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LETTER

Subfield profitability analysis reveals an economic case for cropland diversification

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Abstract

Public agencies and private enterprises increasingly desire to achieve ecosystem service outcomes in agricultural systems, but are limited by perceived conflicts between economic and ecosystem service goals and a lack of tools enabling effective operational management. Here we use Iowa—an agriculturally homogeneous state representative of the Maize Belt—to demonstrate an economic rationale for cropland diversification at the subfield scale. We used a novel computational framework that integrates disparate but publicly available data to map ~3.3 million unique potential management polygons (9.3 Mha) and reveal subfield opportunities to increase overall field profitability. We analyzed subfield profitability for maize/soybean fields during 2010–2013—four of the most profitable years in recent history—and projected results for 2015. While cropland operating at a loss of US$ 250 ha^{-1} or more was negligible between 2010 and 2013 at 18 000–190 000 ha (<2% of row-crop land), the extent of highly unprofitable land increased to 2.5 Mha, or 27% of row-crop land, in the 2015 projection. Aggregation of these areas to the township level revealed 'hotspots' for potential management change in Western, Central, and Northeast Iowa. In these least profitable areas, incorporating conservation management that breaks even (e.g., planting low-input perennials), into low-yielding portions of fields could increase overall cropland profitability by 80%. This approach is applicable to the broader region and differs substantially from the status quo of 'top-down' land management for conservation by harnessing private interest to align profitability with the production of ecosystem services.

1. Introduction

In 2008, Donner and Kucharik (2008) predicted the Renewable Fuel Standard's (RFS2) mandate for biofuel production in the US would stimulate shifts of crop and conservation land to maize for ethanol production, resulting in a net expansion of maize acreage and a net increase in N export from the Mississippi River Basin. Scientists also predicted declines in soil carbon (Gelfand *et al* 2011), biocontrol services (Landis *et al* 2008), and pollinators and bird species of conservation concern in the Upper Midwest (Meehan *et al* 2010, Bennett *et al* 2014) with limited impact on overall emissions of heat-trapping gases (Hill *et al* 2006). Recently, Lark *et al* (2015) showed record grain prices and changing agriculture policy in the last decade have indeed led to net expansion of cropland, largely at the expense of forage and conservation land. Their analysis showed that between 2008 and 2012, 2.97 million ha were converted to cropland, most commonly from grassland (2.3 million ha), shrub and forest land (0.32 million ha), and wetland (0.06 million

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ha) to maize, wheat, or soybean; much of this gross cropland expansion occurred in the US Maize Belt.

Many have demonstrated that incorporating perennial vegetation can disproportionately enhance ecosystem services from extensively managed croplands, including erosion control, improvements in water quality, and pest control (Helmers *et al* 2012, Gopalakrishnan *et al* 2012, Liebman *et al* 2013, Meehan *et al* 2013, Asbjornsen *et al* 2014, Daigh *et al* 2014), but usually at an economic penalty under current market and policy conditions (Manatt *et al* 2013, Guerry *et al* 2015). Top-down land management schemes are widespread (Osmond *et al* 2012) but have had limited implementation success in the Maize Belt because they do not align with many social and economic constraints, notably land tenure (Morton and Brown 2011). New insight enabled by public data and precision agriculture technology could possibly remove these constraints, and actually allow economic motivation to drive conservation goals.

High resolution yield monitoring associated with precision agriculture shows that even high yielding fields include areas of low productivity due to erosion, water logging, or poor soil quality (Muth and Bryden 2012). Case studies also show that subfield areas of lowest profitability coincide with those of highest environmental risks (Lerch *et al* 2005, Muth 2014). However, no larger scale studies have been published on the combined goal of providing economic benefits to farmers *and* improving ecosystem services. While addressing subfield heterogeneity in yield through precision agriculture is already widely adopted within the agricultural community, the concept is being expanded to consider improved ecosystem services through 'precision conservation' (Berry *et al* 2005).

Using the lens of precision conservation, here we develop a framework for farmers, other private enterprises, and public entities to identify within-field variability of cropland profitability and understand its implication for management decisions. A spatially explicit, subfield level accounting model is applied to (1) determine profit variability within individual maize/soybean fields and (2) identify hot spots where low profitability provides a compelling case for management change. We use the state of Iowa to depict this framework, although the concept is more broadly applicable to extensive agricultural regions worldwide.

Iowa's agricultural homogeneity makes it a good proxy for the Midwest maize/soy agroecosystem—the largest US agricultural region. Nearly 8% of all US prime cropland is in Iowa (USDA 2015a), which includes 12.3 million ha devoted to crop production and 9.5 million ha dedicated to maize and soybean (NASS 2015, RFA 2015). The state has been plagued by poor water quality for decades (Alexander *et al* 2008, Iowa Department of Natural Resources 2012), and the recent Iowa Nutrient Reduction Strategy (2013) spotlights the need to incorporate more perennial vegetation within the agricultural landscape, either as part of crop rotations or as semi-permanent cover, to meet state and national goals for water quality improvement in the Mississippi River Basin. An opportunity to improve farm profitability can encourage farmers to grow less intensively managed perennial crops on targeted areas currently managed in row crops to meet the strategy's target of 41% reduction in N and 29% reduction in P to surface waters. The state also figures prominently into the national pollinator health strategy (Pollinator Health Task Force 2015), especially through providing breeding and nectaring habitat for the declining monarch butterfly.

We compare 2010–2013, four of the most profitable years in recent history, with a projection for 2015, when commodity markets have moderated from recent highs. We specifically investigate whether substantial economic rationale exists for diversification of extensively managed cropland. If identified, financial motivation to implement conservation management practices in low-yielding portions of fields could drive broader societal, economic, and environmental benefits.

2. Methods

We analyzed subfield profitability of Iowa farmland continuously in either maize or soybean production between 2010 and 2013. We chose 2010–2013 because they include some of the most profitable crop years on record for the Maize Belt (Johanns and Plastina 2014), and compared them to a scenario projected for 2015, when grain markets have moderated. We drew on publicly available data to obtain information on field boundaries and land cover, soil properties, yields, cash rents, crop production costs, and grain prices (table 1 and S1). As outlined below, we modeled cash rents and yields by differentiating survey data of county averages into high resolution spatial maps.

