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Repository Citation

Zandonadi, Rodrigo S.; Luck, Joe D.; Stombaugh, Timothy S.; Sama, Michael P.; and Shearer, Scott A., "A Computational Tool for Estimating Off-Target Application Areas in Agricultural Fields" (2011). *Biosystems and Agricultural Engineering Faculty Publications*. 143.
https://uknowledge.uky.edu/bae_facpub/143

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Notes/Citation Information
Published in *Transactions of the ASABE*, v. 54, issue 1, p. 41-49.

Digital Object Identifier (DOI)
https://doi.org/10.13031/2013.36251

A COMPUTATIONAL TOOL FOR ESTIMATING OFF-TARGET APPLICATION AREAS IN AGRICULTURAL FIELDS

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ABSTRACT. *A computational method for estimating off-target application areas based on the machine-controlled section width and the field shape was developed and implemented in software with a graphical user interface written in the MatLab environment. The program, which is called the Field Coverage Analysis Tool (FieldCAT), includes three modules: data import, data preparation, and coverage analysis. Nine field boundaries were evaluated to test the software using controlled section widths from 0.5 to 27 m and various swath orientations. The estimated off-target application area from the widest section width varied from 9% to 24% depending on the shape and size of the field boundary and was reduced to less than 1% with the smallest section width. The simulated results were also compared to actual field data from 25 different fields. The FieldCAT software tool was able to provide reliable quantitative estimates of the off-target application of inputs that would occur because of limited resolution of the machine-controlled section width and the path orientation in different field shapes.*

Keywords. *Boom section control, Off-target spray application, Precision agriculture equipment, Variable-rate application.*

As production agriculture operations have grown in size and competitiveness, the agricultural equipment industry has followed the trend by providing larger and faster machines to satisfy producer demand. At the same time, Global Positioning System (GPS) based technologies for field task improvement have been developed, allowing more precise crop input management and more efficient field operations. Many of these technologies can be quite expensive and relatively complicated to use. Because of the high cost and complexity, a producer's decision of whether to adopt these technologies has become more difficult.

An example of these recent innovations in precision agriculture is automatic section control for application equipment. An automatic section control system continuously records areas that have been covered during a field operation based on GPS positions and then automatically turns on and off sections of the boom to prevent off-target application of inputs. Off-target application can be manifest as either double coverage on a previously treated area, such as a headland, or application in areas outside of the field boundary. Luck et al. (2010a) conducted an analysis of three irregular fields in central Kentucky that had been sprayed using an automatic section control system. The treated area was computed based on the data recorded by the application system and compared with the area that would have been treated if the sprayer had not used automatic section control. The reductions of the treated area in the three fields were 17.5%, 16.2%, and 15.2%. Reductions in off-target application in these fields were largely due to the irregular shape of the fields; less reduction would be observed in rectangular fields. Another study conducted on a wider variety of field shapes and sizes indicated that substantial reductions in off-target application could be achieved with the implementation of automatic section control using only seven independently controlled sections (Luck et al., 2010b).

Economic analyses have proven that the benefits of automatic section control increase with an increase in farm size, especially in areas with waterways, drainage ditches, and similar obstructions (Batte and Ehsani, 2006). However, the scenarios in that study were created hypothetically in order to compute off-target application area and distance traveled. Dillon et al. (2007) concluded that the savings in input expenses justified the adoption of automatic section control technology based on data collected in three irregular fields in Kentucky. Thus, considering the effect of field shape and size on the performance of an automatic section control system, a method or computational tool for estimating the off-target application area based on characteristics of the field boundary and application equipment would be of great value for improving the economic analyses. Producers could use such a tool to evaluate the potential impacts of the technology based on their particular field conditions and application equipment. Currently, there are no simple tools available to provide producers with these quantitative analyses.

OBJECTIVES

The goal of this study was to develop a tool to provide quantitative measures of off-target application in agricultural fields that could be used to assist producers in automatic section control purchase decisions and to assist researchers and

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Submitted for review in March 2010 as manuscript number PM 8498; approved for publication by the Power & Machinery Division of ASABE in December 2010.

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Vol. 54(1): 41-49 ISSN 2151-0032

equipment manufacturers in technology development. This goal was accomplished by:

- Developing a computational method for quantifying off-target application areas in agricultural fields.
- Implementing the unique algorithm in software with a graphical user interface.
- Comparing the output from software runs with field data from a previous study.

