

Effect of field geometry on profitability of automatic section control for chemical application equipment

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Abstract Understanding how field geometry is related to over-application of inputs may help farmers make more informed decisions about investment in automatic section control (ASC) technology. The technology helps reduce input application overlap and therefore reduces input costs. The influence of field geometry on the profitability of ASC technology for chemical application was evaluated using overlap data estimated for 44 farm fields in Tennessee, USA. Reduction in overlap with ASC was defined as the difference in area sprayed controlling the entire boom as one section and area sprayed using seven-section ASC. Perimeter (m)-to-area (m^2) ratio (P/A , m^{-1}) was used to categorize estimated chemical overlap by field size and shape. Estimated median reductions in overlap with ASC were 3.00 % for fields with $P/A = 0.01$, 9.65 % for fields with $P/A = 0.02$ and 13.50 % for fields with $P/A \geq 0.03$. For a typical size cotton farm in Tennessee, investing in ASC was not likely to be profitable for fields with $P/A = 0.01$ but was generally profitable for fields with $P/A \geq 0.02$. The low reduction in overlap for $P/A = 0.01$ with ASC resulted in chemical savings that were too small to pay back the investment in ASC within the useful life assumed for the technology and provide a minimum rate of return. Thus, P/A as a measure of field geometry may be useful for evaluating investments in ASC technologies.

Keywords Chemical application · Economic analysis · Precision spraying

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Introduction

Rising seed, fertilizer and chemical costs in crop production give farmers an additional incentive to use precision agriculture (PA) technologies that improve the efficiency of input application. The National Research Council (1997, p. 17) defines PA as “a management strategy that uses information technologies to bring data from multiple sources to bear on decisions associated with crop production.” These technologies have the potential to improve farm profitability by increasing yields and lowering input costs. PA also has the potential to reduce the negative environmental impacts of crop production through more efficient application of crop inputs.

An example of input application inefficiency is when an input applicator overlaps an area of the field that has already received inputs. Over-application of fertilizer and chemicals increases production costs, may reduce yields and could increase the risk of fertilizer and chemicals moving into surface and ground water sources (Shockley et al. 2012). With increasing adoption of no-till crop production, the problem of over-application of chemical inputs is magnified given that a larger amount of herbicides is applied to substitute for tillage (Luck et al. 2010a). Overlap in input application seems to be affected by field size, field shape and obstructions within fields (Luck et al. 2010a, 2011). Smaller and more irregularly shaped fields result in greater overlapping applications of seed, fertilizer and chemicals during turns at headlands, from infringement in point and end rows and from steering around obstacles within a field (Shockley et al. 2012). Overlap during the application of inputs is also influenced by implement width, direction of the field work tracks and equipment operator accuracy (Velandia et al. 2013).

The PA technology called automatic section control (ASC) automatically turns off sections, nozzles or rows on implements in areas of the field that have already received an application (Shockley et al. 2012). The technology uses the current GNSS co-ordinates of the applicator and a map of previously applied area to regulate individual sections, nozzles or rows on the implement. Research has indicated that the profitability of ASC from reduced input over-application on farm fields is influenced by factors such as the width of the applicator, the value of the inputs saved per unit of land farmed, the size and shape of fields, the presence of field obstructions (e.g. waterways) and the size of the farm operation over which to spread initial investment costs of the technology (Batte and Ehsani 2006; Shockley et al. 2012; Smith et al. 2013; Velandia et al. 2013). However, prior economic analyses have not explicitly correlated measures of field geometry (e.g. field shape and size) to overlap and the corresponding profitability of ASC from reduced input over-application (e.g. Batte and Ehsani 2006; Shockley et al. 2012; Smith et al. 2013; Velandia et al. 2013).

A better understanding of how field geometry is related to over-application of inputs and the subsequent profitability of ASC may help farmers make more informed decisions about investing in this technology. Specifically, associating a measure of field geometry with the profitability of ASC may simplify the decision-making process. This information would be especially useful to producers of high-value, high-input crops, such as cotton, in the rolling uplands region of the Mid-South United States where farm fields tend to be smaller and more irregularly shaped than farm fields in the Mid-West region of the United States (Velandia et al. 2013). Cotton growers make extensive use of costly chemical inputs such as herbicides, insecticides, plant growth regulators and harvest aids. U.S. cotton farmers in 2013 spent \$173 ha⁻¹ on chemicals, more than double the \$71 ha⁻¹ spent on chemicals by corn producers (USDA-ERS 2014). PA technologies have great potential for managing

chemical applications in cotton production. Reducing input levels through more efficient input use was identified by cotton growers as an important consideration in their decision to adopt PA technologies (Torbett et al. 2007, 2008). The overall objective of this research was to evaluate the profitability of ASC for chemical application considering the size and shape of farm fields using data from fields in middle and west Tennessee, USA. The specific research objectives were: (1) to evaluate the relationship between chemical over application and field geometry, (2) to assess the potential chemical cost savings with ASC as influenced by field geometry for a cotton farm in Tennessee and (3) to appraise the profitability of ASC as affected by field geometry for a cotton farm in Tennessee.

Review of literature

Analysis of the profitability of precision spray technologies has focused on variable rate weed control in soybean and corn production (Oriade et al. 1996), variable rate pre-emergence weed control in wheat production (Bennett and Pannell 1998; Young et al. 2003) and guidance and ASC for chemical applicators (Batte and Ehsani 2006; Shockley et al. 2012; Smith et al. 2013). Batte and Ehsani (2006) evaluated the profitability of ASC technology for sprayers using Real-Time Kinematic (RTK) guidance. They evaluated ASC for hypothetical fields of the same size (40.57 ha) shaped either as a rectangle, a parallelogram or a trapezoid and with and without two grass waterways traversing the fields at 45° and 60° angles. They found that the value of chemical inputs saved per unit of farmed area, fuel and operator time cost savings with ASC and guidance was greater in non-rectangular fields with waterways and for applicators with larger boom sizes because of the greater potential for chemical application overlap. Depending on boom length, they estimated that a farm size of between 486 ha and 729 ha was needed to justify an investment in ASC for sprayers. They also found that ASC was more profitable for larger farms because of the ability to spread the fixed costs of investment in ASC technology for applicators over more crop area.

