N^{-1}$ yr^{-1} (0.95 ± 0.41 US\$ $lb\text{-}N^{-1}$ yr^{-1}). This price does not estimate the damage caused by nitrate leaching; instead it represents the price at which a farmer would be indifferent to preventing nitrate leaching (through the construction of a denitrifying bioreactor) versus paying a tax on the quantity of nitrate leached. The denitrifying bioreactor was chosen for this analysis because of the relatively small amount of surface area required (0.5% of the drainage treatment area) compared to other nitrogen removal efforts such as wetland basins (3.5% of the treatment area)(Christianson, Tyndall, & Helmers, 2013). This is important for minimizing the loss of opportunity cost from removing area from primary production.

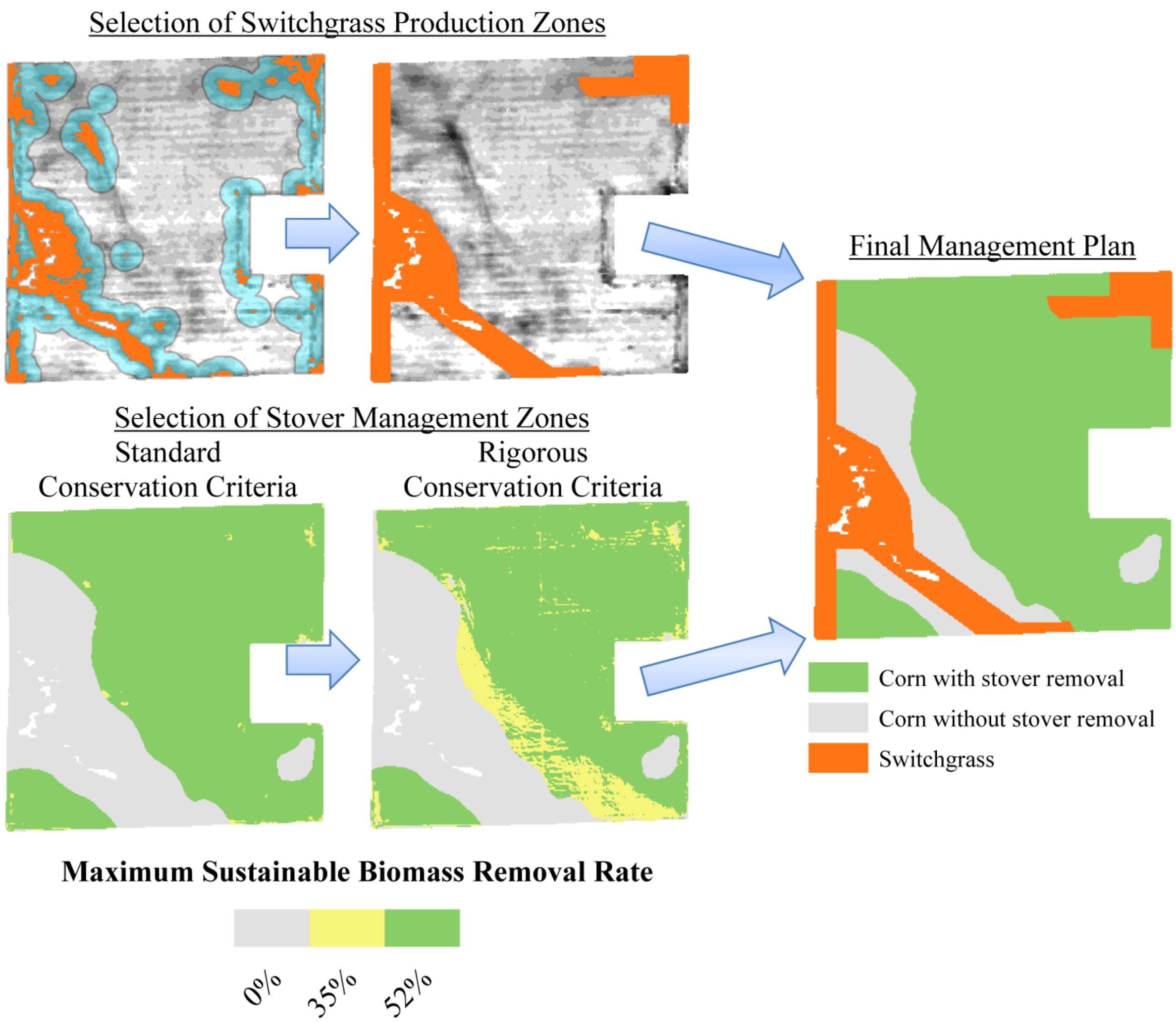

Figure 9. Development of an integrated landscape design where the areas identified through multi-objective optimization are down selected and used to form bounding geometries for switchgrass management zones [top left], and the sustainability of corn stover harvest is used to create stover harvest zones [bottom left], resulting in a field design where corn, corn stover, and switchgrass is produced [right].

Finally, the cost of soil erosion is estimated from 14 different types of environmetnal benefits as presented by Hansen and Ribaudo (2008). The value of environmental benefits is quantified based on travel cost, damage function, replacement cost, and expenditure aversion models. Hansen and Ribaudo (2008) estimated these benefits at the county level and on Hydrologic Unit Codes (HUC). For Cerro Gordo County, Iowa the willingness to pay for reducted soil erosion is estimated at 5.18 US$ Mg^{-1} (4.70 US$ t^{-1}). This estimate is comprised of 1.11 $ Mg^{-1} (1.01 US$ t^{-1}) for the private costs of decreased soil productivity and 4.07 $ Mg^{-1} (3.69 US$ t^{-1}) for the social costs of damage to water-based recreation, steam-electric power plants, and municipal water use and treatment.

2.3.10. Data Analysis

Multi-objective optimization is conducted using JMP 10 software (SAS Institute Inc.; Cary, NC, USA). Geospatial analysis is performed in ArcGIS 10.1 (Esri; Redlands, CA, USA). Exported data is managed and analyzed in Excel 2010 (Microsoft; Redmond, WA, USA).

2.4. Results and Discussion

2.4.1. Delineation of Management Units

