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Article

Opportunities for Energy Crop Production Based on Subfield Scale Distribution of Profitability

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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.

Keywords: biomass; subfield management; switchgrass; corn stover; Landscape Environmental Assessment Framework (LEAF)

1. 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 $Mg\cdot ha^{-1}$ 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.

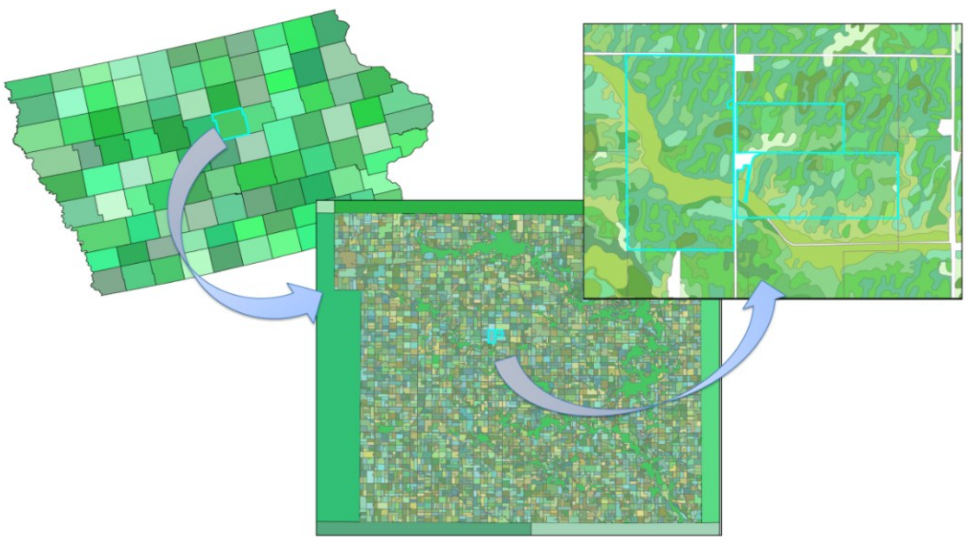
2. Methods

2.1. 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·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**).



2.2. 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:

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

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 $\mathrm{Mg \cdot ha^{-1}}$ 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 $\mathrm{Mg \cdot ha^{-1}}$, minimum yield of 4.6 $\mathrm{Mg \cdot ha^{-1}}$, and maximum yield of 15.1 $\mathrm{Mg \cdot ha^{-1}}$, 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 $\mathrm{Mg \cdot ha^{-1}}$ 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.

2.3. 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 2.1 and 2.2. An average profit for corn production over the entire rotation is then determined and used for this analysis.

2.4. 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].

2.4.1. 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.

2.4.2. 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 glass 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.

2.4.3. 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 2.3. 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.

2.4.4. 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 $<½T$ 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.

2.5. 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).

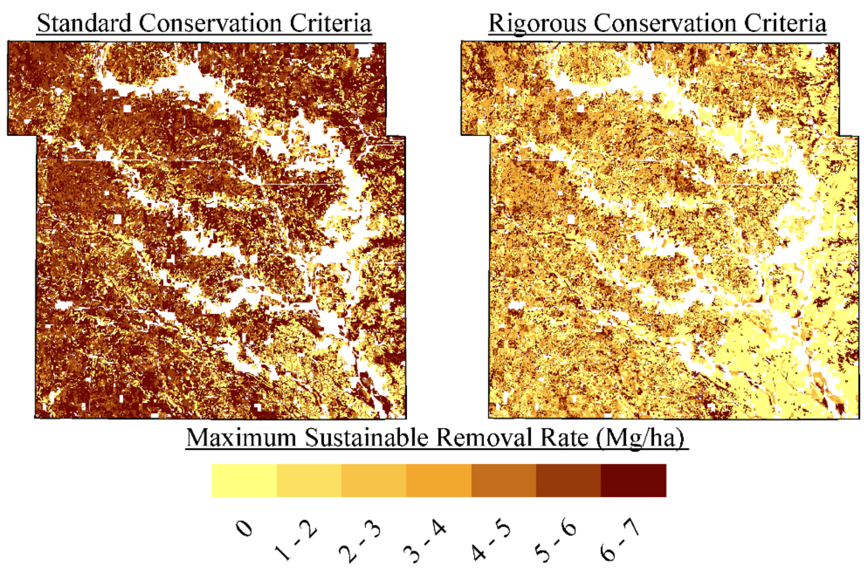
3. Results and Discussion

3.1. 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·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·ha^{-1} with a range of 2.4 to 11.5 Mg·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.

