The Economics of Precision Guidance with Auto-Boom Control for Farmer-Owned Agricultural Sprayers

Marvin T. Batte
Fred N. VanBuren Professor of Farm Management
Department of Agricultural Environmental and Development Economics
The Ohio State University

Mohammad Reza Ehsani
Assistant Professor of Agricultural and Biological Engineering
University of Florida

This is a pre-publication version of a paper ultimately published in *Computers and Electronics in Agriculture*, Vol 53(1) 2006:28-44.

Abstract:
Precision guidance and precision sprayer control have substantial promise to reduce input application overlap, thus saving chemicals, fuel, and time during the application process. In this article we provide preliminary estimates of the magnitude of the private benefits for a precision guidance system combined with auto-boom control for agricultural sprayers (precision spraying). Hypothetical farm fields are analyzed, allowing comparison of the performance of the precision system to a traditional, non-precision system for different field shapes. An analysis of the impact of size of farm on system profitability also is explored. Our analyses suggest that, even when considering only private benefits of input savings, the value derived from a precision spraying system can be substantial. This is especially true when the sprayer patterns become more complex due to non-rectangular fields and due to the presence of waterways, drainage ditches or similar obstructions. Economic benefits of the precision spraying system increase proportionally to the cost of the spray material being applied and with the number of annual applications. Benefits also increase with increases in driver error rates for non-precision systems. Because most of the costs of the precision spraying system relate to the fixed investment, these costs are largely constant regardless of farm size. This translates to net benefits of precision spraying that increase with increased farm size.

Keywords: precision guidance; precision spraying; economic analysis

Introduction

Precision agricultural is not a single technology, but rather a set of many component technologies from which farmers can select to form a system that meets their unique needs and management style. As a result, the rate of adoption for these component technologies varies widely (Batte, *et al*., 2003*)*. Precision guidance is a relatively new addition to the suite of precision farming technologies. Although it has been commercially available only since about 2000, it is increasingly being adopted by farmers, commercial agrichemical applicators, and other agricultural service providers. Batte *et al*. (2003) estimated that 5.2% of Ohio commercial farmers had adopted some form of precision guidance as of March 2003. The adoption percentage was nearly 25% for farmers with annual sales of more than $250,000.

Precision guidance is markedly different from many of the existing precision farming systems. It requires a larger fixed investment than many. Precision guidance is also more of a *turn-key* technology than many of the previous precision farming technologies. Whereas variable rate application of fertilizers requires a systematic data collection (e.g., grid or zone soil sampling) and analysis (fertilizer recommendations may be based on soil testing as well as knowledge of location-specific variables such as elevation, slope, soil type, drainage, etc.) before an effective fertilizer application map can be developed and fertilizers can be applied at variable rate, precision guidance is more transparent and easily understood. This is especially true for simple systems such as lightbar navigation or parallel swathing systems. Because precision guidance offers benefits without a steep learning curve, it can be adopted quickly and produce nearly immediate benefits.

Precision control of applied inputs uses many of the same technologies as precision guidance, and has many of the same user knowledge requirements. The use of a parallel swathing system alone can reduce sprayer overlap significantly, thus saving chemicals, fuel, and time during the application process. A more complete precision spraying system would allow zones or individual spray nozzles to be regulated by a map-based controller. This type of system would allow even greater input savings for fields with irregular shapes, grassed waterways, and other characteristics that typically cause operators to overlap sprayer travel. Anecdotal evidence suggests that precision guidance and precision spraying may allow faster operation of equipment, reduce operator fatigue, and allow longer periods of operation without increased error rates. Precision guidance also allows equipment operation in low light conditions, thus extending operating hours per machine/day. In addition to the private benefits to the adopting farmer, society may also benefit through reduced agrichemical pollution, and ultimately, through reduced cost of food and fiber.

To date, there have been few estimates made of the private benefits of precision guidance systems. In this article we provide preliminary estimates of the magnitude of private benefits for a precision guidance system combined with auto-boom control for agricultural sprayers (precision spraying). Hypothetical farm fields will be analyzed, allowing comparison of the performance of the precision system to a traditional, non-precision system for different field shapes. An analysis of the impact of size of farm on system profitability also will be explored. All monetary quantities are given in US dollars.

Literature Review

Many different types of technologies such as radio frequency, laser, machine vision, and GPS have been attempted for use in navigation of agricultural vehicles (Zuydam et al. (1994), Choi et al. (1990), Nogochi et al. (2002). GPS-based navigation systems are the only navigation technologies that have become commercially available for navigation of farm vehicles. There are two types of GPS based guidance systems; GPS guidance-aided systems and fully automated or "hands-free" GPS guidance systems that actually steer the tractor with the driver only supervising it. The fully automated system is capable of driving the tractor through the field in a straight line with a lateral accuracy of less than two cm. This system uses a highly accurate Real Time Kinematic (RTK) GPS receiver. This system can work with any field and operation, including planting, cultivating and harvest. Since modern agricultural machinery is equipped with many controls, operator fatigue is a serious concern (Tillett, 1991; Noh and Erbach, 1993). Automatic guidance can reduce operator fatigue and improve machinery performance by reducing overlap or skips during field operations such as tillage and chemical application (Tillett, 1991; Klassen et al., 1993).

Many tractor manufacturing companies are now offering the RTK GPS based auto-steering system as an option on their tractors. The position information from RTK GPS can be used for both guidance and other applications such as seed mapping, controlled traffic, and controlled tillage (Reeder, 2002). Ehsani et al. (2004) retrofitted a planter with a series of optical sensors and two single board computers. Using a RTKGPS receiver, they were able to create a seed map. The information from a seed map can be used later for weed control. Abidine et al. (2002) showed that a tractor equipped with an auto-guidance system can be used to cultivate or spray very close to the plant line (about 5 cm) at a very high ground speed (up to 11 km hr^{-1}) and chisel or subsoil a field very close to buried drip tapes without damaging them, allowing the grower to use drip tapes for several years with the need to replace them every year. This application of autosteering could result in significant cost savings for vegetable growers.

Crop inputs such as chemicals and fertilizers are applied with large application equipment with boom widths of 18.2 to 36.5 meters. In order to maintain a quality application with no gaps in coverage, the operator commonly uses a foam marker as a reference point to steer the sprayer through the field. There are errors and limitations associated with using a foam marker system. The foam may drop below the canopy; there may also be uneven distribution on a windy day; it freezes during the winter months, and is hard to see with reduced visibility and evaluate from pass to pass as the spray booms have become wider with more boom bounce. There are several factors that influence the overall accuracy of a foam marker system namely, speed of the machine, elevation of the ground, width of the machine, type of equipment, experience of the driver and type of field. Under an optimal simulated spraying condition, a 2-3% efficiency was observed using a lightbar guidance system compared to a foam marker with an experienced applicator (Ehsani et. al., 2002, Buick and White, 1999). A higher error (up to 10%) has been reported for foam marker systems (Medlin and De-Boer, 2000). Simulated and observed error can not fully explain all the error associated with a foam marker system during the real application of chemical inputs. Ehsani et al (2004) studied the accuracy of a spraying application for two custom applicators with the foam marker system under field conditions. They found a significant variability in terms of pass-to-pass and overall accuracy error between different drivers. For a given driver, the range of overlap was from 0.6% to 26%. They also found that a driver with the average overlap of less than 5% also had many occurrences of application skips.