The multi-objective optimization strategy identifies 11.5% of the field operating at or below a net profit decision point of 305.5 US$ ha^{-1} (123.6 US$ ac^{-1}) as the most desirable land fraction for conversion to energy crops. While this MCDA method of area identification is optimal in a strictly quantitative sense, the grid-cells identified do not naturally form manageable units within the field (Figure 9). It is unreasonable to assume all identified areas of the field would be converted to switchgrass if some of the areas are too isolated or too small to be effectively managed. Therefore, these disparate cells must first be aggregated into practical management units that can be reasonably compared to traditional management. As discussed by Kitchen et al. (2005), this process is best conducted with the participation of relevant stakeholders, as the limiting criteria will be subjective to one's own management styles and tolerance of risk. As such, the outcome of the processes described here should by no means be considered to be the only possible solution, as no one set of guiding assumptions will meet the personal preferences of all land managers. Nevertheless, a similar series of steps may be taken in an actual implementation scenario to encourage informed and sound decision making.

First, all of the subfield candidate areas are grouped based on proximity to one another to identify potential management zones (Figure 9). In this case a maximum distance of 37 m (121 ft) was chosen as gaps of this size would facilitate four headland passes with a twelve row corn header, thus warranting preservation of conventional practice. The grouped areas are then down selected to only those which account for at least 0.81 ha (2 ac) of candidate cells. These final candidate area groups are then translated into bounding geometries where not all candidate cells must be captured if their distance from the primary cluster is too great relative to their area. At the same time the construction of these geometries unavoidably captures areas not identified by the optimization process (i.e., areas operating above the “optimal” net profit decision point) in order to make manageable boundaries. Additionally, the constraints for the final geometries (i.e., straight sides and right angles versus organic shapes; minimum land area; etc.) are subjective based on a particular land manager’s preferences. In this case, the final switchgrass management zones account for 12.4 ha (30.6 ac); 2.3 ha (5.7 ac) of which are operating at net profits $\geq$ 0 US$ ha^{-1}. While this in itself is not desirable, the average net profit from grain production within these management zones is -509 US$ ha^{-1} (-206 US$ ac^{-1}), meaning switchgrass would have to produce a net return greater than this to be economically advantageous and support landscape integration.

