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Precision conservation meets precision agriculture: A case study from southern Ontario

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ABSTRACT

Meeting future food demands for 9 billion people in the next 30 years will require either agricultural expansion or intensification to increase production. However, agriculture is already a major driver of biodiversity loss, as well as freshwater withdrawals, nutrient inputs, and greenhouse gasses, among other pressing environmental issues. In this paper, we look for solutions to this production-conservation challenge at the subfield scale. We use precision agriculture yield data from three farms in Southern Ontario and convert them into "profit maps" that show which regions of a field have management costs that exceed the market value of the commodities produced. We analyse the profit of three farms over time and identify areas that consistently show low or negative profit and thus constitute a compelling case for taking these areas out of production. We find, for example, that up to 14% of farmland can result in money loss and even more than 50% of the land might still not meet minimum revenue expectations. Further, we assess the economic feasibility of conservation strategies on these set-aside lands and find that investing in environmental benefits (even minimally) can often times be inexpensive when compared with economic losses due to failed harvests. We argue that profit mapping can serve as a management tool for farmers that will allow them to identify optimal crop areas, optimize nutrient inputs, plan for ecological intensification, and avoid economic loss all while providing ecosystem services at the local scale.

1. Introduction

The expected human population of 9.7 billion by 2050 will demand a 70% increase in food production (Holt-Giménez and Altieri, 2013; Fraser et al., 2016). Agriculture already produces enough calories for the current population; however, due to systemic problems linked with poverty, approximately 800 million people are undernourished and 2 billion people experience micronutrient deficiency (FAO et al., 2018). On top of this, agriculture is a critical economic activity for the livelihood of 40% of the world's population and represents 30% of the gross domestic product in low-income countries (Ramankutty et al., 2018). As a consequence, there will be a demand for the further expansion or intensification of agricultural production (De Marsily and Abarca-Del-Rio, 2016; Rizvi et al., 2018).

The expansion of agricultural and urban areas has already led to the conversion of 43% of the Earth's land (Barnosky et al., 2011) and is currently the major cause of habitat loss and biodiversity decline (Laurance et al., 2014). Agriculture alone is responsible for the conversion of 70% of grasslands, 50% of savannahs, 45% of temperate deciduous forests, and 27% of tropical forests (Foley et al., 2011; Pagnutti et al., 2013). Industrial agriculture —alongside mining and energy infrastructure —results is the loss of 5 million ha of forests every year (Curtis et al., 2018). Additionally, agriculture demands 70% of freshwater withdrawals and has already pushed two thirds of the global rivers' basins beyond their capacity to buffer nutrient inputs (German et al., 2017). Agricultural and grazing practices combined are responsible for the soil degradation of 23% of the world's arable land (Grunwald et al., 2011), which in turn results in the demand of more land conversion (Laurance et al., 2014). As for greenhouse gasses, agriculture accounts for up to 30% of emissions, including those originating from ruminant animals, land use change, fertilizers use, and fossil fuels (Garnett, 2011).

Approaches for biodiversity conservation have been shifting over time as a result of how relationships between people and nature are viewed (Mace, 2014). Currently, in agricultural systems, part of the conservation debate revolves around the "land sharing / land sparing"

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dilemma (Green et al., 2005). Land sparing refers to strictly protect some land while intensively farming on smaller land footprints, while land sharing intends to establish less areas for strict biodiversity conservation but to carefully utilize larger land footprints (Durán et al., 2014; Kremen, 2015). Although there is evidence to support both alternatives and the debate is ongoing (Kremen, 2015), land sparing is more commonly adopted around the world (Mertz and Mertens, 2017). Nonetheless, in agricultural systems, authors consider than when small and dispersed fragments of land are spared, land-sharing landscapes are created (Kremen, 2015).

Another approach for conservation in agricultural lands has focused on protecting ecosystem services —benefits that people obtain from ecosystems. Agriculture depends on services such as nutrient and water cycling, the maintenance of soil quality, and pest regulation, and in turn provides value services such as crop production, fibres, and energy (Schipanski et al., 2014). However, under appropriate management practices, agricultural lands can also provide non-value ecosystem services —air quality, soil carbon storage, habitat for biodiversity, and landscape aesthetics (Rapidel et al., 2015). For example, crop rotations —as opposed to monocultures— can increase soil carbon and total nitrogen, and soil microbial biomass carbon and nitrogen (McDaniel et al., 2014). Also, pest-tolerant and resistant cultivars can reduce overreliance on pesticides and thus their runoff into natural systems (Barzman et al., 2015). Moreover, cover crops can reduce soil erosion and compaction, better soil structural and hydraulic properties, and supress weed growth (McDaniel et al., 2014; Blanco-Canqui et al., 2015). The interdependence of humans and nature is such, that global ecosystem services have been valued at US$125 trillion/year (Costanza et al., 2014). Acknowledging this economic value can improve the effective management of ecosystems and guide the design of economic incentives such as payment for ecosystem services (Costanza et al., 2017).

Given the spatial heterogeneity of agricultural landscapes (e.g. soil type, slope, nutrient levels, moisture content), the optimization of production and conservation in agroecosystems requires spatially explicit analyses and technologies. The term ‘precision conservation’, has emerged as a way of describing approaches that aim to conserve soil and water in agricultural and natural lands, based on a combination of spatial technologies (such as global positioning systems, remote sensing, or geographic information systems) and procedures (such as map analysis, surface modeling, spatial data mining) (Berry et al., 2005). Precision conservation is also related to ‘precision agriculture’, which is defined as “techniques that monitor and optimize production processes … thereby conceivably increasing yields and outputs and improving the efficiency and effectiveness of inputs” (Fraser, 2018). This includes utilizing technological innovations including ‘robot farmers’, self-driving tractors, software codes, computational models, and the creation and storage of big data on agricultural practices, productivity and yields, and biophysical properties of the land (Fraser, 2018). Environmentally speaking, precision agriculture has been successfully applied to avoid excessive chemical inputs in soil, reduce carbon footprint in field operations, reduce herbicide and pesticide use, and monitor plant health (Schrijver et al., 2016). From an economic standpoint, precision agriculture contributes to food safety by better predicting on the quality and quantity of agricultural products, reducing expenses, and monitoring the food chain (Schrijver et al., 2016). In addition, precision agriculture can help plan for the “sustainable intensification” of agricultural production, as increases in yields should be strategically sought through a context- and location-specific approach (Garnett et al., 2013).

