GLOBAL CHANGE BIOLOGY
BIOENERGY

GCB Bioenergy (2018) **10**, 473–488, doi: 10.1111/gcbb.12516

# Where can switchgrass production be more profitable than corn and soybean? An integrated subfield assessment in Iowa, USA

ELKE BRANDES[1], ALEJANDRO PLASTINA[2] and EMILY A. HEATON[1]

[1]*Department of Agronomy, Iowa State University, Ames, IA 50011, USA,* [2]*Department of Economics, Iowa State University, Ames, IA 50011, USA*

## Abstract

Perennial bioenergy crops are considered an important feedstock for a growing bioeconomy. However, in the USA, production of biofuel from these dedicated, nonfood crops is lagging behind federal mandates and markets have yet to develop. Most studies on the economic potential of perennial biofuel crops have concluded that even high-yielding bioenergy grasses are unprofitable compared to corn/soybeans, the prevailing crops in the United States Corn Belt. However, they did not account for opportunities precision agriculture presents to integrate perennials into agronomically and economically underperforming parts of corn/soybean fields. Using publicly available subfield data and market projections, we identified an upper bound to the areas in Iowa, United States, where the conversion from corn/soybean cropland to an herbaceous bioenergy crop, switchgrass, could be economically viable under different price, land tenancy, and yield scenarios. Assuming owned land, medium crop prices, and a biomass price of US$ 55 $Mg^{-1}$, we showed that 4.3% of corn/soybean cropland could break even when converted to switchgrass yielding up to 10.08 Mg $ha^{-1}$. The annualized change in net present value on each converted subfield patch ranged from just above US$ 0 $ha^{-1}$ to 692 $ha^{-1}$. In the three counties of highest economic opportunity, total annualized producer benefits from converting corn/soybean to switchgrass summed to US$ 2.6 million, 3.4 million, and 7.6 million, respectively. This is the first study to quantify an upper bound to the potential private economic benefits from targeted conversion of unfavorable corn/soybean cropland to switchgrass, leaving arable land already under perennial cover unchanged. Broadly, we conclude that areas with high within-field yield variation provide highest economic opportunities for switchgrass conversion. Our results are relevant for policy design intended to improve the sustainability of agricultural production. While focused on Iowa, this approach is applicable to other intensively farmed regions globally with similar data availability.

*Keywords:* bioenergy, biofuel, cellulosic, landscape, net present value, partial budgets, perennial, precision agriculture

*Received 15 December 2017; revised version received 9 March 2018 and accepted 16 March 2018*

## Introduction

Biofuels play a prominent role in the US sustainable energy portfolio. While conventional, mostly starch-based biofuels have met the US Renewable Fuel Standard's (RFS2, US Environmental Protection Agency, 2010) target of approximately 57 billion liters per year, production of cellulosic biofuels has steadily lagged behind mandates (US Environmental Protection Agency, 2017a). To meet the total renewable biofuel target of approximately 136 billion liters by 2022, nearly 64 billion liters of advanced biofuel still need to be added to the current annual volume (US Environmental Protection Agency, 2017b).

Corn (*Zea mays* L.) stover has been identified as a readily available cellulosic feedstock to meet this gap (Muth *et al*., 2013), but concerns about decreasing soil organic carbon content resulting from extensive residue removal practices justify a careful assessment of environmental consequences. Moreover, overdependence on a single crop increases farm risk which may be mitigated by growing a more diverse crop rotation to reduce the variability of farm profits over time (Chavas & Holt, 1990). Even though efforts to use stover for bioethanol on a commercial scale have been initialized in the Midwest [e.g., Poet-DSM's Project Liberty in Emmetsburg, IA and DuPont's now for-sale plant in Nevada, IA (Eller, 2017)], no fully functioning corn stover facility exists in the United States to date, and the US Environmental Protection Agency reduced mandated amounts of consumed cellulosic ethanol citing low supply (US Environmental Protection Agency, 2017c). Dedicated biofuel crops such as switchgrass (*Panicum virgatum* L.) or giant miscanthus (*Miscanthus* × *giganteus* Greef & Deu.) might open up an opportunity for enterprise diversification, leading to a variety of

Correspondence: Elke Brandes, tel. +49 531 596 – 5235, fax +49 531 596 – 5599, e-mail: elke.brandes@thuenen.de

economic, societal, and environmental benefits, commonly described as ecosystem services (Power, 2010; Burkhard *et al.*, 2014).

Environmental improvements from agricultural diversification with perennial biofuel crops are well described (Schulte *et al.*, 2006; Asbjornsen *et al.*, 2014; Dauber & Miyake, 2016). While a wide range of high-yielding grasses has been studied in field trials (Heggenstaller *et al.*, 2009; Griffith *et al.*, 2011) and economic analyses (Boyer *et al.*, 2015), switchgrass was identified as a promising biofuel crop for North America by the US Department of Energy (McLaughlin & Walsh, 1998) and has been developed as such in recent decades (Mitchell *et al.*, 2016). Still, corn and soybean systems dominate several agricultural regions of the United States, especially the Midwest Corn Belt, a roughly nine-state region that produced 78% of US corn in 2017 (NASS, 2017).

Previous economic analyses of switchgrass integration in the Corn Belt estimated high breakeven prices for biomass from dedicated bioenergy crops like switchgrass or miscanthus to be able to compete with corn/soybean rotations (Jain *et al.*, 2010). Other studies concluded that switchgrass cannot be economically viable, and cellulosic biomass can only be sourced from corn stover in this highly productive region (Dumortier *et al.*, 2017; Efroymson & Langholtz, 2017). However, these studies did not take into account the heterogeneity of growing conditions within corn and soybean fields, which exist even in the fertile Corn Belt (but see Soldavini & Tyner, 2018). In Iowa, the heart of the Corn Belt, Brandes et al. (2016), showed that differences in profitability across subfield areas within a farm can be substantial and estimated that a significant portion of the state's cropland, up to 25%, could have been incurring economic losses in the last decade.

The development of precision agriculture technology has made it feasible to manage a field 'acre by acre' and increase not only grain yield, but also return on investment; that is, grain revenue in relation to input costs (Muth, 2014). Converting underperforming corn/soybean land to switchgrass, a low-input perennial crop lasting at least 10 years might help farmers to decrease fertilizer, pesticide, and operational input costs and provide a net economic benefit. This benefit could compensate for risks and sunk costs associated with conversion to a new crop. In this way, agricultural land already in perennial cover, such as pastures and land set aside under the USDA Conservation Reserve Program (CRP), might be excluded from conversion to avoid negative environmental effects such as carbon release to the atmosphere (Zenone *et al.*, 2013; Qin *et al.*, 2016) or loss of diversity (Bakker & Higgins, 2009). However, there is a gap in the literature on the economic viability of perennial biofuel crop production in subfield areas that consistently generate economic losses in a corn/soybean system. This study addresses this gap by conducting an integrated subfield profitability assessment of switchgrass as an alternative to corn/soybean crop systems in Iowa, the top corn and the second largest soybean producing state in the United States (USDA, 2017a).

With the overarching aim to find sustainable ways to grow dedicated bioenergy crops without converting land already under perennial cover, our goals in this study were (1) to identify the spatial distribution of subfield areas suitable for conversion from corn/soybean to switchgrass as indicated by agronomic, management, and economic criteria; and (2) to evaluate the distribution of breakeven switchgrass yields and net producer benefits in the State of Iowa, USA, under alternative scenarios. While focused on Iowa, this approach is applicable to other intensively farmed regions globally with similar data availability.

## Materials and methods

### *Methods summary*

We used a three-step approach to identify the areas suitable for switchgrass conversion in Iowa. First, we used agronomic criteria to identify subfield areas where switchgrass might perform better than the status quo, corn/soybean. Second, we applied spatial constraint criteria to the target area to exclude subfield portions where switchgrass management would be impractical. Third, from these downselected subfield areas, we identified those where switchgrass production would be viable using economic criteria. We did this by considering alternative scenarios combining three levels of commodity prices (low, medium, and high), two land tenure regimes (all land either rented or fully owned by producers), and three levels of switchgrass yields (low, medium, and high).

Finally, in a fourth step, we calculated the statewide change in total producer benefits from conversion to switchgrass across all economically viable subfield areas with a breakeven yield of up to 10.08 Mg ha$^{-1}$ (4.5 short tons acre$^{-1}$).

### *Data*

Subfield areas were distinguished by soil properties and field boundaries as described in Brandes et al. (2016). A spatial layer was created by intersecting the latest publicly available common land unit boundaries (CLU, USDA, 2008) with soil survey delineations (NRCS, 2016). For 2012–2015, the years for which we had all necessary data, fields were assigned a crop cover by overlaying the cropland data layer (NASS, 2016a). Fields in either corn or soybeans were identified in each year as described in Gelder *et al.* (2008). Only fields in corn and/or soybean in all four years were included in the analysis (98.4% of the average corn/soybean cropland 2012–2015). Distinct patches of the same soil property in a given field were treated as individual polygons to discriminate patches by size and location. Economic data consisting of corn and soybean price and cost projections for 2017–2026 were sourced from the US Department of Agriculture (USDA, 2017b). Production costs were categorized into land costs, harvest costs (dependent on estimated subfield yields), and other costs. Land costs were kept separate from other production costs and postharvest costs for two reasons: (1) cash rents have a large impact on total production cost; they account for 36% and 48% of total costs of corn and soybean production in Iowa, respectively (Plastina, 2017); and (2) land costs are strongly related to soil quality and can be reasonably estimated using statistical and soil data. The estimated costs of crop production for 2016 were derived from detailed corn, soybean, and switchgrass budget estimates from Iowa State University (Hart, 2015; Plastina, 2017). Harvesting costs and other costs were projected into 2026 by applying the annual percentage change calculated from the cost projections from the US Department of Agriculture (USDA, 2017b).