Methods

The analyses conducted here will estimate the value of inputs saved for a precision spraying system as compared to a traditional, non-precision system. The approach is to use a set of hypothetical fields, each of 40.47 hectare size, which differ in shape. We will also estimate the impact of field features, such as grass waterways, on the costs for these two systems.

The non-precision spraying system is described as a self-propelled spray machine without any form of GPS for guidance assistance or sprayer control. Three spray boom widths are analyzed: 18.3, 27.4 and 36.6 meter widths. The non-precision sprayer is assumed to have multiple "zones" that can be turned on or off manually. The 18.3 m system is assumed to have 3 zones; the 27.4 m system has 5 zones; and the 36.6 m system has 6 zones. The non-precision spray machine is assumed to be identical to the precision spraying machine in all other aspects.

The precision spraying system uses a Real Time Kinematic (RTK) global positioning systems (GPS) to provide both guidance and to control individual sprayer nozzles. RTK GPS systems are accurate to within 2.5 cm. The RTK system requires a base station. The correction signal from the base station is transmitted to the tractor using a radio transmitter. The current maximum communication distance is approximately 10 kilometers and requires line-of-sight between the base station and receiver. A repeater can be used to increase the distance or reach over a ridge. The cost for an RTK GPS system is about $30,000.

Autosteering systems involve the use of three main components; the hydraulic components that will be added to the steering system, RTK GPS system, and a display monitor with guidance algorithm. A typical hydraulic component system might cost $7,000 for a single tractor or sprayer. Finally, the precision sprayer uses a nozzle controller that uses location information from the GPS system to precisely calculate the location of each nozzle on the sprayer boom. A shut-off valve must be installed on each nozzle. The computer can turn each nozzle on or off based on its exact location. For example, if a nozzle is positioned over an area that already has been sprayed, that nozzle will turn off to avoid overlap. The controller also can be programmed to avoid spraying certain sections of the field such as grass waterways or outside the field boundary. The extra cost for a precision controlled sprayer with an 18.3 meter boom would be about $8,700. Finally, in order to use the map-based guidance and control system, a field boundary map must first be completed. Commercial mapping services typically charge $5 - 10 per hectare to map field boundaries including waterways and other physical features.

The following analyses are based on a set of assumed parameters of system accuracy, spray material costs, number of annual spray passes, fuel efficiency and cost, and opportunity cost of operator labor (table 1). We use partial budgeting techniques to estimate the profitability of the precision spraying system. With partial budgeting, profitability is calculated as the difference in revenues and costs for the two alternatives -- in this case the change from traditional to precision spraying.

In our analyses, we assume that the operator of the non-precision system drives conservatively so as to minimize the chance of sprayer skip between swathes. The cost of this driving strategy is wasted time, fuel, and spray material due to overlap. We assume that application of the material at double-the-intended-rate (overlap) has no impact on the performance of the crop. The other possible driver error is sprayer skips due to too wide a swath. The cost of this error is more difficult to quantify because yield is likely to be impacted in the skipped area. To quantify this impact would require the use of a biological model to estimate the impact of pests, and detailed assumptions about pest or weed population, etc. This is beyond the scope of the current study. We also do not address other potential impacts on the farming operation that might be facilitated by adoption of the precision spraying system. For instance, the ability to spray longer days due to reduced operator fatigue, the ability to operate in low-light conditions, or the ability to operate at higher speeds may suggest that a smaller, lower investment spray equipment set may be possible with precision spraying, or that a larger farm size may be possible with a given size of precision sprayer due to the increased area capacity per day.

Our analyses consider only private costs and benefits. That is, we consider only the change in input costs, revenues and costs associated with ownership of the precision spraying system. We do not consider benefits to society, including the benefits of reduced pollution that might arise from a more precise application of spray materials with less overlap.

Our analyses considers three field shapes: A rectangular field (Fig. 1), a parallelogram with field ends that are 10 degrees off perpendicular (Fig. 2), and a trapezoid that requires point rows in the spraying pattern (Fig. 3). For each field type, we also consider the presence of two grass waterways that cross the field at angles of 45 degrees or 30 degrees relative to the direction of travel.

Fig. 1 represents a 40.47 hectare field of rectangular shape. The field is 610 meters wide and 664 meters long. Because the field ends are perpendicular to the row, there is no inherent overlap of spray area due to the angle of the field end. However, there is potential for either sprayer overlap or skip in the parallel swathing of the sprayer without precision guidance. To add richness to the analysis, we have also added two grass waterways to the field design. One of these is 518 meters in length and has a 45 degree incidence relative to the row direction. The second waterway is 457 meters in length and has a 30 degree angle of incidence.

Fig. 4 illustrates the two waterways in the context of the rectangular field A. With a non precision spraying system, the operator will typically spray the field by first outlining the waterway with a single boundary spray pass. Because the non-precision system does not allow individual control of spray nozzles, spray overlap is inevitable. Fig. 4 illustrates the amount of overlapped spray area that might occur. For an 18.3 meter spray boom, the area of overlap is 0.034 hectares per swath for the waterway with 45 degree incidence, and .019 hectares per swatch for the 30 degree waterway.[1] These areas increase to 0.075 and 0.043 hectares for a 27.4

meter spray boom, and 0.130 and 0.077 hectares for a 36.6 meter spray boom for the 45 and 30 degree waterways, respectively. For a precision spraying system with individually controllable spray nozzles, this overlapped area is assumed to be zero. In addition to wasted spray material due to overlap, the outline spray pass for the waterway boundaries means additional fuel and operator time is required to complete the spray task. This outline spray pattern is not needed for the precision spray system.

Fig. 2 depicts Field B -- a parallelogram-shaped field of 40.47 hectares. This field has ends that are not perpendicular to the rows -- they are 10 degrees off-square. The sprayer operator will typically make a spray pass across the field end. However, without precision control of individual spray nozzles, sprayer overlap will occur in this end area with each sprayer swath. The area of overlapped spray is 0.006, 0.013, and 0.023 hectares per swath for 18.3, 27.4, and 36.6 meter spray booms, respectively. This field has the same potential for parallel swathing errors (overlap or skips) as does rectangular field A.

Field C (Fig. 3) is trapezoidal in shape and totals 40.47 hectares in area. The trapezoidal shape creates the need for point rows in the spray pattern, which inherently create an overlapping of spray areas for non-precision spraying systems. The insert in Fig. 4 illustrates the incidence of sprayer overlap for a spray machine with three controllable spray zones. The area of overlap with the non-precision system would be 0.002 hectare for an 18.3 meter boom with 3 equal-width manually-controllable zones, 0.002 hectare for 27.4 meter boom with 5 controllable zones, and 0.003 hectare for a 36.6 meter boom with 6 controllable zones. For a precision spraying system with individually controllable spray nozzles, this overlapped area is assumed to be zero.