One particular use of precision agriculture, profit mapping, has gained momentum as a tool to motivate producers to set aside unprofitable lands for conservation for addressing areas that are prone to environmental risks such as soil erosion (Muth, 2014). Brandes et al. (2016), in a similar analysis, identified “hotspots” for “potential management change”. In this paper, we use precision agriculture data to demonstrate how precision agriculture technologies can be used to increase environmental benefits in Southern Ontario's agricultural lands by putting agricultural production and alternate management scenarios on the same economic footing. We show the use of precision agriculture yield crop data as a way of developing high-resolution profit maps of farms. We then use these maps to identify areas, at the subfield scale, that consistently show low or negative profit and thus could be set aside for conservation and increased ecosystem services. We also assess the economic feasibility of eight strategies that could promote biodiversity and ecosystem services on such low profit areas. We work under two hypotheses: a) areas of consistent low or negative profit can be detected by the use of precision agriculture and profit mapping, and b) investing in conservation strategies on these low profit areas can be more economically feasible than investing (and losing money) in agriculture.

2. Methods

2.1. Study area

The province of Ontario accounts for 25% of Canada's farmland and 20% of the country's gross farm receipts (Statistics Canada, 2017). In Ontario, 50,000 farms spread over 5 million ha (OMAFRA 2017). Soybeans and corn find their largest production in this province, accounting for almost 60 and 50% of their cultivated area, respectively. To enhance biodiversity, interrupt pest cycles, and increase nutrient efficiency, soybean and corn are usually rotated with wheat (Statistics Canada, 2017). We worked on three farms —namely A (82.15 ha), B (23.07 ha), and C (29.95 ha)— that have been on a soybean, corn, and wheat rotation for the past 10 years. The farms are located in Wellington County (between 80° and 81°W, and 43°30′ and 44°N), near the cities of Fergus and Rockwood. Although in this County the farm average size is 56.25 ha, farmers are likely responsible for grater extents of land, as most of them work their own farms and rent additional land (Cummings et al., 2006). In this area, the surface deposits are in its majority of glacial origin and formed the parent material from which soils have developed (typically loamy soils within the study region). The terrain also presents many low broad oval hills with smooth slopes characteristic of drumlins. Overall, the soils are well drained and suitable for agriculture (Hoffman et al., 1963; Chapman and Putnam, 1984).

2.2. Calculation of profitability

We obtained precision agriculture data from the farm owners, who conduct yield and plant population monitoring and use Geographic Positioning Systems (GPS) technologies to produce high-resolution maps of their farm yield. The data we used consisted on yield measurements (bushels acre^{-1}) obtained from harvest yield monitors. These monitors use optical sensors to measure yield and are installed on combines. Here, we converted yield data to kg ha^{-1} assuming corn weighs 25.40 kg bushel^{-1} (OMAFRA, 2018a) whereas soybeans and wheat weigh 27.70 kg bushel^{-1} (OMAFRA 2018b and 2018c). Yield data points were spaced out between 1.5 and 10 m, resulting in an average density of 808 yield points ha^{-1} for farm A, 919 yield points ha^{-1} for farm B, and 755 yield points ha^{-1} for farm C.

We used four years (2013–16) of data for farm A, five years for farm B (2011, 2013–16), and nine years (2001, 2003–04, 2006, 2010–11, 2014–16) for farm C. To estimate profitability, we consulted the Ontario Ministry for Agriculture, Food, and Rural Affairs' (OMAFRA) provincial estimates of field crop budgets and grain market prices for each year. Estimates of field crop budgets included the cost of growing each crop based on operating (e.g. seeds, fertilizers, herbicides, tractor and machine expenses, crop insurance, labour work) and overhead (e.g. depreciation of machinery, interest on investment) expenses per acre (OMAFRA, 2001–2016). Grain market prices consisted on the provincial average market price per bushel (OMAFRA, 2018d). We converted bushels to kg and acres to ha. All prices are expressed in Canadian dollars (CAD).

Each one of the yield points (kg ha^{-1}) from the precision agriculture dataset was converted into a profit value (CAD ha^{-1}). Profitability P of crop i in year j for yield point k, was calculated as (modified from Brandes et al., 2016):

$$P_{ijk} = (Y_{ijk} \times GP_{ij}) - CP_{ijk}$$

where Y_{ijk} is the yield for crop i in year j on yield point k; GP_{ij} is the grain price for crop i in year j; and, CP_{ijk} is the crop production cost for crop i in year j on yield point k.

Once each yield point had been converted into a profit value, we created a continuous profit map using a Kriging interpolation with a spherical model. This is a geostatistical interpolation method that fits a mathematical function to some sample points to determine output values for all the other locations in the map, and is best suited for when there are spatially correlated distances (Oliver and Webster, 1990). Kriging interpolations are typically used to generate profit maps using precision agriculture data (Bazzi et al., 2016; Betzek et al., 2017). For our continuous profit map we used a spatial resolution of 25 m^2 because some management operations in the farm are conducted at this scale.

2.3. Economic feasibility of alternative management scenarios

Next, we needed to assess the extent to which there were economically feasible alternatives to cropping in unprofitable areas. This is because lands taken out of production might act as a reservoir of pests and weeds (Valkó et al., 2016) and hence it is critical that they are properly managed. Here, we proposed eight alternative management scenarios that provide a variety of environmental benefits (Table 1) and tested their economic feasibility in each set-aside land. Costs for each scenario were based on local suppliers (Table 1). For each potential set-aside land identified in the farms, we assessed —using a one-sample t-test and a level of significance of 5%—whether the cost of implementing an alternative scenario was significantly different than the average (positive or negative) revenue obtained from conventional agriculture. This test allowed us to discern if conventional agriculture and alternative management scenarios were equal in terms of cost or if either of them made the producer incur in higher expenses.

Table 2
Crop yields from the three farms under study in Southern Ontario.

Farm	Year	Crop	Yield (kg ha^{-1})			
			Mean	SD	Min.	Max.
A	2013	SB	3360	828	315	5692
A	2014	C/W	9241/3711	1942/1868	1192/336	16,633/9999
A	2015	SB	3052	808	329	6557
A	2016	C	11,607	1885	314	19,326
B	2011	SB	2602	828	361	5712
B	2013	SB	2717	691	311	5892
B	2014	C	10,270	2053	1309	18,193
B	2015	SB	2548	943	650	6720
B	2016	SB	5346	1757	338	11,760
C	2000	W	4608	1587	483	13,359
C	2001	C	10780	2560	627	25,091
C	2003	C	7436	2022	628	22,423
C	2004	C/SB	2651/3001	1780/582	632/352	20,537/12552
C	2006	SB	1074	282	338	6475
C	2010	W	4710	1606	336	96,581
C	2011	SB	3701	915	353	7859
C	2014	SB	2964	654	342	5311
C	2015	SB	4759	1190	307	7997
C	2016	SB	3387	768	366	6911

SB: soybeans, C: corn, W: winter wheat, SD: standard deviation.