2.1. Spatial data

Field boundaries were obtained from the 2008 USDA Farm Service Agency common land unit (CLU) layer (USDA 2008). Crop-specific land cover was identified with the USDA National Agricultural Statistics Service cropland data layer (CDL), a spatially-explicit raster data layer indicating the annual land cover at 30 m resolution across the conterminous US based on satellite imagery (USDA 2014). Fields were assigned a single maize or soybean crop from 2010 to 2013 using the CLU-CDL intersection from that year to identify the crop occupying the greatest area within the field (CLU). If a crop or land cover other than maize or soybeans was determined to be dominant in any year, the field was eliminated from the analysis. This spatially-explicit approach allowed us to focus on dedicated maize/soybean land, capturing actual distribution of maize–soybean rotation patterns in Iowa (continuous maize, maize–soybean rotation, and

Table 1. A summary of data used in the analyses. 'Crop type' refers to which crop (maize or soybean) was present in a field.

Input variables	2010–2013	2015
Crop type	As in CDL 2010–2013	As in CDL 2013
Yields	From ISPAID, adjusted to 2010–2013 NASS county averages	From ISPAID, adjusted to 2015 county yield trends
Grain prices	Annual average price for 2010–2013 marketing years (September–August)	Season average maize and soybean price projected for 2015 in the World Agricultural Supply and Demand Estimates report
Cash rental rates	Derived from CSR, adjusted to 2010–2013 rental rates survey	Derived from CSR, adjusted to 2015 rental rates survey
Crop production costs	Crop budgets estimated by ISU Extension and Outreach Ag Decision Maker Tool (Plastina 2015) for 2010–2013	Crop budgets estimated by ISU Extension and Outreach Ag Decision Maker Tool (Plastina 2015) for 2015

soybean following two or three years of maize). Although some land was excluded, 80% of cropland (9.3 Mha) in Iowa met this constraint.

To capture the influence of subfield variations in soil properties on yield and cash rent, we then integrated the National Soil Survey Geographic (SSURGO) Database (NRCS 2013) into the analysis. SSURGO map units were intersected with CLU boundaries, resulting in ~3.3 million unique soil-field polygons for Iowa.

2.2. Calculation of profitability

For each soil-field polygon, we calculated profitability according to:

$$P_{ijk} = (Y_{ijk} \times \mathrm{GP}_{ij}) - (\mathrm{CP}_{ijk} + R_{jl}), \qquad (1)$$

where P_{ijk} is the profitability of crop i in year j for soil-field polygon k, Y_{ijk} is the yield for crop i in year j on soil-field polygon k, GP_{ij} is the grain price for crop i in year j, CP_{ijk} is the crop production cost for crop i in year j on soil-field polygon k, and R_{jl} is the cash rent in year j on field l. Equation (1) represents net operating profit for a land-renting farmer. For a land-owning farmer, equation (1) measures operating profit less what the farmer could have received had the land been rented to another farmer.

2.3. Yield estimate

Maize and soybean yields were estimated for each unique soil-field polygon. The Iowa Soil Properties and Interpretations Database (ISPAID, Miller *et al* 2010) includes estimates of typical maize yields on each soil map unit (SMU). An SMU combines soil type, slope class, and erosion phase. Parent material, slope, erosion, natural drainage class, subsoil characteristics, flooding potential, and weather conditions are factored in to project potential maize yields as an indicator of inherent crop production capacity. Soybean yields are calculated from a linear modification of maize yields (Miller *et al* 2010). In general, these yield estimates are higher than actual yields reported by the USDA Agricultural Statistics Service (NASS 2015). To achieve more realistic estimates, we normalized ISPAID results with the annual reported county average yields for maize and soybean according to Bonner *et al* (2014). This approach provided a dataset of high spatial resolution reflecting yield variations of the analyzed years. For our 2015 projection, we normalized the ISPAID results with county yield trends produced by the United States Department of Agriculture's Risk Management Agency (USDA 2015b).

2.4. Grain prices

Grain prices for 2010–2013 were taken from monthly commodity price listings for Iowa (Johanns 2015) and averaged over each marketing year, starting on 1 September of each year and ending on 31 August of the following year. For the 2015 projection, the season average maize and soybean prices, as projected in the World Agricultural Supply and Demand Estimates report of May 2015 (USDA 2015c), were used.

2.5. Crop production costs and cash rents

Crop production costs were calculated using net operation costs with local standard practices from the Iowa State University Extension and Outreach Ag Decision Maker Tool, which is generated from annual Iowa Farm Business Association reports, data collected by Iowa State University, and a survey of agricultural cooperatives and other suppliers in Iowa (Plastina 2015). Representative values for maize following maize, maize following soybeans, and soybeans were used according to the crop in the current and preceding year for each CLU. We assumed the seeding rate for maize at 74 130 seeds ha^{-1} (30 000 seeds ac^{-1}) and for soybeans at 346 000 seeds ha^{-1} (140 000 seeds ac^{-1}). P application was assumed to be 69.5 kg ha^{-1} (62 lbs ac^{-1}), 76.2 kg ha^{-1} (68 lbs ac^{-1}), and 44.8 kg ha^{-1} (40 lbs ac^{-1}) for maize following maize, maize following soybeans, and soybeans, respectively. K application was set at 56 kg ha^{-1} (50 lbs ac^{-1}), 60.5 kg ha^{-1} (54 lbs ac^{-1}), and 84 kg ha^{-1} (75 lbs ac^{-1}) for maize following maize, maize following soybeans, and soybeans, respectively. N application rates for maize production were calculated according to the Regional Nitrogen Rate Guidelines (Sawyer *et al* 2015) with the corn nitrogen rate calculator to find the most profitable N rate based on

fertilizer cost and maize price in each year. Rates ranged between 204 kg ha^{-1} (182 lbs ac^{-1}) and 230.9 kg ha^{-1} (206 lbs ac^{-1}) for maize following maize, and between 144.6 kg ha^{-1} (129 lbs ac^{-1}) and 169.2 kg ha^{-1} (151 lbs ac^{-1}) for maize following soybeans. Harvest machinery costs were scaled with modeled yields. For cash rents, we calculated a coefficient D for each county m (table S2) to describe the increase in cash rent per unit increase in corn suitability rating (CSR):

