Precision Agric (2015) 16:46–61
DOI 10.1007/s11119-014-9382-5

The economic and environmental impacts of precision agriculture and interactions with agro-environmental policy

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Published online: 7 October 2014

Abstract A whole-farm model was used to investigate the interacting effects of precision agriculture technology and agro-environmental policy on the production choices of a representative grain farm. Although some precision agriculture technologies did increase efficiency of resource use, they also decreased the effectiveness of policy, especially policies that rely on economic incentives (e.g., emission taxes). Precision agriculture can lead to higher marginal abatement costs in the form of forgone profits, decreasing producers' responsiveness to those policies. Policy-makers targeting pollution reductions from agriculture should take into account the increasing use of precision agriculture techniques and their varying effects on agro-environmental policy.

Keywords Whole-farm modeling · Agro-environmental policy · Auto-steer · Variable rate application · Automatic section control

Abbreviations

ASC	Automatic section control
DSSAT	Decision Support System for Agrotechnology Transfer
EU	European Union
GPS	Global Positioning System
RTK	Real-time kinematic auto-steer
US	United States
VRA	Variable rate application

Introduction

Two competing demands faced by agricultural producers and policy makers are the production of food for a growing population and the reduction of the environmental impacts

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associated with that production (Robertson and Swinton 2005). Two particular issues stand out and are investigated in this paper. First, agricultural nutrients run off and substantially impair water quality in many areas, such as the United States (US) (US-EPA 2009). Second, greenhouse gases generated both directly and indirectly by agricultural production contribute to the growing threat of climate change (Schneider and Kumar 2008).

To control pollution such as nutrient runoff and greenhouse gases, governments have considered and implemented a variety of policy instruments, each with its own advantages and disadvantages (Goulder and Parry 2008; Keohane et al. 1998). For example, the European Union's (EU) 1991 Nitrates Directive includes a 170 kg/ha limit on the annual application of nitrogen fertilizers (European Union 2010). This illustrates the use of a performance standard, applying an emission limit uniformly across a class of polluters, which can reduce cost-effectiveness when abatement cost functions differ across those pollution sources (Newell and Stavins 2003). In this context, cost-effectiveness refers to minimizing the cost of achieving a given policy goal. To mitigate this problem, economists often recommend the use of incentive-based approaches, such as taxes or tradable permits, which establish a price for the pollution but allow emission levels to vary across sources. The EU's Emissions Trading System addresses greenhouse gases via tradable permits, while Australia implemented a carbon tax of AUD 10 per megagram (tonne) in 2012, with plans to raise the tax and eventually switch to a tradable permit approach (although the policy was repealed in 2014).

By increasing the efficiency of machinery and input use, precision agriculture provides an opportunity to simultaneously reduce environmental impacts and improve productivity and profits on the farm (Bongiovanni and Lowenberg-DeBoer 2004; Berry et al. 2003). For example, navigational aids can reduce overlap in multiple passes of farm machinery, thereby decreasing the use of fossil fuels and other inputs. Variable-rate application of nutrients or pesticides can potentially reduce the use of those inputs, thereby saving on costs, as well as reducing the amount of harmful runoff into waterways.

In addition to increasing efficiency, however, precision agriculture also alters the economics of agricultural production. Many agro-environmental policies use economic incentives to promote adoption of production practices with lower environmental impacts. When precision agriculture changes the incentives and constraints faced by producers, policy measures calibrated to farms using standard production practices may yield unintended consequences (Schieffer and Dillon 2013).

Policy-makers would benefit from an improved understanding of how precision agriculture changes the constraints that frame producers' decisions and how those differences interact with the incentives created by agro-environmental policy. The present study investigated the relationships among the adoption of precision agriculture technologies, the economic welfare of the farm, the environmental impacts from farm operation (focusing on nitrogen runoff and carbon footprint), and the effectiveness of agro-environmental policy. Focusing on large corn and soybean farms, this paper explores the following questions:

1. How does the adoption of each of several precision agriculture technologies (auto-steer tractor, variable rate nitrogen application, and a sprayer with automatic section control) affect the economic, agronomic, and environmental performance of the farm?
2. How does the adoption of precision agriculture technologies interact with different types of agro-environmental policies (emission limits and taxes) and change the relative effectiveness of those policies?
3. How do the answers to the above questions depend on situational variables such as crop prices and rotations?

Materials and methods

Production decisions on a western Kentucky corn (*Zea mays*) and soybean (*Glycine max*) farm were simulated with a whole-farm model developed following Shockley et al. (2011). The model incorporated constraints reflecting the availability of different production technologies (e.g., traditional or precision agriculture methods) and the policy environment in which the farm operated. The simulated site was a 1 052-ha farm in Henderson County, Kentucky, USA, representative of large farms in the Ohio Valley region in the western part of the state (Pierce 2008). The majority of agricultural production in the U.S. and similar regions, especially for corn and soybeans, occurs on large farms. In addition, large farms have tended to adopt precision agriculture technologies more readily than have smaller operations. For these reasons, this study focused on large farms, and the results should be interpreted accordingly.