Finally, stover management zones must be identified for the remaining row crop producing areas to ensure only sustainably available corn stover is being collected. Areas of the field that cannot support sustainable stover harvest at least at a low removal rate under the standard conservation criteria are designated as no-harvest zones. The remaining field area is then assigned a single stover removal rate capable of meeting at least the standard sustainability criteria. The final integrated landscape design consists of two switchgrass and corn production areas with two stover harvest zones (Figure 9).

2.4.2. Evaluating Site Productivity

Changes to field performance are evaluated by comparing the optimally designed field management plan on subfield and field-level bases to conventional management where the entire field is managed for corn with stover removal. The integrated landscape scenario results in a loss of 95.3 Mg (3,750 US bushels; where 1 bu = 25.4 kg) of corn per year (14%) due to the decrease in corn producing land. However, the production rate relative to the area in corn is raised from 10.8 to 11.5 Mg ha^{-1} (171 to 184 US bu ac^{-1}) as a result of utilizing only the most productive portions of the field. Similarly, the economics of row crop production shift from a net profit of 2,900 to 7,500 US$ yr^{-1} under the conventional and integrated landscape scenarios, respectively. The difference between these profits is essentially the tolerable profit loss by switchgrass production to justify landscape integration.

A total of 319 Mg yr^{-1} (351 t yr^{-1}) of corn stover is collected in the conventional scenario when no sustainability restrictions are imposed, while 313 Mg yr^{-1} (345 t yr^{-1}) of stover and switchgrass is produced by the integrated landscape scenario (Figure 10). Both scenarios have comparable yields of biomass because of the adoption of no-stover harvest zones in the integrated landscape scenario to meet sustainability criteria for biomass collection. This exclusion of unsustainable stover from annual biomass collection is effectively countered by the increased yield of switchgrass. When the sustainability of all biomass collection is taken into consideration a large portion of the stover collected in the conventional scenario fails to meet minimum sustainability criteria, while 99% of the biomass collected in the integrated landscape scenario meets at least standard conservation criteria (Figure 10). When limited to sustainably available biomass the conventional scenario only supports 232 Mg yr^{-1} (256 t yr^{-1}). In this regard, adoption of the integrated landscape design results in a 35% increase to annual sustainable biomass availability.

2.4.3. Environmental Impacts

In addition to the sustainability metrics used to qualify biomass collection, the modeled soil mass balance and WQIag scores can be used to further describe changes to environmental impacts as a result of the integrated landscape design. Compared to the conventional corn scenario, the integrated landscape design reduces annual nitrate leaching by 32% (1.3 Mg yr^{-1}; 1.4 t yr^{-1}) due to improved nitrogen utilization by switchgrass on the areas of the field with the poorest performance under conventional management (Figure 11). Similarly, the field average annual change to soil organic carbon is estimated to increase by 69% (7.9 Mg yr^{-1}; 8.7 t yr^{-1}) due to the high above- and below-ground biomass retention from switchgrass and the elimination of stover collection from sensitive areas of the field. This same trend of course reduces wind and water soil erosion by stabilizing and protecting sensitive soils, decreasing annual field soil losses from 4.4 to only 1.6 Mg yr^{-1} (4.9 to 1.8 t yr^{-1}).