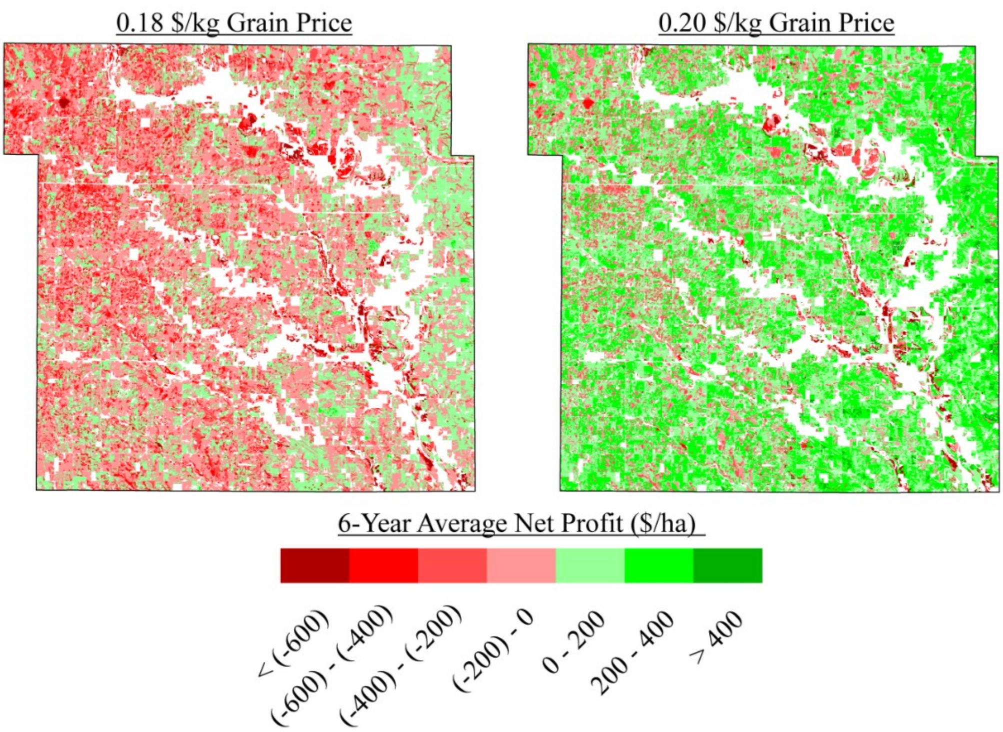
Figure 2. Six year average maximum sustainable corn stover availability resulting from the annually adjusted Iowa Soil Properties and Interpretations Database (ISPAID) data and Landscape Environmental Analysis Framework (LEAF) analysis adhering to crop rotations observed from 2007 to 2012 for Hardin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



3.2. 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 $\$\cdot kg^{-1}$ (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.