$$D_m = \overline{R_m}/\overline{\mathrm{CSR}_m}, \quad (2)$$

where $\overline{R_m}$ is the average cash rental rate for county m reported by farmers, landowners, agricultural lenders, and professional farm managers in an annual survey (Edwards *et al* 2015), and $\overline{\mathrm{CSR}}_m$ is the area weighted mean of CSR for county m from the USDA National Resources Conservation Service Soil Survey (NRCS 2013). Using this coefficient (table S2), we calculated a cash rental rate for each soil-field polygon k as:

$$R_k = D_m \times \mathrm{CSR}_k \quad (3)$$

where CSR_k is the CSR value of soil-field polygon k. Since cash rents are paid on a field basis, we calculated area weighted averages for each CLU. A comparison demonstrated that our calculated cash rent distribution agreed with that of the survey data (figure S1). Crop insurance premiums are highly variable depending on the level of coverage purchased and were not included in the crop budgets. For each year, crop production costs were linked with spatial data based on crop type and yield (table 1). Because maize and soybean are commonly annually rotated and the 2015 CDL will not be released until 2016, we used the 2013 CDL for the 2015 projection.

To visualize spatial variation in maize and soybean yields, yields for each soil-field polygon were separated by crop and area weighted averages were calculated for each township (figures S2 and S3). Likewise, area weighted township means of cash rent and crop production cost were calculated and mapped (figures S4 and S5). To visualize the percentage of each township area that was in row crop production from 2010 to 2013, CLU area was summed for each township and divided by township total area (figure S6). The proportion of maize to soybean cropland in each township was calculated from the CLU areas and the crop cover in each year (figure S7). Area weighted histograms of cost and revenue (figure 1) and yield (figure S8) were created after rounding the raw data (cost and revenue to zero decimals, yields to two decimals) and aggregating to equal values to reduce the number of records.

2.6. Scenarios and sensitivity analysis

We visualized profitability results for the whole state for the retrospective (2010–2013) and projected (2015) analyses as raster maps of 100 m^2 resolution using ArcGIS 10 (ESRI 2015, Redlands, CA). We focused on cropland that loses ⩾US$ 250 ha^{-1}, as potential target areas for diversification. The ⩾US$ 250 ha^{-1} loss cut-off was deemed appropriate for a conservative assumption that a farmer is likely to pursue management alternatives on land that consistently loses this much each year. To reveal hotspots of low profitability, we displayed numbers of hectares operating at ⩽US$ −250 ha^{-1} per township in maps by joining tables queried from the PostgreSQL database with a geospatial layer of political township boundaries of Iowa, using the QGIS Open Source Geographic Information System. To assign each CLU to a township, the CLU layer was intersected with the political township boundaries. CLUs that overlapped two or more townships were assigned to the township that they overlapped with their largest portion. Polygons with profit losses ⩾US$ 250 ha^{-1} were selected and their areas summed for each township. Because some of the townships, many of them municipalities, included very few hectares of CLUs in row crop, we filtered out political units that contained less than 700 ha in row crop production. These were not considered representative of farmland area in Iowa. For the least profitable townships, defined by an area of more than 3 500 ha that loses ⩾US$ 250 ha^{-1}, we ran a scenario in which all areas losing ⩾US$ 250 ha^{-1} are enrolled in a government program, such as the USDA Agricultural Conservation Easement Program, Conservation Reserve Program, or Pollinator Habitat Planting program, allowing previously unprofitable parcels to break even. To assess the impact of different variables on profitability, we altered crop production costs, yields, and commodity prices in the 2015 projection. For crop production costs, we changed the 2015 maize production cost by ± US$ 120 ha^{-1} in steps of US$ 30, and soybean production costs by ± US$ 80 ha^{-1} in steps of US$ 20. These ranges were derived from maximum changes in crop production costs from 2010 to 2015 based on average yields observed in these crops. The impact of yield on profitability was assessed by changing the yields for maize and soybean by ±30% in steps of 10% based on the trend projections for 2015. Commodity prices were simultaneously increased from US$ 0.1 kg^{-1} to US$ 0.3 kg^{-1} (US$ 2.49 bu^{-1} to US$ 7.64 bu^{-1}; maize) and from US$ 0.27 kg^{-1} to US$ 0.57 kg^{-1} (US$ 7.37 bu^{-1} to US$ 15.52 bu^{-1}; soybeans) by steps of US $ 0.04 kg^{-1} (maize) and US$ 0.06 kg^{-1} (soybeans), respectively. For each step of the sensitivity analyses, profitability for each soil-field polygon was calculated as described above, and unprofitable farmland losing ⩾US$ 250 ha^{-1} was summed at the state level.

3. Results

The retrospective analysis of 2010–2013 reveals spatial and temporal variability in profitability (figures 2 and 3). An interactive map providing the ability to zoom in on individual fields is accessible at http://mesonet.