Materials and Methods

Our intention was to develop a software program that could accept field boundary information from a common Geographic Information System (GIS) file format (namely a shape file), allow the user to select the machine parameters, and then produce results showing anticipated off-target application areas for a straight parallel swath approach to field coverage. The program focused only on the overlap caused by swaths intersecting headlands at non-right angles, which implicitly assumed that there was no overlap or skips between adjacent headlands or parallel swaths. The field topography was not considered in the proposed method since, according to findings by Stombaugh et al. (2007), topography does not have a significant impact on machine overlap. The software tool, which is called the Field Coverage Analysis Tool (FieldCAT), was developed in MatLab (MathWorks, 2009) using customized functions and routines from the MatLab Mapping Toolbox.

The first task in developing the software was to develop the analysis algorithm. Once this algorithm was completed, it was apparent that several preprocessing steps were required on the field boundaries to make the program work more efficiently. Some preprocessing steps could be automated, and some required user input. Given these requirements, data input and editing modules were designed to facilitate input of field boundaries to the algorithm. Consequently, the overall program could be divided into three different modules: data import, data preparation (or editing), and coverage analysis (fig. 1). These modules were integrated with a graphical user interface (GUI) to facilitate FieldCAT usage and are discussed in more detail below.

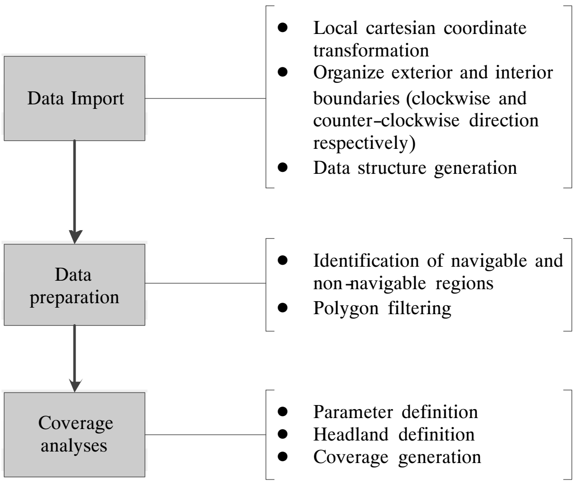


Figure 1. Summary of the basic functionality of each of the three FieldCAT modules.

Two analyses were performed to evaluate the performance of the FieldCAT software. The first analysis was designed to demonstrate the off-target calculation capabilities of the program, including analyses of section control resolution and path orientation. It involved detailed evaluation of nine different field boundaries. The second analysis was intended to provide validation of the program output by comparing the FieldCAT simulation output with actual field performance data from 25 different fields.

Program Module Development

Data Import

Shape files are loaded into FieldCAT using the built-in MatLab "shaperead" function. The field boundary coordinates are converted to a local Cartesian coordinate system with a reference at the southwestern limits of the field boundary to make all easting and northing coordinates positive and relatively small. The coordinates of the exterior field polygon boundaries are ordered in a clockwise traverse of the boundary, and the coordinates of isolated polygons within field boundaries are ordered counter-clockwise. At this point, a data structure is created to manage the information throughout the process. The data structure allows multiple "callback" routines triggered from the GUI to access and share data without creating global variables. Some of the data contained in the data structure include the complete set of boundary coordinates, navigable and non-navigable boundary coordinates, filtered boundary coordinates, headland width, and swath width.

Data Preparation

After field boundary data are imported into the program, there are two primary tasks that are completed in the edit mode of the program. The first task involves identification of portions of the boundary as navigable or non-navigable, and the second task involves filtering the boundary data to reduce the number of vertices used to describe the boundaries.

Identification of Navigable Areas

In the program's edit mode, the user is able to select portions of the field boundaries using the GUI and define them as navigable or non-navigable. This distinction is critical for accurate assessment of off-target application, particularly in fields with internal waterways or other obstructions. Exterior field boundaries are normally considered non-navigable, meaning that machines physically cannot cross the boundary. For example, if a waterway boundary is navigable, meaning that the machine can traverse the obstruction, then the operator will not need to make a headland pass around the obstruction boundary. On the other hand, if the obstruction is non-navigable, such as a deep ditch or tree, then the operator would normally need to make a headland pass along the boundary of the obstruction. This extra headland coverage will have a significant impact on the computation of the off-target application area. Once the regions are selected and individually saved, the final boundary is updated in the data structure.