### *Step 1: Identifying subfield target areas for switchgrass conversion using agronomic criteria*

Using the spatial layer of subfield polygons, we identified eligible subfield areas based on estimated yield performance from 2012 to 2015. Subfield-level yields were estimated as described in Brandes et al. (2016). Yields are strongly dependent on soil properties and are therefore highly variable in fields of varying soil characteristics. We used the integrated soil quality index CSR2 (corn suitability rating, Burras *et al.*, 2015) for the *i*-th polygon ($CSR2^i$) as a yield indicator for potential corn yields ($\widetilde{Y}_i^C$) and potential soybean yields ($\widetilde{Y}_i^B$; both in bushels acre$^{-1}$) by applying the following formulas (Sassman *et al.*, 2015):

$$\widetilde{Y}_i^C = \left(1.6 \times CSR2^i + 80\right) \quad (1)$$

$$\widetilde{Y}_i^B = 0.29 \times Y_i^C \quad (2)$$

Equations (1) and (2) were re-expressed into Mg ha$^{-1}$ using conversion factors (1 bushel of corn acre$^{-1}$ = 0.0628 Mg of corn ha$^{-1}$; 1 bushel of soybeans acre$^{-1}$ = 0.0673 Mg of soybeans ha$^{-1}$):

$$Y_i^C = \widetilde{Y}_i^C \times 0.0628 \quad (3)$$

$$Y_i^B = \widetilde{Y}_i^B \times 0.0673 \quad (4)$$

All data and calculations hereafter are expressed in metric units. These potential yields do not take into account weather-related temporal and spatial variability. Therefore, following Bonner *et al.* (2014), we normalized potential yields in each polygon to county averages reported by the USDA National Agricultural Statistics Service (NASS) for each assessment year (2012–2015). We did this by first calculating potential annual total grain production per county as:

$$Y_{jt}^m = \sum^i a_m^{ijt} \times Y_i^m \quad (5)$$

where $a_m^{ijt}$ is the area in ha of a given polygon *i* in county *j* planted to cash crop *m* ($m$ = {$C$ = Corn; $B$ = Soyabeans}) in year *t*. Then, county- and year-specific unitless correction factors (CF) were calculated as:

$$CF_{jt}^m = \frac{NY_{jt}^m}{Y_{jt}^m} \quad (6)$$

where $NY_{jt}^m$ is the NASS reported total grain production for cash crop *m* in county *j* and year *t*. So the normalized yields ($\breve{Y}$) for the *i*-th polygon were estimated as:

$$\breve{Y}_{it}^m = Y_i^m \times CF_{jt}^m \quad (7)$$

As discussed in Bonner et al. (2014), this normalization allows us to maintain the expected value of county yields equal to the county average yields reported by NASS, while reflecting subfield yield variability according to subfield agronomic conditions: $\sum^i a_m^{ijt} \times \breve{Y}_{it}^m = NY_{jt}^m$. However, this method does not consider areas of fields that perform better than their average in a particularly dry year, for example water logged patches, and might therefore underestimate the average performance of these areas.

The normalized annual yields were then compared to historic county average yields. They provided the agronomic criteria used to identify subfield targets for switchgrass integration: polygons that yielded below a county-specific threshold yield in each and every year of the reference period (2012–2015) were considered as target area for switchgrass conversion. The threshold yield level for each county was set to the second lowest NASS reported county yield in the 2000 to 2015 period (NASS, 2016b, Table S1). Due to a severe and widespread draught, yields in 2012 were the lowest over the 2000–2015 period for most counties in Iowa.

*Step 2: Subfield spatial selection based on management feasibility criteria*

Contiguous target polygons (i.e., polygons sharing border lines) were merged, and isolated polygons of less than 1 ha that were located at a distance of >20 m to larger target polygons were excluded from the target population. This spatial processing was performed to account for management feasibility and assumes producers would not be able or inclined to manage small, disparate areas of switchgrass. The downselection process resulted in 445,988 ha of target area, or 4.8% of total cropland in corn/soybeans in Iowa during 2012–2015. Data analysis was performed in a PostgreSQL database and spatial processing was performed in ArcGIS 10.4 (ESRI, Redlands, CA, USA).

*Step 3: Subfield selection based on economic viability criteria*

In the third step, we used a partial budget approach (Kay *et al.*, 2017) to compare the net present value (NPV) of the existing corn/soybean rotation with the NPV of switchgrass production for each of the polygons comprising the eligible area, except those polygons with unusual corn/soybean rotations. We excluded rotations with two or more consecutive years in soybeans between 2012 and 2015 (0.4% of total corn/soybean cropland in Iowa; for a list of included rotations see Table S2). Following the logic of partial budgets, if the net present value of switchgrass production is positive and exceeds that of the status quo (corn/soybean) for a particular polygon, then such polygon is deemed viable for switchgrass conversion. Otherwise, it is deemed unviable for switchgrass conversion. Note that it is possible for the net present value of both the current rotation and switchgrass production to be negative for some polygons under certain circumstances. In that case, the best possible alternative is to discontinue production in those polygons.

Given the prospective approach and intrinsic uncertainty associated with the calculation of net present value, 24 internally consistent scenarios were developed in a factorial design of crop prices (low, medium, and high), land tenancy arrangements (all cropland cash rented, all cropland owned by farm operator), and switchgrass yields (low, medium, and high; Table 1). Combining these factors resulted in six scenarios for the economic analysis of corn/soybean cropland (i.e., 3 corn/soybean prices × 2 land tenancies = 6) and 18 scenarios for the economic analysis of switchgrass (i.e., 3 switchgrass price × 2 land tenancies × 3 switchgrass yields = 18). Projections span over a 10-year period, starting in 2017.

*Step 3a: NPV for corn/soybean rotations*

We assumed no change in crop rotations in the future and carried the rotations of the reference period (2012–2015) forward into the future, always assuming the least possible continuous corn years. For example, for the rotation C,B,C,C in 2012–2015, we assumed a sequence of B,C,C,C,B,C,C,C,B,C for 2017–2026. For the rotation B, C,C,C in 2012–2015, we assumed a sequence of C,C,C,B, C,C,C,B,C,C for 2017–2026. Under these assumptions, we projected 2017–2026 corn and soybean yields in each polygon equal to the polygon-specific average yields over 2012–2015:

$$\bar{Y}_i^m = \frac{\sum_{t=2012}^{2015} \check{Y}_{it}^m}{T_i^m} \quad (8)$$

where $T_i^m$ is the number of times crop $m$ was planted in polygon $i$ between 2012 and 2015. For example, the projected corn yield for a polygon that was in continuous corn in the reference period equals the simple average of the four yields estimated for that polygon; alternatively, for a polygon in C,B,C,B rotation in 2012–2015, the projected corn yield is the simple average of two estimated corn yields, and the projected soybean yield is the simple average of two estimated soybean yields for that polygon. Although Iowa corn yields have trended upward since the mid-1990s (Li *et al.*, 2014), we assume that land quality in the selected subfield areas is a limiting factor to such trend. If corn and soybean yields in the selected subfield areas grow over the simulation period, everything else being equal, the net benefits from switchgrass adoption will be lower than currently projected.

The NPV of crop production in the $i$-th polygon under scenario s ($s$ = 1,. . .,6) was calculated as:

$$\mathrm{NPV}_s^i = A^i \sum_{t=1}^{10} \frac{D_t^i\left[\left(P_{\mathrm{st}}^C - H_t^C\right)\bar{Y}_i^C - \mathrm{NLC}_t^{\mathrm{C}i}\right] + \left(1 - D_t^i\right)\left[\left(P_{\mathrm{st}}^B - H_t^B\right)\bar{Y}_t^B - \mathrm{NLC}_t^{\mathrm{B}i}\right] - \mathrm{LC}_{\mathrm{st}}^i}{(1+d)^t} \quad (9)$$

**Table 1** Factors, levels, and values considered in analyzed scenarios. Corn and soybean prices are listed in Table 2; low, medium, and high switchgrass prices were, respectively, US$ 44, 55, and 66 $Mg^{-1}$ (US$ 40, 50, and 60 short $ton^{-1}$); low, medium, and high switchgrass yields were, respectively, 8.41, 10.08, and 11.76 Mg $ha^{-1}$ (3.75, 4.5, and 5.25 short tons $acre^{-1}$). The fourth and fifth columns indicate the crop for which the factors were considered in the economic analyses

| Factor | Levels | Values | Used for corn/soybean | Used for switchgrass |
|---|---|---|---|---|
| Corn/soybean price | 3 | Low; medium; high | X | – |
| Switchgrass price | 3 | 44; 55; 66 US$ $Mg^{-1}$ | – | X |
| Land tenure | 2 | Owned; cash rented | X | X |
| Switchgrass yield | 3 | 8.41; 10.08; 11.76 Mg $ha^{-1}$ | – | X |

where $A^i$ is the area of the $i$-th polygon expressed in ha; $D_t^i$ is an indicator variable that takes the value of 1 if corn is projected to be planted on the $i$-th polygon in year $t$, and zero otherwise; $P_{st}^m$ is the projected price per Mg for commodity $m$ ($m$ = {$C$ = Corn; $B$ = Soyabeans}) in year $t$ ($t$ = 1,...,10) under scenario $s$; $H_t^m$ is the time- and crop-specific postharvest cost per Mg (hauling, drying, and handling costs); $\mathrm{LC}_{st}^i$ is the time-specific land cost (cash rent or land ownership cost) per ha under scenario $s$; $\mathrm{NLC}_t^{mi}$ is the per ha crop- and time-specific nonland cost of production excluding postharvest costs (i.e., land preparation, planting, crop protection, crop insurance, own and hired labor, interest on operating loan); and $d$ is a discount factor equal to 8%. The average annual interest rate for operating loans in the US Midwest between 1992 and 2016 (25 years) was 7.51% (Federal Reserve Bank of Chicago, 2017). A lower discount rate, given that the projected corn and soybean prices follow an increasing trend, would result in higher NPV for scenarios 1–6 and, everything else being equal, the net benefits from switchgrass adoption will be lower than currently projected. The rotation under analysis determines the combination of commodity $m$ and year $t$ for each polygon $i$. Note that $\mathrm{LC}_{st}^i$ does not depend on $m$, that is, the land costs are assumed to be independent of the crop planted. The NPV calculation was made as of March 2017, so all the results are expressed in US dollars of 2017. Adjusting the calculations to any other point in time requires multiplying the results by a scalar, so the relative rankings of results within and across scenarios would remain unchanged.

For medium annual corn and soybean prices, we used the price projections reported by the US Department of Agriculture (USDA, 2017b) for 2017–2026. Low (high) corn and soybean prices were generated by multiplying their respective medium annual prices by 0.9 (1.1).

Postharvest and other crop production costs, $H_t^m$ and $LC_t^{m,i}$, were calibrated for 2017 using crop budget estimates generated at Iowa State University (Plastina, 2017). For the following years, $H_t^m$ and $\mathrm{NLC}_t^{m,i}$ were adjusted using the corresponding percentage change in projected variable costs published by the USDA (2017b).