3. Results

3.1. Insights on farm yields and profit

Average yields in all farms showed variability over time, and also variability among and within crops (Table 2). For example, in farm A, corn yields in 2014 and 2016 showed over 2000 kg ha^{-1} difference. In farm B, soybeans average yields fluctuated between 2548.15 and 5346.40 kg ha^{-1}. Farm C, for which we have more years of data, has also seen variations in yield, especially in corn —average lows of 2651.31 and average highs of 10,779.64 kg ha^{-1}. Table 2 shows the descriptive statistics of yield data as estimated by the harvest yield monitors.

Farm profitability also differed greatly over time. Figs. 1, 2, and 3 show the Kernel density distribution of profit for farms A, B, and C, respectively. These Kernel density plots of profit are essentially

Table 1
Proposed alternative environmental scenarios for set-aside lands, their associated seeding rate, and annual costs.

Scenario	Seeding rate (kg ha^{-1})	Cost per year (CAD ha^{-1})[a]	Environmental benefits
Wildflowers (e.g. *Monarda fistulosa, Rudbeckia hirta, Oenothera biennis, Helianthus petiolaris*)	14.82	\$1976 (in first year) \$123.50 (in subsequent years)	Increase foraging resources for invertebrates (Williams et al., 2015, Grass et al., 2016, Haddaway et al., 2016).
Red clover (*Trifolium pratense* L.)	8.97	62.24	Animal fodder production (Rundlöf et al., 2014), incorporation of nitrogen in the soil, weed supression (Schipanski et al., 2014), support of bumble bee populations (Rundlöf et al., 2014)
White clover (*Trifolium repens* L.)	8.97	103.74	Nitrogen fixation, reduction of nutrient leaching, provision of dense soil cover that prevents erosion and weed invasion (Parente and Frame, 1993Sturludóttir et al., 2014).
Alfalfa (*Medicago sativa*)	20.15	284.79	Breaking up compacted layers of soil and thus improvement of soil infiltration and permeability. It also fixates nitrogen (OMAFRA, 2012a).
Lacy phacelia (*Phacelia tanacetifolia*	5.60	271.70	Attraction of wild bee species (Warzecha et al., 2018) and hoverflies, formation of arbuscular mycorrhizal fungi associations, quick decomposition, capture of excess nitrates in the soil (USDA, 2016).
Common buckwheat (*Fagopyrum esculentum*)	56.02	123.50	Suppression and shade of perennial weeds, attraction of beneficial insects, provision of fast ground cover (OMAFRA, 2012b).
Untreated oats (*Avena sativa* L.)	112.04	88.92	Erosion control, suppression of weeds (OMAFRA, 2012c).
Peas (*Pisum sativum* L.) and oats (*Avena sativa* L.)	112.04	106.21	Optimization of nitrogen sources, leading to higher productivity and little need for nitrogen fertilizers (Neugschwandtner and Kaul, 2015).

[a] Includes application rate of 24.70 CAD ha^{-1}.

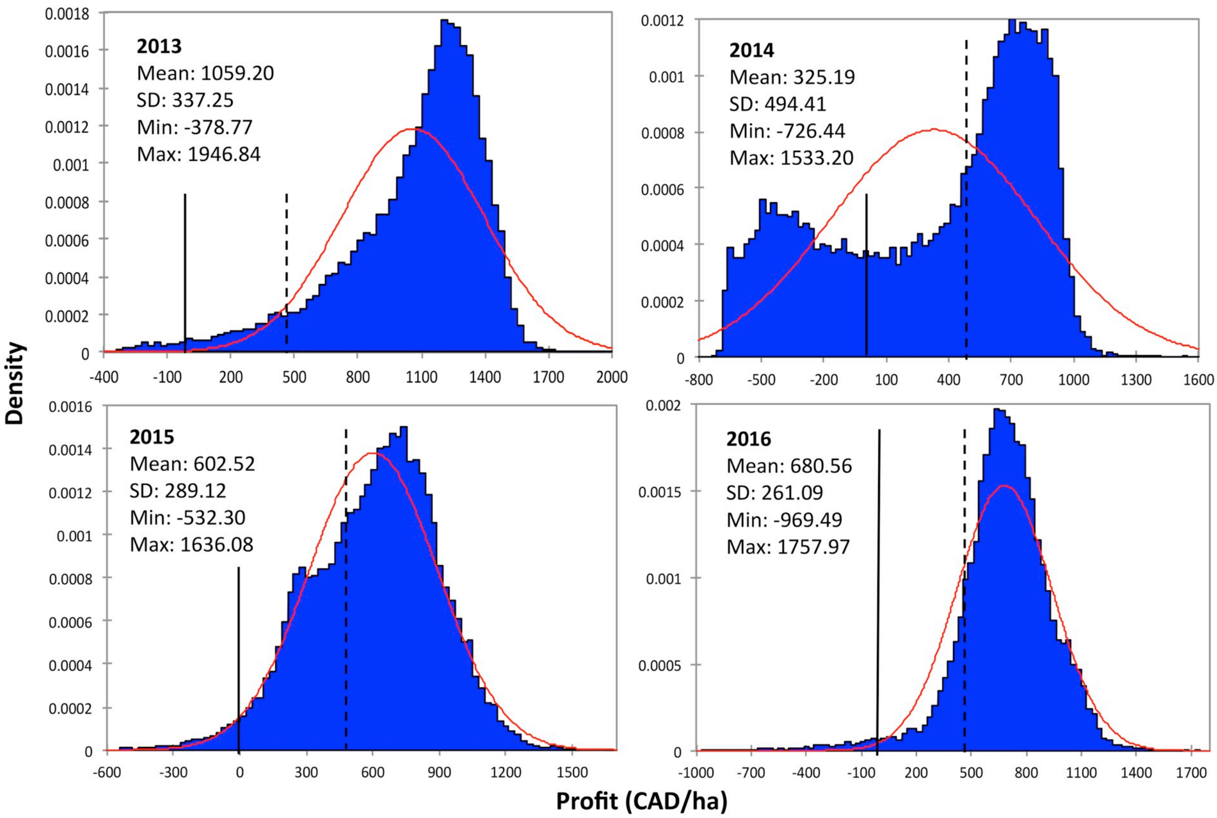

Fig. 1. Kernel density distribution of profit in farm A. Red curve: normal curve; black vertical line: zero profit; black dashed vertical line: minimum profit assumed to be expected by producers. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