Shockley et al. (2012) evaluated the profitability of ASC technology coupled with guidance for planting and spraying operations on an 850 ha representative corn and soybean farm in Kentucky, USA. They used data from four farm fields representing a spectrum of field sizes and shapes to evaluate the profitability of ASC for a self-propelled chemical applicator with a 24 m boom and a 16 row planter that was 12 m wide. They estimated overlap for the fields using the Field Coverage Analysis Tool (FieldCAT) (Zandonadi et al. 2011). They found that overlapped area as a percentage of total field area was larger for the two more irregularly shaped and smaller field sizes. Thus, the estimated input savings were the greatest on the two smallest fields. They also stated that field shape was less important in determining the profitability of ASC for the two largest fields, but did not explicitly evaluate the relationship between field geometry and profitability of ASC.

Smith et al. (2013) evaluated the profitability of guidance systems and ASC technology for sprayers in Colorado, Kansas and Nebraska, USA. Forty high school students collected data from fields that were representative of their farm operation as part of a course project. Field parameters describing field size and shape were collected from 553 fields in the study area. Field parameters estimated using the Farm Works Mapping program (Farm Works Information Management, Hamilton, IN, USA) were field size, maximum field width perpendicular to the field works tracks and the running distance of headlands to cover the field. Data for each field was assigned to the USDA Crop Reporting District that it

originated from and was used to estimate an area-weighted representative field for each Crop Reporting District. They found that the profitability of ASC varied by Crop Reporting District depending on the size and shape of the representative field in the district with higher profitability in districts with smaller more irregularly shaped fields.

The aforementioned economic studies provide valuable insights into how the profitability of ASC technology is affected by the amount of input savings, field shape and size and the size of the farm operation. However, these analyses did not explicitly use measures of field geometry (e.g. perimeter-to-area ratio) and its correlation with input application overlap to evaluate the profitability of investing in ASC technology. In an analysis of the profitability of ASC for planters in Tennessee, USA, Velandia et al. (2013) grouped farm fields based on double-planted area as a percentage of total planted area. However, they also did not explicitly present any measure of field geometry or its association with profitability of ASC on planters.

Luck et al. (2011) and Jernigan (2012) evaluated the relationship between input application overlap and different measures of field geometry. Luck et al. (2011) used single and multiple explanatory variable regression models to predict chemical application overlap for three boom section control system scenarios based on six field geometry measures for 74 fields in Kentucky, USA. Single factor explanatory variable regressions were analyzed comparing each geometry measure to overlap for each applicator configuration. Perimeter (m)-to-area (m^2) ratio ($P/A, \text{m}^{-1}$) was found to be the best predictor of overlap with R^2 (correlation) values of 0.57 (0.75), 0.65 (0.80) and 0.59 (0.77) for five-section manual section control, seven-section ASC and nine-section ASC, respectively. Multiple regressions comparing linear combinations of the six field geometry measures of overlap for each applicator boom configuration showed that no combination of explanatory variables greatly improved model goodness of fit when compared to the single explanatory variable model using only P/A . Jernigan (2012) evaluated the relationship between planter overlap and 22 field geometry measures including P/A using data from 52 fields in Tennessee, USA. Variable selection and Principal Component Analysis were conducted to develop best fit models for predicting double-planted area and validated using single and multiple explanatory variable linear regressions. Similar to Luck et al. (2011), he found that P/A was consistently the strongest predictor of overlapped area.

The review of literature indicates that prior economic research has not explicitly evaluated the effects of field geometry on the profitability of using ASC to reduce overlapping applications of inputs in farm fields. The present study aims to fill that gap in the literature through a profitability analysis using field geometry and overlap data from farm fields in middle and west Tennessee that have different sizes and shapes. Based on the results of Luck et al. (2011) and Jernigan (2012), P/A was the measure of field geometry used in this study to evaluate the effects of field size and shape on the profitability of investment in ASC technology for chemical applicators.

Data and methods

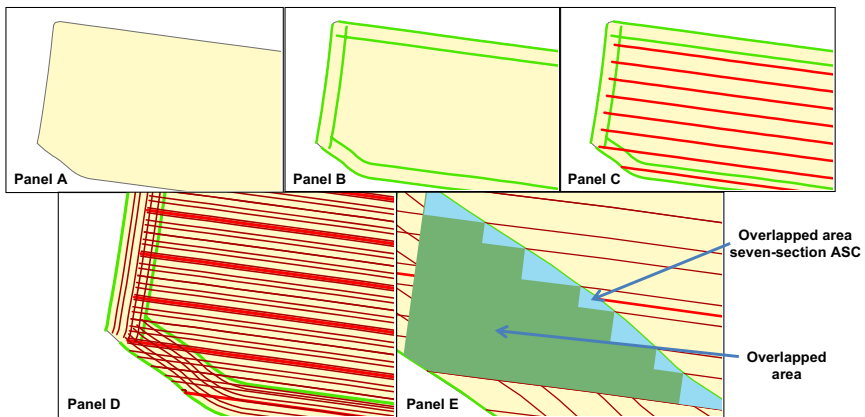
Chemical application overlap data

The sample of fields for the chemical application overlap analysis was from a study of the profitability of ASC for planters on farm fields in middle and west Tennessee (Velandia et al. 2013). Field information used for the current analysis included field size and path

orientation. Path orientation was defined by the farmer for each field in the sample. The longest path was the most common orientation path used by farmers. Although direction of the implement path orientation has an impact on overlap, there is a tradeoff between the effect of path orientation on overlap and the machine field efficiency defined as the time required to complete a field operation (Velandia et al. 2013). Thus, it was assumed that the chemical applicator path orientation was that determined by the farmer.

The manual procedure described by Velandia et al. (2013) was used to calculate chemical application overlap for each field in the sample. The procedure is similar to the algorithm used in FieldCAT (Zandonadi et al. 2011) to estimate overlap. An advantage of this manual procedure is that the exact angle of the path orientation for each application pass can be replicated which is sometimes difficult to replicate with FieldCAT, especially in fields with irregular shapes where operators deviate from the desired path on headlands, through curves and near end rows. The manual procedure used the tractor path defined by the producer, which in most of the fields was the longest path as described previously. In contrast, FieldCAT path orientation is defined by the user who specifies an angle that determines the orientation. Changes of one or two degrees in the specified angle may change overlap area by 2 % or more. The applicator modeled in the analysis had a 27.4 m wide boom with seven respective sections of 4.6, 3.0, 4.6, 3.0, 4.6, 3.0 and 4.6 m. Reduction in overlapped area was defined as the difference in area that was over-sprayed when controlling the entire boom as one section (i.e. no ASC), which is a typical option on applicators (Luck et al. 2010b), and area over-sprayed with seven-section ASC. Luck et al. (2010a, p. 686) observed that manual section control was essentially the same as controlling the entire boom as one section because the applicator operator in their field study had little time “to actuate individual sections while steering and throttling down to make turns” due to the speed of the applicator.