As the model was calibrated by integrating data from different sources, some adjustments were necessary to keep the internal consistency of the analysis. In particular, the annual difference between the simulated crop revenues and nonland costs is consistently lower than the 2017 average cash rental rate for cropland in Iowa (Plastina & Johanns, 2017). Consequently, calibrating $\mathrm{LC}_{s,t}^i$ trajectories in a fashion similar to the one used for $H_t^m$ and $\mathrm{NLC}_t^{m,i}$ would result in consistently negative profits on corn and soybean production for all counties. As cash rents depend partly on the regional profitability of crop production, we calibrated a cash rental rate for each polygon assuming that the average operator-tenant in each county is able to consistently break even in corn production every year in the projected period. We first calculated the breakeven annual cash rents per acre for each county as:

$$R_{jt} = \left(P_{\mathrm{Med},t}^C - H_t^C\right)\overline{\mathrm{NY}}_j^C - \mathrm{NLC}_t^C \qquad (10)$$

where $P_{\mathrm{Med},t}^C$ is the medium projected price for corn; $\mathrm{NLC}_t^C$ is the projected nonland cost per ha; $\overline{\mathrm{NY}}_j^C$ is the projected county average corn yield [simple average over 2013–2015 (NASS, 2016a)]; yields from 2012 were excluded because a severe draught resulted in unusually low yields in Iowa. Using yields in years prior to 2012 to project future yields might artificially penalize corn and soybean yields over the next decade (Li et al., 2014), which we tried to avoid; and $H_t^C$ is defined as above. For each county, the breakeven annual cash rents were expressed in dollars per CSR2 point (Brandes et al., 2016) as:

$$\mathrm{UR}_{jt} = R_{jt}/\overline{\mathrm{CSR2}}_j \qquad (11)$$

where $\overline{\mathrm{CSR2}}_j$ is the area weighted mean of CSR2 for the $j$-th county from the USDA National Resources Conservation Service Soil Survey (NRCS, 2016). The annual cash rental rate for the $i$-th subfield polygon in US$ $ha^{-1}$ was calculated as:

$$R_t^i = \mathrm{UR}_{jt} \times \mathrm{CSR2}^i \qquad (12)$$

The projected cash rents in Eqn (12) characterize half of our scenarios, namely those that assume that all selected land in Step 2 is operated by tenants, such that $LC^i_{s=\text{leased},t} = R^i_t$. The other three scenarios assume that all selected land in Step 2 is operated by owners. For these scenarios, land costs per ha are assumed to represent 1.5% of the land value:

$$LC^i_{s=\text{owned},t} = \left(0.015 \times R^i_t \times \overline{LV}\right)/\bar{R} \qquad (13)$$

where $\overline{LV}$ is the state average land value per ha over 2012–2015 (Zhang, 2016), and $\bar{R}$ is the state average cash rent per ha over the same period (Plastina & Johanns, 2017).

### *Step 3b: NPV for switchgrass*

The net present value of switchgrass production in the $i$-th polygon under scenario $s$ ($s$ = 7,...,24) is calculated as:

$$NPVSG^i_s = A^i \sum_{t=1}^{10} \frac{\left(P^G_{st} - H^G_t\right)\alpha_t Y^G_i - \left(NLC^{Gi}_t + LC^i_{st}\right)}{(1+g)^t} \qquad (14)$$

where $P^G_{st}$ is the farm gate projected price per Mg of switchgrass in year $t$ ($t$ = 1,...,10) under scenario $s$; $H^G_t$ is the time-specific cost per Mg to bale switchgrass and move bales to an on-site storage; $Y^G_i$ is the polygon-specific average annual projected switchgrass yield; $\alpha_t$ is the proportion of the mature yield achieved in year $t$; $NLC^{Gi}_t$ is the per hectare time-specific nonland cost of switchgrass production excluding postharvest costs (i.e., land preparation, planting, crop protection, own and hired labor, interest on operating loan); $g$ is a discount factor equal to 10% ($g > d$ to reflect greater uncertainty in production in comparison to the status quo); and $LC^i_{st}$ and $A^i$ are defined as above.

Price projections for switchgrass are not publicly available. We therefore set the low, medium, and high farm gate prices for switchgrass within a range previously published at US$ 44, 55, and 66 $Mg^{-1}$ (US $ 40, 50, and 60 short $ton^{-1}$). These values resulted from a recent US market simulation study (Langholtz *et al.*, 2012).

Switchgrass yields were determined from preliminary experimental data of the switchgrass cultivar Liberty (registration: Vogel *et al.*, 2014) grown over multiple locations throughout the US Midwest (CenUSA Bioenergy, 2014). Mature yields of 8.41, 10.08, and 11.76 Mg $ha^{-1}$ (3.75, 4.5, and 5.25 short tons $acre^{-1}$) were chosen for the low, medium and high yield, respectively, representing average yields over a 10-year period (Hart, 2015). Mature switchgrass yields are assumed to be achieved 3 years after establishment, so the model was calibrated using $\alpha_1 = 0.25$, $\alpha_2 = 0.50$, and $\alpha_t = 1$ for $t > 2$.

Crop production costs were taken from a budget developed specifically for the Liberty variety of switchgrass at Iowa State University (Hart, 2015) and adjusted for field preparation appropriate for switchgrass following row crops. Cash rents and land costs were accounted for in the same way as in the row crop projection. Table 2 lists selected parameter values used in the calculation of net present values.

### *Step 3c: Breakeven yields for switchgrass*

Comparing results from steps 3a and 3b, we addressed the question of whether each polygon would generate positive and higher profits in switchgrass than in the current rotation under 6 and 18 different scenarios for corn/soybean and switchgrass, respectively. For the switchgrass scenarios, simulations were conducted for three sets of switchgrass yields, but in each simulation, the same switchgrass yields were applied to all polygons. In step 3c, we introduced heterogeneity in switchgrass yields at the subfield level by identifying the minimum switchgrass yield for each polygon that would leave the producer indifferent between switchgrass production and the status quo corn/soybean rotation (i.e., the polygon-specific breakeven yield that would generate the same NPV in switchgrass production as in the current rotation). The formula for the breakeven switchgrass yield (BEYSG) was obtained by equating (9) and (14) and solving for the polygon-specific mature switchgrass yields:

$$\text{if } NPV^i_s > 0 : BEYSG^i_s = \frac{\left(\frac{NPV^i_s}{A^i} + \sum_{t=1}^{10} \frac{\left(NLC^{Gi}_t + LC^i_{st}\right)}{(1+g)^t}\right)}{\sum_{t=1}^{10} \frac{\left(P^G_{st} - H^G_t\right)\alpha_t}{(1+g)^t}} \qquad (15)$$

$$\text{if } NPV^i_s \leq 0 : BEYSG^i_s = \frac{\left(\sum_{t=1}^{10} \frac{\left(NLC^{Gi}_t + LC^i_{st}\right)}{(1+g)^t}\right)}{\sum_{t=1}^{10} \frac{\left(P^G_{st} - H^G_t\right)\alpha_t}{(1+g)^t}} \qquad (16)$$

After calculating the breakeven switchgrass yields for each polygon, we were able to calculate the total area that would benefit from switchgrass conversion, its spatial distribution, and the total economic impact of switchgrass conversion in Iowa for a specific threshold breakeven yield. Based on our experience with Iowa farmers, we set 10.08 Mg $ha^{-1}$ (4.5 short tons $acre^{-1}$) as a unique threshold for mature switchgrass breakeven yield to quantify those areas that require a yield of no more than 10.08 Mg $ha^{-1}$ to break even with

**Table 2** Select parameter values used for the 10-year projection (2017–2026). See Table S3 for values in Imperial units

| Crop | Parameter | Unit | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Corn | Projected price | US$/Mg | 129.92 | 131.88 | 131.88 | 135.82 | 137.79 | 139.76 | 141.73 | 143.69 | 143.69 | 145.66 |
| Corn | Postharvest costs | US$/Mg | 11.02 | 11.24 | 11.36 | 11.58 | 11.58 | 11.70 | 11.93 | 12.05 | 12.17 | 12.29 |
| Corn | Nonland costs | US$/ha | 882 | 900 | 909 | 927 | 927 | 936 | 955 | 965 | 974 | 984 |
| Soybeans | Projected price | US$/Mg | 343.56 | 345.39 | 345.39 | 347.23 | 347.23 | 349.07 | 350.90 | 350.90 | 350.90 | 350.90 |
| Soybeans | Postharvest costs | US$/Mg | 4.41 | 4.50 | 4.54 | 4.63 | 4.68 | 4.73 | 4.82 | 4.87 | 4.92 | 4.97 |
| Soybeans | Nonland costs | US$/ha | 610 | 623 | 629 | 641 | 648 | 654 | 667 | 674 | 681 | 688 |
| Switchgrass | Projected price | US$/Mg | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 |
| Switchgrass | Postharvest costs | US$/Mg | 23.36 | 23.36 | 23.36 | 23.36 | 23.36 | 23.36 | 23.36 | 23.36 | 23.36 | 23.36 |
| Switchgrass | Nonland costs | US$/ha | 425.75 | 207.81 | 138.77 | 138.77 | 138.77 | 138.77 | 138.77 | 138.77 | 138.77 | 138.77 |
| All | State average cash rent | US$/ha | 346 | 346 | 334 | 356 | 378 | 388 | 385 | 395 | 385 | 395 |
| All | State average land ownership costs | US$/ha | 164 | 164 | 159 | 169 | 180 | 184 | 183 | 188 | 183 | 188 |

corn/soybean production. We assume that farmers who could break even with a switchgrass yield at or below this threshold are likely to convert from corn/soy to switchgrass. The total area that would benefit from switchgrass conversion in Iowa was calculated as:

$$\mathrm{TA} = \sum\nolimits_{\left\{i:\mathrm{BEYSG}_s^i \leq 10.08\ \mathrm{Mg\,ha^{-1}}\right\}} A^i \tag{17}$$

*Step 4: Change in total producer benefit*

The change in total producer benefit, ΔTPB, resulting from switchgrass conversion in Iowa is measured as the sum of the difference between the NPV of switchgrass production and the NPV of the current rotation across those polygons where $\mathrm{BEYSG}_s^i \leq 10.08$ Mg ha$^{-1}$:

$$\Delta\mathrm{TPB} = \sum\nolimits_{\left\{i:\mathrm{BEYSG}_s^i \leq 10.08\ \mathrm{Mg\,ha^{-1}}\right\}} \left(\mathrm{NPVSG}^i_{s\left\{Y_i^G = A^i \times 10.08\ \mathrm{Mg\,ha^{-1}}\right\}} - \mathrm{NPV}_s^i\right) = \sum\nolimits_{\left\{i:\mathrm{BEYSG}_s^i \leq 10.08\ \mathrm{Mg\,ha^{-1}}\right\}} \left\{A^i \sum_{t=1}^{10} \frac{(P_{s,t}^G - H_t^G)\alpha_t 10.08\ \mathrm{Mg\,ha^{-1}} - (\mathrm{NLC_t^{Gi}} + \mathrm{LC_{st}^i})}{(1+g)^t} - \mathrm{NPV}_s^i\right\} \tag{18}$$

Note that two types of polygons will enter Eqn (18): polygons with positive net present values in the current rotation ($\mathrm{NPV}_s^i > 0$); and polygons with nonpositive net present values in the current rotation ($\mathrm{NPV}_s^i \leq 0$). For the first type of polygons, the change in producer benefits measures the additional benefits from switchgrass conversion on top of the expected benefits from repeating the current rotation into the future. For the second type of polygons, the change in producer benefits measures both the positive benefits from switchgrass conversion plus the avoidance of losses associated with maintaining the current rotation into the future. We calculated ΔTPB for the state, county, and township level.