continuous, smooth histogram of the data. The highest average profit obtained from Farm A was \$1059.20 ha^{-1} in 2013, although that same year some 1.32% of the farm suffered losses of up to \$378.77 ha^{-1}and 6.18% made profits below \$494 ha^{-1}. Profits of \$494 ha^{-1} are typically the minimum revenue expected by producers and the average income in our study area. Farm's A lowest average profit was observed in 2014, when the average profits were \$356.11.69 ha^{-1} —below the \$494 ha^{-1} minimum expected by producers. In 2015, the average profit was \$602.52 ha^{-1}, but still 31.18% of the farm showed profits between \$0 and \$494 ha^{-1}, and 2.42% of the farm indeed resulted in a loss of money. A similar situation occurred in 2016, where the average profit was \$680.56 ha^{-1}, but 15.17% of the farm perceived \$0–\$494 ha^{-1},

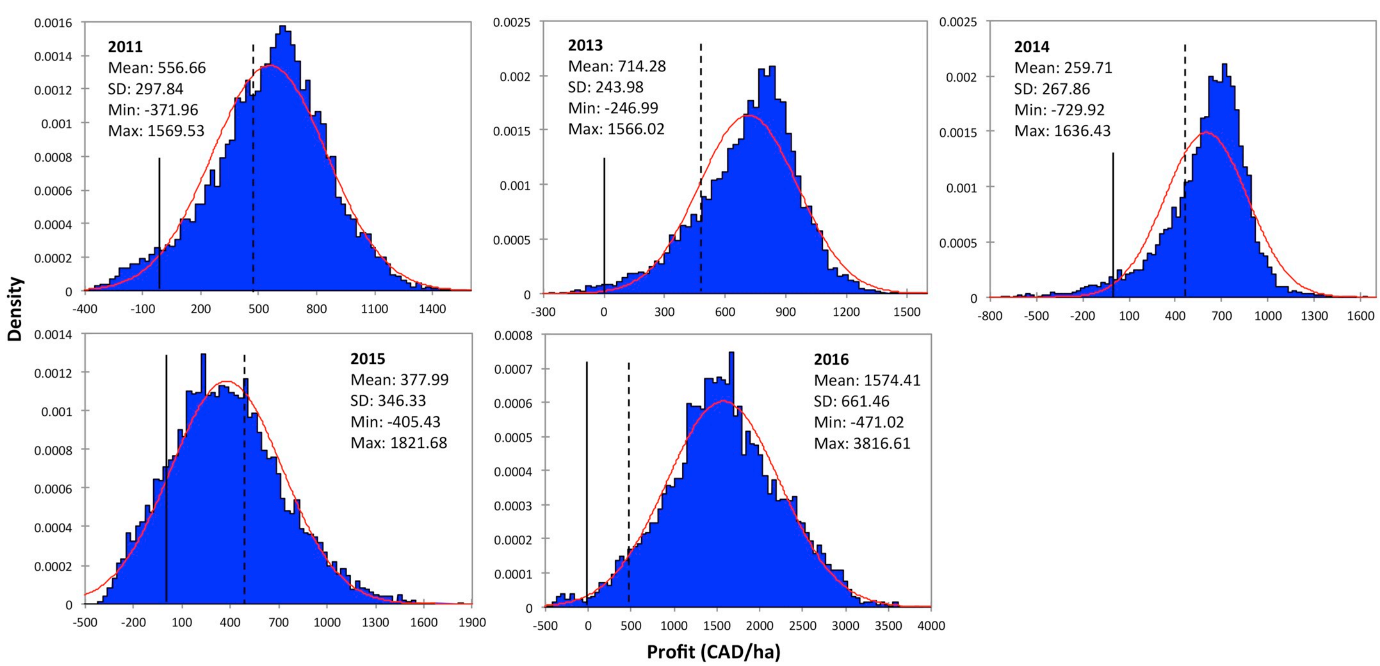

Fig. 2. Kernel density distribution of profit in farm B. Red curve: normal curve; black vertical line: zero profit; black dashed vertical line: minimum profit assumed to be expected by producers. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