The procedure used to estimate overlap is illustrated in Fig. 1. Shapefiles containing field boundaries for each pass of a planter were imported into ArcGIS [ArcGIS v9.3, ESRI



Panel A: Imported shape file with field boundary
Panel B: Creation of headland boundary for the chemical applicator
Panel C: Creation of boom applicator field pass centerlines
Panel D: Creation of boom ASC seven-section boundary lines (enlarged view to show detail)
Panel E: Creation of polygons representing overlapped area in the field (enlarged view to show detail).

Fig. 1 Step-by-step procedure to manually estimate reduction in overlap for seven-section automatic section control (ASC) on a 27.4 m boom chemical applicator

(Redlands, CA, USA)]. A trace of the field boundary was made to represent the field area and the outer edge of the head row using new polyline shapes (Fig. 1, Panel A). The field boundary area was used to calculate total field area sprayed (ha) and perimeter of sprayed area (m) for each field. The perimeter of the sprayed area (m) was divided by the sprayed area (m^2) to estimate P/A (m^{-1}). To complete the head row, the copy parallel feature in ArcMAP was used to make an applicator head row 22.9 m wide (Fig. 1, Panel B). The head row width assumes that a farmer would make the applicator head row as wide as the planter head row. Once the head row was completed, a length of half the width of the chemical applicator, 13.7 m, was measured from the inside of the head row to create a new polyline shapefile defining the chemical applicator center line. This new line became an applicator center line. The rest of the applicator center lines were created using the copy parallel feature in ArcMAP with a distance of 27.4 m between each line (Fig. 1, Panel C). To replicate the seven-section ASC of the sprayer, all the center lines were selected, and the copy parallel feature was used once again at distances of 1.5, 6.1, 9.1 and 13.7 m on either side of each center line (Fig. 1, Panel D). This created seven respective sections of 4.6, 3.0, 4.6, 3.0, 4.6, 3.0 and 4.6 m wide from one side of the applicator boom to the other side for each applicator pass.

Polygons were drawn such that overlapped areas in each field would represent minimum overlapped area in the field. This was accomplished by drawing perpendicular lines from where the lagging chemical applicator section edge crossed the inside edge of the headrow boundary to where the leading chemical applicator section edge had traveled in relation to the inside boundary of the head row (Fig. 1, Panel E). Polygon areas were estimated using the calculate geometry tool in ArcGIS. Estimated polygon areas were summed for each scenario (seven-section ASC and no ASC) to obtain the minimum over-sprayed area in each field for both chemical applications with ASC and without ASC. Given that boom sections rather than individual spray nozzles were assumed to be controlled with ASC, the estimates used in this analysis measured the difference between over-sprayed area with seven-section ASC and over-sprayed area controlling the entire boom as one section.

Statistical analysis

The estimated data for reduction of overlap as a proportion of total field area sprayed when passing from controlling the entire boom as one section to seven-section ASC were sorted into three P/A categories: 0.01, 0.02 and ≥ 0.03 (Table 1). Examples of fields used in this study for the various P/A categories are presented in Fig. 2. The association between field area sprayed and the reduction in overlap and the association between P/A and the reduction in overlap were evaluated by estimating Pearson correlation coefficients. Estimated correlation coefficients were compared with estimated correlations for field size and overlap and P/A and overlap reported in Luck et al. (2011) for 74 farm fields in Kentucky, USA. Potential differences in the distributions of the reduction in overlap by P/A were also evaluated using the non-parametric Wilcoxon rank-sum test (Gibbons and Chakraborti 2011). The null hypothesis was that the distribution of the reduction in overlap with ASC for a P/A category is not smaller than the distribution for a comparison P/A category, i.e. the reduction in overlap for P/A = 0.01 is not smaller than the reduction in overlap for P/A = 0.02, the reduction in overlap for P/A = 0.01 is not smaller than the reduction in overlap for P/A = 0.03 and the reduction in overlap in P/A = 0.02 is not smaller than reduction in overlap in P/A ≥ 0.03 . The median value of the reduction in overlapped area as a proportion of total field area sprayed for each P/A was estimated and used to estimate

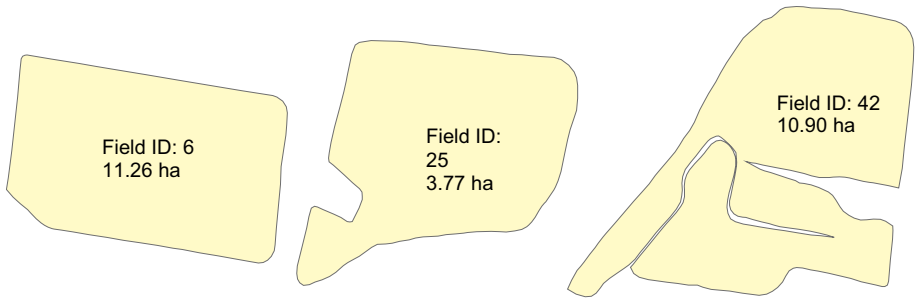


Fig. 2 Examples of field sizes and shapes associated with a $P/A = 0.01$ (left), $P/A = 0.02$ (center) and $P/A \geq 0.03$ (right)

chemical cost savings for seven-section ASC when compared with controlling the entire boom as one section for the profitability analysis.

ASC profitability analysis

Net Present Value (NPV) is a standard capital budgeting method that can be used to evaluate the profitability of PA technologies (Maine et al. 2009). The method uses the time value of money to measure the difference between the present value of cash inflows and the present value of cash outflows over the total life of the investment. The time value of money is accounted for through the discount rate and represents the compounded rate of return on the next best alternative use of capital. Future cash flows from the investment are discounted back to present value in time $t = 0$, the year the investment is undertaken. A positive NPV indicates that the investment in a PA technology is profitable because the investment provides a compounded rate of return that is greater than the next best alternative use of capital. However, farmers may prefer to make investments in PA technologies that provide a quick pay back because of the potential for rapid obsolescence of the technologies (Lowenberg-DeBoer 1999).