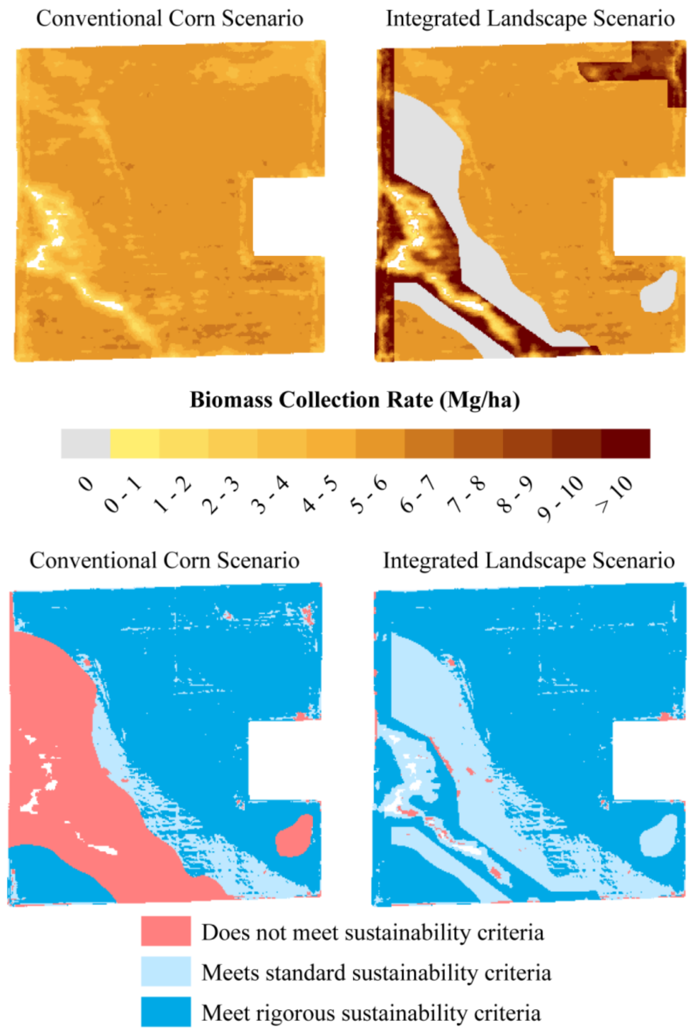

Figure 10. Biomass collection rate [top] and sustainability of biomass collection [bottom] for the conventional corn and integrated landscape scenarios where standard conservation criteria requires biomass collection to result in annual erosion < T and SCI >0, while the rigorous criteria requires annual erosion to be < ½ T and SCI and SCI-OM to both be > 0.

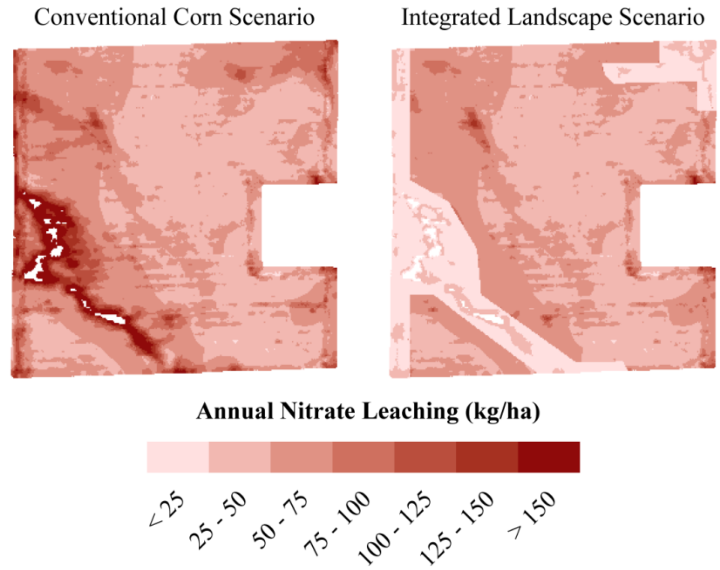

Figure 11. Subfield nitrate leaching under conventional corn management [left] and the integrated landscape design [right].

These increases to soil health also reduce the risk to surface water contamination as indicated by the Water Quality Index (Figure 12). The areas where switchgrass is integrated have dramatic increases to the WQIag score (indicating a greatly reduced risk to surface water quality); transitioning the highest risk areas of the field to some of the lowest risk areas. The adoption of switchgrass on sensitive portions of the field was considered to act as a perennial grass conservation practice, resulting in a slight WQIag score improvement to the entire field. Although the corn areas in both cases still receive relatively poor scores and represent an increased risk to surface waters, the field average WQIag score increases from 4.1 under continuous corn to 6.0 under the integrated landscape scenario. While not considered here, further improvements to the WQIag score could be accomplished through the adoption of a cover crop or conservation tillage. In addition to preserving soil resources, previous research has shown these additional conservation practices to increase the amount of corn stover that can be collected sustainably, providing an economic incentive when properly managed (Bonner et al., 2014b; Pratt, Tyner, Muth, & Kladivko, 2014).