## Results

### *Subfield areas eligible for switchgrass conversion*

Whether a subfield portion was eligible for economic analysis was determined by its estimated yield in relation to historic county yields and by its size and proximity to other eligible areas. Total eligible area per county varied from 40 ha (<1% of corn/soybean cropland) in Davis County (South Iowa) to 22,000 ha (17.5% of corn/soybean cropland) in Harrison County (West Iowa, Fig. 1). In total, these eligible areas amounted to 4.8% of corn/soybean cropland in Iowa during 2012–2015. A small fraction of this cropland (0.4% of total corn/soybean cropland) was excluded from further economic analysis because it was in unusual crop rotations with two or more continuous years in soybeans.

### *Subfield areas economically viable for switchgrass conversion*

The majority of the eligible subfield portions showed a negative net present value (NPV) if managed in corn/soybeans for the next 10 years (Fig. 2). The total area managed in corn/soybeans with negative NPV was robust to land tenure and grain price specifications. If managed in switchgrass, more area had a positive NPV, and more areas were profitable when cropland was

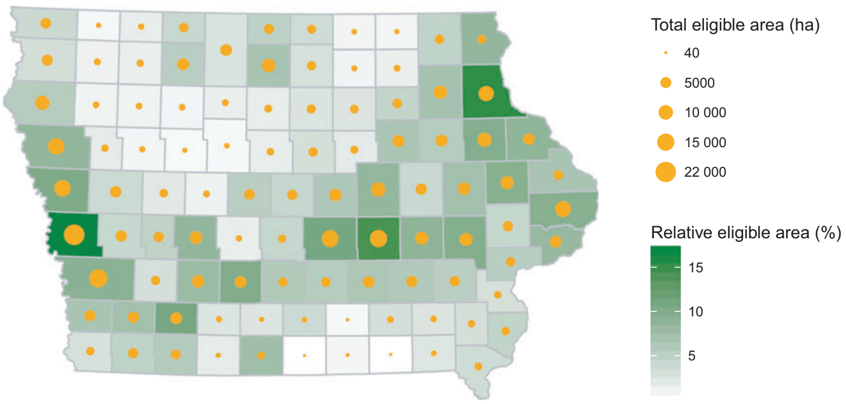


**Fig. 1** Absolute (orange dots) and relative (green shades) area per Iowa county that was eligible for switchgrass conversion based on agronomic (county-specific corn/soybean yield thresholds) and management feasibility criteria.

owned by the operator (Fig. 3). In the interest of brevity and focus, from this point forward, we limit our discussion to results from medium switchgrass yield (10.08 Mg ha$^{-1}$) scenarios; results from the other scenarios can be found in the online supporting information. At the state level, the area that was identified to be economically viable assuming medium switchgrass yields (i.e., breaking even at switchgrass yields of 10.08 Mg ha$^{-1}$ or lower) under the different scenarios ranged from 7000 ha to 408 000 ha and was strongly dependent on land tenure and switchgrass price. The grain price variations in the model (±10% of the projected grain price) had only a minor effect on the results (Table 3). Therefore, we only show the results for medium grain prices in the following county level maps (Fig. 4). At a low switchgrass price and assuming all

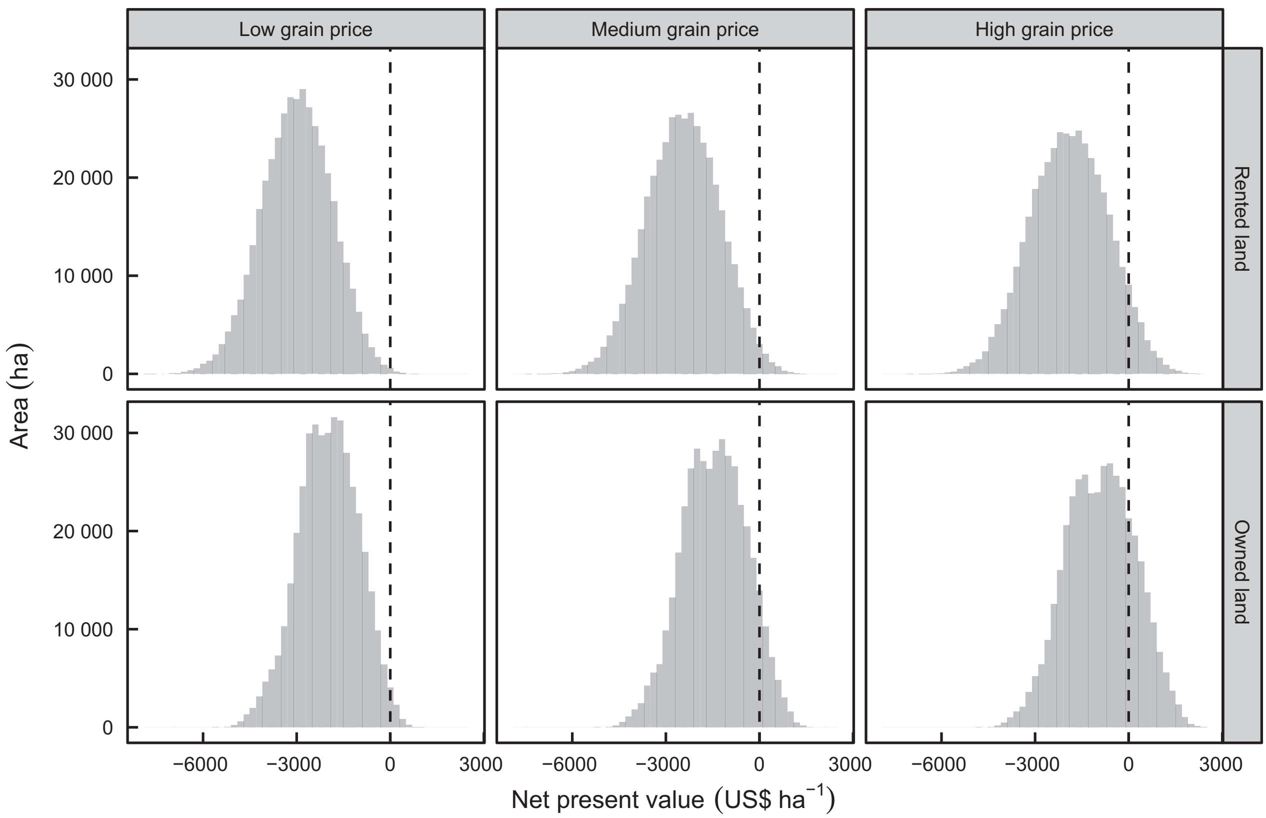


**Fig. 2** Net present value (NPV) distributions on eligible areas if left in corn/soybeans, under the different scenarios. The vertical dashed lines mark a NPV of 0 to facilitate interpretation.

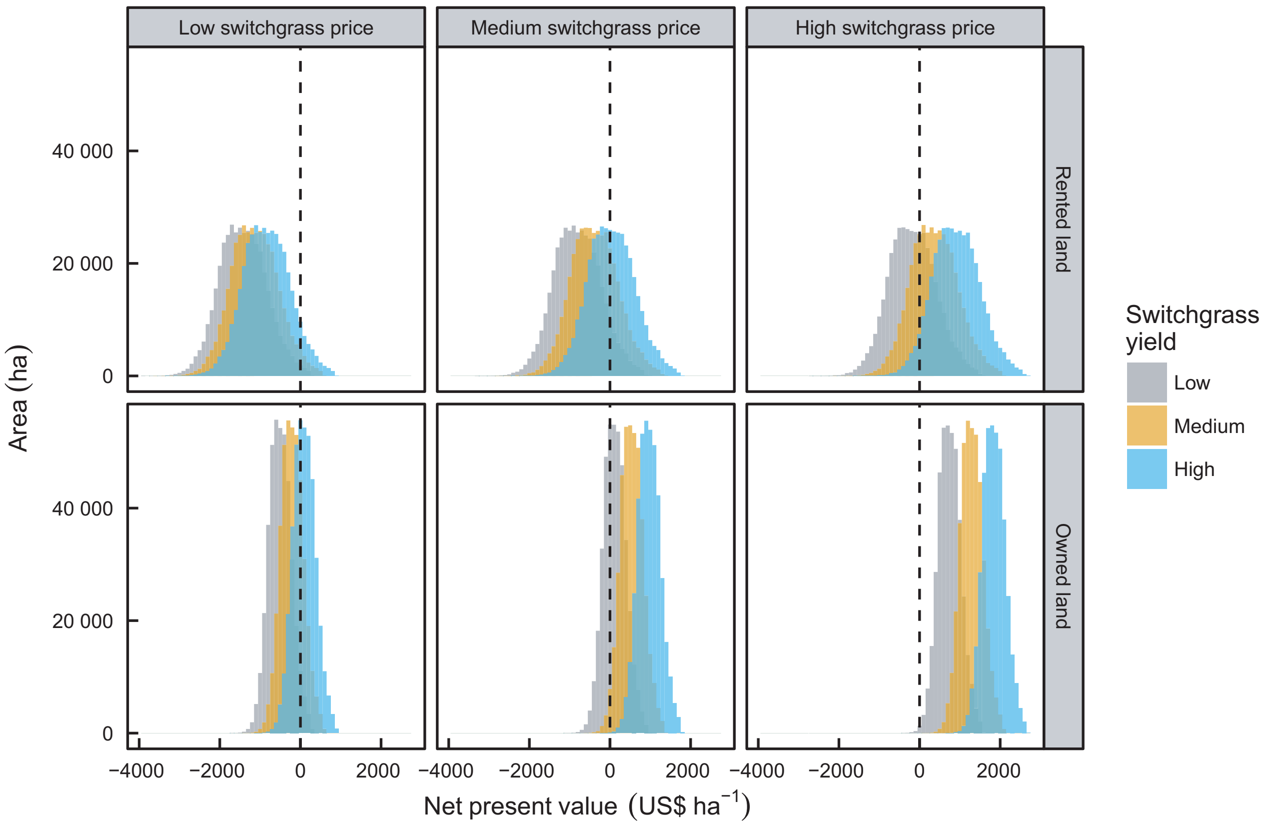


**Fig. 3** Net present value (NPV) distributions on eligible areas if planted in switchgrass, under the different scenarios (low, medium, and high switchgrass price: US$ 44 Mg$^{-1}$, US$ 55 Mg$^{-1}$, and US$ 66 Mg$^{-1}$, respectively; low, medium, and high switchgrass yield: 8.41, 10.08, and 11.76 Mg ha$^{-1}$, respectively). The vertical dashed lines mark an NPV of 0 to facilitate interpretation.