Discounted payback period

The discounted payback period (DPP) is another capital budgeting method that can be used to evaluate the profitability of investments with uncertain useful lives such as PA technology (Bhandari 2009). Discounted future cash inflows are compared with the initial investment cash outflow to give the number of years that it takes for the cumulative NPV to be equal to zero. For an investment with a DPP that is less than the useful life of the investment, $NPV > 0$ beyond the breakeven time identified by the DPP and the investment produces economic profits (Bhandari 2009). The DPP criterion provides an indication of how liquid the investment is through how fast the initial investment is paid back through discounted future net cash inflows (Bhandari 2009). It also provides the same investment accept-reject decisions as the NPV and Internal Rate of Return criteria for investments with conventional cash flows (i.e. an initial negative cash outflow for the investment and positive cash inflows thereafter) (Bhandari 2009).

DPP from investment in ASC was calculated as (Bhandari 2009):

$$DPP = \ln(1 - (INV(r - g)/NCF)) / \ln((1 + g)/(1 + r)), \quad (1)$$

where DPP was the discounted payback period in years, \ln was the natural logarithm, INV was the initial cash outflow for the investment in ASC technology (\$) at year $t = 0$, r was the interest rate ($0 \leq r \leq 1$) used to discount a constant annual net cash flow (NCF , \$ year⁻¹) received from ASC in years $t = 1, 2, 3, \dots, T$ back to present value in $t = 0$ and g ($0 \leq g \leq 1$) was a growth rate factor to adjust the stream of net cash flows in years $t = 1, 2, 3, \dots, T$. The constant annual net cash flow (NCF) in each year of the investment is consistent with the assumption of constant savings of inputs from reduced overlap with ASC (Velandia et al. 2013). The growth rate factor g was used to adjust chemical costs for expected inflation in chemical prices (Velandia et al. 2013).

Annual net cash flow

Annual net cash flow (NCF) in Eq. (1) was calculated using:

$$NCF = A \sum_j (CP_j TC_j POL) - SSF, \quad (2)$$

where A was farm size (ha), CP represented the proportions of cotton and other crops grown on the farm ($0 \leq CP_j \leq 1$), TC was the cost (\$ ha⁻¹) of chemical materials applied without ASC for cotton and other crops grown on the farm, j was an index for cotton and other crops grown on the farm, POL was the reduction in the proportion of the field that was overlapped ($0 \leq POL \leq 1$) with ASC on fields with different geometry as measured by P/A and SSF was an annual satellite subscription fee (\$ year⁻¹). Given that the effects of over-spraying on yields are crop-, crop rotation- and chemical-specific (Smith et al. 2013), the potential for yield changes from overlapping chemical applications were not considered in this analysis. Operator error turning sections on and off manually in headlands is difficult to quantify (Luck et al. 2010a, 2011; Jernigan 2012) and also was not considered in estimating the benefits of ASC. In addition, the potential effects of income taxes and depreciation which shields income from taxes on net cash flows were not considered in the analysis.

Sensitivity analysis

A one-way sensitivity analysis was carried out to assess the effects of the aforementioned variables (A , CP , TC , g , r , INV and SSF) in Eqs. (1) and (2) on the DPP from investment in ASC for fields with P/A values of 0.01, 0.02 and ≥ 0.03 (Clemen and Reilly 2001). The base scenario was specified to represent a typical size cotton farm in Tennessee. The sensitivity analysis was accomplished by changing each variable by 50 % above (upper bound) and below (lower bound) the base scenario value while holding the other variables at their base values. Tornado diagrams were used to present the one-way sensitivity analysis effects of each variable on the DPP for each P/A scenario (Clemen and Reilly 2001). The variables affecting the DPP in the horizontal bars of the tornado diagrams were ordered such that the largest (smallest) bar was at the top (bottom) and indicated that the variable had the largest (smallest) influence on DPP .

Sensitivity analysis data

Values for the variables used in the one-way sensitivity analysis are in Table 2. The base scenario for farm size and the proportion of the farm in cotton was taken from 2012 Census

of Agriculture data for Tennessee (USDA-NASS 2014). The representative Tennessee cotton farm was assumed to have a total crop area of 499 ha [A in Eq. (2)] with 56 % (279 ha) of the crop area in cotton [CP in Eq. (2)] (USDA-NASS 2014). The other representative farm crop used for the analysis of DPP was corn which has lower chemical costs relative to cotton (USDA-ERS 2014). Total chemical costs without ASC [TC in Eq. (2)] for the base scenario for cotton and corn of $\$318 \text{ ha}^{-1}$ and $\$148 \text{ ha}^{-1}$, respectively, were taken from 2013 University of Tennessee Extension no-tillage crop budgets (The University of Tennessee, Department of Agricultural & Resource Economics 2013). The chemical costs from the Extension budgets included operating interest on chemical expenditures of 6 % for 6 months. For cotton, a total of eight passes with the boom applicator over the field were assumed and included one pre-plant herbicide application, three post-planting herbicide applications, one insecticide application, two growth regulator applications and one defoliant and boll opener application before harvest. By comparison, budgeted chemical costs for corn were for four herbicide applications. Chemical costs from the aforementioned budgets were assumed to increase at an annual inflation rate of 2.7 % [g in Eq. (1)] for the base scenario, the average annual percentage change in prices paid by farmers for chemicals between 2003 and 2012 (USDA-NASS 2013).

Interest rates used to discount cash flows by researchers in six studies evaluating investment in PA ranged from 5 to 15 % (Tiffany et al. 2000; Robertson et al. 2007; Wang et al. 2003; Yu et al. 2003; Tozer 2008; Maine et al. 2009). The average discount rate in the aforementioned studies of 10 % was used for the base scenario [r in Eq. (1)]. The 27.4 m wide chemical applicator modeled for this analysis was assumed to be retrofitted for ASC and included a Global Positioning System (GPS) receiver, controller and software capable of controlling sections on the spray boom. The total initial cost of these components [INV in Eq. (1)] was estimated to be $\$19,139$ for the base scenario and was calculated using an average of equipment prices for several manufacturers in the Cotton Precision Agriculture Investment Decision Aid equipment database (Larson et al. 2010). A satellite subscription fee [SSF in Eq. (2)] of $\$800 \text{ year}^{-1}$ was used for calculating expected annual net cash flows for the base scenario (Larson et al. 2010).