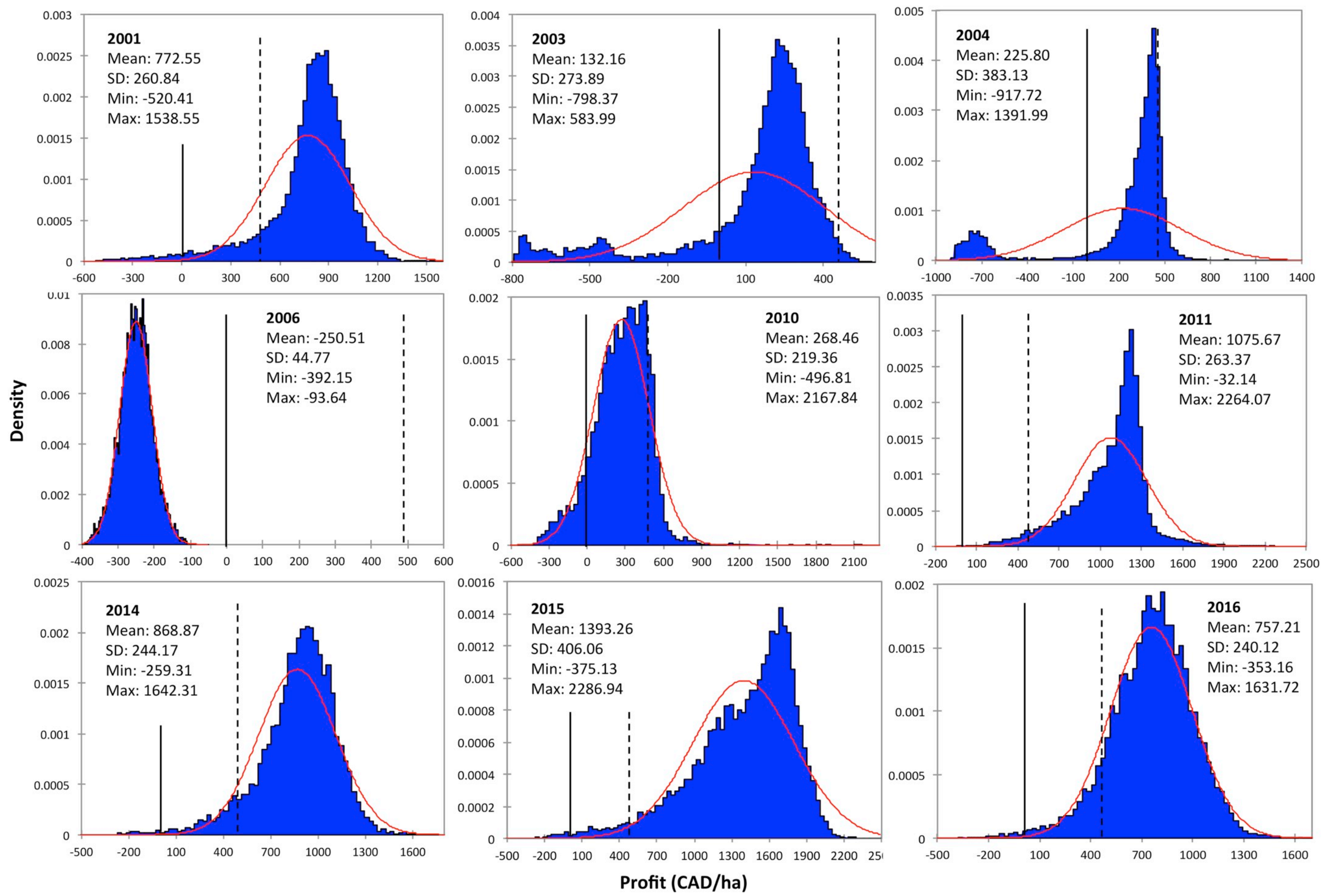

Fig. 3. Kernel density distribution of profit in farm C. Red curve: normal curve; black vertical line: zero profit; black dashed vertical line: minimum profit assumed to be expected by producers. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and 2.15% of the farm yielded a negative profit (Fig. 1).

Farm B showed the lowest average profit in 2015 ($377.99 ha^{-1}), when also 14.25% of the farm resulted in loss of money and 50.75% of the farm had modest revenues up to $494 ha^{-1}. The highest average profit —$1574.41 ha^{-1}— was observed in 2016, but even then 5.51% of the farm resulted in revenues below $494 ha^{-1}. In 2011, 2013, and 2014, average farm profits surpassed the $494 ha^{-1}minimum; however, 4.71%, 0.81%, and 3.62% of the farm yielded negative profits, respectively (Fig. 2). Farm C probably showed the highest variation when it comes to profit, from average losses of $250.51 ha^{-1} in 2006 to average profits of $1393.26 ha^{-1} in 2015. In 2003, 2004, and 2010 most of the farm resulted unprofitable: 17.43%, 14.53%, and 10.75% of the farm showed negative profits; 82.02%, 79.73%, 77.35% exhibited modest profits up to $494 ha^{-1}. From 2011 onwards, profits seemed to have increased, but sectors of the farm still yielded low profits. For example, in 2015, the year of highest average profit —$1393.26 ha^{-1}—, 3.58% of the farm exhibited profits below $494 ha^{-1} (Fig. 3).

3.2. Potential set-aside lands in farms

Based on the spatial distribution of profits and to exemplify the application of profit mapping, we identified the most unprofitable area of each farm. These areas are used to highlight the impact of the set-aside issues proposed, as there are other regions identified on each farm —two in farm A and one in farm C. The potential set-aside lands that we analyse here were located in the bordering areas of farms; however, we recognize that potential set-aside lands can also exist in the more central areas of the farm. The potential set-aside lands we selected have consistently showed lower profit that the expected by producers ($494 ha^{-1}) or exhibited negative profit. In Farm A (Fig. 4), we identified a potential set-aside land (0.29 ha) to the east of the farm, where average profits were negative in two out of the four years analysed —2014 and 2016 (Table 3). In 2013 and 2015 average profits were $416.34 ha^{-1}and $21.09 ha^{-1}, respectively. In the potential set-aside land of Farm B (0.26 ha, Fig. 5, Table 3), 2011 and 2015 showed average negative profits —$-113.35 ha^{-1} and $-81.21 ha^{-1}, respectively. In none of the other years analysed did the profit reach the minimum desirable of $494 ha^{-1}: Average profits were $ 261.80 ha^{-1} (2013), $125.45 ha^{-1} (2014), and $ 21.66 ha^{-1} (2016). In Farm C, the area we identified for conservation (1.38 ha, Fig. 6, Table 3) exhibited average negative profits in 2003 ($-43.92 ha^{-1}) and 2006 ($-320.93 ha^{-1}), and average profits below the $494 ha^{-1} minimum desirable in 2001, 2004, 2010, and 2016. Average profits in this area, however, were better aligned with producers' expectations in 2011 ($766.94 ha^{-1}) and 2015 ($843.33 ha^{-1}). In Figs. 4, 5, and 6, low and negative profits are evidenced by the presence of yellow to red colours.

3.3. Feasibility of conservation scenarios in set-aside lands

Our results indicate that investing in environmental benefits on the potential set-aside lands, and depending on the year and its corresponding profit, could have been cheaper than investing in conventional agriculture. And this is without any subsidies or other economic incentives that could be envisioned to support these activities. In some other cases, the amount of money lost from farming resulted no