Benefits of the Precision System

Table 2 provides estimates of sprayer overlap, material wastage, and extra fuel and operator time required for the non-precision spraying system relative to the RTK-based precision spraying system for the rectangular-shaped field A. Estimates are provided for three sprayer widths for the field both without (Panel A) and with (Panel B) grass waterways. The operator of the non-precision sprayer is assumed to exercise caution to avoid skipped spray areas, and as a result, is assumed to make a sprayer overlap of 7.5% of the sprayer width on parallel swathes. The RTK-based precision guidance system is assumed to be accurate to within 5 cm, hence a 5 cm sprayer overlap is applied for parallel swaths.[2] Based on this difference in swathing accuracy, the non-precision system requires three additional passes across the field with an 18.3 meter spray boom (3.28 ha of overlap), and two additional passes for the 27.4 and 36.6 meter sprayer widths (3.28 ha of overlap). The additional distance traveled to compensate for the increased overlap means greater fuel usage and operator time. Additionally, the overlapped spray area means a higher cost of spray material.

Our estimate of spray material savings for the precision system relative to the traditional system for field A (no waterways) is $4.23/ha for the 18.3 meter sprayer. The fuel savings are $0.05 - 0.07/ha and operator labor savings adds another $0.04-0.06/ha, depending on sprayer width. Thus, total savings for the field A ranges from $4.36 to $4.39/ha for the 18.3 and 36.6 meter sprayer widths, respectively.

The magnitude of input savings for the precision system rises as grass waterways are added to the field. The extra travel required to spray around the waterways approximately doubles the difference in travel between precision and non-precision systems relative to Field A without waterways. Overlapped spray areas increases to as much as 5.45 hectares (more than one tenth of the field area) for the 36.6 meter sprayer width. There is a concomitant increase in the wastage of spray materials, fuel and operator labor. Total savings attributable to precision spraying in Field A with waterways ranged from $5.94 to $7.41 per hectare for the 18.3 and 36.6 meter sprayer widths, respectively.

Table 3 summarizes the measures of input usage for precision and non-precision spraying systems for Field B. The field arrangement results in spray overlap in the end areas that can be avoided with the precision spraying system. The precision system also allows reduction in parallel swathing errors just as for Field A. Overlapped spray areas for this 40.47 hectare field range from 3.47 hectares for the precision spray system with 18.3 meter boom to 3.67 hectares for the non-precision system with 36.6 meter spray width. When waterways are present (Panel B), the overlapped area increases for the non-precision system to 5.84 hectares for the largest sprayer width.

Cost of wasted spray material increases proportionally to overlapped area. Total spray material savings with the precision spraying system ranged from $4.49 to $4.83/ha in the absence of waterways, and increased to a range from $5.94 to $7.73/ha for Field B with waterways. Total input savings were as large as $4.91/ha for the 36.6 meter sprayer in the absence of waterways, and $7.94/ha for the largest sprayer when waterways were present.

Table 4 reports estimates of input savings with the precision spraying system relative to the non-precision system for Field C. This field is wider at one end, and thus requires point rows, and resulting overlap spraying as the rows "point off". We do assume each non-precision sprayer has multiple manually-controlled zones, thus limiting the amount of sprayer overlap with good operator control. The same 5 cm precision and individual nozzle control is assumed for the precision system. For Field C without waterways, the overlapped spray areas range from 0.05 hectare for the precision system to 3.36 hectares for the non-precision system, both for the widest sprayer configuration. This translates to a cost savings for spray material of $4.42/ha for the widest precision spraying system. Total input savings ranged from $4.10/ha for the narrowest sprayer configuration to $4.51/ha for the widest sprayer configuration. When waterways are considered, overlapped spray area increases dramatically for the non-precision system (to 5.54 hectares for the 36.6 m width). For this sprayer width, the cost of wasted spray material was $7.39/ha for the non-precision system as compared to $0.07/ha for the precision spray system. Total input savings in Field C with grass waterways was $5.99/ha for the 18.3 meter system, and nearly $7.53/ha for the 36.6 meter-wide system.

The previous tables have illustrated that the magnitude of input savings with precision spraying varies greatly with the complexity of sprayer travel patterns. Our next step is to consider net returns to the precision spraying investment. Because ownership costs of the system are fixed and are spread over the entire cropped area, it is necessary to make an assumption about farm size. We begin by assuming a farm of 242.8 hectare size, represented by fields of varying complexity of sprayer patterns. Specifically, we assume one field of each type to comprise the 243 hectare farm. The rightmost two columns of Table 5 show the farm total input savings attributable to precision spraying on a total farm and per hectare basis. This amount ranges from $1,275 for the 18.3 meter spray system to $1,485 for the 36.6 meter width.

Economies of Scale and Sensitivity Analyses

The previous analyses have shown substantial input savings for the precision spraying systems. However, there also are costs associated with owning the precision system. Presented in Table 6 are fixed investment requirements, and given an assumed 10 year service life, estimates of the fixed costs of each system. The RTK GPS receiver, base station, and one replicator are estimated to cost $30,000. However, this investment can be used to support precision guidance and additional GPS related activities other than spraying. We have assumed that 10% of the usage of this system is for precision spraying, and thus allocate only 10% of the cost of the RTK system to the spaying activity. Similarly, the costs of developing the field boundary and spray application maps are durable over time and can be used by other GPS-based applications. Thus these costs also are amortized over 10 years and are charged only 10% to the spraying activity. On the other hand, the autosteer controller hardware and precision sprayer controllers are assumed to be permanently mounted on the sprayer, and hence the full fixed costs of these components are charged to the precision spraying activity. Given this assumed total investment of $47,500 for the 18.3 meter system, a weighted real cost of capital of 9% per annum, and using the depreciation method that is prescribed by the ASAE and the AAEA, total fixed costs are $2,911 per year. This fixed cost rises to $3,004 and $3,096 for the 27.4 and 36.6 meter sprayer widths, respectively.

Table 7 summarizes total input savings by category and net return to the precision guidance and spraying system (profit) for various farm sizes. Four farm sizes are assumed. The 243 hectare farm is as previously described. A 486 hectare farm is simply double the 243 hectare farm (2 fields of each type with and without grass waterways). The 728 and 971 hectare farms are three and four replicates of the 243 hectare base farm. We ignore possible pecuniary economies, that is, the potential that larger farms may be able to purchase inputs at lower cost per unit or sell outputs at higher net price. Our analysis considers only the technical efficiencies of spreading the fixed costs of machine ownership over larger sprayed areas. It also is important to recognize that Table 7 is not sufficient to make a judgment as to the optimal size of equipment to use on a particular farm size. This is a partial analysis that only considers the additional costs of adding precision spray controls to a particular-sized sprayer. Thus, this table is useful for judging whether precision spraying would be profitable given a particular farm size and ownership of a specific size of equipment. The net returns to the precision spraying investment are largest for the widest sprayer because this system has both the greatest percentage of overlapped spray area and the lowest precision system investment per meter of sprayer width.