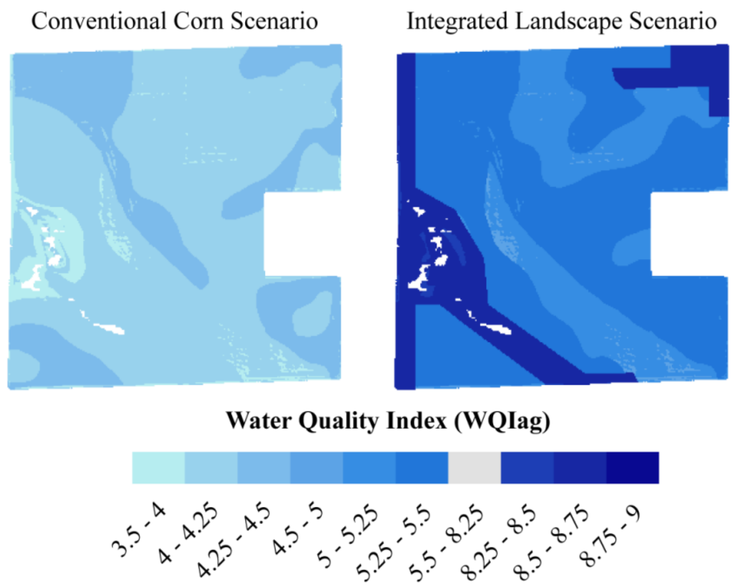

Figure 12. Water Quality Index (WQIag) score under conventional corn management [left] and the integrated landscape design [right] where switchgrass is integrated on a subfield basis.

2.4.4. Alternative Management Approaches

The integrated landscape design described thus far is constructed on the basis of subfield profit as the foundational metric for identifying candidate areas for conversion to switchgrass within the multi-objective optimization procedure. This does not, however, need to be the case should a land manager's primary interest be different. For example, the multi-objective optimization strategy could be based on any number of metrics, such as soil erosion, nitrate leaching, or soil organic carbon. In any such case, the optimization method would seek to find the most desirable land area change, beginning with areas of the poorest performance. To demonstrate the potential tradeoffs between optimizing this case study field based on an environmental metric rather than an economic metric, the optimization and subsequent analyses were reevaluated on the basis of minimizing total soil erosion through integration of switchgrass. The revised management plan consists of 14.6 ha (36 ac) of switchgrass, mostly expanding into the no-stover harvest areas of the previous design (Figure 13). The profit from grain displaced by this management plan would require switchgrass to exceed an average net return of -291 US$ ha^{-1} (118 US$ ac^{-1}) to match the economic performance of the conventional scenario.

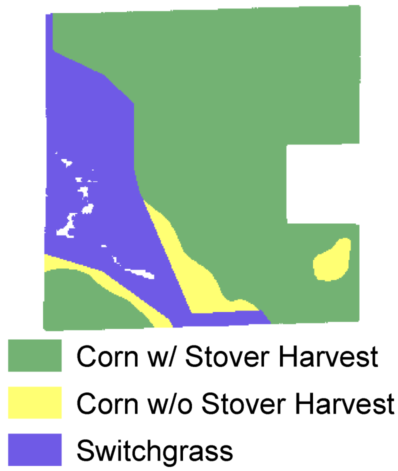

Figure 13. Management zones for an integrated landscape design where soil erosion is used to direct the multi-objective optimization function for identifying areas for conversion to switchgrass.