selected subfield areas are owner-operated (i.e., owned land), the economically viable area did not exceed 620 ha or 0.5% of corn/soybean cropland per county. In the owned land scenario at medium and high switchgrass prices, more than a quarter of Iowa counties show more than 5% of their corn/soybean cropland as economically viable for switchgrass. In particular, three counties had more than 10% viable area: Clayton County in the north east (12.7 and 14.4%), Poweshiek County in central Iowa (13.1 and 13.4%), and Harrison County in the West (16.1 and 16.4% for medium and high switchgrass price, respectively).

### *Economic benefits from switchgrass conversion*

For a closer look at the distribution of subfield areas indicated to be economically viable in switchgrass, we focused on the three counties that showed the largest proportions of that cropland: Clayton, Poweshiek, and Harrison County. Under the assumption of owned land,

**Table 3** Eligible Iowa areas (in total ha and as percent of total corn/soybean cropland) with breakeven switchgrass yields of 10.08 Mg ha$^{-1}$ (4.5 short tons acre$^{-1}$) or less (i.e., where a maximum yield of 10.08 Mg is needed to break even with the baseline crop). Results for break even yields of 8.41 Mg ha$^{-1}$ (3.75 short tons acre$^{-1}$) and 11.76 Mg ha$^{-1}$ (5.25 short tons acre$^{-1}$) are shown in the supporting information (Tables S4 and S5)

| Land | Grain price | Swg price low (ha) | % | Swg price med (ha) | % | Swg price high (ha) | % |
|---|---|---|---|---|---|---|---|
| Rented | Low | 9366.5 | 0.1 | 100029.7 | 1.1 | 310194.2 | 3.4 |
| Rented | Medium | 8489.1 | 0.1 | 98843.5 | 1.1 | 310194.2 | 3.4 |
| Rented | High | 7086.2 | 0.1 | 92664.2 | 1.0 | 307318.7 | 3.3 |
| Owned | Low | 86180.2 | 0.9 | 403206.4 | 4.4 | 407829.3 | 4.4 |
| Owned | Medium | 78420.4 | 0.9 | 398201.1 | 4.3 | 407829.3 | 4.4 |
| Owned | High | 65572.6 | 0.7 | 372189.8 | 4.0 | 403136.1 | 4.4 |

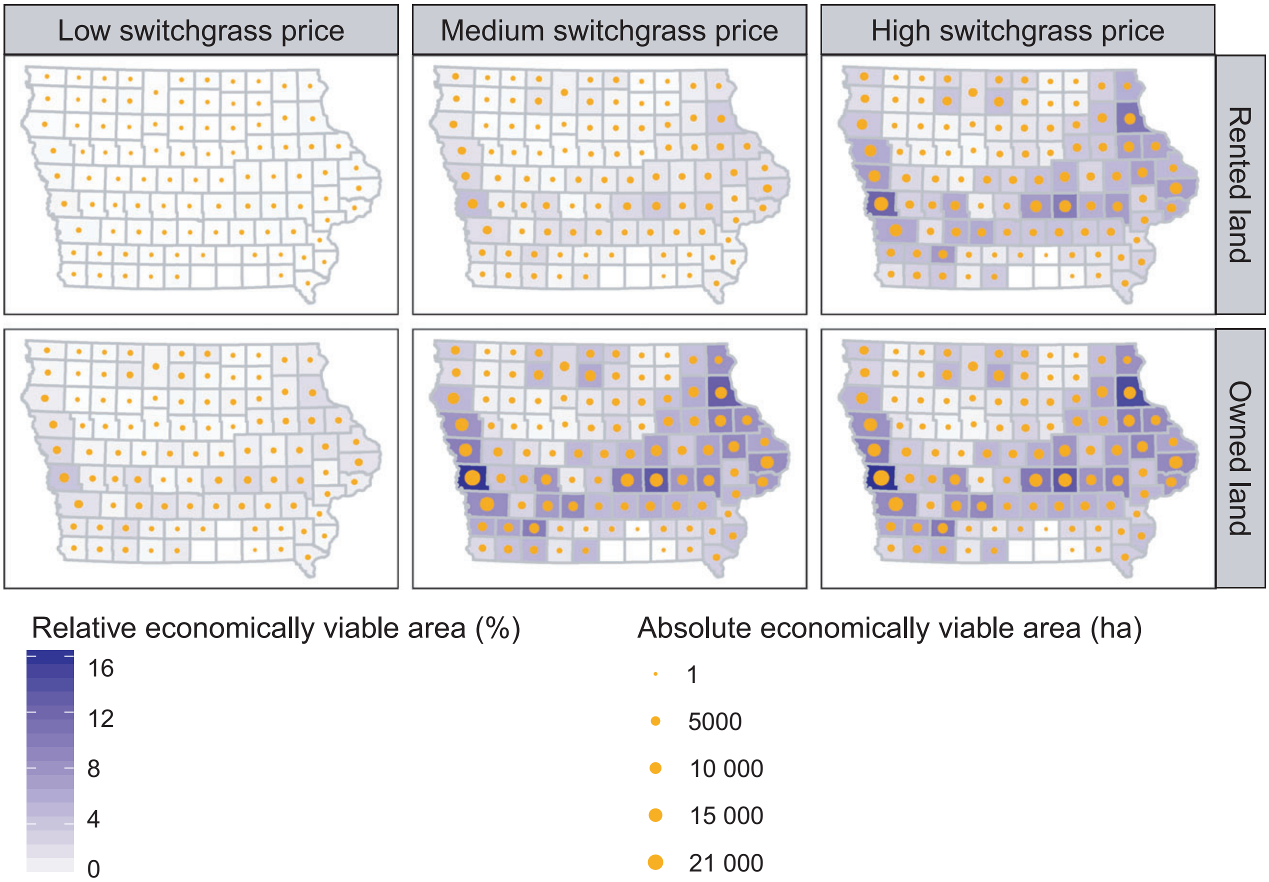


**Fig. 4** Corn/soybean cropland areas where switchgrass would be economically viable at yields of 10.08 Mg ha$^{-1}$ (4.5 short tons acre$^{-1}$), assuming medium grain prices. Orange dots represent the total area per county. Counties without a dot did not contain any economically viable area for switchgrass. Purple shades indicate the relative area per county as a percent of total corn/soy cropland between 2012 and 2015.

projected (medium) grain prices, medium switchgrass price (US\$ 55 Mg$^{-1}$), and medium switchgrass yield (10.08 Mg ha$^{-1}$), the change in NPV per ha (ΔNPV) on each subfield patch in these counties ranged from just above US\$ 0 ha$^{-1}$ up to US\$ 4,255 ha$^{-1}$ over the 10-year projection period (Fig. 5). These values summed to US\$ 16.1 million, 21.1 million, and 47.0 million of extra total producer benefits (TPB) in Clayton, Poweshiek, and Harrison County, respectively. We aggregated the subfield results to the township level by calculating average ΔNPV per ha resulting from targeted switchgrass conversion. This is the average benefit per ha of corn/soybean cropland that a farmer in a given township can generate over 10 years by converting the economically viable subfield areas of a corn/soybean field to switchgrass. The values are small (<US\$ 15 ha$^{-1}$ yr$^{-1}$) in most townships in northern and central Iowa, but they were particularly high (up to US\$ 374 ha$^{-1}$ yr$^{-1}$) in east and west Iowa and in some townships in the south of the state (Fig. 6). Economic benefits scaled to whole state, presented as aggregate annualized changes in total producer benefit "Δ" TPB) (Table 4) varied with switchgrass yield, biomass price, and land tenancy, ranging from US\$ 2 million to US\$ 218 million.