Based on American Society of Agricultural and Biological Engineers (ASABE) equipment standards (ASABE 2011) and the aforementioned crop budgets, the upper bound values on farm size of 749 ha and area in cotton of 84 % implies that the applicator would be used 289 h year^{-1} on 5513 total ha (eight spray trips across the field for cotton and four spray trips across the field for corn) and the applicator would have an estimated useful life of 5.18 years. Applicator useful lives were longer for the other farm size and cotton proportion scenarios. While several factors may influence how many chemical applicators are used on a single farm (e.g., timeliness of spray operations), the ~ 5 year useful life for this scenario serves as an assumed upper bound on the DDP (i.e. DPP ≤ 5 years) needed to provide the minimum compounded rate of return represented by the discount rate and a NPV = 0.

Results and discussion

Applicator overlap and P/A

Table 1 presents total field area sprayed (ha), estimated reduction in overlapped area (ha) and percentage reduction in overlapped area (i.e. the percentage difference in overlap

Table 1 Estimated reductions in overlap for seven-section automatic section control versus single-section control on a 27.4 m boom chemical applicator for 44 fields in middle and west Tennessee sorted by perimeter (m)-to-area (m²) ratio (P/A m⁻¹) and field area

P/A (m ⁻¹)	Field ID	Total sprayed area (ha)	Reduction in overlap	
			Area (ha)	Percent (%)
0.01	1	8.25	0.34	4.10
	2	8.85	0.10	1.20
	3	9.65	0.44	4.60
	4	10.50	0.65	6.20
	5	10.66	0.65	6.10
	6	11.26	0.04	0.40
	7	12.27	1.03	8.40
	8	12.85	0.67	5.20
	9	12.90	0.23	1.70
	10	12.96	0.30	2.30
	11	13.08	0.94	7.20
	12	13.39	1.61	12.00
	13	15.24	0.80	5.20
	14	15.41	1.40	9.10
	15	16.38	1.14	7.00
	16	26.91	0.05	0.16
	17	28.09	0.42	1.50
	18	28.89	0.21	0.80
	19	31.36	0.94	3.00
	20	32.34	0.11	0.40
	21	35.94	0.87	2.40
	22	42.73	0.09	0.26
	23	42.89	0.48	1.10
Mean (n = 23)		19.69	0.59	3.93
Median (n = 23)		13.39	0.48	3.00
SD		11.18	0.45	3.30
0.02	24	2.67	0.28	10.50
	25	3.77	0.27	7.10
	26	7.36	0.18	2.50
	27	8.12	0.47	5.70
	28	9.48	0.86	9.10
	29	9.74	1.08	11.00
	30	13.94	1.36	9.70
	31	17.19	2.24	13.00
	32	18.18	1.85	10.20
	33	23.79	2.27	9.60
	Mean (n = 10)		11.42	1.09
Median (n = 10)		9.61	0.97	9.65
SD		6.73	0.81	3.00
≥0.03	34 ^a	1.43	0.16	11.20

Table 1 continued

P/A (m ⁻¹)	Field ID	Total sprayed area (ha)	Reduction in overlap	
			Area (ha)	Percent (%)
	35 ^b	1.69	0.22	13.00
	36 ^a	3.41	0.16	4.70
	37 ^b	3.68	0.46	12.50
	38 ^b	5.39	0.80	14.90
	39 ^a	6.75	1.08	16.00
	40 ^b	9.07	1.23	13.50
	41 ^b	10.72	1.49	13.90
	42 ^b	10.90	1.10	10.00
	43 ^a	12.95	2.32	17.90
	44 ^b	14.18	2.51	17.70
Mean (n = 11)		7.29	1.05	13.21
Median (n = 11)		6.75	1.08	13.50
SD		4.53	0.82	3.75

^a P/A = 0.04^b P/A = 0.03

between single-section control and seven-section control) for each of the 44 fields in the sample. Field area sprayed ranged from 1 ha to 43 ha and the span of P/A values was from 0.01 to 0.04. The reduction in overlapped area averaged 7.36 % of total sprayed area and ranged from 0.16 to 17.90 % in the sample. Overlap in Table 1 is sorted by P/A with 23 fields having a P/A = 0.01, ten fields having a P/A = 0.02 and 11 fields having a P/A ≥ 0.03 (seven fields with P/A = 0.03 and four fields with P/A = 0.04). Correlation between field area sprayed and P/A in the sample was -0.50 ($p \leq 0.01$). The inverse relationship between P/A and field area sprayed (ha) was generally consistent with Luck et al. (2011) who found a correlation coefficient of -0.76 on 74 fields. Fields with the lowest P/A value of 0.01 had an average sprayed area of 19.69 ha. By comparison, field areas sprayed were generally smaller for P/A = 0.02 and P/A ≥ 0.03 with mean areas of 11.42 ha and 7.29 ha, respectively. The estimated correlation between the percentage reduction in overlapped area and P/A in the sample was 0.73 ($p \leq 0.01$). Thus, the relationship between the reduction in overlapped area and P/A in the sample was generally positive and consistent with Luck et al. (2011) who also found a positive correlation on 74 farm fields.

The median reductions in overlapped area with ASC for fields with P/A values of 0.01, 0.02 and ≥ 0.03 were 3.00, 9.65 and 13.50 %, respectively (Table 2). Results from the Wilcoxon rank-sum test indicate that percentage reduction in overlapped area for P/A = 0.01 was smaller than the percentage reduction in overlapped area for P/A = 0.02 ($p \leq 0.01$), the percentage reduction in overlap for P/A = 0.01 was smaller than the percentage overlap for P/A ≥ 0.03 ($p \leq 0.01$) and the percentage reduction in overlapped area for P/A = 0.02 was smaller than the percentage reduction in overlapped area for P/A ≥ 0.03 ($p \leq 0.01$) (Table 3). The non-parametric test findings indicate that the three P/A categories had relatively distinct distributions of the percentage reduction in overlapped area with ASC based on the P/A. Therefore, P/A as a criterion to categorize the reduction in overlap with ASC may be useful in making choices about investment in ASC