Each of the primary metrics for measuring site productivity, economics, and environmental impacts are easily compared using a radar plot to highlight the relative performance of all three management strategies (Figure 14). From this graphic, it is clear that the two integrated landscape methods yield similar results despite different land area's being targeted for conversion to switchgrass. The erosion-oriented landscape has the lowest grain production due to the largest displacement of corn, but the greatest annual biomass production; 57% higher than the conventional case. Interestingly, the annual soil erosion rates, nitrate leaching rates, and WQIag scores are nearly identical to those of the profit-oriented scenario, though the rate of soil organic carbon gain is 3.6 Mg yr^{-1} (4.0 t yr^{-1}) less than that of the profit-oriented scenario. These results support the case that areas of a field demonstrating poor economic return can be used to effectively identify and construct management strategies that meet or exceed the environmental benefits of conservation-focused strategies. While the erosion-based optimization results in desirable field performance, the profit-based scenario requires less land to be converted and at a lower minimum profit for switchgrass, making integrated landscapes more tenable.

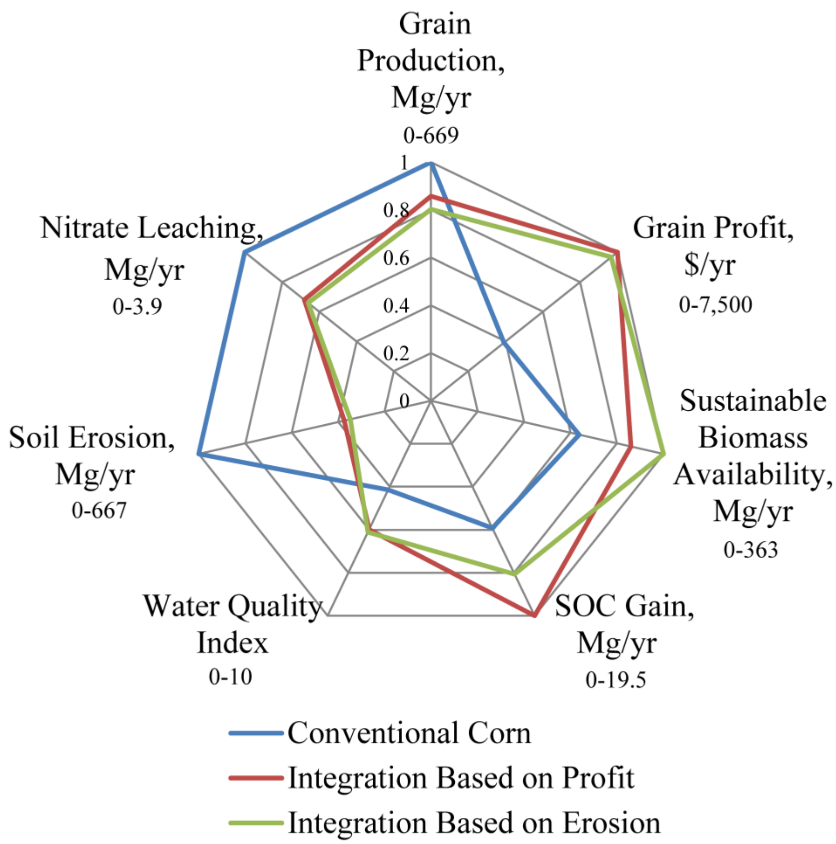

Figure 14. Comparison of the economic, production, and environmental performance metrics of the conventional corn scenario to both integrated landscape scenarios.

2.4.5. Financial Benefits from Environmental Improvement

The economic conditions required for landscape integration have thus far only been discussed relative to the lost opportunity cost from displacing corn. The basic mechanism of this concept is simple – the difference between the costs and revenue associated with producing an energy crop on a subfield scale must exceed that of the contiguous conventional crop. While survey results show that this financial advantage plays a large role in a grower's willingness to convert lands to an energy crop (Bergtold, Fewell, & Williams, 2014; Smith, Schulman, Current, & Easter, 2011), the method does not account for any financial value associated with improved environmental performance. English, Tyner, Sesmero, Owens, and Muth (2013) showed that a grower's willingness to adopt conservation management practices can be influenced by the private and social costs of soil erosion and existence of a biomass market. Similarly, if the social costs of environmental performance are internalized and combined with private costs, this composite value can be used to further define the opportunities and barriers facing bioenergy landscape designs.

Table 2. Total private and social costs for environmental metrics of soil organic carbon change, soil erosion, and nitrate leaching including cost savings from integrated landscape scenarios.