First, we consider the base-case analysis. For the smallest farm size, total net returns to precision spraying are negative for all sprayer widths, ranging from -$1,612 to -$1,636 total for the farm: The value of input savings provided by the precision spraying investment are smaller than the annual fixed costs of precision system ownership for this farm size. For the largest two farm sizes, precision spraying is profitable, regardless of sprayer width. However, at the 486 hectare farm size, the precision and non-precision spraying systems are nearly equal in net return, earning a loss of about $0.31 per hectare when using the widest sprayer.

Our analysis of input savings relies on a number of assumptions. In order to explore the sensitivity of our results to these assumptions, we have solved the model for breakeven values for several key variables. These breakeven values are presented in the rightmost columns of Table 7. In each case, all other parameters are held constant at their base-case levels.

Driver accuracy can vary substantially for non-precision systems. As discussed in the literature review, previous studies have found error rates as high as 10 percent of the sprayer width. Currently, there is little knowledge as to how this error rate might relate to the width of the sprayer. Because this is a critical assumption with little supporting knowledge, we performed a breakeven analysis on this variable with all other model parameters held constant. For the 18.3 meter sprayer width, breakeven occurred for the smallest farm size when the percent overlap for the non-precision system reached 16.9 percent (3.09 m). This means that if the non-precision system operator can operate with less than 16.9 percent error, then the non-precision system will be most cost effective, but if the driver error is expected to be more than 16.9 percent, the input savings of the precision system would more than cover the annual cost of the system. As farm size increased, with the resulting decline in average fixed costs, breakeven overlap declined to as little as 4.1 percent (0.75 m) for the largest farm size. Similar patterns exist for the other sprayer widths; however, the reader is cautioned that these numbers are in percentages of sprayer widths. For instance, for the largest sprayer width and the largest farm size, the breakeven driver error percentage is 2.8, which translates to 1.02 meters, somewhat larger than the 4.1 percent / 0.75 meter error for the largest farms and the narrowest sprayer.

The cost of the materials being sprayed can also vary substantially among crops and other situations. The greater is the cost of the spray material, the greater is the savings due to reduced sprayer overlap. The breakeven analysis for cost of spray material suggests that, for the smallest farm size and with all other parameters unchanged, spray materials that cost more that about $60 per hectare (intended application rate) will result in sufficient benefits to offset the costs of added precision spray investment costs. If the spray material costs less than this amount, the non-precision system will be more profitable. Breakeven material costs decrease to about $15 per hectare for the largest farm size.

In a similar vein, the number of applications that are made annually will influence the value derived from a precision spraying system. Additional passes not only mean more potential to save spray material, but also potential to save additional time, fuel, and other application costs. For the smallest farm size, more than 4 annual applications (with chemicals at $27 per hectare and all other parameters constant at their base levels) would be required to make precision spraying more profitable than the non-precision system. With the largest farm size, just over one annual application is all that would be required to be profitable.

The final analysis deals with breakeven farm size. From the leftmost columns in Table 7, it is clear that breakeven farm size is somewhere between 486 and 729 hectares for all three machine sizes. The rightmost column displays the breakeven calculation for farm size.[3] For instance, with the smallest machine and smallest farm size, breakeven farm size is 555 hectares. With all other parameters constant at their base level, a farm with more than 555 hectares and an 18.3 m sprayer would be more profitable with a precision spraying system and smaller farms would be more profitable with the non-precision system. Breakeven hectarages are smaller for the 36.6 m system, again because this system tends to have greater areas of spray duplication than does narrower sprayers.

Summary and Conclusions

The results of our analyses suggest that, even when considering only private benefits of input savings, the value derived from a precision spraying system can be substantial. These benefits will increase proportionally to the cost of the spray material being applied and will increase with the number of annual applications and with the driver error rate for the non-precision system. Because most of the costs of the precision spraying system relate to the fixed investment, these costs diminish per hectare as farm size increases. Hence, the precision spraying system will make most sense economically for larger farms that make several applications annually of relatively expensive spray materials. These estimates clearly are in alignment with the relatively rapid adoption of precision guidance systems by large farmers during the past few years.

Although our study provides valuable insight into the economics of such systems, more research is needed. Our study starts with assumptions of driver accuracy followed by sensitivity analyses. It would be useful for researchers to further quantify the actual error rates for skilled machine operators. This could be done by asking them to steer without guidance, but using GPS systems to trace their actual path. This method could also examine the impacts of driver fatigue on error rates.

Our study also ignored driver errors that resulted in sprayer skips. This is a challenging problem that will require careful biological modeling. For instance, the impact of insect pests may be rather small if the areas of skips are small and infrequent, but may increase exponentially as the skip patterns become large. In the case of weed pests, the impact of sprayer skips may be largely a linear function of area. Although research to quantify this impact may be interesting, it may be unnecessary if the precision system is profitable in most cases without considering this potential added value. Our study also ignores benefits other than input savings. Specifically, any value deriving from controlled traffic, or the potential to expand farm size due to greater speed of operation, time savings, or ability to extend the day into periods of low-light conditions. These benefits may be substantial.

Finally, our work ignores externalities, the largest being the potential reduction in surface or ground water contamination from agricultural chemicals. Our estimates here demonstrate that the area of overlapped application may be substantial, exceeding 10% of field area for large sprayers in fields with waterways under our base scenario. If agrichemical pollution is proportional to application, then external costs may be substantially different between precision and non-precision spraying systems. However, such externalities are site specific, depending on local hazards for groundwater contamination and the local area's assimilative capacity for the specific chemical applied. Careful analysis of the potential to reduce such external costs will be useful to policy makers who may consider policies to speed the adoption of precision spraying methods as a strategy to mitigate pollution.

References

AAEA. 2000. Commodity costs and returns estimation handbook. American Agricultural Economics Association, Ames, IA.

Abidine, A., B. C. Heidman, S. K. Upadhyaya, and D. J. Hills. 2002. Application of RTK GPS based auto-guidance system in agricultural production. ASAE Paper No. 021152. St. Joseph, Mich.: ASAE.

ASAE. 2001. ASAE Standards 2001, 48th ed. American Society of Agricultural Engineers, St. Joseph, MI.

Batte, Marvin T., Craig Pohlman, D. Lynn Forster, and Brent Sohngen. "Adoption and Use of Precision Farming Technologies: Results of a 2003 Survey of Ohio Farmers." AED Economics Report AEDE-RP-0039-03. Department of Agricultural, Environmental, and Development Economics, The Ohio State University, December, 2003.

Buick, R. and E. White. 1999. Comparing GPS guidance with foam marker guidance. In: Proc. of the 4th Int'l Conf. on Precision Agriculture, editors: R.H. Rust and W.E. Larson, ASA/CSSA/SSSA, Madison, WI.

Choi, C. H., D. C. Erbach, and R. J. Smith. 1990. Navigational tractor guidance system. *Trans. ASAE* 33(3): 699-706.