The underlying production function for the farm was represented by a biophysical simulation model, Decision Support System for Agrotechnology Transfer (DSSAT). This model mapped agricultural yields to management decisions, soil characteristics, and historical weather patterns. The simulation used a soil profile of 75 % silt loam and 25 % silt clay, reflecting the typical soils for the county as reported by the Natural Resources Conservation Service. Top soil depths were 80 % deep and 20 % shallow. The University of Kentucky Agricultural Weather Center (University of Kentucky 2008), provided 30 years of historical weather data for the county.

The model allowed the simulated producer to choose from a range of production practices (Table 1) that affected the yields of corn (*Zea mays*) and soybean (*Glycine max*) production. The options allowed for each production practice reflected typical choices in the area and recommendations drawn from University of Kentucky Cooperative Extension Service Bulletins.

The Base technology set was defined as a complement of machinery typical for large Kentucky corn-and-soybean farms. This technology set reflects the no-till approach increasingly common in the state, employed on 63.9 % of corn field area in 2005 and 79.5 % of soybean field area in 2006 (Horowitz et al. 2010). The adoption of precision agriculture was reflected in four potential changes to the Base technology set. First, an integral valve auto-steer system with a real-time kinematic (RTK) Global Positioning System (GPS) receiver, referred to as RTK auto-steer, could be added to the farm's tractor. The RTK auto-steer system improves machinery performance and reduces input use in several ways (Stombaugh et al. 2005). The system reduces the overlap of multiple passes with the tractor that are caused by operator error or fatigue. The ability to increase speeds during headland turns and more quickly identify reentry points can reduce machinery time requirements by 5 % for planting and 10 % for fertilizer application (Shockley et al. 2011). Improved performance during planting and fertilizer application and reduced input use led to cost savings of approximately 2.4, 2.2 and 10.4 % for seed, fertilizer and tractor fuel, respectively (Shockley et al. 2011). The reduction in input requirements is associated only with operations using the tractor; applications of herbicide and insecticide with the self-propelled sprayer were not affected. Also, these input reductions are estimated for a specific field size and configuration (Shockley et al. 2011); savings will vary across different configurations.

Second, the farm could employ a variable-rate spreader for the application of nitrogen (VRA) to the corn crop. VRA allows for the applied nitrogen level to vary with soil type, increasing nitrogen use where the crops will respond to it and reducing use where it will not increase yields as substantially. Third, the farm could employ automatic section control

Table 1 Production practices experimental design

Production practice	Options
Corn (*Zea mays*)	
Planting date	March 25, April 1, April 8, April 15, April 22, April 29, May 6, May 13, and May 20
Cultivar (maturity in growing degree days)	2 600–2 650, 2 650–2 700, and 2 700–2 750
Plant population (plants/ha)	59 280; 69 160; and 79 040
Row spacing (cm)	76.2
Nitrogen application (kg/ha)	112, 168, 196, 224, and 252
Soybeans (*Glycine max*)	
Planting date	April 22, April 29, May 6, May 13, May 20, May 27, June 3, June 10, and June 17
Cultivar (maturity group)	Maturity groups 2, 3, and 4
Plant population (plants/ha)	274 170, 343 330, and 412 490
Row spacing (cm)	38.1 and 76.2

Source Shockley et al. 2011

(ASC) on its self-propelled sprayer. ASC regulates the nozzles on the sprayer boom, turning them off when passing over previously sprayed areas or non-field patches of ground, thereby reducing the use of the applied inputs (insecticide and pre- and post-planting herbicides) by 10.5 %, for a specific field size and configuration (Shockley et al. 2012). In addition, ASC allows for reduced overlap in irregularly shaped fields, decreasing sprayer fuel requirements by 15.6 %. Finally, the farm could employ all three of the precision agriculture technologies in combination. An exhaustive survey of available precision agriculture technologies, both individually and in various combinations, was beyond the scope of this study. The three technologies discussed above were selected to reflect those adopted in the study region, as well as to encompass both information-intensive and embodied-knowledge technologies. The combination of the three technologies was modeled to provide some insight into how interaction effects would influence the results.

Farm site variables (soil and weather) and production practices were input into the DSSAT model to predict crop yields. For validation, these yields were checked for consistency with empirically-observed properties, such as a quadratic response to nitrogen (Schmidt et al. 2002; Cerrato and Blackmer 1990). A statistical comparison of simulated and actual historical county yields was also conducted. The two distributions were found to be consistent (with a significance of 99 %). Discussions with specialists provided further evidence that both the biophysical simulation models and the economic models produced reasonable results. Observed net returns and management practices were comparable to the results of the model. Thus, this simulation approach was deemed suitable as a framework for comparing the technology adoption and changes in the policy environment. See Shockley et al. (2011) for further details regarding validation.