	Conventional Corn Baseline	Integrated Landscape, Profit Oriented	Integrated Landscape, Erosion Oriented
	Annual Resource Value ($ yr^{-1})		
Soil Organic Carbon	1,450	2,440	1,970
Erosion	-1,660	-1,290	-1,200
NO_3 Leaching[*]	-1,860 (±800)	-1,260 (±550)	-1,230 (±530)
	Field-Level Annual Savings from Landscape Integration ($ yr^{-1})		
Soil Organic Carbon	-	1,000	520
Erosion	-	360	450
NO_3 Leaching[*]	-	590 (±250)	630 (±270)
Total Savings	-	1,700 to 2,210	1,330 to 1,880
	Area Weighted Savings from Landscape Integration ($ ha^{-1} yr^{-1})		
Total Savings	-	137 to 179	90 to 127

[*] Values in parenthesis represent the potential range of costs presented by Christianson, Tyndall, and Helmers (2013)

Under conventional management this field's soil resources (annual SOC change, erosion, and nitrate leaching) are valued at 1,450, -1,660, and -1,860 US$ yr^{-1}, respectively, where the latter two negative values represent an annual loss rather than a gain (Table 2). Improving the field's environmental performance through landscape integration is reflected in improvements to each of these values or loses. The improvement to annual SOC gain represents a 69% increase in value for the profit-oriented scenario, and a 36% improvement in the erosion-oriented scenario. Annual reductions in soil erosion deceases the field level loss by 22% and 27% under the respective integrated landscape scenarios while decreased nitrate leaching reduces costs by 32% and 34%, respectively. When presented on a relative basis to the area of land converted to switchgrass, these costs represent 80.6 US$ ha^{-1} (32.6 US$ ac^{-1}) in improved SOC, 29.4 US$ ha^{-1} (11.9 US$ ac^{-1}) in reduced erosion, and 48.1 ± 20.7 US$ ha^{-1} (19.5 ± 8.4 US$ yr^{-1}) in reduced nitrate leaching for the profit-oriented scenario and 35.3 US$ ha^{-1} (14.3 US$ ac^{-1}) in improved SOC, 30.7 US$ ha^{-1} (12.4 US$ ac^{-1}) in reduced erosion, and 42.8 ± 18.5 US$ ha^{-1} (17.3 ± 7.5 US$ ac^{-1}) in reduced nitrate leaching for the erosion-oriented scenario. In total, the improved environmental performance of the profit oriented scenario results in a savings of 158 ± 21 US$ ha^{-1} yr^{-1} (64 ± 8 US$ ac^{-1} yr^{-1}) while the erosion-oriented scenario saves 109 ± 18 US$ ha^{-1} yr^{-1} (44 ± 7 US$ ac^{-1} yr^{-1})(Table 2).

Inclusion of these costs in the economic comparison between conventional management and an integrated landscape scenario increases the favorability of energy crop production by widening the economic performance gap between alternatives. For example, in the profit-oriented integrated landscape, the opportunity cost lost from displacing corn production was -509 US\$ ha^{-1} (-206 US\$ ac^{-1}); by including the improvements to environmental costs to this consideration, the minimum net return of switchgrass production would need only be -667 US\$ ha^{-1} (-270 US\$ ac^{-1}) to equal the performance of corn. Of course, the return on switchgrass and its ability to meet or exceed the opportunity cost of corn is dependent on its value as a feedstock. Figure 15 shows the sensitivity of this return as influenced by the value of switchgrass compared to the return from corn when using an average switchgrass yield of 7.8 Mg ha^{-1} (3.5 t ac^{-1}) and environmental benefit of 158 \$ ha^{-1} (64 US\$ ac^{-1} yr^{-1}). The intersection between the return of both crops represents the critical feedstock price at which landscape integration matches conventional practices. In this case, a minimum feedstock price of 107 US\$ Mg^{-1} (97 US\$ t^{-1}) is required. This price is quite high, especially when considering that the costs of storage and transportation must still be incurred to supply an end-user. With this in mind, the linear relationship between switchgrass value and return can be used to interpret the necessity of other cost-saving mechanisms to enable an integrated landscape. For example, if the value of switchgrass was established at 88 US\$ Mg^{-1} (80 US\$ t^{-1}), other financial benefits such as reduced management costs, increased yields, or incentives programs would then need to amount to 19 US\$ Mg^{-1} (17 US\$ t^{-1}) to meet the critical point. In this regard, every 1.1 US\$ Mg^{-1} (1 US\$ t^{-1}) increase to feedstock price (or alternatively reduction in production costs) above the critical point results in a field level savings of 107 US\$ yr^{-1}.