Filtering Polygon Vertices

In agricultural settings, field boundary coordinates are usually collected with a GPS receiver connected to a data logger. Typically, position data along the boundary are recorded at a constant frequency as the data logging equipment traverses the boundary, which can produce a high density of data points along the boundary depending on the data logging frequency and vehicle speed. Large numbers of points might be necessary to define a sharp curve in the field boundary, but considerably fewer points may adequately define straight edges of the boundary. Furthermore, the number of iterations of the analysis algorithm is directly dependent on the number of field polygon vertices. Consequently, a filtering algorithm to reduce the number of boundary points was implemented using MatLab's "reducem.m" function, which is based on the Douglas-Peucker line simplification algorithm (MathWorks, 2009). The Douglas-Peucker method recursively subdivides a polygon until a window of points can be replaced by a straight line segment, where no point in the window can deviate from the straight line by more than a defined distance tolerance. A tolerance in terms of the percentage of the polygon area is more intuitive for this application; therefore, the FieldCAT user inputs the maximum area error tolerance, and the length tolerance is computed automatically. The area error is computed by comparing the initial area and the area of the reduced polygon. If the area error is greater than the desired tolerance, then the length tolerance is recursively decreased until the area tolerance is less than the desired error. A filtering procedure to check for self-intersecting segments of the polygon is also implemented to compensate for changes in vehicle direction while GPS field boundaries were being logged. A message box reporting the percentage area error for the navigable and non-navigable regions and a graphical presentation of the filtered boundary allow the user to visually judge if the filtering process produces satisfactory results.

COVERAGE ANALYSIS

Parameter Definition

Once the field editing is completed, FieldCAT enters the coverage mode. At this point, the controlled section and headland widths are defined along with the path orientation. The user is able to either select a single fixed path direction for field coverage or multiple directions, thereby allowing the program to rotate the path direction by a user-selectable angle increment.

Headland Generation

The headland areas are created prior to the coverage generation. The coordinates of the headland are computed by buffering the clockwise non-navigable boundaries towards the interior of the polygon and buffering the counter-clockwise non-navigable obstruction boundaries towards the outside the polygon. If a portion of the outside field boundary has been selected as navigable, that region is clipped by the headland polygon. The program then resolves issues with overlapping headland areas and navigable waterways by clipping or combining regions as appropriate.

Coverage Generation

The coverage analysis algorithm (fig. 2) implemented in FieldCAT, as stated earlier, focuses only on the overlap caused by swaths intersecting headlands at non-right angles. It overlays a series of straight parallel swaths onto the field boundary and then computes the encroachment of those swaths into the headland areas of the field or extension outside the field boundary. It does this by first constructing a series of parallel lines separated by the machine or section width and oriented at the defined angle to the boundary. Two adjacent lines define the edges of a swath. For each swath, all vertices of the headland boundary polygon that fall within the swath are identified. Then lines orthogonal to the swath lines passing through each vertex within the swath region are constructed (fig. 3). The orthogonal lines are sorted based on northing offset. The intersection of two consecutive orthogonal lines with the swath boundary lines forms a rectangle, which is either totally within the field area or partially in the field area and partially in the headland or outside the field boundary.

Using the polygon Boolean operation function, the portions of the rectangle that fall inside and outside the headland or field boundaries are computed (fig. 4). For instance, if the portion of a rectangle area that does not intersect the headland polygon is the same as the area of the original rectangle, then the rectangle is considered totally included in the field area; consequently, it would receive only a single coverage. If the rectangle is partially included in the headland area, then the intersecting region is separated from the original rectangle and that portion of the area is classified as a double coverage area, while the rest of the rectangle is classified as single coverage.

The algorithm also accounts for machine travel into areas outside of navigable boundaries (e.g., waterways). With a similar Boolean approach, the portions of rectangles extending across navigable boundaries into the exterior of the field boundary are classified as wasted application. If a rectangle is completely outside the field boundary area in a navigable boundary region, this area is classified as "no application" since the machine should be shut off by the operator even without the use of automatic section control. This area does not affect off-target area calculation.

This entire classification process is repeated for every rectangle bounded by two adjacent orthogonal lines along each swath of the field. The number of algorithm iterations is dependent on the number of vertices of the headland polygon; thus, the polygon filtering operation is an important step to reduce algorithm execution time.