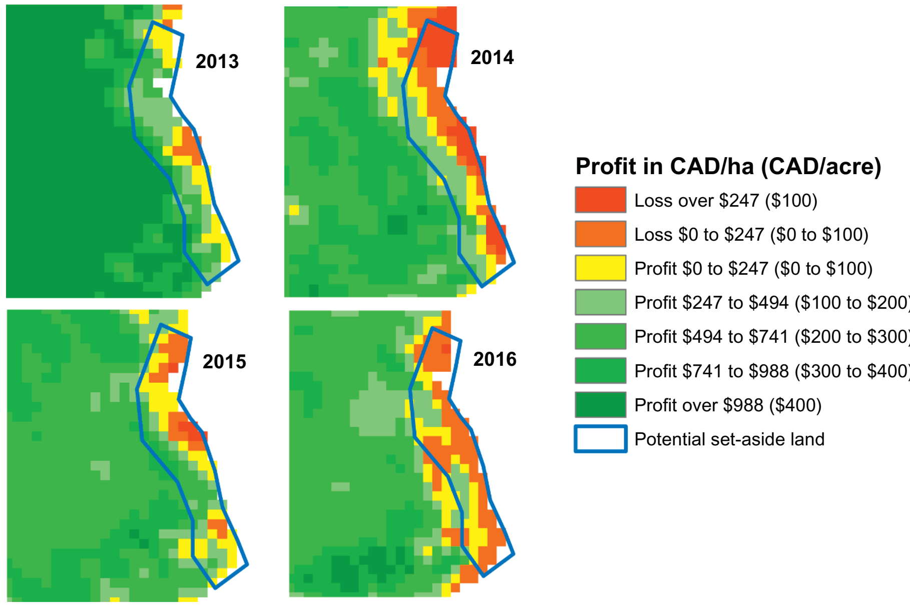

Fig. 4. Spatial distribution of profit in the potential set-aside land identified in Farm A.

difference than the amount of money that alternative management scenarios would have cost (Table 3). On the set-aside land of farm A, in 2016, most conservation scenarios —except for alfalfa and phacelia (the most expensive)— would have provided an advantage over agriculture or resulted in the same amount of money spent. Two of the cheapest scenarios proposed here —red clover and untreated oats— would have also been more opportune in 2014. Essentially, in half of the years analysed, the profit from agriculture was so low that investing in environmental benefits would have been more suitable (Table 3).

As for the set-aside area of farm B, alternative scenarios would have been economically feasible in 2011 and 2015. Comparing these years, however, the wildflower scenario would not have been economically feasible in 2011 as this would have been the year of establishment ($1976 ha^{-1}), whereas it would have been feasible in 2015, a year of

Table 3
Economic feasibility of alternative environmental management scenarios for set-aside lands.

Farm	Year	Average profit (CAD ha^{-1}) of set-aside land	Alternative environmental management scenarios							
			Wild-flowers	Red clover	White clover	Alfalfa	Buck.	Peas-oats	Untr. oats	Phac.
A	2013	416.34	A	A	A	A	A	A	A	A
	2014	-35.57	A	AC	A	A	A	A	AC	A
	2015	21.09	A	A	A	A	A	A	A	A
	2016	-159.41	AC	C	AC	A	AC	AC	AC	A
B	2011	-113.35	A	C	AC	A	AC	AC	AC	A
	2013	261.80	A	A	A	A	A	A	A	A
	2014	125.45	A	A	A	A	A	A	A	A
	2015	-81.21	AC	AC	AC	A	AC	AC	AC	A
	2016	21.66	A	A	A	A	A	A	A	A
C	2001	247.02	A	A	A	A	A	A	A	A
	2003	-43.92	A	A	A	A	A	A	A	A
	2004	232.77	A	A	A	A	A	A	A	A
	2006	-320.93	C	C	C	C	C	C	C	C
	2010	31.42	A	A	A	A	A	A	A	A
	2011	766.94	A	A	A	A	A	A	A	A
	2014	588.11	A	A	A	A	A	A	A	A
	2015	843.33	A	A	A	A	A	A	A	A
	2016	324.71	A	A	A	A	A	A	A	A

C (in green): conservation is more economically feasible; A (in yellow): conventional agriculture is more economically feasible; AC (in grey): no significant difference between conventional agriculture and conservation scenarios; Buck: buckwheat; Phac: lacy phacelia.

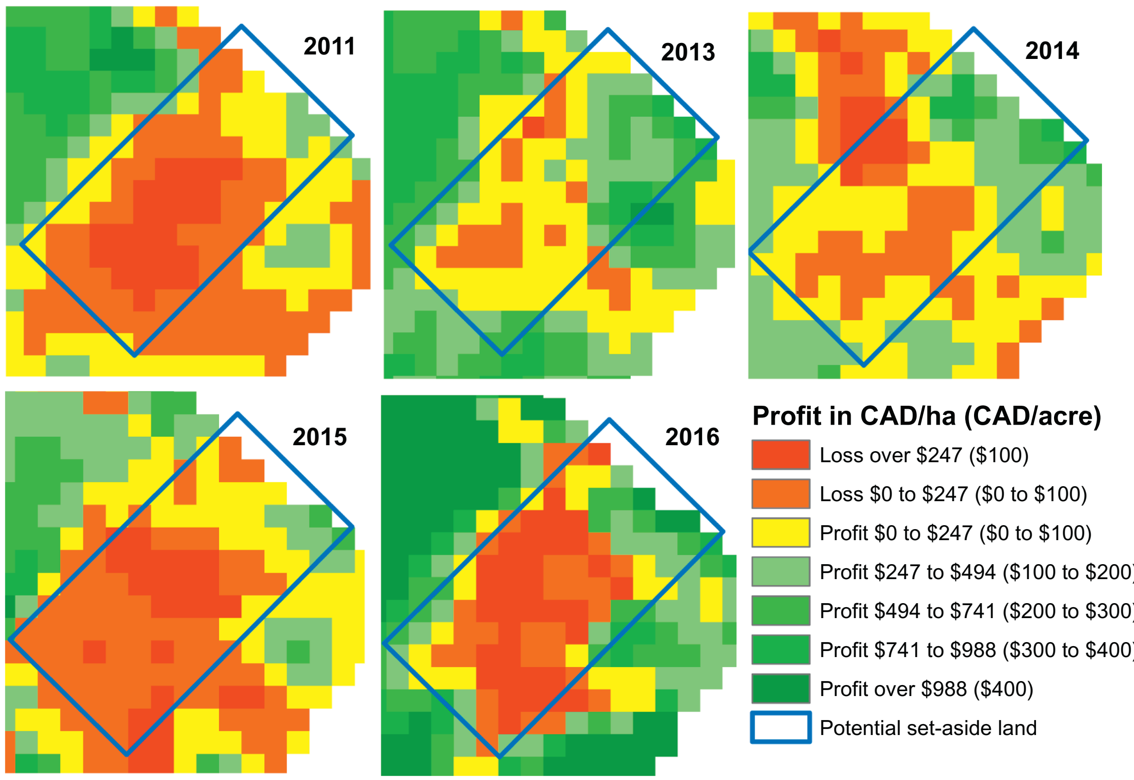

Fig. 5. Spatial distribution of profit in the potential set-aside land identified in Farm B.