Ehsani, M. R., M. Sullivan, J. Walker, and T. Zimmerman. 2002. A method of evaluating different guidance systems. ASAE Paper No. 02-1155. St. Joseph, MI: ASAE.

Ehsani, M.R., M. D. Sullivan, and T. Zimmerman. 2004. Field Evaluation of the Percentage of Overlap for Crop Protection Inputs with a Foam Marker System Using Real-Time Kinematic (RTK) GPS. Institute of Navigation (ION) 60th Annual Meeting, Dayton, Ohio.

Ehsani, M.R., S.K. Upadhyaya, M. L. Mattson. 2004. Seed Location Mapping Using RTK-GPS. *Trans. ASAE*. Vol. 47(3): 909-914

Klassen, N. D., R. J. Wilson, J. N. Wilson. 1993. Agricultural vehicle guidance sensor. ASAE Paper No. 931008. St. Joseph, Mich.: ASAE

Lazarus, William and Roger Selley. 2005. "Farm Machinery Costs Estimates for Late 2005." University of Minnesota Extension Service. Accessed 3-2-2006 at http://www.apec.umn.edu/faculty/wlazarus/mf2005late.pdf

Medlin, C. and J. Lowenberg-DeBoer. 2000. Increasing cost effectiveness of weed control. In: Precision Farming Profitability, SSM-3, editor: K. Erickson. Purdue University, West Lafayette, IN pp. 44-51.

Noguchi, N., M. Kise, K. Ishii, and H. Terao. 2002. Field automation using robot tractor. ASAE paper No. 701P0502July 26-27 conference publication: 239-245.

Noh, K. M., and D. C. Erbach. 1993. Self-tuning controller for farm tractor guidance. *Trans. ASAE* 36(6): 1583-94.

Reeder, R. 2002. Maximizing performance in conservation tillage systems: An overview. ASAE Paper No. 021134. St. Joseph, Mich.: ASAE.

Tillet, N. D. 1991. Automatic guidance sensors for agricultural field machines: A review. *Journal Agricultural Engineering Research* 50 (3): 167-187.

Zuydam, R., P. Van and C. Sonneveld. 1994. Test of an automatic precision guidance system for cultivation implements. *J. Agricultural Engineering Research* 59 (4): 239-243.

Table 1. Precision and non-precision spray system descriptions and parameter assumptions.

	Non precision system	Precision Spray System
Precision Guidance	None	RTK
Sprayer Control	Controlled manually by zones (18.3 m sprayer has 3 equal-length zones, 27.4 m sprayer has 5 zones, and the 36.6 m sprayer has 6 zones).	Each nozzle is GPS-controlled
Accuracy (swath overlap)	7.5% of sprayer width	5 cm
Travel speed	16 kph	16 kph
Fuel consumption per hour)	22 liter/hour	22 liter/hour
Fuel cost	$0.50/liter	$0.50/liter
Cost of Spray materials (at intended application rate) per application	$27/hectare	$27/hectare
Number of spray applications made per year	2	2
Opportunity wage rate for machine operator ($/hour)	$10	$10
Weighted real cost of capital	6%	6%
Annual insurance cost (percent of new value)	0.85%	0.85%
Annual repair cost (percent of new value)	1%	1%

Table 2. Estimates of sprayer overlapped area, wasted time and materials and total savings for field A with and without waterways.

	Overlap[a]	Per 40.47 hectare field: Required transverses of field	Per 40.47 hectare field: Extra travel distance (m)	Per 40.47 hectare field: Overlapped spray area (hectare)	Per hectare: Cost of wasted spray material[b] ($/ha)	Per hectare: Spray Material savings ($/ha)	Per hectare: Fuel Savings ($/ha)[c]	Per hectare: Operator time savings ($/ha)[d]	Per hectare: Total savings ($/ha)
Panel A - Field without waterways									
18.3 meter spray boom									
RTK System	5 cm	34		0.11	0.15	4.23	0.07	0.06	4.36
Non-precision system	1.37 m	37	1,992	3.28	4.37				
27.4 meter spray boom									
RTK System	5 cm	23		0.07	0.10	4.28	0.05	0.04	4.36
Non-precision system	2.06 m	25	1,328	3.28	4.37				
36.6 meter spray boom									
RTK System	5 cm	17		0.05	0.07	4.30	0.05	0.04	4.39
Non-precision system	2.74 m	19	1,328	3.28	4.37				
Panel B - Field with waterways									
18.3 meter spray boom									
RTK System	5 cm	34		0.11	0.15	5.68	0.13	0.12	5.94
Non-precision system	1.37 m	37	3,942	4.37	5.83				
27.4 meter spray boom									
RTK System	5 cm	23		0.07	0.10	6.46	0.11	0.10	6.67
Non-precision system	2.06 m	25	3,278	4.91	6.55				
36.6 meter spray boom									
RTK System	5 cm	17		0.05	0.07	7.20	0.11	0.10	7.41
Non-precision system	2.74 m	19	3278.43	5.45	7.27				

a Assumes a 7.5% overlap on non-precision systems, 5 cm overlap on precision system

b Assume $27/hectare material cost per application, no extra yield benefit or penalty for double sprayed areas.

c Fuel cost is $0.50/liter, travel speed is 16 kph, fuel usage per hour is 22 liters.

d Opportunity cost of operator labor is $10/hour.

Table 3. Estimates of sprayer overlapped area, wasted time and materials and total savings for field B with and without waterways.

		Per 40.47 hectare field			Per hectare				
	Overlap[a]	Required transverses of field	Extra travel distance (m)	Overlapped spray area (hectare)	Cost of wasted spray material[b] ($/ha)	Spray Material savings ($/ha)	Fuel Savings ($/ha)[c]	Operator time savings ($/ha)[d]	Total savings ($/ha)
Panel A - Field without waterways									
18.3 meter spray boom									
RTK System	5 cm	34		0.11	0.15	4.49	0.07	0.06	4.62
Non-precision system	1.37 m	37	1,992	3.47	4.64				
27.4 meter spray boom									
RTK System	5 cm	23		0.07	0.10	4.67	0.05	0.04	4.76
Non-precision system	2.06 m	25	1,328	3.57	4.77				
36.6 meter spray boom									
RTK System	5 cm	17		0.05	0.07	4.83	0.05	0.04	4.91
Non-precision system	2.74 m	19	1,328	3.67	4.90				
Panel B - Field with waterways									
18.3 meter spray boom									
RTK System	5 cm	34		0.11	0.15	5.94	0.13	0.12	6.20
Non-precision system	1.37 m	37	3,942	4.56	6.09				
27.4 meter spray boom									
RTK System	5 cm	23		0.07	0.10	6.85	0.11	0.10	7.06
Non-precision system	2.06 m	25	3,278	5.21	6.95				
36.6 meter spray boom									
RTK System	5 cm	17		0.05	0.07	7.73	0.11	0.10	7.94
Non-precision system	2.74 m	19	3278.43	5.84	7.80				

a Assumes a 7.5% overlap on non-precision systems, 5 cm overlap on precision system

b Assume $27/hectare material cost per application, no extra yield benefit or penalty for double sprayed areas.

c Fuel cost is $0.50/liter, travel speed is 16 kph, fuel usage per hour is 22 liters.

d Opportunity cost of operator labor is $10/hour.