The areas of each region and their respective coordinates are stored in the data structure. The total off-target area reported is the sum of the double coverage and wasted application areas. The program output is generated based on the field data structure information stored during the computations. A summary containing the simulation parameters as well as the area information is displayed at the end of the process (fig. 5). The summary is also saved in a comma delimited text file, and the field data structure is saved in a .mat file.

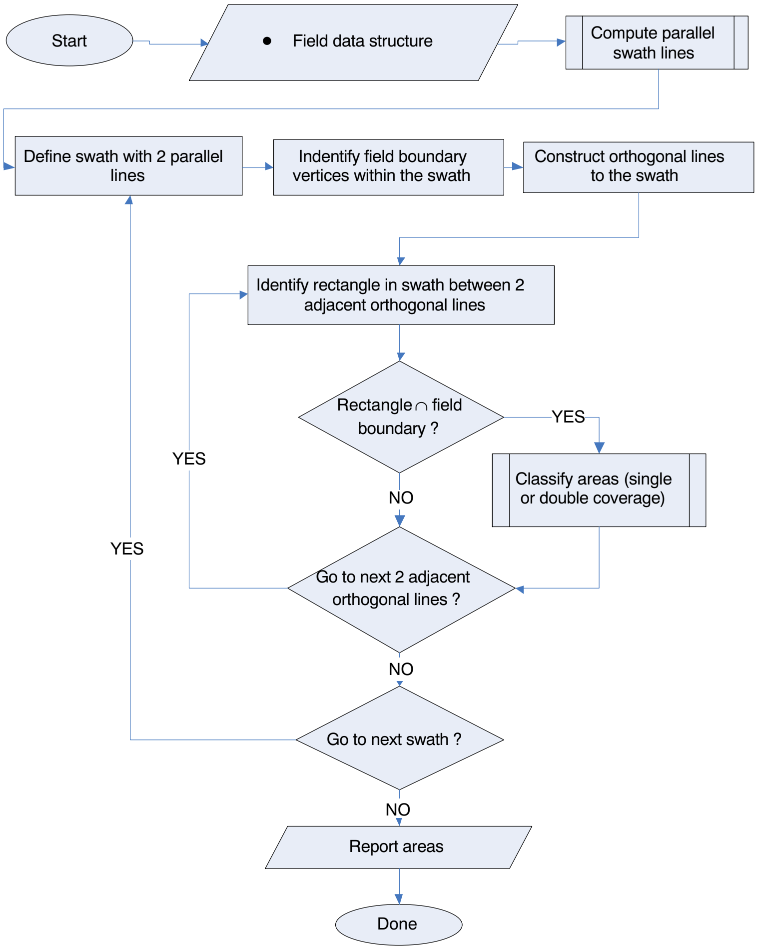


Figure 2. Structure of FieldCAT coverage simulation algorithm.

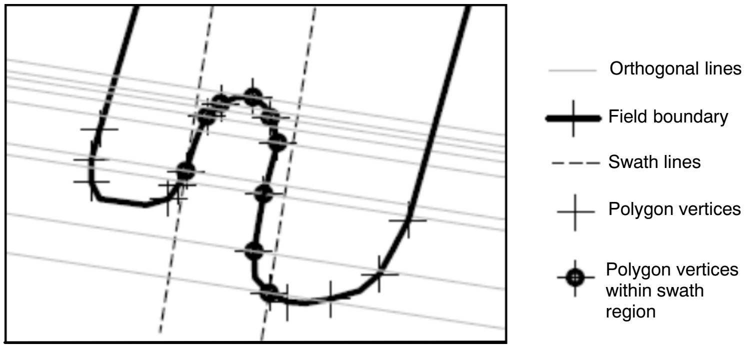


Figure 3. Identification of boundary vertices within a swath and construction of orthogonal lines through each of those vertices.