Table 2 One-way sensitivity analysis base values and lower and upper bound values of the variables used to evaluate the discounted payback period from investment in automatic section control (ASC) for fields with different perimeter (m)-to-area (m^2) ratios ($P/A m^{-1}$)

Variable description	Variable name	Sensitivity analysis scenario ^a		
		Base value	Lower bound	Upper bound
Farm size (ha)	<i>A</i>	499 ^b	250	749
Area in cotton (%)	<i>CP</i>	56.00 % ^c	28.00 %	84.00 %
Median reduction in overlap with ASC	<i>POL</i>			
Fields with $P/A = 0.01$		3.00 %	–	–
Fields with $P/A = 0.02$		9.65 %	–	–
Fields with $P/A \geq 0.03$		13.50 %	–	–
Chemical costs ha^{-1} without ASC	<i>TC</i>			
Cotton ($\$ ha^{-1}$)		\$318 ^d	\$159	\$477
Corn ($\$ ha^{-1}$)		\$148 ^e	\$74	\$222
Chemical price inflation rate (%)	<i>G</i>	2.70 % ^f	1.35 %	4.05 %
Discount rate (%)	<i>R</i>	10.00 % ^g	5.00 %	15.00 %
ASC investment cost (\$)	<i>INV</i>	\$19 139 ^h	\$9569	\$28 708
Annual satellite subscription fee ($\$ year^{-1}$)	<i>SSF</i>	\$800 ⁱ	\$400	\$1200

^a Lower bound values are 50 % of the base values and the upper bound values are 150 % of the base values

^b Average total harvested crop area reported for farms classified as cotton farms in Tennessee in the 2012 Census of Agriculture (USDA-NASS 2014)

^c Average total harvested crop area in cotton (%) reported for farms classified as cotton farms in Tennessee in the 2012 Census of Agriculture (USDA-NASS 2014)

^d Chemical costs for cotton were from a University of Tennessee Extension budget (The University of Tennessee, Department of Agricultural & Resource Economics 2013). The budget assumed eight spray operations $year^{-1}$ using a boom applicator: one pre-plant herbicide application, three post-planting herbicide applications, one insecticide application, two growth regulator applications and one defoliant and boll opener application before harvest

^e Chemical costs for corn were from a University of Tennessee Extension budget (The University of Tennessee, Department of Agricultural & Resource Economics 2013). The budget assumed four herbicide applications $year^{-1}$ using a boom applicator

^f Average annual percentage change in prices paid by farmers for chemicals between 2003 and 2012 (USDA-NASS 2013)

^g Average value of the discount rates used in six studies that evaluated investment in precision agriculture technologies (Tiffany et al. 2000; Wang et al. 2003; Yu et al. 2003; Robertson et al. 2007; Torbett et al. 2008; Maine et al. 2009)

^h The 27.4 m wide chemical applicator modeled was assumed to be retrofitted for ASC and included a Global Positioning System (GPS) receiver, controller and software capable of controlling sections on the spray boom. The total cost of these components was estimated to be \$19 139 and was based on an average of prices for several manufacturers in the Cotton Precision Agriculture Investment Decision Aid equipment database (Larson et al. 2010)

ⁱ Average of prices for several providers in the Cotton Precision Agriculture Investment Decision Aid equipment database (Larson et al. 2010)

for chemical applicators. The estimated median reduction in overlap with ASC (controlling the boom with seven-section ASC versus controlling the entire boom as one section) for each P/A was used for the analysis of chemical cost savings and the profitability of ASC (Table 2).

Table 3 Relationship between perimeter (m)-to-area (m^2) ($P/A \text{ m}^{-1}$) for 44 fields in middle and west Tennessee and distribution of the reduction in overlap for seven-section automatic section control versus single-section control on a 27.4 m boom chemical applicator

Reduction in overlap (%) distribution comparisons for different P/A categories	Wilcoxon Rank-Sum test ^{a,b}		
	Rank sum	z-statistic	p value
P/A = 0.01 versus P/A = 0.02	305.50	-3.33	<0.01
P/A = 0.01 versus P/A = 0.03	70.50	-2.75	<0.01
P/A = 0.02 versus P/A = 0.03	287.00	-4.24	<0.01

^a The number of observations in each P/A category are: 23 for P/A = 0.01, 10 for P/A = 0.02 and 11 for P/A \geq 0.03

^b Null hypothesis: The distribution of the reduction in overlap (%) was not smaller for the first P/A in the comparison; Alternative hypothesis: The distribution of the reduction in overlap (%) was smaller for the first P/A in the comparison

Chemical cost savings with ASC

Table 4 presents the estimated chemical cost savings in $\$ \text{ year}^{-1}$ from ASC for fields with different P/A for the base, lower bound and upper bound values of farm size and the percentage of crop area in cotton (in Table 2). For the base farm size of 499 ha and 56 % of crop area in cotton (279 ha), the expected chemical cost reduction with ASC on fields with P/A = 0.01 was $\$3640 \text{ year}^{-1}$. Cost savings for the base farm size and area in cotton scenario were 3.2 and 4.5 times greater ($\$11,708 \text{ year}^{-1}$ and $\$16,379 \text{ year}^{-1}$), respectively, for fields with P/A of 0.02 and ≥ 0.03 . Results indicate that field size and shape as

Table 4 Estimated annual chemical cost savings for different farm size, percentage of crop area in cotton and perimeter (m)-to-area (m^2) ($P/A \text{ m}^{-1}$) scenarios for seven-section control automatic section control (ASC) versus single-section control on a 27.4 m boom applicator

Sensitivity analysis variables ^a		P/A ($\$ \text{ year}^{-1}$)		
Farm size (ha)	Percentage area in cotton (%)	0.01 ^b	0.02 ^c	≥ 0.03 ^d
499	56	3640	11,708	16,379
	28	2925	9410	13,164
	84	4354	14,005	19,593
250	56	1824	5866	8206
	28	1466	4715	6595
	84	2181	7017	9816
749	28	4391	14,125	19,760
	56	5463	17,573	24,585
	84	6535	21,022	29,409

^a The one-way sensitivity analysis base values and the lower and upper bound values of the farm size and the percentage of area in cotton variables used to evaluate chemical savings are defined in Table 2

^b Median reduction in overlap with ASC of 3.00 % on total crop area sprayed

^c Median reduction in overlap with ASC of 9.65 % on total crop area sprayed

^d Median reduction in overlap with ASC of 13.50 % on total crop area sprayed

measured through the P/A had a substantial impact on expected annual savings in chemical costs with ASC. These findings are also consistent with Shockley et al. (2012) and Velandia et al. (2013) who observed that the reduction in overlap and the input savings with ASC were larger for more irregularly shaped and smaller field sizes.