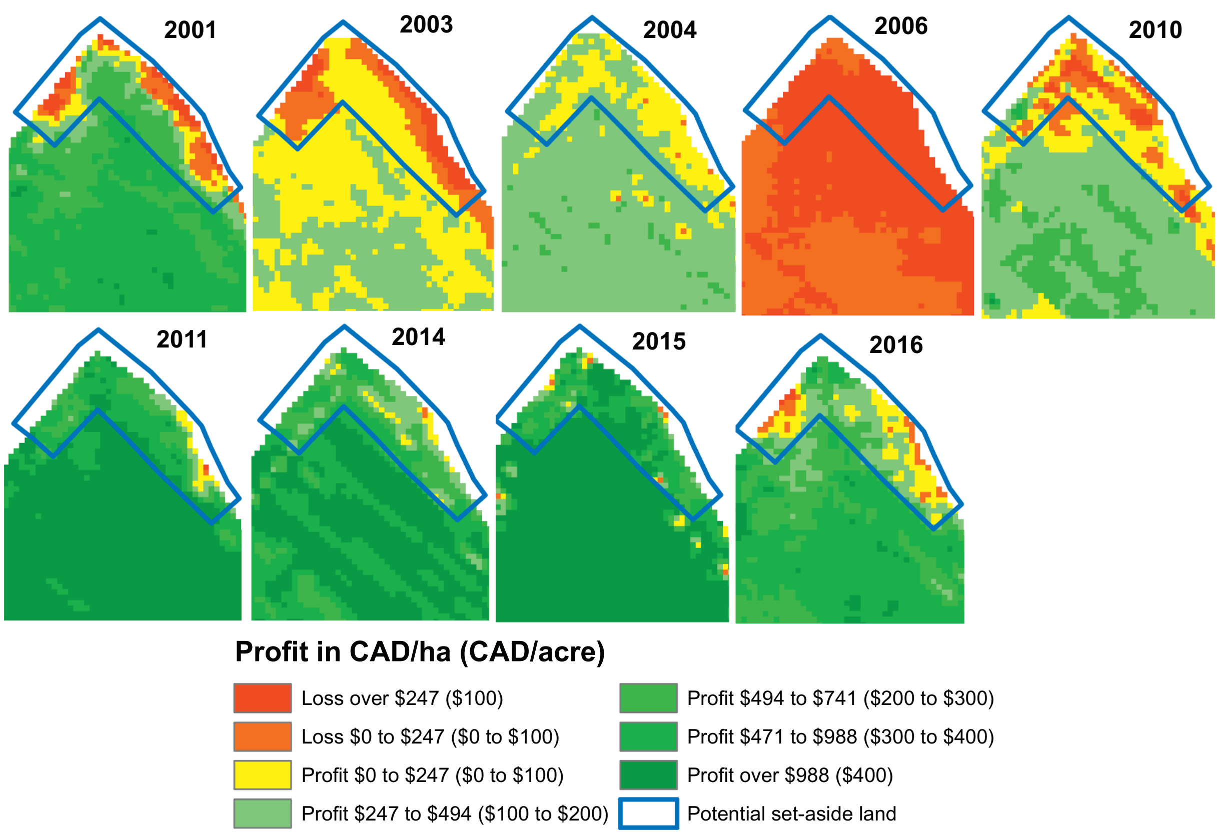

Fig. 6. Spatial distribution of profit in the potential set-aside land identified in Farm C.

maintenance (\$123.50 ha^{-1}). Similar to farm A, alfalfa and lacy phacelia might not have been as convenient as the other options due to higher costs (Table 3). In Farm C, and despite its low average profits, only in 2006 investing in conservation would have been cheaper than incurring in money loss from agriculture (Table 3).

4. Discussion

In this paper, we combine precision agriculture data, economic data for commodity yields, and cost of investing in alternative environmental management scenarios to develop a novel approach to mapping areas within fields that are profitable for farmers. In this way, we demonstrate that the tools of "precision agriculture" provide us a way to identify lands within farms where investing in conservation and ecosystem services can be more economically feasible than conventional agriculture. In the three areas studied, up to 14% of farmland resulted in lost money and more than 50% of this land did not generate the minimum revenues farmers expected. While our sample size is small, these indicative results suggest that there need to be a reconsideration of how farms are managed. Despite this idea gaining momentum over the past few years (Muth, 2014; Brandes et al., 2016), to our knowledge, this is the first study to estimate the economic feasibility of set aside lands for the enhancement of ecosystem services.

4.1. The use of precision agriculture data as a tool for farm risk management

The use of profit maps is not new and has been exploited by consultants and retailers since 1990s (Muth, 2014). Still, a generalized access to and use of such technologies is limited (Daberkow and McBride, 2003; Adrian et al., 2005). More recently, however, some tools —yield and soil maps, GPS on tractors and combines, variable-rate technologies— have become more accessible and easier to use, and thus the adoption of precision agriculture seems to be on the rise (Schimmelpfennig, 2016). On top of this, governments have been investing in the application of precision agriculture. In Canada, examples are SCAN (Soil, Crop, Atmosphere and Nitrogen) — a decision-making tool to optimize the use of fertilizers— and the Agricultural Clean Technology Program —targeted to reducing greenhouse emissions (AAFC, 2017, 2018).

The expansion of precision agriculture is bringing numerous benefits to producers, one of the main ones being the optimization of fertilizer use. Given Ontario farms spend \$816 million on fertilizer and lime annually (Bucknell et al., 2016) and agriculture is partly responsible for nutrient enrichment in water bodies (Sunohara et al., 2015; Thomas et al., 2018), technologies that help decide on appropriate varying application rate of nutrients are critical to sustain agriculture (Hedley, 2015). Alternatively, profit mapping can show how some areas are prone to remain unproductive and, hence, incorporating conservation strategies might reduce both investment expenses and nutrient inputs.

As seen in our results, areas of exceptional yield and profitability that could be explored for intensification also exist. Ideally, however, this intensification should fall along the lines of 'ecological or sustainable intensification', which aims to first comprehend the natural functionalities and complexity of the system to then produce more food, fibre, energy, and ecological services with minimum environment impact (Cassman, 1999; Garnett et al., 2013; Caron et al., 2014; Tittonell, 2014). In this work, we only address precision agriculture at the subfield scale as a model of ecological intensification, but expect that both the expansion of profit mapping as a risk management tool and other models of ecological intensification —organic agriculture, nature mimicry, agroforestry (Tittonell, 2014) will jointly support conservation and sustainable food production.