3.3. Opportunity for Energy Crops

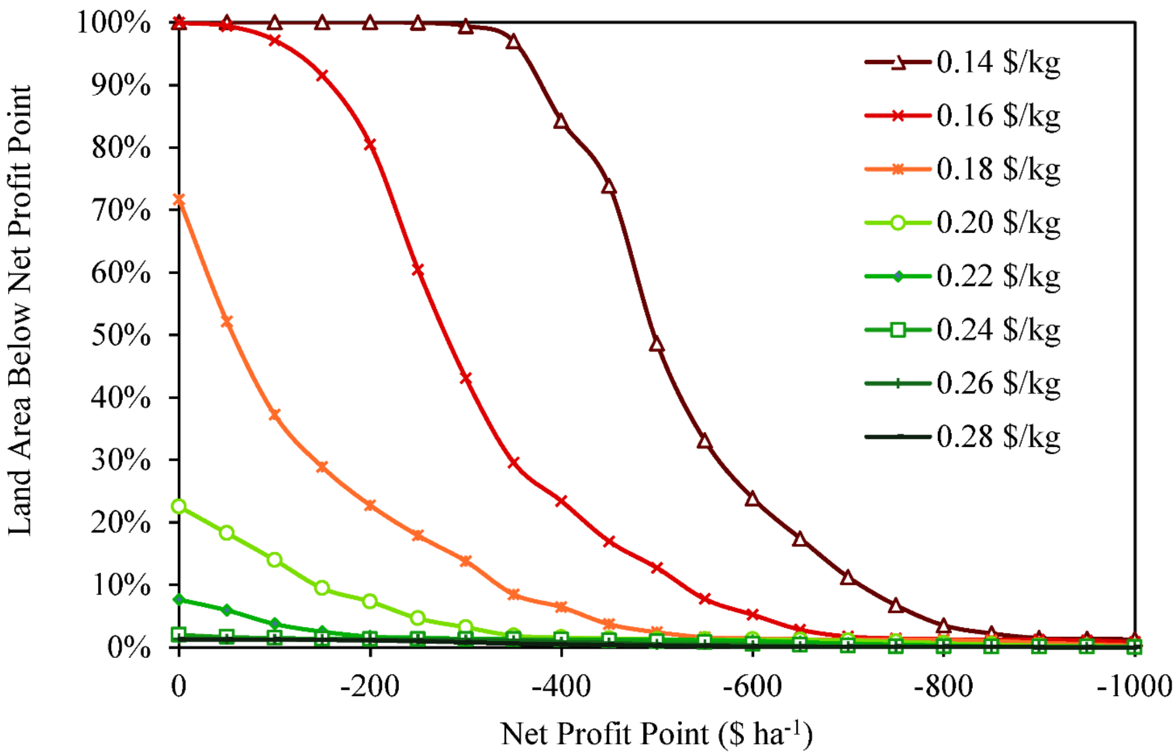
The variability of within-field profit presents itself as an important potential entry point for energy crops. Candidate areas can be identified by assessing the amount of land within the county losing more than any given $\$\cdot ha^{-1}$ amount. If energy crops can be implemented and managed on a subfield 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 ≤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 $·ha^{-1} net loss. For example, at a 0.18 $·kg^{-1} grain price, nearly 17,000 ha (14% of the corn producing land) are estimated to operate at a net profit of ≤−300 $·ha^{-1}, though at a 0.20 $·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 $·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.



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

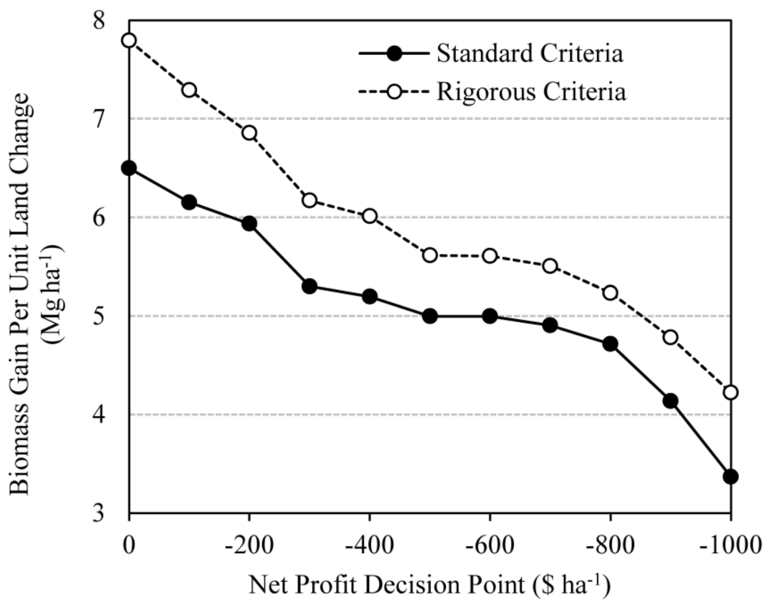
The quantity of candidate areas for conversion to switchgrass at a 0.20 $·kg^{-1} grain price ranges from 800 ha (1% of the total corn producing area in the county) at a net profit decision point of −800 $·ha^{-1} to 27,600 ha (22% of the total area) at a 0 $·ha^{-1} net profit decision point (Figure 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·year^{-1} under the most generous decision point (0 $·ha^{-1} net operating cost) and standard conservation criteria; a 180,000 Mg·year^{-1} increasing from the baseline. The rate of biomass increase per unit land change ranges from 3.4 to 6.5 Mg·ha^{-1} under the standard conservation criteria and 4.2 to 7.8 Mg·ha^{-1} under the rigorous conservation criteria (Figure 5).