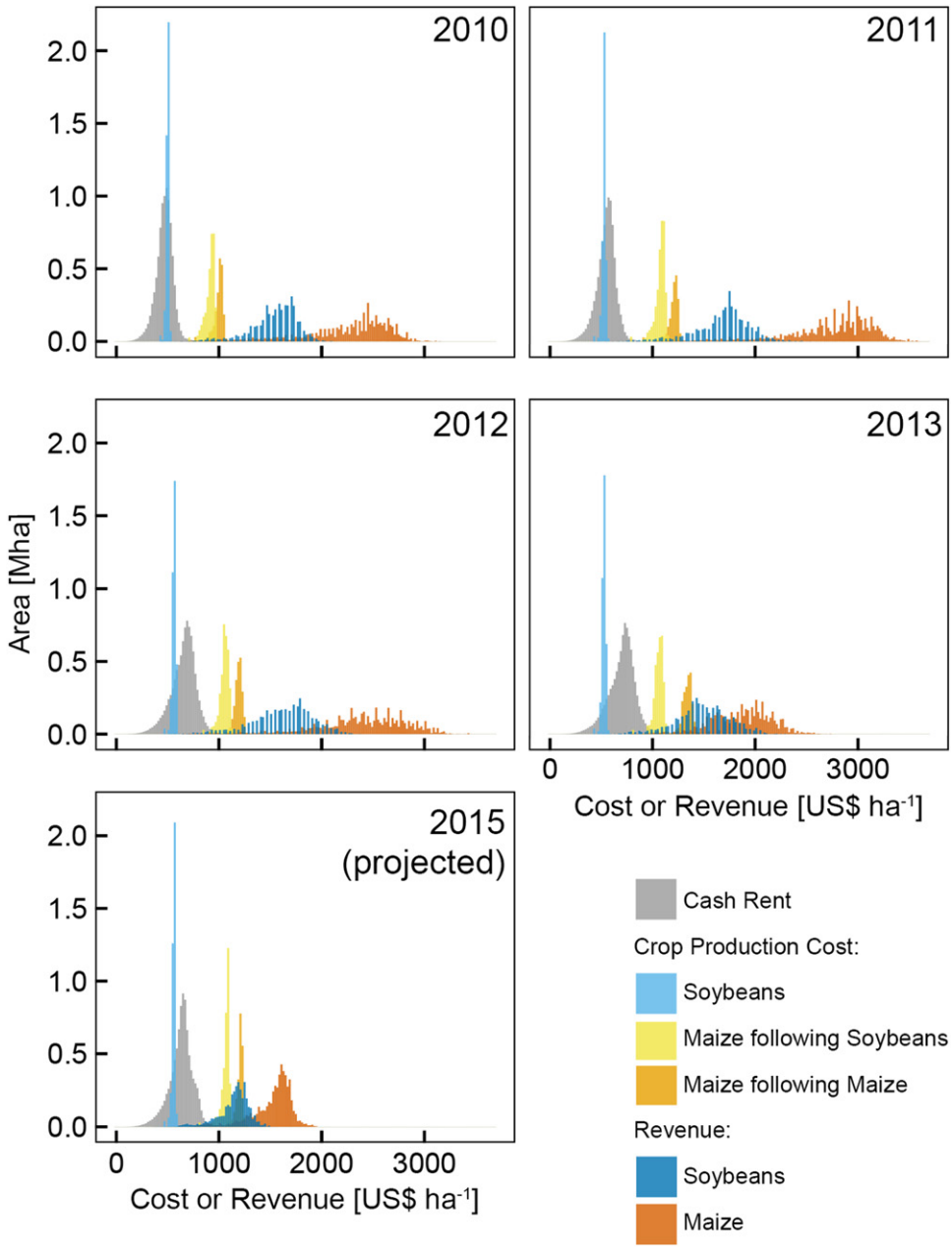

Figure 1. Area weighted distributions of modeled cash rents, crop production costs, and crop revenues in Iowa. Data are grouped into bins of US$ 20 ha^{-1}.

agron.iastate.edu/GIS/apps/profit/. Mean profitability was highest in 2011 at US$ 880 ha^{-1} and lowest in 2013 at US$ 103 ha^{-1}. Overall, the extent of highly unprofitable cropland, or cropland losing ⩾US$ 250 ha^{-1}, increased in each consecutive year from 2011 through 2013. While the extent of highly unprofitable croplands was negligible in 2010 and 2011 at 45 338 and 17 874 ha, respectively, these areas increased to 189 620 ha in 2012 and 1 023 035 ha in 2013. The spatial distribution of highly unprofitable cropland also varied over time. While largely relegated to large river floodplains and the margins of the state in 2010–2012, by 2013 extensive areas of highly unprofitable cropland were found in most counties and were particularly concentrated in Central Iowa; specifically, Carroll, Hamilton, and Story County, with 56 868 ha, 60 614 ha, and 52 576 ha, respectively (figure 2 and S9).

Temporal and spatial variation in profitability between 2010 and 2013 was a function of grain price, yield, cash rental rate, crop production cost, and maize to soybean ratio (table 2). Following historic highs in 2011 and 2012, maize price decreased in 2013. Soybean price showed a similar pattern. While farmers benefited from high yields in 2011, low yields associated with a persistent drought (Khong *et al* 2015) were evident in both crops in the following years (figures S2, S3, and S8). Area weighted township average cash rents ranged from US$ 271 ha^{-1} to US$ 955 ha^{-1} across Iowa in these four years and exhibited