## Discussion

Our results indicate that high within-field variability in profits from corn/soybean systems could make it economically viable to convert some subfield areas of corn/soybean cropland to switchgrass in Iowa. The first selection step identified cropland areas based on their site-specific average (2012–2015) yields as compared to a county-specific long-term yield threshold. Consequently, regions with relatively low temporal and/or spatial yield variability show fewer target areas for switchgrass conversion. This is the case on the Des Moines Lobe, a region of highly fertile soils (Fig. S1). In some of the southern Iowa counties where pasture is a predominant land use, few target areas were found for

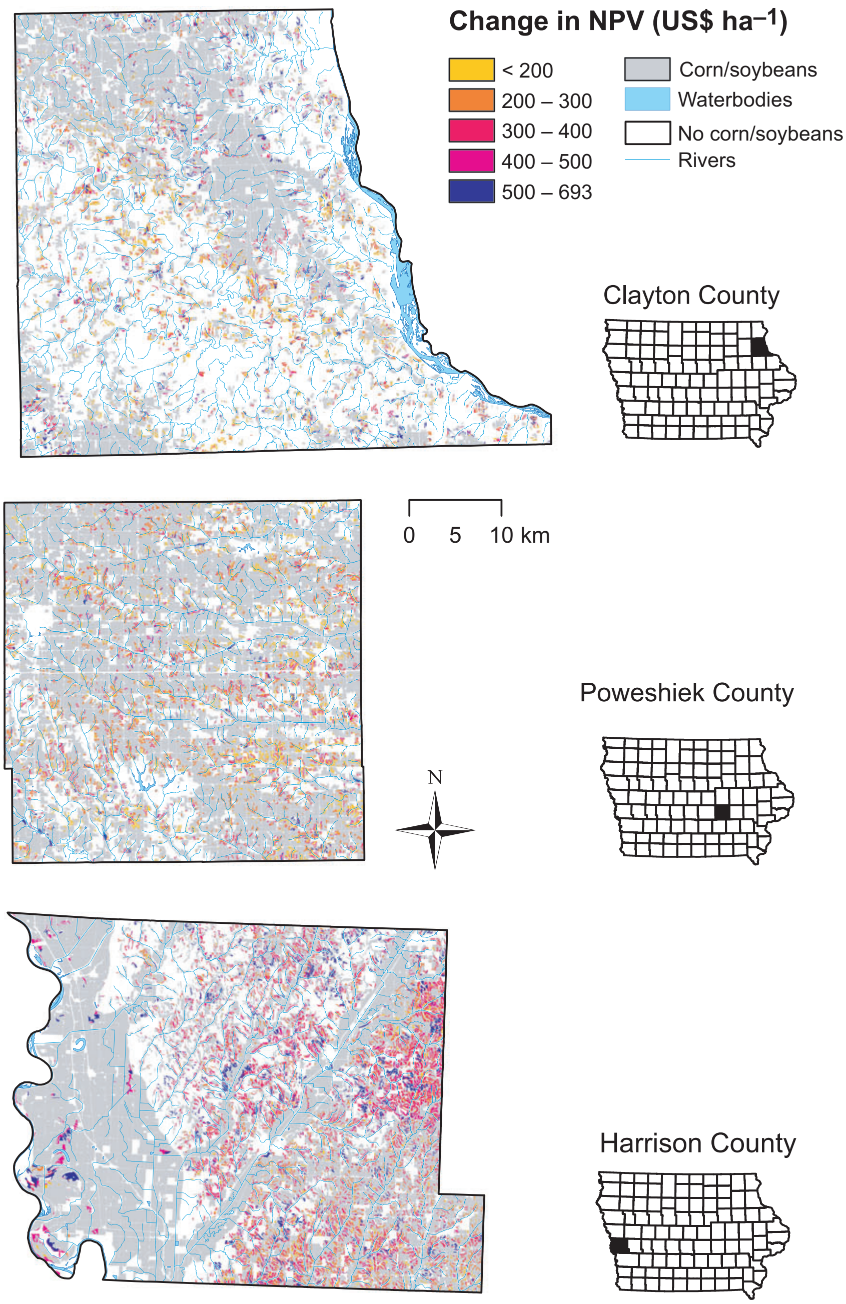


**Fig. 5** Annualized changes in net present value (ΔNPV) when economically underperforming cropland is converted from corn/soybean to switchgrass. Subfield areas that are economically viable (i.e., present greater economic opportunity than the status quo corn/soybean) for switchgrass conversion in three select counties in Iowa are shown in the color scale. Gray areas represent cropland that is not economically viable for switchgrass conversion. White areas represent all land not continuously in corn/soybean during 2012–2015. The results assume USDA projected (medium) grain prices, medium switchgrass price, medium switchgrass yield, and that all land is owned by the farm operator.

different reasons: (1) corn/soybean cropland covers a relatively small portion of the agricultural land; and (2) lower subfield heterogeneity of yields can be expected, as lower productivity land is likely in pasture and only better land is in corn/soybeans. A logical conclusion from our approach is the heuristic that regions of highest within-field yield variation provide highest economic opportunities for switchgrass conversion.

The negative net present value in most of the cropland areas selected based on agronomic and

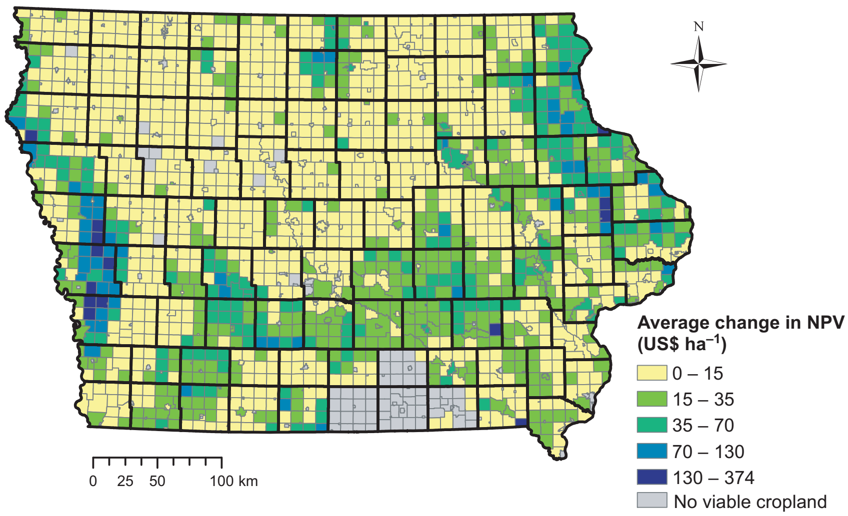


**Fig. 6** Average annualized changes in net present value (ΔNPV) when economically underperforming cropland is converted from corn/soybean to switchgrass. Values (in US$ ha$^{-1}$) are calculated by dividing the sum of annualized ΔNPV by the total corn/soybean cropland area per township. Gray areas represent townships without any cropland economically viable in switchgrass. The results assume USDA projected (medium) grain prices, medium switchgrass price, medium switchgrass yield, and that all land is owned by the farm operator.

**Table 4** Aggregate annualized changes in total producer benefit (ΔTPB) for Iowa if all economically viable areas at a switchgrass yield of 10.08 Mg ha$^{-1}$ (see areas in Table 3) were converted to switchgrass. The numbers are total sums for Iowa in million US$. They include both the positive margin generated from producing switchgrass and the avoided losses by not producing corn or soybeans. All results assume medium corn and soybean prices

| Land | Switchgrass yield | Low switchgrass price (Million US$) | Medium switchgrass price (Million US$) | High switchgrass price (Million US$) |
|---|---|---|---|---|
| Rented | Low | 2.07 | 26.85 | 107.64 |
| Rented | Medium | 2.60 | 33.99 | 134.14 |
| Rented | High | 3.14 | 41.12 | 160.65 |
| Owned | Low | 14.92 | 101.93 | 145.02 |
| Owned | Medium | 18.91 | 129.18 | 181.54 |
| Owned | High | 22.90 | 156.42 | 218.06 |

management criteria (Fig. 2) reflects the robustness of the strategy chosen to identify potentially viable areas for switchgrass conversion (steps 1 and 2). To calculate the changes in total producer benefits, we only accounted for those areas with breakeven yields lower than 10.08 Mg ha$^{-1}$. If we had chosen a lower (higher) threshold for the breakeven yield, the total economic benefits from switchgrass conversion would be smaller (larger) than reported (Tables S6, S7). Although it is widely assumed that perennial crops are better adapted to marginal soil conditions than corn/soybeans (Gelfand *et al.*, 2013), more research is needed on site-specific management to optimize agronomic and economic outcomes of these target areas (Voigtl *et al.*, 2012; Blanco-Canqui, 2016).

The heterogeneous distribution of cropland that is economically viable for switchgrass conversion highlights the usefulness of a spatially explicit analysis of high granularity. Our results reveal the potential value of switchgrass to a corn/soybean dominated agroecosystem that has been missed by previous studies that analyzed the economic feasibility of a management change to perennial bioenergy crops. Dumortier *et al.* (2017) and Jain *et al.* (2010) used data aggregated to the county level, and therefore, their results do not account for differences on a subfield level. Noe *et al.* (2016) modeled profitability of prairie biomass production over commodity crops, but based the grain budgets on the most profitable years in recent history (2008–2012) and assumed cash rents for pasture on the marginal land selected for conversion. Our approach to project economic outcomes into the upcoming ten years and assume cash rents that result in breakeven corn/soybean production on average per county should be more useful for producers and decision makers as they reflect a more realistic planning horizon. The breakeven price for switchgrass calculated by Jain et al. (2010) is much higher (US$ 140–178 $Mg^{-1}$ in Iowa) than the assumed prices in our study, however, that study was based on 2007 grain prices and county average yields. Our approach to preselect underperforming cropland revealed opportunities that remain hidden in the above-mentioned studies that used aggregated data. In a recent study, Soldavini & Tyner (2018) estimated break-even biomass prices for individual fields in Iowa when underperforming subfield areas were converted to switchgrass, using actual yield monitoring data. The higher breakeven price ($191 $Mg^{-1}$) they found can be explained by their corn price assumption ($187 $Mg^{-1}$, or 35% higher than the average projected corn price in Table 2), the addition of transport costs to a facility, and increasing of harvest costs by 10% to account for management inefficiencies of patch farming.

### *Uncertainties*

The present study does not include a complete analysis of sources of uncertainties; therefore, our results have to be interpreted as one set of outcomes amongst many possibilities. While ten-year commodity price projections exist in the literature for corn and soybean, they vary only slightly depending on the source. Therefore, we compared our results to an alternative analysis that used projections by the Food and Agricultural Policy Research Institute (FAPRI, 2017) and achieved similar results. The lack of an existing switchgrass feedstock market results in much higher uncertainties around its projected prices. Therefore, we included three price levels in a sensitivity analysis. Our results show a high sensitivity of the economic viability of switchgrass on feedstock prices and highlight the wide range of expected outcomes. Our results of ΔTPB per township/county can be interpreted as one possible set of outcomes without a measure of probability. The underlying assumptions describe an upper bound of the resulting switchgrass adoption rate, that is, they indicate that a biomass price of US$ 55 $Mg^{-1}$ and a yield of 10.08 Mg $ha^{-1}$ as well as land ownership would be necessary to achieve these benefits.

### *Assumptions and limitations*

Our results present an upper bound to the potential conversion of corn/soybean cropland areas into switchgrass production, that is, they indicate the conditions, such as biomass price and switchgrass yield, necessary to achieve economic benefits. We used a higher discount rate for switchgrass than for corn/soybean in the calculation of NPV ($g > d$; *cf.* Eqns 9 and 14) to account for higher risk and sunk costs associated with the adoption of a new crop. Increasing the gap between the discount factors for switchgrass and corn/soybeans, for example, due to additional costs associated with patch farming, would result in fewer economically viable areas for switchgrass conversion. Clear markets for biomass, increased familiarity with biomass grasses, as well as soft-loans or monetary transfers to switchgrass adopters would cause the difference between the two discount rates to decrease. This analysis excludes the environmental benefits of switchgrass conversion (Brandes *et al.*, 2017), which might support the case for additional revenue from nutrient reduction or carbon markets that could incentivize its adoption, especially during the first few years when yields are below potential.