Table 4. Estimates of sprayer overlapped area, wasted time and materials and total savings for field C with and without waterways.

	Overlap[a]	Per 40.47 hectare field: Required transverses of field	Extra travel distance (m)	Overlapped spray area (hectare)	Cost of wasted spray material[b] ($/ha)	Per hectare: Spray Material savings ($/ha)	Fuel Savings ($/ha)[c]	Operator time savings ($/ha)[d]	Total savings ($/ha)
Panel A - Field without waterways									
18.3 meter spray boom									
RTK System	5 cm	34		0.11	0.15	4.29	0.07	0.06	4.41
Non-precision system	1.37 m	37	1,992	3.32	4.43				
27.4 meter spray boom									
RTK System	5 cm	23		0.07	0.10	4.36	0.05	0.04	4.45
Non-precision system	2.06 m	25	1,328	3.34	4.46				
36.6 meter spray boom									
RTK System	5 cm	17		0.05	0.07	4.42	0.05	0.04	4.51
Non-precision system	2.74 m	19	1,328	3.36	4.49				
Panel B - Field with waterways									
18.3 meter spray boom									
RTK System	5 cm	34		0.11	0.15	5.74	0.13	0.12	5.99
Non-precision system	1.37 m	37	3,942	4.41	5.88				
27.4 meter spray boom									
RTK System	5 cm	23		0.07	0.10	6.54	0.11	0.10	6.76
Non-precision system	2.06 m	25	3,278	4.98	6.64				
36.6 meter spray boom									
RTK System	5 cm	17		0.05	0.07	7.32	0.11	0.10	7.53
Non-precision system	2.74 m	19	3278.43	5.54	7.39				

a Assumes a 7.5% overlap on non-precision systems, 5 cm overlap on precision system

b Assume $27/hectare material cost per application, no extra yield benefit or penalty for double sprayed areas.

c Fuel cost is $0.50/liter, travel speed is 16 kph, fuel usage per hour is 22 liters.

d Opportunity cost of operator labor is $10/hour.

Table 5. Total input savings for a 243 hectare farm comprised of the six case study fields.

	Field A - no waterways	Field A - with waterways	Field B - no waterways	Field B - with waterways	Field C - no waterways	Field C - with waterways	Farm Total (242.8 hectare)	Average ($/ha)
18.3 meter spray boom								
Material savings ($)	171.10	229.85	181.71	240.46	173.44	232.19	1,228.75	$ 5.06
Fuel Savings ($)	2.74	5.42	2.74	5.42	2.74	5.42	24.48	$ 0.10
Operator time savings ($)	2.49	4.93	2.49	4.93	2.49	4.93	22.25	$ 0.09
Total savings ($)	176.33	240.20	186.94	250.81	178.67	242.54	1,275.48	$ 5.25
27.4 meter spray boom								
Material savings ($)	173.07	261.31	188.99	277.23	176.58	264.82	1,342.01	$ 5.53
Fuel Savings ($)	1.83	4.51	1.83	4.51	1.83	4.51	19.00	$ 0.08
Operator time savings ($)	1.66	4.10	1.66	4.10	1.66	4.10	17.27	$ 0.07
Total savings ($)	176.56	269.91	192.48	285.84	180.07	273.43	1,378.28	$ 5.68
36.6 meter spray boom								
Material savings ($)	174.15	291.43	195.38	312.67	178.83	296.12	1,448.57	$ 5.97
Fuel Savings ($)	1.83	4.51	1.83	4.51	1.83	4.51	19.00	$ 0.08
Operator time savings ($)	1.66	4.10	1.66	4.10	1.66	4.10	17.27	$ 0.07
Total savings ($)	177.63	300.04	198.86	321.27	182.32	304.73	1,484.84	$ 6.12

Table 6. Additional investment in RTK guidance and precision spraying equipment with associated annual fixed costs.

	Investment ($)	Service life (years)	Depreciation + interest on salvage value[a]	Annual repairs[b]	Annual insurance costs[c]	Total fixed costs	Percent usage for spraying[d]	Total fixed costs allocated to the spray activity ($)
RTK GPS Receiver, Base Station and replicators	30,000	10	4,076.04	255.00	300.00	4,631.04	10%	463
Autosteer hardware	7,000	10	951.08	59.50	70.00	1,080.58	100%	1,081
Boundary mapping of field	1,800	10	244.56			244.56	10%	24
Precision Spray controller - 18.3 m. width	8,700	10	1,182.05	73.95	87.00	1,343.00	100%	1,343
Precision Spray controller - 27.4 m. width	9,300	10	1,263.57	79.05	93.00	1,435.62	100%	1,436
Precision Spray controller - 36.6 m. width	9,900	10	1,345.09	84.15	99.00	1,528.24	100%	1,528
Total Fixed costs - 18.3 m. width								2,887
Total Fixed costs - 27.4 m. width								2,979
Total Fixed costs - 36.6 m width								3,072

a Depreciation and interest on salvage value is calculated based on the ASAE and AAEA method for fixed cost calculation.

$$(PP - dSV) \times \frac{i(1+i)^n}{(1+i)^n - 1} + (dSV \times i)$$

Where PP is the purchase price, dSV is the discounted salvage value, I is the real weighted cost of capital, and n is the service life of the asset. A zero salvage is used. The weighted real cost of capital is assumed to be 6%.

b Annual repair costs are estimated as 0.85% of the initial purchase price (Lazarus and Shelley).

c Annual insurance costs are estimated as 1.0% of the initial purchase price.

d Assumes only the specified percentage of usage (and cost) is attributable to the spraying activity.

Table 7. Sensitivity analyses for return above total costs for various farm sizes.

Farm Size (ha)	Base Case[a] Value of input savings	Fixed costs	Net return to Precision Guidance and Spraying - Farm Total	Net return to Precision Guidance and Spraying - per Hectare	Breakeven values for selected model parameters with all other parameters held constant at base case levels[b] Percent Overlap for the NonPrecision System	Per Hectare cost of the spray material	Number of annual Spray Passes	Farm Size
18.3 meter spray boom								
243	1,275	2,911	-1,636	-6.73	16.90	62.94	4.56	555
486	2,551	2,935	-384	-0.79	8.90	31.22	2.30	559
729	3,826	2,959	867	1.19	5.70	20.65	1.55	564
972	5,102	2,983	2,119	2.18	4.10	15.36	1.17	568
27.4 meter spray boom								
243	1,378	3,004	-1,625	-6.69	17.40	59.70	4.36	530
486	2,757	3,028	-271	-0.56	8.50	29.73	2.2	534
729	4,135	3,052	1,083	1.49	5.20	19.74	1.48	538
972	5,513	3,076	2,437	2.51	3.40	14.74	1.12	542
36.6 meter spray boom								
243	1,485	3,096	-1,612	-6.63	16.90	57.04	4.17	507
486	2,970	3,120	-151	-0.31	8.00	28.4	2.1	511
729	4,455	3,144	1,310	1.80	4.80	18.86	1.41	515
972	5,939	3,168	2,771	2.85	2.80	14.09	1.07	519

a The 243 hectare farm is comprised of the six 40.47 hectare case study fields. Larger farms are double, triple or quadruple the base farm.

b The net return calculation is solved for the value of the named variable that will result in a zero net return. All other variables are maintained at their base case level -- 7.5% overlap for nonprecision systems and 5cm overlap for precision systems; $27/ha spray material cost; 2 spray applications made per year.