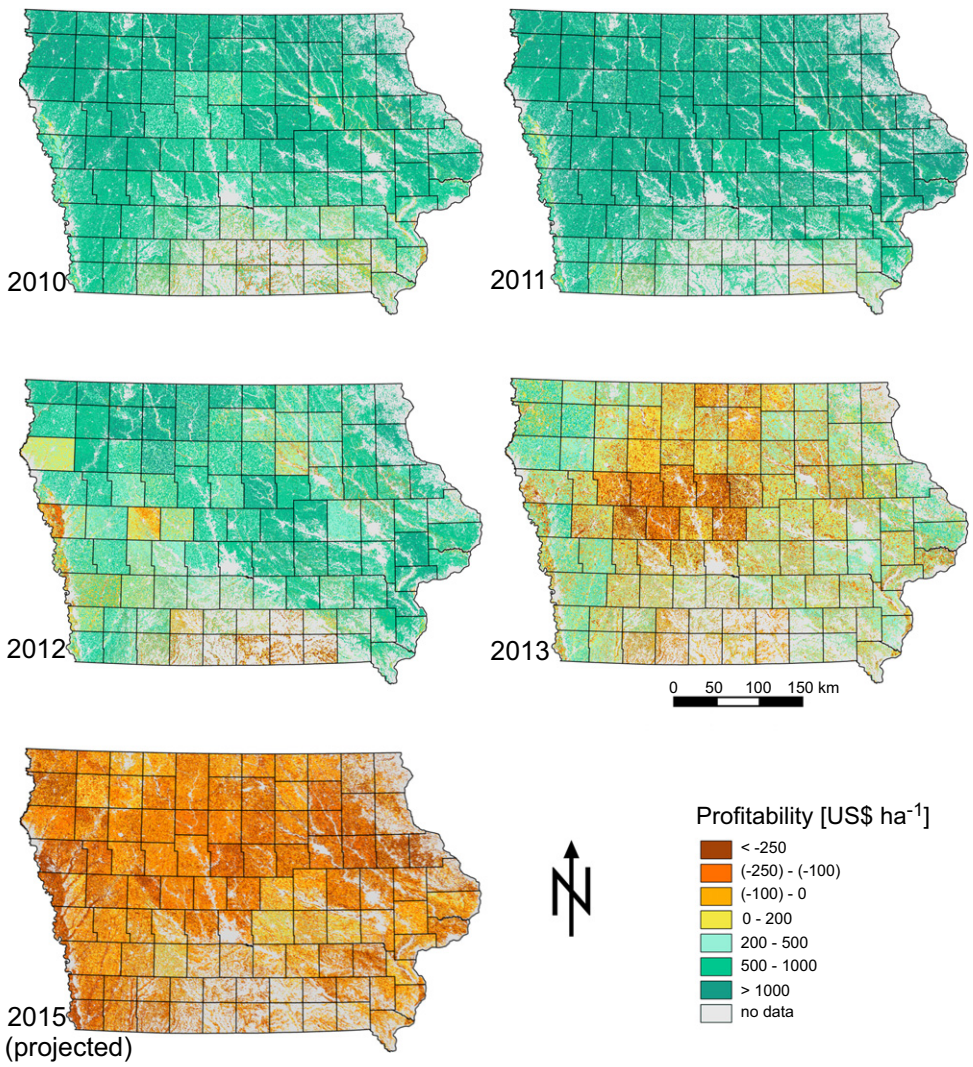

Figure 2. Distribution of subfield Iowa cropland profitability, 2010–2013, and projected profitability for 2015. Profitability was only calculated for crop fields in maize or soybeans in all four years (2010–2013). Other areas are shown as gray.

substantial variability (figure S4); the lowest rents were found in Southern Iowa and the highest rents were found in West Central, Central, and East Central Iowa. Cash rents steadily increased from 2010 to 2013 (figure 1), increasing US$ 214 ha^{-1} on average over this period. Overall crop production costs were consistently highest in North and East central Iowa and lowest in the South (figure S5). While production costs for soybean have stayed relatively stable in the four years, those for maize following maize increased considerably from 2010 to 2013 (figure 1). Revenues (yield x grain price) decreased from an average of US$ 2731 ha^{-1} and US$ 1686 ha^{-1} in 2011 to US$ 1861 ha^{-1} and US$ 1490 ha^{-1} in 2013 for maize and soybeans, respectively (figure 1). The ratio of land planted in maize to that planted in soybeans increased slightly from 2010 to 2011 and then stayed at a relatively stable level of 1.5 (table 2, figure S7).

The projection for 2015 resulted in a mean profitability of US$ −158 ha^{-1}, with most areas operating at US$ 200 ha^{-1} or less (figures 2 and 3). The total area operating at and below US$ −250 ha^{-1} is 2 513 915 ha, or 27% of all cropland in Iowa (figure 3). By comparison, mean yields and yield variability in 2015 were comparable to the 2011 value and distributions (table 2, figures S2 and S3). Row crops were planted on between 4% and 100% of the farmland in any given township in 2010–2015, varying greatly with geographic location (figure S6).

A closer look at three exemplary townships across a diagonal transect of the state reveals the granularity of the subfield analysis (Providence Township in Buena Vista County, Beaver Township in Boone County, and Crawford Township in Washington County, figure 4). Profitability can be differentiated by crop type on the majority of cropland, with soybean being more profitable than maize. Contrastingly, many fields situated close to waterways (Beaver Creek in Providence Township, North Raccoon River in Beaver Township, and East Fork Crooked Creek in Crawford) show high within-field variability and include areas losing >US$ 500 ha^{-1}.

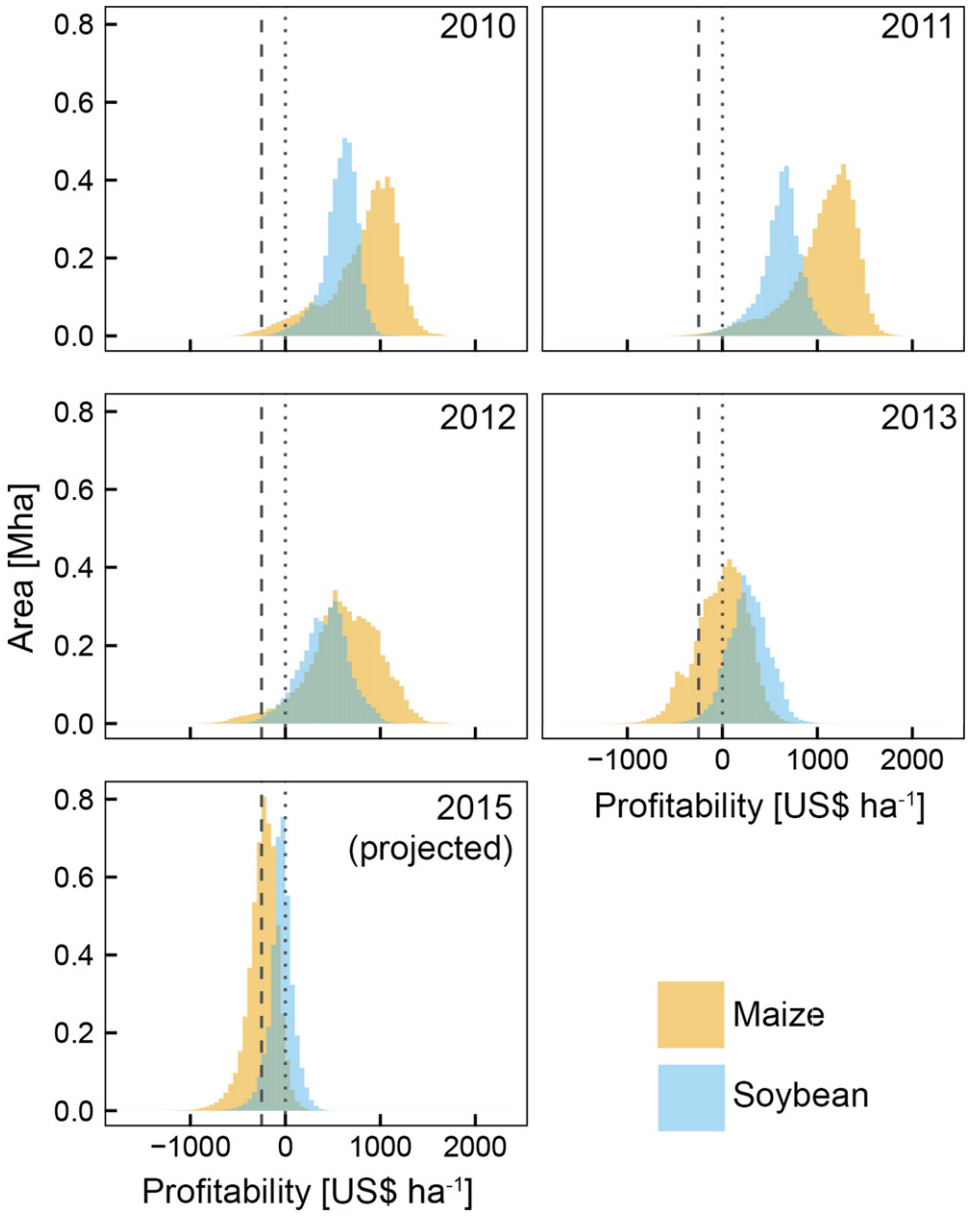

Figure 3. Distribution of Iowa cropland profitability, 2010–2013, and projected profitability for 2015. The vertical dashed and dotted lines respectively mark the profitability cut-offs of US$ −250 ha^{-1} and US$ 0 ha^{-1}.