One critical factor influencing the adoption of conservation through precision agriculture is land tenure. In Ontario, farmers can spend between \$309 and \$741 ha^{-1} in rent (Deaton, 2017). Despite these high rates, many farmers decide to rent because of the restrictive prices of land acquisition and the unstable commodity market conditions (Rotz et al., 2017). These high rental values, however, drive Ontario farmers to crop even on unproductive and low yielding sectors of their farm (Rotz et al., 2017). To complicate matters, farmers in short-term leases are less likely to adopt conservation practices such as cover crops (Fraser, 2004; Nadella et al., 2014) and invest in agroecological health (Rotz et al., 2017). In our work, we show that event without paying rent farmers can struggle to make a profit (Figs. 1–3); hence, if rent entered our profitability equation, the overall revenue of the farms would be further compromised. In this scenario where the land is seen as a short-term investment, precision agriculture data could help farmers with decision-making. While farmers might decide to crop everywhere since "some yield is better than nothing if they are paying for rent anyways" (Rotz et al., 2017), profit mapping might provide a compelling case for land use and management changes. As shown in this work, conservation strategies might be cheaper than agriculture for some sectors of the farm. Additionally, identifying potential areas for intensification and nutrient input optimization could also help offset high rental costs.

Management practices that are environmentally friendly are now valued in the market. There is currently a pressure on the food sector to turn operations sustainable and to remodel supply chains through eco-branding —"product differentiation based on sustainable attributes"— and certifications —"a guarantee of product and process adherence to certain environmental, social, and ethical standards at different stages in the value chain"—(Chkanikova and Lehner, 2015). Enhancing conservation and sustainable production through precision agriculture could thus help producers to better brand their products, and secure and enter new markets. Also, the adoption of profit mapping could improve the performance of crop producers on environmental and economic indicators such as percentage of agricultural land under biodiversity-friendly practices or nutrient management practices, percentage of terrestrial area designated for conservation, yield gap, and crop water productivity (Rasmussen et al., 2017).

4.2. The use of precision agriculture data to complement biodiversity conservation

The creation of protected areas is challenging, as a great proportion of the remaining unprotected land across the globe is in private hands and governments do not have the purchasing power to acquire them (Selinske et al., 2015). Seeking opportunities for conservation in private lands has thus become a popular approach (Kamal et al., 2015; Selinske et al., 2015). In our case study, we have shown examples of relatively small areas within each farm that could be taken out of production without impacting the economic revenues for the producer. In addition, we have also shown how investing in alternative environmental management can be less expensive than the costs of a failed harvest. Nonetheless, we argue that the decision of taking land out of production will be likely made based on not only multi-year assessments of yield and commodity prices, but also factors such as size and location of these set-aside lands. Ultimately, the objective of profit mapping is that producers can make informed management decisions on their farm.

The set-aside lands that we propose with this approach are not strictly protected areas of course but can be managed for biodiversity conservation while owned by individuals or corporations. This is a characteristic of 'private land conservation areas' (Clements et al., 2016). Our approach fulfils two requirement of conservation in working landscapes: conservation measures have to be compatible with production (Kitchen et al., 2005), and the involvement of stakeholders is critical if the joint achievement of conservation and socioeconomic outcomes is desired (Oldekop et al., 2016). We argue, however, that our approach will benefit from the development of new ideas and technologies that reduce the costs of biodiversity conservation and make alternative management scenarios (e.g. wildflowers, hedgerows) as affordable as cover crops.

There has been debate over the effectiveness of set-aside lands in agricultural systems. At the local scale, there is enough evidence to suggest that lands removed from production can sustain higher richness and densities of animals and plants (van Buskirk and Willi, 2004). We wonder, however, what would be the minimum size required for this function, as the set-aside lands identified in this work might not be deemed large enough for this. Here we argue that even small set-aside lands can enhance biodiversity and ecosystem services locally by resulting in erosion control, improved nutrient levels and soil infiltration, suppression of weeds, habitat for invertebrates, and the creation of arbuscular mycorrhizal fungi associations, depending on the conservation scenario selected and the time since establishment. We also argue that these set-aside lands can contribute to the maintenance of populations at the landscape scale, as previously observed for grassland birds (Yeiser et al., 2018), grass species (Lindborg et al., 2014), and carabid beetles and spiders —in areas as small as 0.004 ha (Knapp and Řezáč, 2015). In fact, small conservation areas have been shown to have non-linear effects: small areas of perennial vegetation can result in disproportionately large benefits for conservation (Liebman and Schulte, 2015). Also, resident and migratory birds prefer agricultural fields with cover crops (Wilcoxen et al., 2018), so even our most affordable conservation scenarios could provide habitat, potentially serving as stepping stones for species to move across the agricultural matrix. The conservation effectiveness of subfield scale lands will need to be determined, but will likely be an emergent property of the number, size, and spatial arrangement of set-aside lands and other land uses across the landscape.

Profit mapping could also guide the estimation of payments for ecosystem services. As of now, the economic valuation of ecosystem services relies on two methods: revealed —direct value of the product extracted from the environment— and stated preferences —peoples' response to hypothetical scenarios (Costanza et al., 2017). Ecosystem services provided by set-aside lands, however, might be challenging to quantify, since agricultural production on those lands also have a value. We argue that if incentives were to be offered to take agricultural lands out of production, producers will likely expect a compensation that matches the crop production value that their lands has, regardless of the perceived value that ecosystem services will provide once set-aside lands are established.

5. Conclusion

Precision agriculture technologies can take farm heterogeneity —usually associated with uncertainty and management risk— and put it at the service of farm optimization for food production and biodiversity conservation. Here we show that precision agriculture yield data can be used to identify areas within the farm that are unprofitable over time and thus could be set-aside for conservation with no economic impact for the producer. Furthermore, we find evidence that, often times, investing in conservation strategies (e.g. red and white clover, alfalfa, buckwheat, wildflowers, peas-oats, untreated oats, lacy phacelia) can be more economically convenient than agriculture. This is key, as it means that conservation at the subfield scale might not necessarily depend upon external economic aid. Barriers to the adoption of precision agriculture and conservation strategies, such as farmers' computer literacy and precarious land tenure schemes, still need to be brought down to successfully engage stakeholders. In the current scenario of increasing food demands, high biodiversity loss rates, shortage of ecosystem services, and economic limitations for the creation of new protected areas, profit mapping by means of precision agriculture data has great potential to bridge the gap between production and conservation objectives.

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