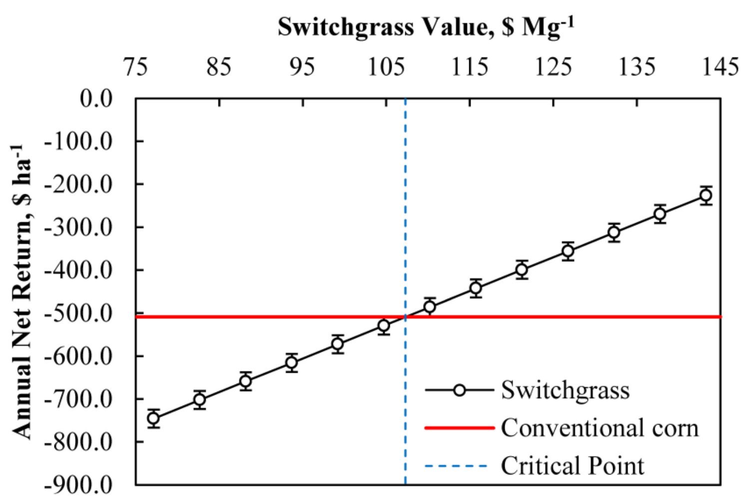

Figure 15. Influence of feedstock value on the net return from switchgrass production in the profit oriented integrated landscape scenario. Error bars represent the range of returns caused by variable environmental performance costs.

It is important to remember that the outcome of this analysis depends on internalization of social costs for environmental performance and the existence of a feedstock market (both of which have uncertainties and sensitivities). These results are nevertheless encouraging in that energy crops may be more favorable than current practices when considered as an economic loss mitigation strategy and conservation practice. It is also worth restating that the field performance used in this work is based on annual averages and thus does not portray the year-to-year variability that would be expected for both corn and energy crop production. In addition, the economics of biomass storage and transportation and the variability in corn grain prices are considered beyond the scope of this work, though inclusion of these costs and sensitives in large scale analyses is critical in order to fully understand the costs and benefits of integrated bioenergy landscapes. Finally, this research does not consider how land tenure influences the adoption of integrated landscape practices. Altering agronomic practices to include perennial crops that operate on rotations up to a decade is in conflict with many existing short term rental contracts. Changing to a mix of annual and perennial crops could imply a change in rental arrangements.

2.5. Summary and Conclusions

The bioenergy landscape integration strategy presented here shows that field productivity, profitability, and environmental performance can all be improved through selective identification of areas for conversion to switchgrass and stover management. Depending on the objective focus of subfield optimization, sustainable biomass yields can increase by 35% to 57%, comprised of 26% or 34% switchgrass, respectively. Each of these cases, however, requires switchgrass to operate at different net returns in order to justify the displacement of row crops. Of the two cases described, the profit-based optimization results in a lower land conversion rate, lower minimum return for switchgrass, and higher value environmental improvement compared to the erosion-based optimization. The potential benefits of an integrated landscape management are clear; however, the success of this method of energy crop production and natural resource conservation depends on grower adoption. Demonstration of sufficient benefit to land managers must be accomplished though continued analysis and outreach, field studies, and establishment of a biomass market that provides demand for dedicated energy crops. It will also be necessary to develop policy incentives to internalize the environmental benefits to farmer decision-making.

2.6. Acknowledgments

This work is supported by the U.S. Department of Energy's Office of Energy Efficiency & Renewable Energy, Bioenergy Technologies Office, under DOE Idaho Operations Office Contract DE-AC07-05ID14517. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

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