By summing these highly unprofitable areas for all townships, regions with a high density of unprofitable farmland were identified as 'hot spots' for management change (figure 5). A typically sized township covers 9323 ha (36 mi^2); highly unprofitable areas ranged between 78 and 7694 ha per township (1%–66% of total township area), and a total of 104 townships contained more than 3500 ha of highly unprofitable land, adding up to 447 436 ha (55% of the cropland in the hot spots and almost 5% of all cropland in Iowa). While hot spots were scattered throughout the state (figure 5), our analysis reveals aggregations along the Missouri River Alluvial Plain and Loess Hills in the West, on the edges of the Des Moines Lobe landform in Central Iowa, and on the Iowan surface in the East (figure S10). These comprise areas to target for management change based on purely economic rationale. If land operating at ⩽ US$ −250 ha^{-1} were taken out of row crop production and placed into break-even management, such as provided by existing government programs, the profitability of these soil-field polygons becomes US$ 0 and the average profitability of the 104 hot spots townships is raised by 80%, from US$ −272.87 ha^{-1} to US$ −54.53 ha^{-1}.

3.1. Sensitivity analysis

From the baseline of ∼2.5 Mha of highly unprofitable farmland in 2015, an increase in crop production cost of US$ 60 ha^{-1} (maize) and US$ 40 ha^{-1} (soybean) increases the amount of highly unprofitable land by 44% to 3.6 Mha, whereas a decrease by the same amounts decreases the area by 36% to 1.6 Mha (figure 6(a)). Profitability is even more sensitive to

Table 2. Summary statistics for calculation of Iowa cropland profitability, 2010–2013, and projected profitability for 2015.

	2010	2011	2012	2013	2015 (projected)
Maize price (US\$ kg^{-1}) (US\$ $bushel^{-1}$)[a]	0.21 (5.46)	0.25 (6.35)	0.27 (6.94)	0.18 (4.51)	0.14[b] (3.50)
Soybean price (US\$ kg^{-1}) (US\$ $bushel^{-1}$)[a]	0.44 (12.08)	0.48 (13.08)	0.53 (14.54)	0.49 (13.38)	0.33[b] (9.00)
Average maize yield (Mg ha^{-1})[c] ± StDev	10.43 ± 2.01	10.91 ± 1.72	8.65 ± 1.68	10.46 ± 1.7	10.91 ± 1.7
Average soybean yield (Mg ha^{-1})[c] ± StDev	3.47 ± 0.49	3.51 ± 0.55	3.02 ± 0.55	3.02 ± 0.54	3.43 ± 0.54
Average cash rental rates (US\$ ha^{-1}) ± StDev	446.46 ± 92.58	519.88 ± 106.06	617.39 ± 139.47	660.25 ± 146.53	635.64 ± 137.79
Average crop production cost (US\$ ha^{-1})[d] ± StDev	747.13 ± 222.45	872.27 ± 291.30	880.12 ± 268.48	897.50 ± 331.44	861.16 ± 178.64
Ratio of land in maize versus land in soybean	1.35	1.55	1.54	1.46	1.46[e]

[a] Average of the marketing year (01 September–31 August) (Johanns 2015).
[b] Projected average prices for the season 2015/16 (USDA 2015b).
[c] County average yields normalized to ISPAID estimates ± standard deviation.
[d] Cash rent and crop insurance premium not included. Area-weighted average of crop production cost ± standard deviation.
[e] Crop distribution is assumed to be similar to 2013.