A mathematical programming model was developed to identify optimal producer behavior. Given constraints representing the available production technology and the policy environment, the producer was assumed to choose production practices in order to maximize expected net returns over selected costs, with the historical distribution of weather conditions representing a stochastic element. Net returns were defined as the revenues from the sale of crops minus selected costs. Net returns differ from profits in that certain costs are omitted (i.e., not subtracted). In this analysis, the cost of management and overhead labor were assumed to be constant over all scenarios and were omitted. Likewise, the cost of the Base machinery complement was omitted, although additional costs (annualized) from the adoption of precision agriculture technology were subtracted where appropriate. Additionally, the model imposed a rotation constraint allowing at most 50 % of land to be allocated to corn and 50 % to soybeans, consistent with the two-year crop rotation typical for large grain farms in this region.

This two-year rotation assumption reflects observed practice at the individual farm level. In addition, the aggregate land areas in Kentucky harvested for soybean (563 000 ha in 2010) and corn for grain (498 000 ha in 2010) further support this assumption. This distribution of 53 % soybean and 47 % corn corresponds closely to the 50 % levels for each implied by a two year rotation (NASS 2011). Furthermore, yields estimated through DSSAT most closely represented those sustainable through sound crop management practices, including desirable rotations. Nonetheless, it is recognized that relaxing this rotation constraint may better reflect the short-run flexibility possible for optimal management. Sensitivity analysis was conducted by relaxing this rotation constraint to allow for 100 % corn production, as discussed later.

Output prices were taken from the median estimates from the World Agricultural Outlook Board (2013) less Kentucky's basis and hauling costs. The producer prices were

USD 0.1653 per kg for corn and USD 0.4409 per kg for soybeans. Input prices were taken from budgets developed by the University of Kentucky Cooperative Extension Service (Halich 2009).

Results and discussion

The benchmark for analysis was the use of standard production techniques (Base technology) in the absence of agro-environmental policy (no policy). Table 2 shows the economic, agronomic, and environmental outcomes from the producer's optimal production choices in this scenario. Economic results are presented in terms of net returns (in USD) to the farm. Agronomic results are represented by crop yields. Environmental results include two indicators of environmental impacts: nitrogen use and carbon emissions. Nitrogen use is the quantity of nitrogen applied as fertilizer, which was used as a proxy for harms caused by nitrogen runoff following precipitation. The change in nitrogen loading in the receiving waterway would be the best measure of nitrogen impacts. However, incorporating this measure into the analysis would require modeling of nitrogen uptake by crops, conservation practices such as the use of riparian buffers, and hydrologic transport from the field to the waterway. These factors were beyond the scope of the present analysis, but provide an opportunity for further research. To the extent that adoption of precision agriculture and changes in related production practices do not affect the proportion of nitrogen that leaches into the watershed, the nitrogen application levels can approximate the environmental impacts from nitrogen runoff. The carbon footprint includes direct emissions from the operation of farm machinery, as well as indirect emissions embodied in the production of inputs (fertilizer, herbicide, insecticide, seed, etc.). These emissions are calculated from estimates by Lal (2004) of the carbon equivalent for each of these inputs.

Several agro-environmental policy measures were then considered, which targeted the nitrogen- and carbon-related impacts. First, a quantity-based limit on each pollutant, representing a 20 % reduction in emissions from the *Base-No Policy* scenario, could be employed. Second, a tax on nitrogen use or carbon emissions could be employed. The tax rate was calibrated to achieve the same reduction in emissions as the quantity restriction, for a farm using the baseline technology. For such a farm, a tax of USD 1.72 per kilogram of nitrogen would lead to a 20.2 % reduction in nitrogen use relative to the *Base-No Policy* level. Similarly, a tax of USD 0.64 per kilogram of carbon equivalents would reduce carbon footprint by 23.6 % in comparison to the *Base-No Policy* level. Due to the discrete, stepwise nature of linear programming solutions, the tax policies were unable to induce an exact 20 % decrease in the targeted emissions, so the tax levels that came closest were selected for comparison.

The introduction of agro-environmental policy reduced net returns with the Base technology, and the tax policies reduced net returns more substantially than did the corresponding quantity-based limits. Under a quantity-based limit, the producer incurred abatement costs in the form of forgone profits. Under a tax policy, the producer both incurred that abatement cost and paid the tax for each remaining unit of the pollutant. With a carbon tax, the greenhouse gas emissions embodied in inputs would be reflected in higher input prices, rather than in a tax levied directly on the farmer, but the effect on net returns would be equivalent.