The cross-impact of reduced corn/soybean production (in areas converted to switchgrass production) on commodity prices is not taken into account in this analysis that covers only Iowa as an exemplary US Corn Belt state. On a national scale we would expect a substantial cross-impact that might reduce the potential for switchgrass conversion by pushing international corn and soybean prices higher (Dumortier et al., 2017).

Moreover, this methodology does not directly address the impacts on net cash flows and therefore credit needs and finance availability. This consideration is indirectly addressed through the differences in discount rates ($g > d$). However, it is important to understand that even if NPV of switchgrass > NPV of corn/soybean rotation, producers will need to be able to withstand a few years of negative profits in switchgrass production before achieving mature yields. Still, this effect is attenuated in our model because most of the targeted subfield polygons are already projected to incur losses under corn/soybean rotations in the future.

Given the combination of uncertainties and costly reversibility associated with perennials, farmers are unlikely to switch unless they sign long-term contracts specifying trading conditions (payments, production, and delivery conditions, etc.). Several studies have illustrated how contract design can strongly influence farmer participation, renegotiation incentives, efficiency, and risk distribution (Alexander *et al.*, 2012; Yoder *et al.*, 2015; Yang *et al.*, 2016). The lack of consideration for contract design in the present analysis limits the interpretation of the results to an upper bound estimate of switchgrass conversion under a set of necessary conditions for adoption (instead of a lower bound estimate based on sufficient conditions for adoption).

This study addresses the farmer's decision making at a point in time, using expected discounted profits. But the model is not designed to evaluate repeated farmer decisions with the possibility of reverting from switchgrass back to the original corn/soybean rotation, or even changing the rotations into the future (Dumortier et al., 2017).

The enterprise budgets we assume for corn/soybean and switchgrass were not adjusted to reflect potential higher costs associated with small or fragmented fields, for several reasons: (1) our identified target fields vary widely in terms of size, shape, and fragmentation, therefore, a standardized adjustment to the budget, as assumed by Soldavini & Tyner (2018), would not improve the model, (2) we are not accounting for increased costs in corn/soybean fields of small sizes or odd shapes that are currently farmed, and (3) we are not similarly accounting for potential positive economic effects. For example, integrating perennials into corn/soybean fields could have a positive effect when placed strategically, by re-shaping odd cropland shapes into tidy rectangles that can be farmed more efficiently (Tyndall *et al.*, 2013; Schulte *et al.*, 2017).

The costs and benefits associated with corn stover removal are not included in the NPV calculation for corn. In areas where corn stover can be profitably harvested and sold for cellulosic biofuels production, farmers' incentives to adopt switchgrass will be lower, all things being equal, than in areas where corn stover removal is not profitable. However, corn stover removal is unlikely to have a meaningful impact on our results. Although it is currently available and considered a suitable cellulosic biofuel source, cellulosic ethanol from stover is not being produced at any appreciable level in the United States to the present date (Eller, 2017). Further, according to an analysis by Muth & Bryden (2013) that considered corn yields to calculate sustainable corn stover removal rates, the areas that we identified as most suitable for conversion to switchgrass are those with rather low stover removal rates under current tilling practices. North Central Iowa is the region with best potential for stover removal, and this region showed least economic opportunity for switchgrass integration due to spatially consistent, high corn yields (Fig. 6). Corn stover payment by facilities accounts for the additional fertilizer input necessary to replace the nutrients taken off the field during residue collection, and therefore does not qualify as an extra income source.

Finally, our analysis was performed under the assumption that current policies affecting agricultural production, such as the federally sponsored crop insurance program and the Biomass Crop Assistance Program (BCAP), will remain unchanged. Miao & Khanna (2017) highlight that the BCAP has the potential to favor corn stover production under low biomass prices, and perennial energy crop production under high biomass prices, but 'the impact of the program is limited due to its budget' (Miao & Khanna, 2017), which was reduced from an original US$ 25 million to US$ 3 million in FY 2017 appropriations (http://farmenergy.org/farm-bill-policy/farm-bill-clean-energy-appropriations).

### *Practical application*

Our results can be valuable information for private and public decision makers as they identify land in Iowa or similar areas where conversion of corn/soybeans to switchgrass could be economically feasible on a substantial portion of cropland under a certain set of assumptions. We have purposefully performed a policy-free analysis for the following reasons: (1) policies are unstable and can change quickly, and (2) the supporting policies currently in place are much higher for corn/soybeans than for perennial biofuel crops, which partially explains the high percentage of corn/soybean cropland in the US Midwest (see also Brandes *et al.*, 2016). Amended by additional assumptions, such as supporting farm programs, this information could not only be incorporated into farm enterprise management, but also into planning of conservation programs, for example to achieve nutrient reduction goals without economic penalty. In a previous modeling study, Brandes et al. (2017) showed that nitrate leaching could be reduced by 18% in Iowa if 12% of corn/soybean cropland was converted to switchgrass. Our analysis revealed that three counties in Iowa could reach this percentage of switchgrass cover, while simultaneously increasing total producer benefit by millions of dollars, when converting all corn/soybean cropland areas with breakeven switchgrass yields of up to 10.08 Mg ha$^{-1}$, assuming all land is owned and medium switchgrass price (Fig. 4).

The change in NPV per township (Fig. 6) shows the local value added with the management change. Comparing the aggregate ΔNPV of a township's total cropland with and without the conversion of underperforming corn/soybean land to switchgrass shows how much more economic value could be generated (resulting in higher net farm income and a wider tax base for local governments) with switchgrass conversion.

As the modeled yields and land costs used here are estimates derived from soil properties, the resulting economic data are not intended to be used as an enterprise-level decision making tool. However, the publicly available data we used could be exchanged by enterprise specific information to achieve an individual analysis. For simplicity, we have chosen solely switchgrass as the alternative land management in this analysis. Other studies have found that giant miscanthus can be comparable or even better suited for bioenergy feedstock due to its higher yields (Jain et al., 2010). As we target areas that are generally unprofitable in corn/soybean production, our approach could also be used to assess feasibility of miscanthus or other alternative crops in those areas.

### *Outlook*

Our assumptions for the price of switchgrass are highly uncertain due to the lack of established markets for cellulosic biofuel or other biomaterial feedstocks. However, the integration of perennial, low-input crops bears the potential of long-term environmental and socio-economic benefits that do not currently appear in an enterprise's accounting, such as water quality improvement, carbon sequestration, or recreational valorization. If externalities such as the economic value of ecosystem services resulting from the conversion to a perennial grass (Noe et al., 2016) were included, higher total (private and social) economic benefits could be expected.

This is the first study to quantify an upper bound to the potential private economic benefits from converting targeted unfavorable corn/soybean cropland to switchgrass. It shows that there is economic potential for switchgrass conversion when edaphic conditions related with corn/soybean yields on a subfield scale are taken into account. Although based on simplified assumptions and limited by data availability and future uncertainties, this analysis provides guidance to individual as well as legislative decision making to improve economic sustainability of agricultural production in Iowa. The approach is scalable to other agricultural regions worldwide.

## Acknowledgements

This project was funded by the Iowa State University Department of Agronomy Anonymous Endowment, the Iowa Nutrient Research Center, the USDA National Institute of Food and Agriculture, Hatch projects 221195 and 1010309, and the Hatch/Multi-State Project IOW05521. The authors thank David Muth and Gabe McNunn for providing the underlying subfield geodata, and Lisa Schulte for her valuable conceptual input to the project. We are grateful to the four anonymous reviewers for their constructive recommendations to improve the manuscript, especially for highlighting the distinction between necessary and sufficient conditions for switchgrass adoption.

## References

Alexander C, Ivanic R, Rosch S, Tyner W, Wu SY, Yoder JR (2012) Contract theory and implications for perennial energy crop contracting. *Energy Economics*, **34**, 970–979.

Asbjornsen H, Hernandez-Santana V, Liebman M *et al.* (2014) Targeting perennial vegetation in agricultural landscapes for enhancing ecosystem services. *Renewable Agriculture and Food Systems*, **29**, 101–125.

Bakker KK, Higgins KF (2009) Planted Grasslands and Native Sod Prairie: Equivalent Habitat for Grassland Birds?. *Western North American Naturalist*, **69**, 235–242.

Blanco-Canqui H (2016) Growing dedicated energy crops on marginal lands and ecosystem services. *Soil Science Society of America Journal*, **80**, 845–858.

Bonner IJ, Cafferty KG, Muth DJ, Tomer MD, James DE, Porter SA, Karlen DL (2014) Opportunities for energy crop production based on subfield scale distribution of profitability. *Energies*, **7**, 6509–6526.

Boyer CN, Griffith AP, McIntosh DW, Bates GE, Keyser PD, English BC (2015) Breakeven price of biomass from switchgrass, big bluestem, and indian grass in a dual-purpose production system in Tennessee. *Biomass and Bioenergy*, **83**, 284–289.

Brandes E, McNunn GS, Schulte LA *et al.* (2016) Subfield profitability analysis reveals an economic case for cropland diversification. *Environmental Research Letters*, **11**, 014009.

Brandes E, McNunn GS, Schulte LA, Muth DJ, VanLoocke A, Heaton EA (2017) Targeted subfield switchgrass integration could improve the farm economy, water quality, and bioenergy feedstock production. *GCB Bioenergy*, **10**, 199–212.

Burkhard B, Kandziora M, Hou Y, Müller F (2014) Ecosystem service potentials, flows and demands-concepts for spatial localisation, indication and quantification. *Landscape Online*, **34**, 1–32.

Burras C, Miller GA, Fenton T, Sassman A (2015) Corn Suitability Rating 2 (CSR2) equation and component values. Available at: http://www.extension.iastate.edu/soils/suitabilities-interpretations (accessed 27 January 2017).

CenUSA Bioenergy (2014) Sustainable production and distribution of bioenergy for the central USA. Available at: https://cenusa.iastate.edu/ (accessed 23 June 2017).

Chavas J-P, Holt MT (1990) Acreage decisions under risk: The case of corn and soybeans. *American Journal of Agricultural Economics*, **72**, 529–538.