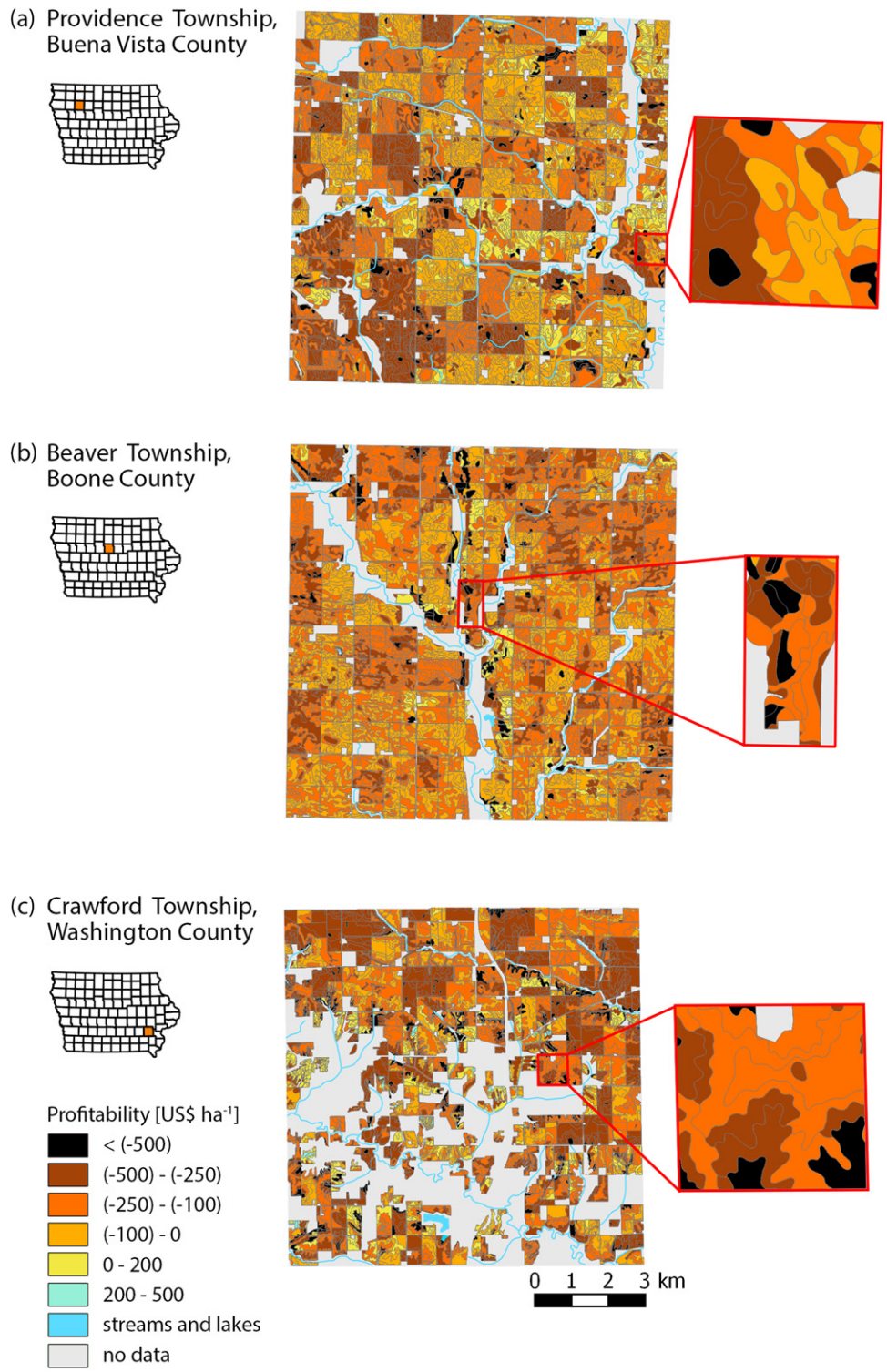

Figure 4. Subfield profitability projection in three exemplary townships in Iowa in 2015. Gray lines represent boundaries between soil-field polygons. One field (common land unit (CLU)) for each township is enlarged for visibility.

yield variability (figure 6(b)) and to changes in commodity prices (figure 6(c)).

4. Discussion

The results presented here project drastic profit reduction for Iowa farmers in 2015. Using crop production cost estimates and trend yields published by Iowa State University Extension, Hart (2015) has also projected negative gross profit margins for maize and soybeans in Iowa beginning July 2014 and decreasing below −200 and −300 US$ ha^{-1} for soybean and maize, respectively, by April 2015. Our subfield analysis bolsters Hart's results with a spatially explicit expression of profit risk.

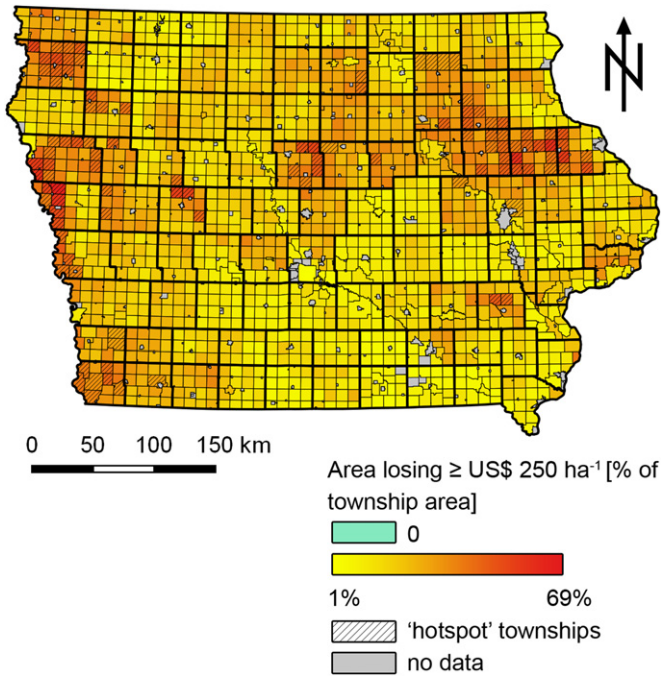

Figure 5. Projected distribution of Iowa cropland losing $\geqslant$ US$ 250 ha^{-1} for 2015 aggregated by township (an average township is 9 323 ha) in % of total township area. Hatch lines indicate 'hotspot' townships with $\geqslant$ 3500 ha of highly unprofitable land.