Agro-environmental policy also affected the corn yields of the farm. Both the nitrogen and the carbon policies reduced nitrogen use and thus corn yields, since nitrogen fertilizer

Table 2 Economic, agronomic, and environmental impacts of alternative agro-environmental policies under base (no precision agriculture) technology

Outcome	Policy				
	No policy	Nitrogen limit	Nitrogen tax	Carbon limit	Carbon tax
Net return (USD)	563 458	556 738	517 904	547 909	458 946
% of base-no policy	100.0	98.8	91.9	97.2	81.5
Nitrogen use (kg)	79 742.2	63 793.7	63 647.9	53 019.5	48 166.0
% of base-no policy	100.0	80.0	79.8	66.5	60.4
Carbon emissions (kg)	173 866.1	153 135.6	152 946.0	139 092.9	132 784.2
% of base-no policy	100.0	88.1	88.0	80.0	76.4
Corn yield (kg/ha)	10 371.7	10 098.0	10 095.5	9 849.5	9 739.0
% of base-no policy	100.0	97.4	97.3	95.0	93.9
Soybean yield (kg/ha)	4 185.0	4 185.0	4 185.0	4 185.0	4 185.0
% of base-no policy	100.0	100.0	100.0	100.0	100.0

is a substantial contributor to the carbon footprint of the farm. Other input choices were unaffected by the introduction of policy, as were soybean yields.

The effects of adopting precision agriculture technologies

The producer's optimal choices in response to the introduction of the various precision agriculture technologies were determined for each policy scenario. Table 3 presents the key economic, agronomic, and environmental results for the adoption of RTK auto-steer technology for the tractor. Tables 4, 5, and 6 present the corresponding results for variable rate application of nitrogen, automatic section control on the self-propelled sprayer, and the combination of all three precision agriculture technologies, respectively. Table 7 shows the usage of selected inputs across these technology and policy scenarios. The level of each input—herbicide and insecticide, fuel for tractor and self-propelled sprayer, and seed—for each scenario is presented as a percentage of the amount of that input used in the *Base-No Policy* scenario.

Precision agriculture improved the net returns of the farm in the *No-Policy* scenario. Expected net returns increased by 0.3 % with RTK auto-steer, by 0.9 % with VRA, and by 0.8 % for ASC (Tables 3, 4, and 5). With the combination of technologies, expected returns increased by 2.9 % (Table 6). Precision agriculture also affected the agronomic results. Corn yields increased by 0.8–1.8 % with the adoption of RTK auto-steer, variable rate application of nitrogen, and the combination of technologies, while yields remained constant with the adoption of automatic section control (Tables 3, 4, 5, 6).

Even in the absence of agro-environmental policy, the adoption of precision agriculture technology affected the farm's environmental impacts. Use of RTK auto-steer increased both nitrogen use and carbon footprint, by 7.2 and 3.3 %, respectively (Table 3). The increase in carbon footprint is due to increased use of nitrogen fertilizer, as other input amounts remained constant or decreased (Table 7). This illustrates the so-called "rebound effect," in which more efficient use of a resource (e.g., nitrogen) increases consumption of that resource by lowering the effective cost of obtaining the benefit (e.g., higher crop yield) that it provides. Variable-rate nitrogen application (Table 4) also increased both environmental impacts, by 1.1 % for nitrogen and 0.7 % for carbon footprint (via increased

Table 3 Economic, agronomic, and environmental impacts of alternative agro-environmental policies under RTK auto-steer technology

	Policy				
Outcome	No policy	Nitrogen limit	Nitrogen tax	Carbon limit	Carbon tax
Net return (USD)	565 207	559 047	520 385	551 288	462 465
% of base-no policy	100.3	99.2	92.4	97.8	82.1
Nitrogen use (kg)	85 505.9	63 793.7	69 843.4	54 335.7	62 224.8
% of base-no policy	107.2	80.0	87.6	68.1	78.0
Carbon footprint (kg)	179 609.4	151 386.9	159 250.5	139 092.9	149 347.5
% of base-no policy	103.3	87.1	91.6	80.0	85.9
Corn yield (kg/ha)	10 453.9	10 126.9	10 249.3	9 912.2	10 095.5
% of base-no policy	100.8	97.6	98.8	95.6	97.3
Soybean yield (kg/ha)	4 185.0	4 185.0	4 185.0	4 185.0	4 185.0
% of base-no policy	100.0	100.0	100.0	100.0	100.0

Table 4 Economic, agronomic, and environmental impacts of alternative agro-environmental policies under variable rate application (nitrogen) technology

	Policy				
Outcome	No policy	Nitrogen limit	Nitrogen tax	Carbon limit	Carbon tax
Net return (USD)	568 737	561 091	523 366	544 766	463 780
% of base-no policy	100.9	99.6	92.9	96.7	82.3
Nitrogen use (kg)	80 643.5	63 793.7	66 688.9	52 990.4	65 487.3
% of base-no policy	101.1	80.0	83.6	66.5	82.1
Carbon footprint (kg)	175 037.9	153 135.6	156 898.8	139 092.9	155 337.0
% of base-no policy	100.7	88.1	90.2	80.0	89.3
Corn yield (kg/ha)	10 561.3	10 268.1	10 340.9	9 920.4	10 316.5
% of base-no policy	101.8	99.0	99.7	95.6	99.5
Soybean yield (kg/ha)	4 185.0	4 185.0	4 185.0	4 185.0	4 185.0
% of base-no policy	100.0	100.0	100.0	100.0	100.0

nitrogen use). Although VRA can be expected to reduce the quantity of nitrogen necessary to achieve a given yield, it also opens up the possibility that a heavier average application could be used to increase yields and net returns, as was the case in this simulation. Use of automatic section control (Table 5) did not affect nitrogen use but did reduce carbon footprint by 1.7 % through reductions in herbicide, insecticide, and sprayer fuel (Table 7). Although ASC increases efficiency of input use, it does not suffer the rebound effect because the desired levels of insecticide and pesticide application are constant in this model. If these amounts were variable, some rebound effect might occur to offset the more efficient application of those inputs.