Dauber J, Miyake S (2016) To integrate or to segregate food crop and energy crop cultivation at the landscape scale? Perspectives on biodiversity conservation in agriculture in Europe. *Energy, Sustainability and Society*, **6**, 25.

Dumortier J, Kauffman N, Hayes DJ (2017) Production and spatial distribution of switchgrass and miscanthus in the United States under uncertainty and sunk cost. *Energy Economics*, **67**, 300–314.

Efroymson RA, Langholtz MH (2017) 2016 billion-ton report: Advancing domestic resources for a thriving bioeconomy, volume 2: Environmental sustainability effects of select scenarios from volume 1. Available at: http://www.osti.gov/scitech/servlets/purl/1338837 (accessed 06 December 2017).

Eller D (2017) DowDuPont shutters Nevada cellulosic ethanol plant, looks for a buyer. *Des Moines Register* Nov. 2, 2017. Available at: https://www.desmoinesregister.com/story/money/agriculture/2017/11/02/dowdupont-shutters-nevada-cellulosic-ethanol-plant-looks-buyer/824606001/ (accessed 24 February 2018).

FAPRI (2017) FAPRI-MU Baseline Outlook. Available at: https://www.fapri.missouri.edu/publications/outlook/ (accessed 18 November 2017).

Federal Reserve Bank of Chicago (2017) Seventh District Credit Conditions. Available at: https://www.chicagofed.org/publications/agletter/index (accessed 18 November 2017).

Gelder B, Cruse R, Kaleita A (2008) Automated determination of management units for precision conservation. *Journal of Soil and Water Conservation*, **63**, 273–279.

Gelfand I, Sahajpal R, Zhang X, Izaurralde RC, Gross KL, Robertson GP (2013) Sustainable bioenergy production from marginal lands in the US Midwest. *Nature*, **493**, 514–517.

Griffith AP, Epplin FM, Fuhlendorf SD, Gillen R (2011) A comparison of perennial polycultures and monocultures for producing biomass for biorefinery feedstock. *Agronomy Journal*, **103**, 617–627.

Hart C (2015) Estimated Cost of Establishment and Production of "Liberty" Switchgrass. Available at: https://www.extension.iastate.edu/agdm/crops/html/a1-29.html (accessed 23 June 2017).

Heggenstaller AH, Moore KJ, Liebman M, Anex RP (2009) Nitrogen Influences Biomass and Nutrient Partitioning by Perennial, Warm-Season Grasses. *Agronomy Journal*, **101**, 1363–1371.

Jain AK, Khanna M, Erickson M, Huang H (2010) An integrated biogeochemical and economic analysis of bioenergy crops in the Midwestern United States. *GCB Bioenergy*, **2**, 217–234.

Kay RD, Edwards WM, Duffy PA (2017) *Farm management*. McGraw-Hill, New York, NY.

Langholtz M, Graham R, Eaton L, Perlack R, Hellwinkel C, Ugarte DGDLT (2012) Price projections of feedstocks for biofuels and biopower in the U.S. *Energy Policy*, **41**, 484–493.

Li L, Hayes D, Hart C (2014) Weather Adjusted Yield Trends for Corn: A Look at Iowa. Available at: https://www.card.iastate.edu/ag_policy_review/ (accessed 18 November 2017).

McLaughlin S, Walsh M (1998) Evaluating environmental consequences of producing herbaceous crops for bioenergy. *Biomass and Bioenergy*, **14**, 317–324.

Miao R, Khanna M (2017) Effectiveness of the biomass crop assistance program: Roles of behavioral factors, credit constraint, and program design. *Applied Economic Perspectives and Policy*, **39**, 584–608.

Mitchell RB, Schmer MR, Anderson WF *et al*. (2016) Dedicated energy crops and crop residues for bioenergy feedstocks in the central and eastern USA. *BioEnergy Research*, **9**, 384–398.

Muth D (2014) Profitability versus environmental performance: Are they competing? *Journal of Soil and Water Conservation*, **69**, 203a–206a.

Muth D, Bryden K (2013) An integrated model for assessment of sustainable agricultural residue removal limits for bioenergy systems. *Environmental Modelling & Software*, **39**, 50–69.

Muth D, Bryden K, Nelson R (2013) Sustainable agricultural residue removal for bioenergy: A spatially comprehensive us national assessment. *Applied Energy*, **102**, 403–417.

NASS (2016a) National Agricultural Statistics Service, U.S. Department of Agriculture Cropland Data Layer. Available at: https://www.nass.usda.gov/Research_and_Science/Cropland/SARS1a.php (accessed 27 February 2017).

NASS (2016b) National Agricultural Statistics Service, U.S. Department of Agriculture Quick Stats. Available at: https://quickstats.nass.usda.gov/ (accessed 27 February 2017).

NASS (2017) National Agricultural Statistics Service, U.S. Department of Agriculture Quick Stats. Available at: https://quickstats.nass.usda.gov/ (accessed 29 November 2017).

Noe RR, Nachman ER, Heavenrich HR, Keeler BL, Hernández DL, Hill JD (2016) Assessing uncertainty in the profitability of prairie biomass production with ecosystem service compensation. *Ecosystem Services*, **21**, 103–108.

NRCS (2016) Natural Resources Conservation Service, U.S. Department of Agriculture Web Soil Survey. Available at: https://websoilsurvey.sc.egov.usda.gov/ (accessed 27 February 2017).

Plastina A (2017) Estimated Costs of Crop Production in Iowa. Iowa State University Extension and Outreach. Available at: http://www.extension.iastate.edu/agdm/crops/html/a1-20.html (accessed 07 December 2017).

Plastina A, Johanns A (2017) Cash Rental Rates for Iowa Survey. Available at: https://www.extension.iastate.edu/agdm/wholefarm/html/c2-10.html (accessed 07 December 2017).

Power AG (2010) Ecosystem services and agriculture: Tradeoffs and synergies. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, **365**, 2959–2971.

Qin Z, Dunn JB, Kwon H, Mueller S, Wander MM (2016) Soil carbon sequestration and land use change associated with biofuel production: Empirical evidence. *GCB Bioenergy*, **8**, 66–80.

Sassman A, Miller GA, Burras C (2015) Soil Survey & Digital Soil Data: ISPAID. Available at: http://www.extension.iastate.edu/soils/ispaid (accessed 27 February 2017).

Schulte LA, Asbjornsen H, Liebman M, Crow TR (2006) Agroecosystem restoration through strategic integration of perennials. *Journal of Soil and Water Conservation*, **61**, 164A–169A.

Schulte LA, Niemi J, Helmers MJ *et al*. (2017) Prairie strips improve biodiversity and the delivery of multiple ecosystem services from corn–soybean croplands. *Proceedings of the National Academy of Sciences*, **114**, 11247–11252.

Soldavini S, Tyner WE (2018) Determining switchgrass breakeven prices in a landscape design system. *BioEnergy Research*, **11**, 191–208.

Tyndall JC, Schulte LA, Liebman M, Helmers M (2013) Field-Level Financial Assessment of Contour Prairie Strips for Enhancement of Environmental Quality. *Environmental Management*, **52**, 736–747.

US Environmental Protection Agency (2010) Regulation of fuels and fuel additives: Changes to renewable fuel standard program; final rule. Available at: https://www.epa.gov/renewable-fuel-standard-program/renewable-fuel-standard-rfs2-final-rule (accessed 07 December 2017).

US Environmental Protection Agency (2017a) 2016 Renewable Fuel Standard Data. Available at: https://www.epa.gov/fuels-registration-reporting-and-compliance-help/2016-renewable-fuel-standard-data (accessed 08 November 2017).

US Environmental Protection Agency (2017b) Renewable fuel standard program: Standards for 2017 and biomass-based diesel volume for 2018. Available at: https://www.epa.gov/renewable-fuel-standard-program/final-renewable-fuel-standards-2017-and-biomass-based-diesel-volume (accessed 07 December 2017).

US Environmental Protection Agency (2017c) Renewable Fuel Standard Program: Standards for 2018 and Biomass-Based Diesel Volume for 2019. Available at: https://www.gpo.gov/fdsys/pkg/FR-2017-12-12/pdf/2017-26426.pdf (accessed 24 February 2018).

USDA (2008) U.S. Department of Agriculture Common Land Unit. Available at: https://www.fsa.usda.gov/programs-and-services/aerial-photography/imagery-products/common-land-unit-clu/index (accessed 27 February 2017).

USDA (2017a) U.S. Department of Agriculture Economic Research Service. Available at: https://www.ers.usda.gov/data-products/state-fact-sheets/ (accessed 18 November 2017).

USDA (2017b) U.S. Department of Agriculture Office of the Chief Economist. Agricultural projections to 2026. Available at: https://www.usda.gov/oce/commodity/projections/ (accessed 23 June 2017).

Vogel KP, Mitchell RB, Casler MD, Sarath G (2014) Registration of 'Liberty' Switchgrass. *Journal of Plant Registrations*, **8**, 242.

Voigtl TB, Lee DK, Kling GJ (2012) Perennial herbaceous crops with potential for biofuel production in the temperate regions of the USA. *CAB Reviews*, **66**, 1–13.

Yang X, Paulson ND, Khanna M (2016) Optimal mix of vertical integration and contracting for energy crops: Effect of risk preferences and land quality. *Applied Economic Perspectives and Policy*, **38**, 632–654.

Yoder JR, Alexander C, Ivanic R, Rosch S, Tyner W, Wu SY (2015) Risk versus reward, a financial analysis of alternative contract specifications for the miscanthus lignocellulosic supply chain. *BioEnergy Research*, **8**, 644–656.

Zenone T, Gelfand I, Chen J, Hamilton SK, Robertson GP (2013) From set-aside grassland to annual and perennial cellulosic biofuel crops: Effects of land use change on carbon balance. *Agricultural and Forest Meteorology*, **182–183**, 1–12.

Zhang W (2016) Farmland Value Survey Iowa State University. Iowa State University Extension and Outreach. Available at: https://www.extension.iastate.edu/agdm/wholefarm/html/c2-70.html (accessed 07 December 2017).

## Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

**Table S1.** List of threshold yields per county.
**Table S2.** List of corn/soybean rotations included in the analysis.
**Table S3.** As an addition to Table 2, this table shows the same parameter values in Imperial units used for the 10 year projection (2017–2026).
**Tables S4–S7.** These tables show additional results with different switchgrass yield assumptions, as an addition to Tables 3 and 4.
**Figure S1.** A map displaying the Major Landform Regions of Iowa to facilitate the understanding of the spatial results.