Chemical cost savings from ASC were also substantially influenced by the interaction of farm size with field geometry as measured by the P/A. For example, estimated chemical cost savings were \$5866 year⁻¹ for the 250 ha lower bound and field geometry of P/A = 0.02 and \$5463 for 749 ha upper bound and field geometry of P/A = 0.01 (assuming both scenarios had 56 % of the crop area in cotton). Results indicate that the chemical savings and the subsequent profitability of ASC for different sized farms may be substantially influenced by the geometry of fields on a farm as represented by P/A. More generally, these results should apply to other crops besides cotton that also have larger chemical costs. Farm size results are consistent with Velandia et al. (2013) who categorized farm fields into low, moderate and high double-planted area categories and evaluated total savings for different farm sizes. They found that seed cost savings increased with the percentage of fields on the farm in the high double-planted area category. With the availability of satellite mapping services that can be used to calculate P/A for fields, this measure of field geometry may be easier to use for analysis of ASC than the subjectively assessed over-application categories developed by Velandia et al. (2013).

ASC profitability analysis

Figure 3 illustrates the DPP in years from investment in ASC for fields with geometry represented by P/A = 0.01 and an estimated median reduction in overlap of 3.00 % from using seven-section ASC versus controlling the entire boom as one section. The base scenario assumed a farm size of 499 ha, crop area in cotton of 56 % (279 ha), savings in chemical costs of \$3640 year⁻¹, chemical cost inflation rate of 2.7 % year⁻¹, discount rate of 10 %, investment cost in ASC of \$19 139 and satellite subscription fee of \$800 year⁻¹ (Tables 2 and 4). Given the aforementioned base scenario values, the DPP was 9.9 years for fields with a P/A = 0.01. Results indicate that the chemical cost savings were not

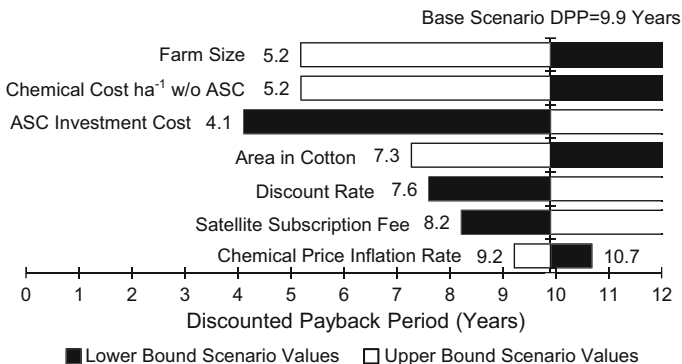


Fig. 3 Sensitivity analysis of the discounted payback period (DPP) from investment in automatic section control (ASC) for fields with a perimeter (m)-to-area (m²) = 0.01 and median reduction in overlap of 3.00 % with seven-section ASC versus single-section control on a 27.4 m boom chemical applicator. The sensitivity analysis base values and the lower and upper bound values of the variables used to evaluate the DPP from investment in ASC are defined in Table 2

sufficient for ASC to be profitable, i.e. provide the minimum compounded rate of return on investment of 10 % as indicated by the discount rate and give a NPV >0 within the ~ 5 years useful life of ASC assumed for this analysis.

For the $P/A = 0.01$ sensitivity analysis, most of the maximum DPP values for the lower and upper bound values of the variables were much greater than the base scenario DPP value of 9.9 years. Therefore, the maximum DPP value on the x-axis of the tornado diagram in Fig. 3 was set at 12 years to focus on the variables that had the greatest influence on lowering the DPP below the base scenario DPP = 9.9 year value. The variables having the largest influence on DPP for fields with $P/A = 0.01$ were farm size, chemical costs ha^{-1} without ASC and ASC investment cost. DPP values were essentially infinite for the lower bound values of farm size (250 ha) and chemical costs ha^{-1} without ASC (\$159 ha^{-1} for cotton and \$74 ha^{-1} for corn). Chemical cost savings were too small to pay back the \$19 139 investment in ASC within the useful life assumed for the technology and provide a NPV > 0 for any DPP under the two lower bound sensitivity scenarios.

By contrast, increasing farm size (749 ha) or increasing chemical costs ha^{-1} without ASC (\$477 ha^{-1} for cotton and \$222 ha^{-1} for corn) by 50 % above their base values reduced DPP from 9.9 years for the base scenario to 5.2 years for each variable. Reducing ASC investment cost by 50 % decreased the DPP from 9.9 years to 4.1 years and would potentially provide a NPV > 0 if the useful life of ASC was ~ 5 years, all other variables set at their base values. Results indicate that ASC investment cost had the largest influence on reducing the DPP and providing a NPV > 0 for the base scenario cotton farm having fields with a $P/A = 0.01$. This result suggests that farmers using the technology for other PA applications besides ASC, thereby spreading investment costs over more applications, may find it profitable to use ASC on fields with $P/A = 0.01$. Results also suggest that voluntary government programs such as the USDA Natural Resource Conservation Service Environmental Quality Incentive Program (EQIP) that provide cost shares for investment in VRT may make it profitable for a cotton farmer to invest in ASC with fields having $P/A = 0.01$. The EQIP program reduces the investment cost of PA technologies for farmers who invest in the technologies. The variables that had the least impact on reducing DPP below the base value of 9.9 years for fields with $P/A = 0.01$ were area in cotton, the discount rate, the satellite subscription fee and the chemical price inflation rate.

For the base cotton farm scenario, the DPP was much shorter for smaller and more irregularly shaped fields as measured by $P/A = 0.02$ and $P/A \geq 0.03$. Given a $P/A = 0.02$ and a median reduction in overlap with ASC of 9.65 % (with expected savings of \$11 708 year^{-1} , Table 4), the DPP was 2.0 years for the base cotton farm scenario (Fig. 4). DPP was only 1.4 years for fields with $P/A \geq 0.03$ and a median reduction in overlap with ASC of 13.5 % (with expected savings of \$16 379 year^{-1} , Table 4) for the base cotton farm scenario (Fig. 5). Results indicate that investment in ASC for the base cotton farm scenario having fields with a $P/A \geq 0.02$ would likely achieve a NPV > 0 within the ~ 5 year useful life of the technology assumed in this analysis.