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%	-

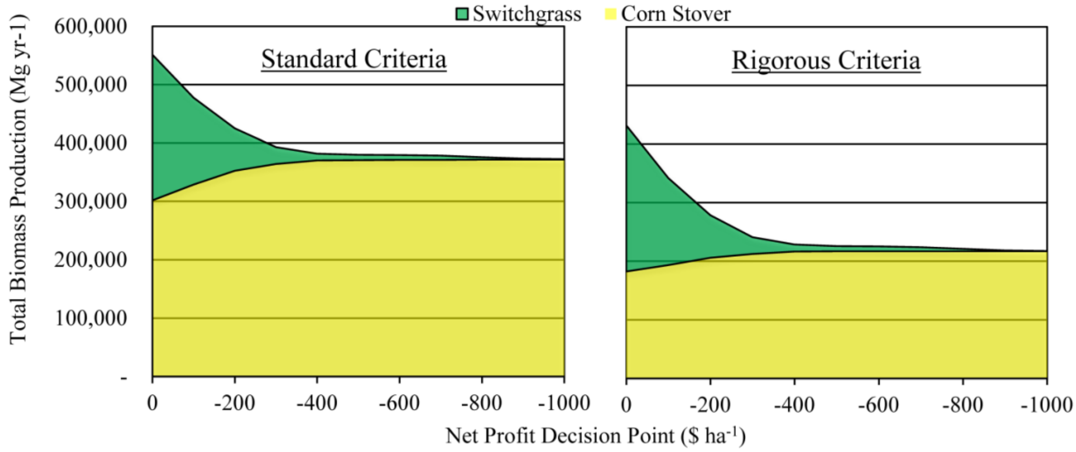
[a] Biomass increase relative to sustainable corn stover availability when no landscape integration is considered; [b] Mean change in area of only the fields affected by landscape integration at each respective decision point; [c] All profit calculations are relative to the remaining row crop area of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

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 $·ha^{-1} decision points. Once the decision point is increased above −500 $·ha^{-1}, the rate of biomass gain begins to rise once more. As a result of these increased rates and increased occurrence of land areas operating at less negative decision points we see county level biomass availability increase rapidly (Figure 6). In the standard conservation scenario biomass availability is increased by 28% at the −100·$ 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 $·ha^{-1} decision point, if switchgrass yields were 25% lower than corn yields the total biomass availability would drop to 305,000 Mg·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.

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}.



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.

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 $\$\cdot ha^{-1}$ (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.

4. 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.

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Author Contributions

The concept of this research was conceived by David Muth and Douglas Karlen. Field boundary delineations and crop rotations were created by Mark Tomer, David James, and Sarah Porter. Crop budgets and LEAF analysis were prepared by David Muth. Spatial data management, data processing and interpretation, and manuscript preparation were completed by Kara Cafferty and Ian Bonner. All authors contributed to the editing and reviewing of this document.

Conflicts of Interest

The authors declare no conflict of interest.

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