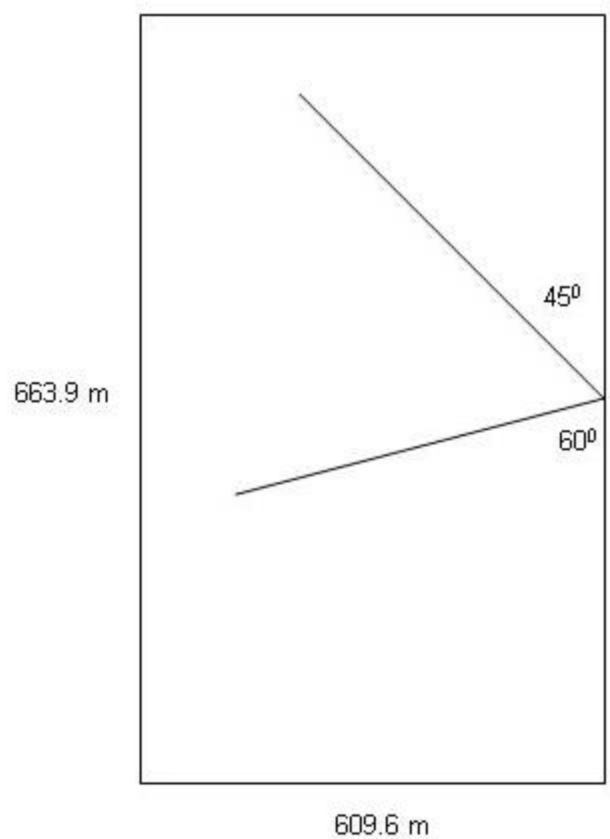

Fig. 1. Field A - Rectangular field with grass waterways.

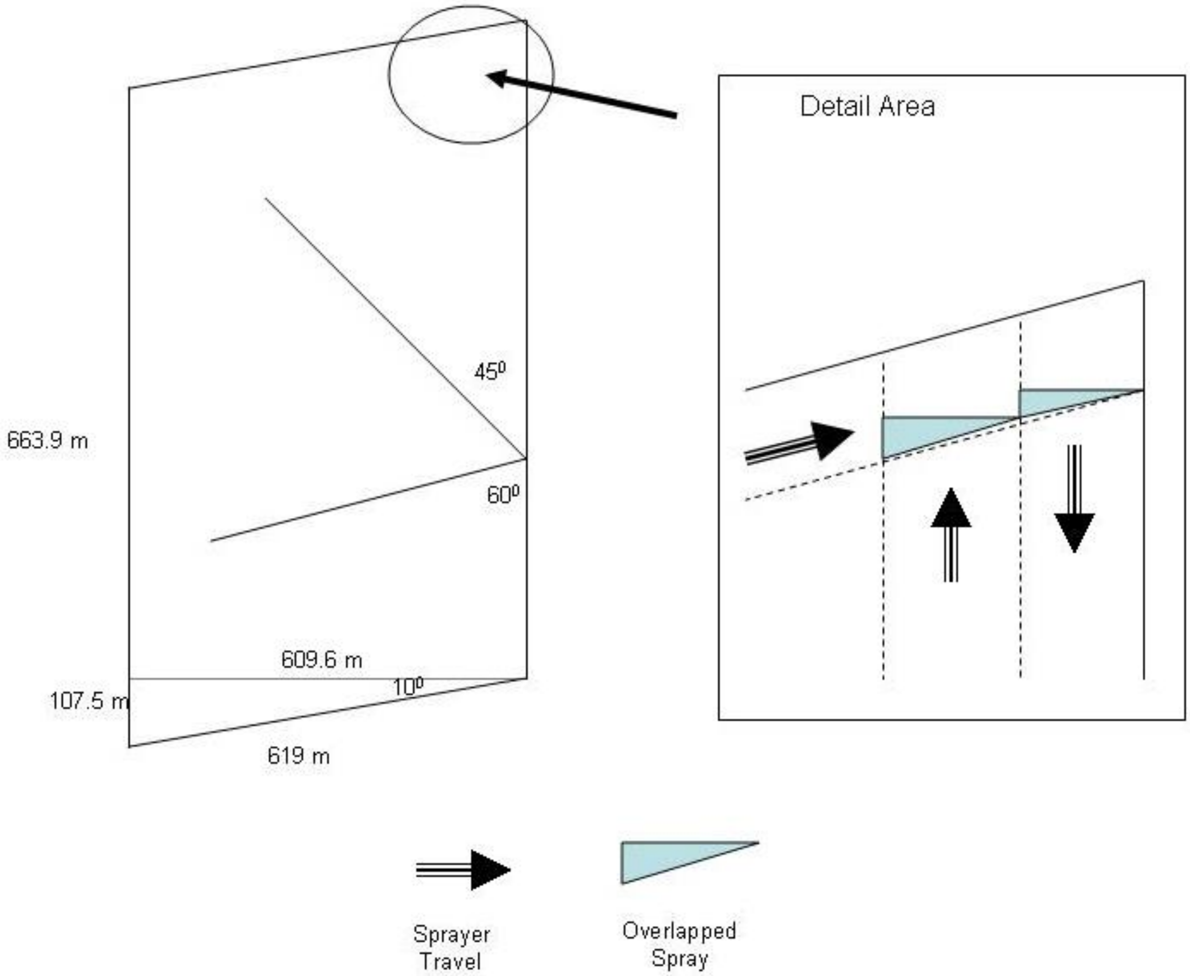

Fig. 2. Example of overlap with non-precision sprayers due to non-perpendicular field ends.