Interestingly, the combination of all three precision agriculture technologies (Table 6) reduced nitrogen use by 1.1 %, even though nitrogen use either increased or remained constant for each technology individually. Similarly, the combination decreased carbon footprint by 3.4 %, even though the sum of the individual technology effects was a 2.3 %

Table 5 Economic, agronomic, and environmental impacts of alternative agro-environmental policies under automatic section control technology

	Policy				
Outcome	No policy	Nitrogen limit	Nitrogen tax	Carbon limit	Carbon tax
Net return (USD)	568 004	561 284	522 451	554 328	465 391
% of base-no policy	100.8	99.6	92.7	98.4	82.6
Nitrogen use (kg)	79 742.2	63 793.7	63 647.9	55 301.8	48 166.0
% of base-no policy	100.0	80.0	79.8	69.4	60.4
Carbon footprint (kg)	170 899.4	150 168.9	149 979.2	139 092.9	129 817.5
% of base-no policy	98.3	86.4	86.3	80.0	74.7
Corn yield (kg/ha)	10 371.7	10 098.0	10 095.5	9 900.9	9 739.0
% of base-no policy	100.0	97.4	97.3	95.5	93.9
Soybean yield (kg/ha)	4 185.0	4 185.0	4 185.0	4 185.0	4 185.0
% of base-no policy	100.0	100.0	100.0	100.0	100.0

Table 6 Economic, agronomic, and environmental impacts of alternative agro-environmental policies under combination of precision agriculture technologies

	Policy				
Outcome	No policy	Nitrogen limit	Nitrogen tax	Carbon limit	Carbon tax
Net return (USD)	579 878	573 777	535 171	563 874	478 893
% of base-no policy	102.9	101.8	95.0	100.1	85.0
Nitrogen use (kg)	78 840.4	63 793.7	65 197.8	56 618.1	64 023.1
% of base-no policy	98.9	80.0	81.8	71.0	80.3
Carbon footprint (kg)	167 978.7	148 420.2	150 245.2	139 092.9	148 718.3
% of base-no policy	96.6	85.4	86.4	80.0	85.5
Corn yield (kg/ha)	10 561.3	10 310.2	10 340.9	10 091.8	10 316.5
% of base-no policy	101.8	99.4	99.7	97.3	99.5
Soybean yield (kg/ha)	4 185.0	4 185.0	4 185.0	4 185.0	4 185.0
% of base-no policy	100.0	100.0	100.0	100.0	100.0

increase. Interaction effects among the precision agriculture technologies allow for a greater scope to reduce environmental impacts while also increasing net returns. Overall, these results suggest that adoption of precision agriculture technology will not always result in a clear improvement with regard to a farm's environmental impacts. The net impact depends on the specific technology or combination of technologies, as well as the market situation faced by the farm.

Technology-policy interactions

The modeling results allowed analysis of how policies calibrated for farms using traditional production practices (Base technology scenario) affected the choices and outcomes for farms that had adopted precision agriculture methods. Tables 8, 9, and 10 summarize the effects on net returns, nitrogen use, and carbon footprint, respectively, of the possible

Table 7 Relative farm-level input usage results (% of *Base-No Policy*)

		No policy	Nitrogen limit	Nitrogen tax	Carbon limit	Carbon tax
Nitrogen	Base	100.0	80.0	79.8	66.5	60.4
	RTK	107.2	80.0	87.6	68.1	78.0
	VRA	101.1	80.0	83.6	66.5	82.1
	ASC	100.0	80.0	79.8	69.4	60.4
	All	98.9	80.0	81.8	71.0	80.3
Herbicide/insecticide	Base	100.0	100.0	100.0	100.0	100.0
	RTK	100.0	100.0	100.0	100.0	100.0
	VRA	100.0	100.0	100.0	100.0	100.0
	ASC	89.5	89.5	89.5	89.5	89.5
	All	89.5	89.5	89.5	89.5	89.5
Sprayer fuel	Base	100.0	100.0	100.0	100.0	100.0
	RTK	100.0	100.0	100.0	100.0	100.0
	VRA	100.0	100.0	100.0	100.0	100.0
	ASC	84.4	84.4	84.4	84.4	84.4
	All	84.4	84.4	84.4	84.4	84.4
Tractor fuel	Base	100.0	100.0	100.0	100.0	100.0
	RTK	89.6	89.6	89.6	89.6	89.6
	VRA	100.0	100.0	100.0	100.0	100.0
	ASC	100.0	100.0	100.0	100.0	100.0
	All	89.6	89.6	89.6	89.6	89.6
Seed	Base	100.0	100.0	100.0	99.8	99.8
	RTK	97.6	97.6	97.6	97.6	97.6
	VRA	100.0	100.0	100.0	100.0	100.0
	ASC	100.0	100.0	100.0	99.8	99.8
	All	97.6	97.6	97.6	97.6	97.6