The one-way sensitivity analysis for fields with $P/A = 0.02$ and $P/A \geq 0.03$ also indicated that the variables having the largest influence on DPP were chemical costs ha^{-1} without ASC, farm size and ASC investment cost. For the $P/A = 0.02$ field geometry scenario, the DPP increased from 2.0 years for the base scenario to 4.7 years when chemical cost ha^{-1} without ASC was reduced to the lower bound value (\$159 ha^{-1} for cotton and \$74 ha^{-1} for corn) or farm size was reduced to the lower bound value (250 ha) (Fig. 4). For the $P/A \geq 0.03$ field geometry scenario, reducing the farm size or chemical costs ha^{-1} without ASC by 50 % from their base values increased the DPP from 1.4 years for the base scenario to 3.0 years and 3.1 years, respectively (Fig. 5). Results indicate that

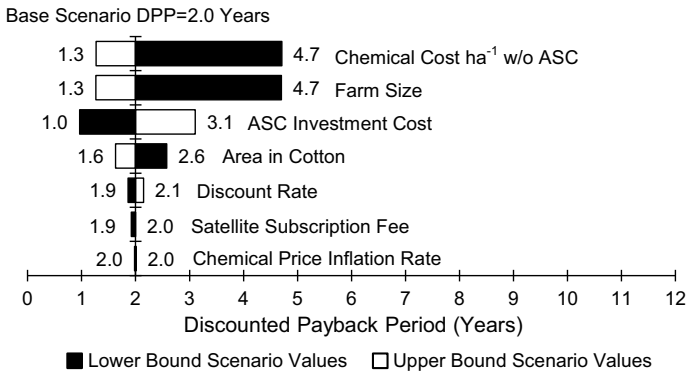


Fig. 4 Sensitivity analysis of the discounted payback period (DPP) from investment in automatic section control (ASC) for fields with a perimeter (m)-to-area (m²) = 0.02 and median reduction in overlap of 9.65 % with seven-section ASC versus single-section control on a 27.4 m boom chemical applicator. The sensitivity analysis base values and the lower and upper bound values of the variables used to evaluate the DPP from investment in ASC are defined in Table 2

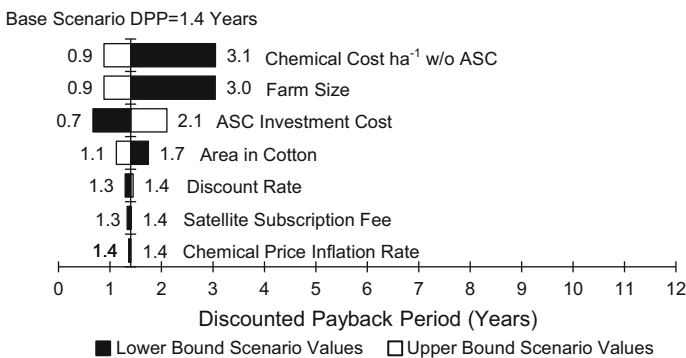


Fig. 5 Sensitivity analysis of the discounted payback period (DPP) from investment in automatic section control (ASC) for fields with a perimeter (m)-to-area (m²) ≥ 0.03 and median reduction in overlap of 13.50 % with seven-section ASC versus single-section control on a 27.4 m boom chemical applicator. The sensitivity analysis base values and the lower and upper bound values of the variables used to evaluate the DPP from investment in ASC are defined in Table 2

investment in ASC would likely produce a NPV > 0 within the ~5 year useful life of the technology for a wide range of farm sizes and chemical costs for farms with fields with a P/A ≥ 0.02. Results also indicate that investment in ASC was more profitable for a cotton farm having fields with a P/A ≥ 0.02 than for a cotton farm having fields with a P/A = 0.01 because of the short DPPs required to achieve a NPV > 0 relative to the expected useful life of ASC equipment.

Conclusions

Results of this study indicate that field geometry factors including field size and field shape have a large influence on the profitability of automatic section control (ASC) for boom applicators. Overlapping application of chemicals using a boom applicator occurs from

turns at headlands, from infringement in point and end rows and from steering around obstacles within a field. ASC automatically turns off sections on a boom applicator in areas of the field that have already received an application. Perimeter (m)-to-area (m^2) ratio (P/A , m^{-1}) was used to categorize reduction in overlap with ASC of a 27.4 m boom applicator by field size and field shape for 44 farm fields in Tennessee, USA. Reduction in overlap was defined as the difference in area over-sprayed controlling the entire boom as one section (i.e. no ASC) and over-sprayed with seven-section ASC.

A larger P/A was found to be associated with fields having smaller sizes and more irregular shapes. Estimated median reductions in overlap from using ASC were 3.00 % for fields with $P/A = 0.01$, 9.65 % for fields with $P/A = 0.02$ and 13.50 % for fields with $P/A \geq 0.03$. The discounted payback period to provide a minimum compounded rate of return of 10 % and a net present value = 0 was substantially influenced by the savings in chemical costs associated with field geometry as measured by P/A . Results indicate that investment in ASC was less likely to be profitable for a 499 ha cotton farm in Tennessee having field geometry characterized by $P/A = 0.01$. The discounted payback period was longer than the ~ 5 year useful life of the ASC technology assumed in this analysis and therefore would not provide a net present value > 0 on the investment. By comparison, investment in ASC for a 499 ha cotton farm having field geometry characterized by $P/A \geq 0.02$ would quickly achieve a net present value > 0 within the ~ 5 year useful life of the technology. The variables having the largest influence on the profitability of ASC were chemical costs ha^{-1} without ASC, farm size and ASC investment cost. The variables having the smallest impact on the profitability of ASC were the percentage of area in cotton, the discount rate, the satellite subscription fee and the chemical price inflation rate.

This study showed that P/A as a measure of field geometry may be useful for analyzing the profitability of investment in ASC. With the availability of satellite mapping services such as Google Earth, farmers can calculate P/A to categorize fields on their farms. Crop consultants and Extension personnel may have a role in facilitating decision analysis for investment on ASC technologies using P/A data and the methods used in this study. Results of this study may also be useful to government agencies in identifying farms for the purpose of promoting adoption of PA technologies such as ASC.

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