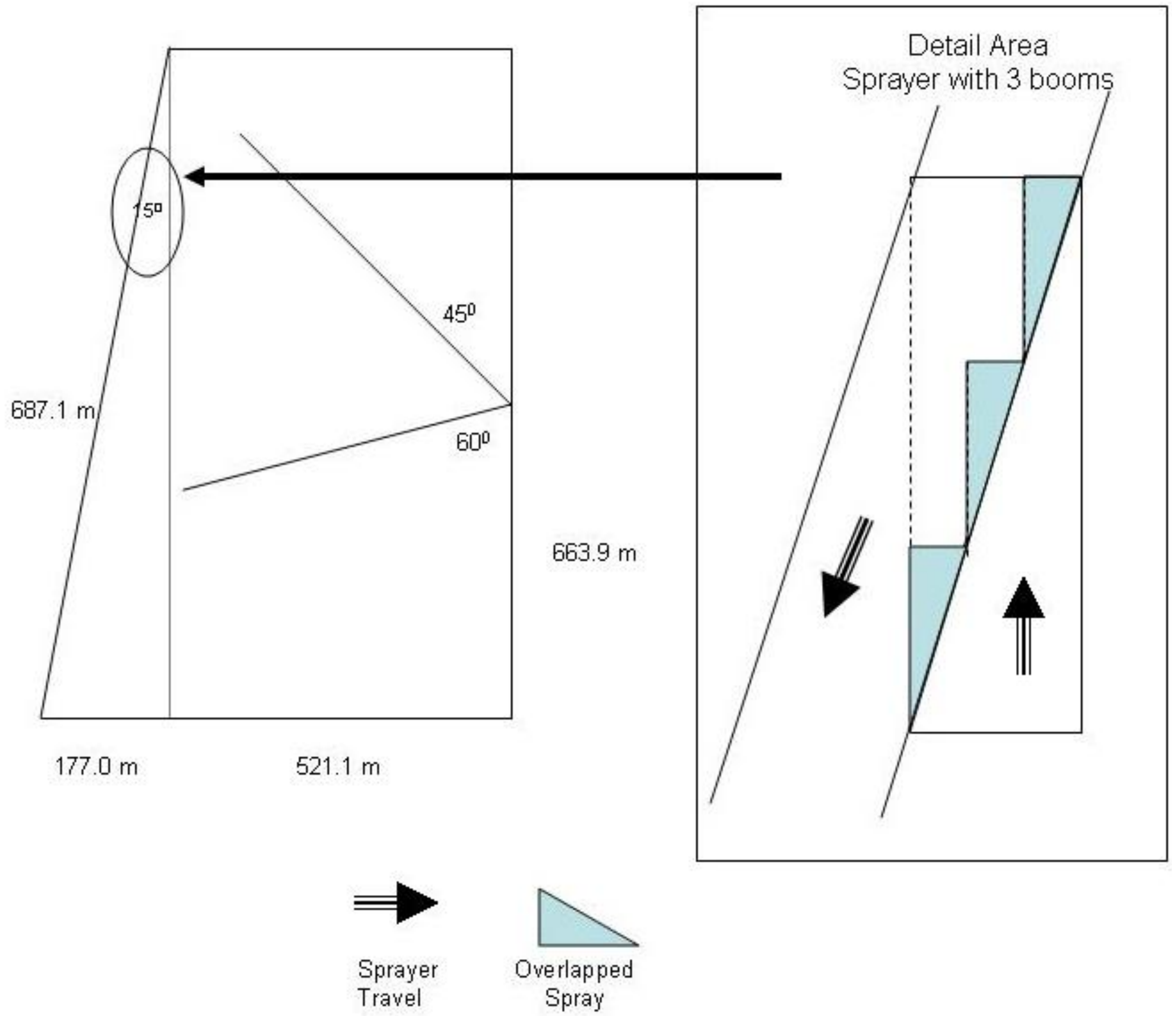

Fig. 3. Field C - Trapezoid field shape with grass waterways.

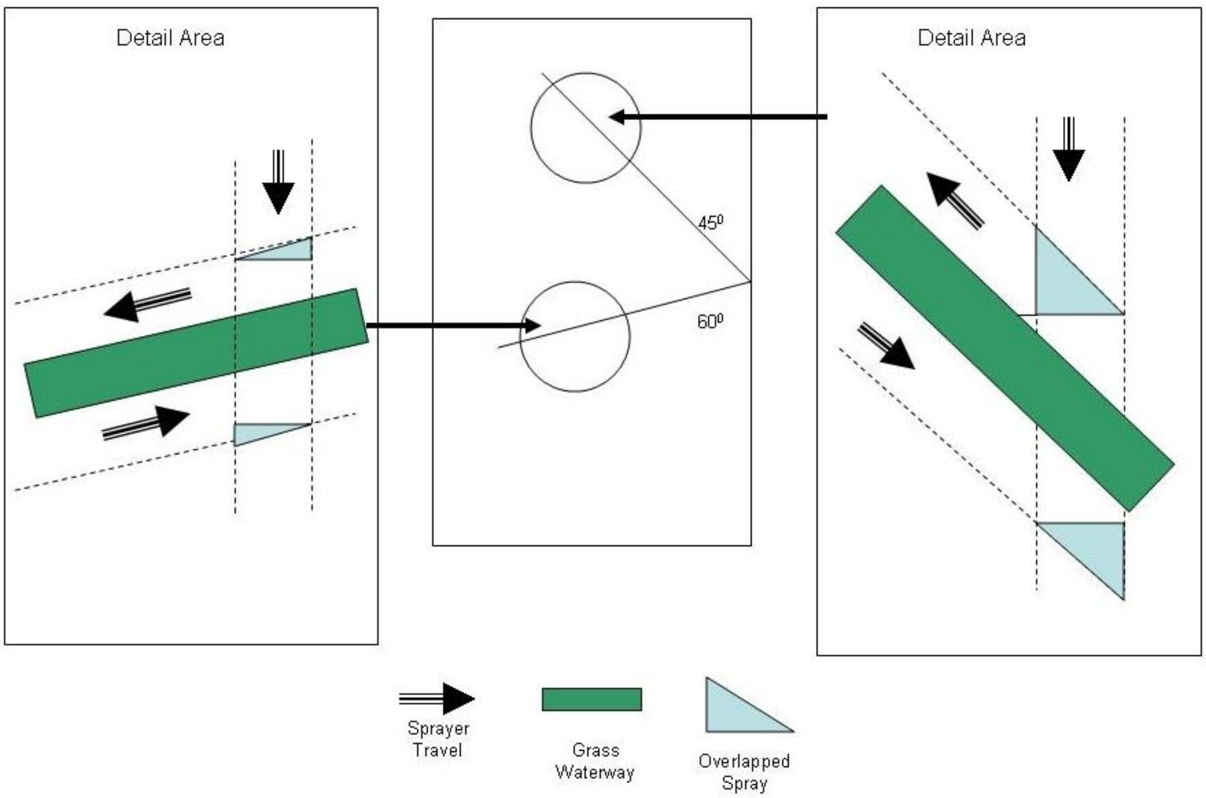

Fig. 4. Illustration of sprayer travel and overlap with non-precision sprayers due to the presence of grass waterways.

Endnotes

[1] Even though the sprayer boom has 3 - 5 manually control zones, we assume that, with operating speeds of 16 k/hr, there is insufficient time to manually shut off each zone. Thus, we assume that the entire boom is shut off as a single unit when the trailing edge of the boom clears the foam marker.
[2] The 5 cm error is expected to have a zero mean between overlap and skip. This would suggest that overlapped spray area would be exactly offset by skipped areas. Our analyses assume that the application map is programmed to have a 5 cm overlap to ensure no skips.
[3] Because mapping costs are estimated as $3 per hectare, total fixed costs actually vary with each machine and farm size combination.