combinations of precision agriculture technology and agro-environmental policy. The results are presented as percentage changes from the levels in the *Base-No Policy* scenario. To facilitate analysis, the effects are decomposed into three elements. First, the *policy main effects* were calculated as the percentage changes in the relevant measure (net returns, nitrogen use, or carbon footprint) from the *Base-No Policy* scenario to the combination of Base technology with each of the potential nitrogen and carbon policies. Second, the *technology main effects* were calculated as the changes in the relevant measure from the *Base-No Policy* scenario due to the adoption of each precision agriculture technology in the absence of policy. Finally, the *interaction effect* is the remainder for a given technology-policy combination after the policy and technology main effects are subtracted from the difference between the *Base-No Policy* result and the gross result for that policy-technology combination. For example, with the combination of variable rate application and the nitrogen tax (*VRA-Nitrogen Tax*), nitrogen use is 16.4 % lower than in the *Base-No Policy* scenario (Table 4). The policy main effect is a 20.2 % decrease (*Base-Nitrogen Tax* vs. *Base-No Policy*, Table 2) and the technology main effect is a 1.1 % increase (*VRA-No Policy* vs. *Base No-Policy*, Table 4). The interaction effect for *VRA-Nitrogen Tax* is thus –16.4 % – (–20.2 %) – 1.1 % = 2.7 %.

The results suggest that the adoption of precision agriculture technology did alter the effectiveness of policies in achieving environmental objectives. Moreover, the difference in policy effectiveness varied with the type of technology adopted. The adoption of RTK auto-steer and variable rate application of nitrogen both follow the same pattern: the nitrogen (Table 9) and carbon taxes (Table 10) were less effective in reducing environmental impacts than were the corresponding quantity-based limits. The technology main effects for RTK and VRA were positive, meaning that adoption of these technologies increased emissions in the absence of policy, as discussed above. With the limit policies, the interaction effects were negative and exactly offset the technology main effects for the targeted pollutant, because the gross environmental impact was constrained to equal the targeted 20 % reduction from the *Base-No Policy* level. These negative interaction effects suggest that the limit policies were in some ways more effective with these technologies, because they reduced the targeted environmental impacts by more than was achieved by the policy alone in the Base technology, when measured from the *No Policy* levels for those technologies. For the tax policies, the interaction effects were positive, meaning that environmental impacts were higher than under those policies with Base technology, even accounting for the increased impacts due to the technology alone. This result suggests that the adoption of those precision agriculture technologies reduced the effectiveness of these policies in reducing environmental impacts. By increasing the marginal returns from nitrogen application (i.e., additional net returns per kg of nitrogen), these two technologies increased the marginal abatement costs of the farm, so that tax-based policy became less effective in reducing nitrogen use. Marginal abatement cost refers to the additional cost of reducing emissions (e.g., nitrogen) by one unit, including both direct costs and opportunity costs such as reduced net returns. In the case of carbon footprint, adoption of RTK auto-steer did reduce the use of some inputs (tractor fuel, seed), decreasing the associated carbon equivalents, but not by enough to completely offset the increase in nitrogen use.

In contrast, adoption of automatic section control did not substantially change the relative effectiveness of the tax policies. For nitrogen use, the technology main effect and both policy interaction effects were zero for ASC. This means that the nitrogen levels under ASC were identical to those under Base technology, for either nitrogen policy and in the absence of policy. The efficiency gains with the self-propelled sprayer had no impact on nitrogen use. For carbon footprint, the technology main effect for ASC was negative, reflecting those efficiency gains with certain inputs: herbicide, insecticide, and sprayer fuel (Table 7). Under a carbon limit, the interaction effect was negative and exactly offset the technology main effect. Because of the efficiency improvements with the sprayer, the farmer did not need to reduce nitrogen use by as much with ASC as he or she would have under Base technology in order to comply with the carbon limit. Thus, the carbon limit was rendered less effective with the adoption of ASC. In contrast, the interaction effect for the carbon tax was zero, meaning that the tax induced the same reductions in carbon footprint with ASC as with Base technology, although the gross reduction was greater for ASC due to efficiency gains even the absence of policy. In essence, the carbon tax induced the same abatement for both technologies because the marginal abatement cost functions are identical.