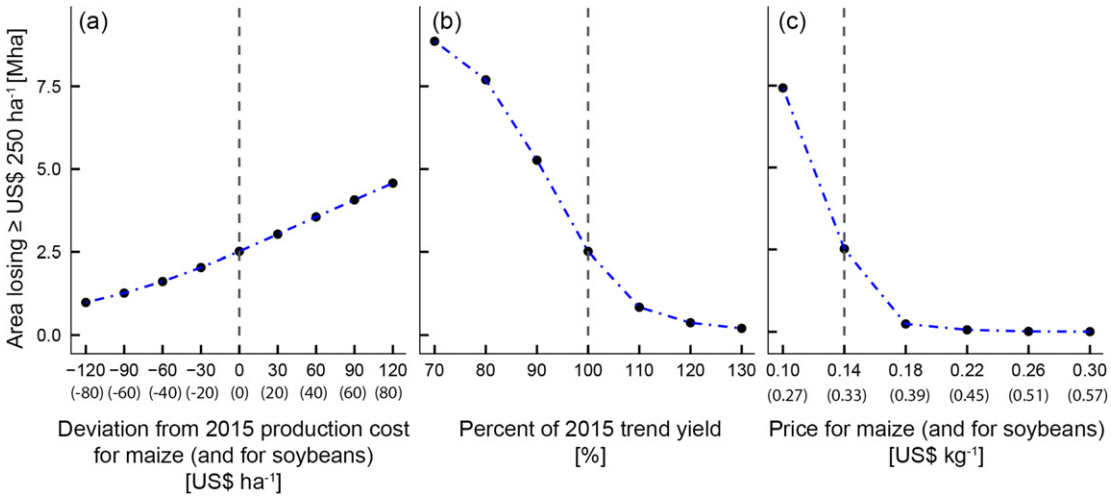

Figure 6. Changes in Iowa cropland area losing $\geqslant$ US$ 250 ha^{-1} with changing crop production cost (a), yields (b), and commodity price (c). (a) The 2015 maize production cost (marked by the dashed line) was changed $\pm$ US$ 120 ha^{-1} by steps of US$ 30, and the soybean production costs was changed $\pm$ US$ 80 by steps of US$ 20. (b) The 2015 yields (indicated by the dashed line) were changed $\pm$ 30% by steps of 10%. Reducing yields by 10% (comparable to 2012 levels at 79% and 88% of 2015 maize and soybean yields, respectively) would increase highly unprofitable area by $>$ 100%. A yield as in 2011 (100% and 102% of 2015 maize and soybean yields, respectively) would only marginally decrease highly unprofitable area. (c) Commodity prices were increased from US$ 0.1 kg^{-1} to US$ 0.3 kg^{-1} by steps of US$ 0.04 kg^{-1} (maize) and from US$ 0.27 kg^{-1} to US$ 0.57 kg^{-1} by steps of US$ 0.06 kg^{-1} (soybeans). The dashed line marks the maize and soybean price projected for 2015 (US$ 0.14 kg^{-1} and US$ 0.33 kg^{-1}, respectively).

According to our analysis, some farmland operated at a loss even in economically favorable years. The low yields in 2012 were compensated by high grain prices, but in 2013, decreased grain prices, increased land rent and unfavorable yields on the Des Moines Lobe caused farmers to lose money on large areas. Although cash rental rates followed the downward trend of grain prices in 2015, they did not fall enough to compensate for substantial losses caused by decreased revenue. Analysis of low profitability 'hotspots' (figure 5) reveals areas that—according to our generalized approach—are poorly adapted to the current market conditions. Along the Missouri River Alluvial Plain in Western Iowa, the edges of the Des Moines Lobe in Central Iowa, and the Iowan Surface in Eastern Iowa (figure S10), farmland in row crop operates to a large extent below a favorable profit, suggesting there is an economic rationale for

management changes in these areas. If shifted to management that at least breaks even, most likely to be achieved by planting low-input perennial cover such as brome, fescue, or prairie and potentially enrolling in a government program (Tyndall *et al* 2013), farmers could reduce costs on low profit areas and mitigate overall profit loss. As an example, Tyndall *et al* (2013) calculate a cost of 80–124 US$ ha^{-1} yr^{-1} for prairie reconstruction when enrolled in the Conservation Reserve Program, depending on cash rental rates. Planting subfield areas into brome or fescue would decrease establishment costs. Dedicated perennial energy crops such as switchgrass or giant miscanthus could extend the range of possible management options. Such perennial crops have higher input costs but also potential revenue from biomass (Manatt *et al* 2013). Increases in ecosystem services would depend on, and be concomitant with, the type of management implemented (Hatfield *et al* 2009, Jones and Schilling 2011, Smith *et al* 2013, Asbjornsen *et al* 2014; table S3).

The rationale for cropland diversification may become even stronger under a scenario of future climate change. Weather patterns have become more variable in recent decades with longer, more severe wet and dry periods and more extreme rain events (Easterling *et al* 2000). Overall yields are expected to decrease with the expected increase in temperature (Walthall *et al* 2012, Urban *et al* 2015), resulting in an expansion of highly unprofitable areas. While our sensitivity analysis for yield does not incorporate the increase in grain prices that will to some extent compensate for systemic crop shortfalls, it also does not account for the increasing value of soil if current rates of erosion are not checked (Cruse *et al* 2013).

We applied simple accounting for input costs and revenues and excluded government insurance and subsidy programs from the main analysis. Although the 2015 scenario includes a variety of input data, there are limitations to predictability. For example, we used the CDL from 2013 as a proxy for 2015 because information on this year's crop cover was not available. Some fields may have been taken out of maize or soybean production in the two-year intervening period by farmers and other private enterprises due to decreasing revenue expectation. While some such transitions are likely to have occurred their number and influence is judged minor as, according to national data, the total area planted in maize and soybean has not changed between 2013 and 2015 (NASS 2015). We also simplified our analysis by assigning cash rents to each field, regardless of whether it is owned or rented by the land manager. In case of ownership, the cash rent represents the land loan payment, or if owned outright, the opportunity cost. Data on regional management variation are not available but would give a more realistic representation of crop production costs. Yields and cash rents were derived from county averages, creating a 'county effect' that overestimates the differences between neighboring counties. The size of highly unprofitable land area is very sensitive to yield, which is management and weather dependent and therefore highly uncertain. In the future we expect to further expand the model framework to integrate a crop model and thereby more fully account for these uncertainties. Furthermore, additional costs (e.g., reduced machinery efficiency) and long-term benefits (e.g., soil-building) for field portions remaining in row crop are not accounted for.

Finally, we did not include crop insurance, though it is an important mechanism for maintaining farm-level profitability, because we could not easily account for the diversity of instruments and heterogeneity in their adoption by farmers. Because more than two thirds of crop insurance payments are tax-funded (Babcock 2013), our analysis highlights the public's role in maintaining private profits in the US Maize Belt. It also highlights the economic efficiency that could be gained by insurers if more spatially precise information on yields and subfield profit losses were to be incorporated into insurance instruments. At present, crop insurance is paid for in aggregate across multiple fields comprising a farm. We assume current legislation that incentivises high-input farming through crop insurance and externalized environmental costs to be the main barrier that prevents the implementation more cost effective management options.

5. Conclusions

Public pressure on agricultural industries and legislators is increasing in Iowa and elsewhere, calling for improved ecosystem services from agricultural landscapes; achieving this goal will require cropland diversification (Iowa Nutrient Reduction Strategy 2013, Pollinator Health Task Force 2015). Our novel high resolution computational framework offers a powerful economic tool that lays the ground for subfield management to enhance cropland diversity and mitigate environmental risk. Farmers and other land managers have an inherent incentive to shore up profitability by managing lower performing areas of their cropland less intensively, thereby achieving a more sustainable farm operation in both economic and environmental terms. The framework could become a robust prediction tool for individual farmers and other land managers by incorporating their input data on yield expectations, cash rents, and production costs. Incorporating budgets for different management options would allow these decision makers to develop alternative scenarios and more precisely optimize their inputs and outputs. While our initial analysis is focused on Iowa, this approach is applicable to the broader region and differs substantially from the status-quo of 'top-down' land management for

conservation by harnessing private interest to align profitability with the production of ecosystem services.

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