With the adoption of all three technologies in combination, the tax policies were less effective than were the limit policies in reducing environmental impacts. The main technology main effects were positive for both environmental impacts, meaning that the combination of all three precision agriculture technologies lowered environmental impacts in the absence of policy. This result contrasts with the higher impacts associated with the adoption of RTK and VRA, and the mixed impacts of ASC (neutral for nitrogen use and lower carbon footprint), indicating that interaction among the technologies allows for

Table 8 Main and interactive effects of technology and policy (% of *Base-No Policy* net revenue) on net return

	Technology main effect[b]	Policy			
		Nitrogen limit	Nitrogen tax	Carbon limit	Carbon tax
Policy main effect[a]		–1.2	–8.1	–2.8	–18.5
Technology					
RTK	0.3	0.1	0.1	0.3	0.3
VRA	0.9	–0.2	0.0	–1.5	–0.1
ASC	0.8	0.0	0.0	0.3	0.3
Combination	2.9	0.1	0.2	–0.1	0.6

[a] The policy main effect is calculated as the percentage change in net return from *No Policy* to the specified policy (e.g., *Nitrogen limit*), under *Base* technology

[b] The technology main effect is calculated as the percentage change in net return from *Base* technology to the specified technology (e.g., *RTK*), under *No Policy*

Table 9 Main and interactive effects of technology and policy (% of *Base-No Policy* nitrogen use) on nitrogen use

	Technology main effect[b]	Policy			
		Nitrogen limit	Nitrogen tax	Carbon limit	Carbon tax
Policy main effect[a]		–20.0	–20.2	–33.5	–39.6
Technology					
RTK	7.2	–7.2	0.5	–5.6	10.4
VRA	1.1	–1.1	2.7	–1.2	20.6
ASC	0.0	0.0	0.0	2.9	0.0
Combination	–1.1	1.1	3.1	5.6	21.0

[a] The policy main effect is calculated as the percentage change in nitrogen use from *No Policy* to the specified policy (e.g., *Nitrogen limit*), under *Base* technology

[b] The technology main effect is calculated as the percentage change in nitrogen use from *Base* technology to the specified technology (e.g., *RTK*), under *No Policy*

better environmental performance than do the technologies in isolation. The interaction effects for the limit policies were positive and exactly offset the technology main effects, meaning that the farmer needed less reduction in nitrogen with the combined technologies than he did with Base technology, in order to meet the limits. Thus, the effectiveness of the limit policy was reduced with the combined technology. The interaction effects for the tax policies were positive, and even greater in absolute magnitude than the technology main effects. Thus, the combined technology reduced the effectiveness of the tax policies, leading to higher levels of nitrogen use and carbon footprint, despite the efficiencies reflected in the technology main effects.

Sensitivity analysis

Tables 11, 12, and 13 present the results of sensitivity analysis. Three variations of the analysis were conducted. In the *High Price* variation, the price of corn was 25 % higher than

Table 10 Main and interactive effects of technology and policy (% of *Base-No Policy* carbon footprint) on carbon footprint

	Technology main effect[b]	Policy			
		Nitrogen limit	Nitrogen tax	Carbon limit	Carbon tax
Policy main effect[a]		–11.9	–12.0	–20.0	–23.6
Technology					
RTK	3.3	–4.3	0.3	–3.3	6.2
VRA	0.7	–0.7	1.6	–0.7	12.3
ASC	–1.7	0.0	0.0	1.7	0.0
Combination	–3.4	0.7	1.8	3.4	12.6

[a] The policy main effect is calculated as the percentage change in carbon footprint from *No Policy* to the specified policy (e.g., *Nitrogen limit*), under *Base* technology

[b] The technology main effect is calculated as the percentage change in carbon footprint from *Base* technology to the specified technology (e.g., *RTK*), under *No Policy*

Table 11 Sensitivity analysis results of a higher (+25 %) corn price (% of *Base-No Policy*)

Technology	Measure	No policy	Nitrogen limit	Nitrogen tax	Carbon limit	Carbon tax
Base	Net return	100.0	99.3	93.9	97.9	82.9
	Nitrogen use	100.0	80.0	78.0	68.2	69.4
	Carbon footprint	100.0	87.4	86.1	80.0	80.8
RTK	Net return	100.2	99.6	94.3	98.5	83.4
	Nitrogen use	97.8	80.0	84.8	69.7	76.2
	Carbon footprint	97.7	86.5	89.5	80.0	84.1
VRA	Net return	100.9	100.4	95.1	98.8	84.0
	Nitrogen use	91.2	80.0	78.9	68.2	72.8
	Carbon footprint	94.5	87.4	86.7	80.0	82.9
ASC	Net return	100.6	99.9	94.5	98.9	83.8
	Nitrogen use	100.0	80.0	78.0	70.7	69.4
	Carbon footprint	98.4	85.8	84.6	80.0	79.2
Combined	Net return	102.4	102.0	96.6	101.2	86.1
	Nitrogen use	94.1	80.0	79.7	72.2	71.1
	Carbon footprint	93.8	84.9	84.7	80.0	79.4

in the main simulation. In the *Low Price* variation, corn price was 25 % lower. In the *Continuous Corn* variation, the rotation constraint was changed to reflect a farm growing all corn and no soybeans. Table 11 reports net returns, nitrogen use, and carbon footprint for each policy-technology combination in the *High Price* variation. The amounts are expressed as a percentage of the *Base-No Policy* amount for that variation. Tables 12 and 13 report the corresponding results for the *Low Price* and *Continuous Corn* variations, respectively.

Sensitivity analysis supports the general patterns observed in the main analysis, although some variations can be seen. Net returns were reduced by implementation of the policies, although this effect was most pronounced in the *Continuous Corn* variation. The largest operational change in response to policy was to limit nitrogen use, which had more effect on net returns with a larger proportion of corn.

Table 12 Sensitivity analysis results of a lower (−25 %) corn price (% of *Base-No Policy*)

Technology	Measure	No policy	Nitrogen limit	Nitrogen tax	Carbon limit	Carbon tax
Base	Net return	100.0	99.0	93.1	97.7	87.8
	Nitrogen use	100.0	80.0	67.4	66.7	67.4
	Carbon footprint	100.0	88.2	81.0	80.0	81.0
RTK	Net return	100.4	99.4	93.5	98.4	88.4
	Nitrogen use	97.8	80.0	87.1	67.5	87.1
	Carbon footprint	97.7	87.1	91.2	80.0	91.2
VRA	Net return	100.3	98.4	93.2	95.5	87.8
	Nitrogen use	101.3	80.0	91.7	66.7	91.7
	Carbon footprint	101.4	88.7	95.9	80.0	95.9
ASC	Net return	101.2	100.2	94.3	99.4	89.3
	Nitrogen use	100.0	80.0	67.4	68.9	67.4
	Carbon footprint	98.2	86.4	79.2	80.0	79.2
Combined	Net return	103.3	101.6	96.3	99.7	91.3
	Nitrogen use	102.2	80.0	89.6	70.4	89.6
	Carbon footprint	99.0	86.0	91.8	80.0	91.8

Table 13 Sensitivity analysis results of a continuous corn rotation (% of *Base-No Policy*)

Technology	Measure	No policy	Nitrogen limit	Nitrogen tax	Carbon limit	Carbon tax
Base	Net return	100.0	95.9	64.2	92.4	39.3
	Nitrogen use	100.0	80.0	80.4	72.7	69.5
	Carbon footprint	100.0	85.4	85.6	80.0	77.7
RTK	Net return	101.8	98.2	66.5	95.3	42.3
	Nitrogen use	102.0	80.0	80.7	73.8	78.6
	Carbon footprint	100.6	84.5	85.0	80.0	83.5
VRA	Net return	105.9	101.9	70.5	96.9	45.5
	Nitrogen use	94.6	80.0	82.3	72.9	81.4
	Carbon footprint	95.9	85.2	86.9	80.0	86.2
ASC	Net return	101.6	97.5	65.8	94.6	41.6
	Nitrogen use	100.0	80.0	80.4	74.0	69.5
	Carbon footprint	99.0	84.4	84.6	80.0	76.7
Combined	Net return	110.8	107.6	76.0	104.6	52.3
	Nitrogen use	92.8	80.0	80.5	75.4	79.5
	Carbon footprint	93.0	83.4	83.8	80.0	83.1

The environmental impacts of adopting precision agriculture in the *No-Policy* scenario remained mixed in the sensitivity analysis. In some variations, the adoption of RTK and VRA reduced nitrogen use and carbon footprint in the absence of policy, rather than increasing those impacts as in the main analysis. The patterns for ASC adoption in the absence of policy were very similar to those seen in the main analysis. Results from adopting all three technologies were similar to those of the individual technologies, although interaction effects were also present.

With regard to the interaction of precision technology and agro-environmental policy, the sensitivity analysis suggested the same dominant trend: adoption of PA technology decreased the relative effectiveness of the tax policies in reducing environmental impacts. In all cases, the nitrogen tax resulted in higher nitrogen use with any of the PA technologies than with Base technology. With the carbon tax, carbon footprint was higher for RTK and VRA than for the Base technology. With the carbon tax and ASC (and with the combination of technologies, in some cases), carbon footprint was less than with Base technology; however, this results from the higher input efficiency gained with ASC regardless of policy, rather than from a larger reduction induced by the tax.

Conclusion

Precision agriculture methods have been increasingly adopted by producers, in response to both higher profit potential and numerous policies (e.g., cost-share programs). Once adopted, this technology in turn affects the framework of costs and benefits surrounding production decisions. The changes in this framework will alter the effectiveness of agro-environmental policies—particularly those that rely on taxes, subsidies, cost-share programs, and similar financial incentives—in changing producer behavior to reduce environmental impacts. Policy failure can occur when such policy is designed for traditional production methods and fails to allow for the changes in abatement costs associated with adoption of precision agriculture methods. Although incentive-based policies are often desirable for pursuing economic efficiency and cost-effectiveness when pollution sources have heterogeneous abatement costs, policies designed without information about the technology mix used by farms may be limited in their effectiveness in reaching environmental goals. Quantity-based policies (e.g., quotas) may be more robust to technological change or uncertainty in terms of achieving targeted environmental improvements.

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