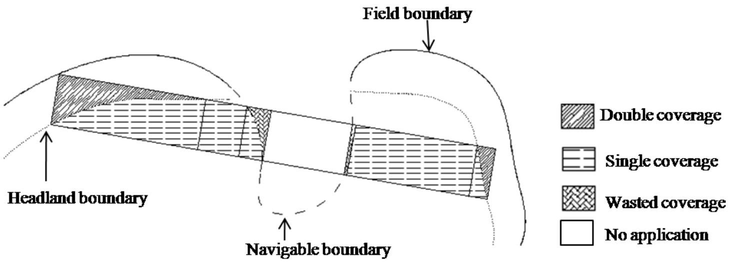
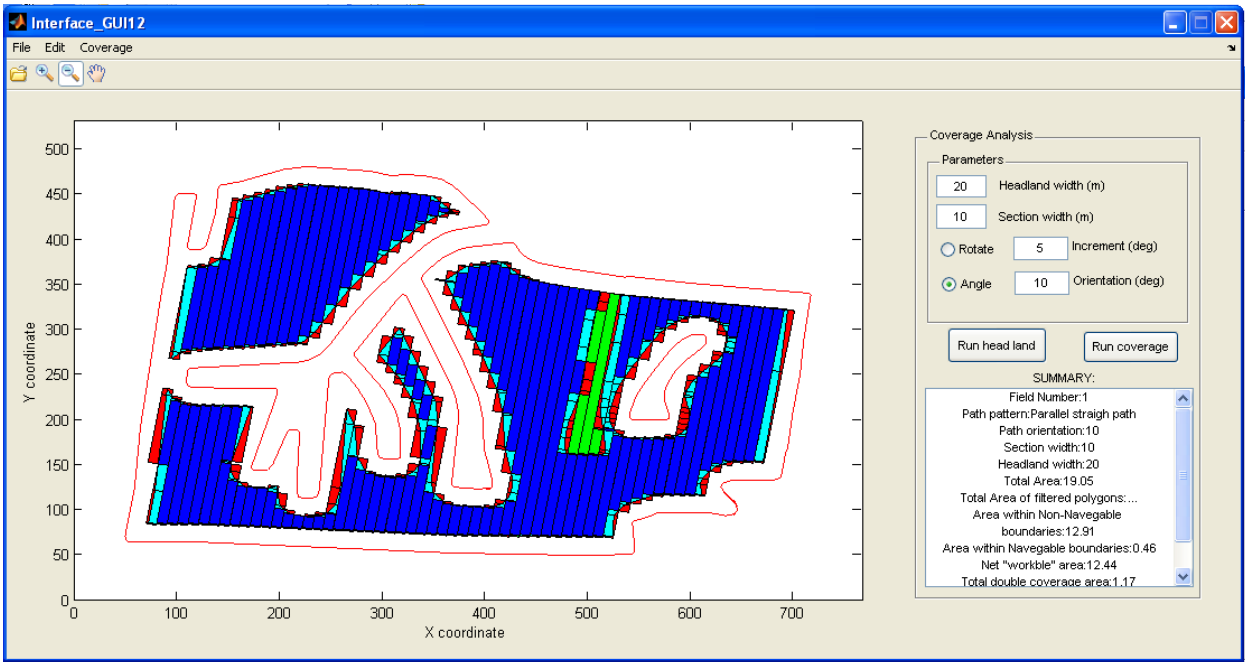


Figure 4. Example of identification and classification of areas in a swath through a navigable boundary that would receive single, double, wasted, or no coverage. The total off-target application area is the sum of the double and wasted coverage areas.



20 Headland width (m)
10 Section width (m)
○ Rotate 5 Increment (deg)
● Angle 10 Orientation (deg)

SUMMARY:
Field Number:1
Path pattern:Parallel straigh path
Path orientation:10
Section width:10
Headland width:20
Total Area:19.05
Total Area of filtered polygons:...
Area within Non-Navegable boundaries:12.91
Area within Navegable boundaries:0.46
Net "workble" area:12.44
Total double coverage area:1.17

Figure 5. Screen capture of the data displayed after a simulation. Red color represents overlap and wasted application (off-target application areas). Cyan and dark blue represent the single coverage area, and green represents "no application" areas.

EXPERIMENTAL PROCEDURE

PROGRAM TEST

Nine irregular field boundaries representing farms in central and western Kentucky (fig. 6) were used as examples to test and demonstrate the algorithm. The performance of the boundary filtering technique was reported for the nine fields, as well as results from evaluation of section control resolution and path rotation effects on off-target application area. A 27 m wide sprayer was used with the smallest controllable section width of 0.5 m. To evaluate the effects of automatic section control, the boom was divided into 2, 3, 6, 9, 18, 27, and 54 sections, which corresponded to controlled section widths of 13.5, 9, 4.5, 3, 1.5, 1 and 0.5 m, respectively. The angle at which the parallel paths were generated was varied from 0° to 175° in 5° increments to evaluate the influence of path orientation on off-target application area. Since eight

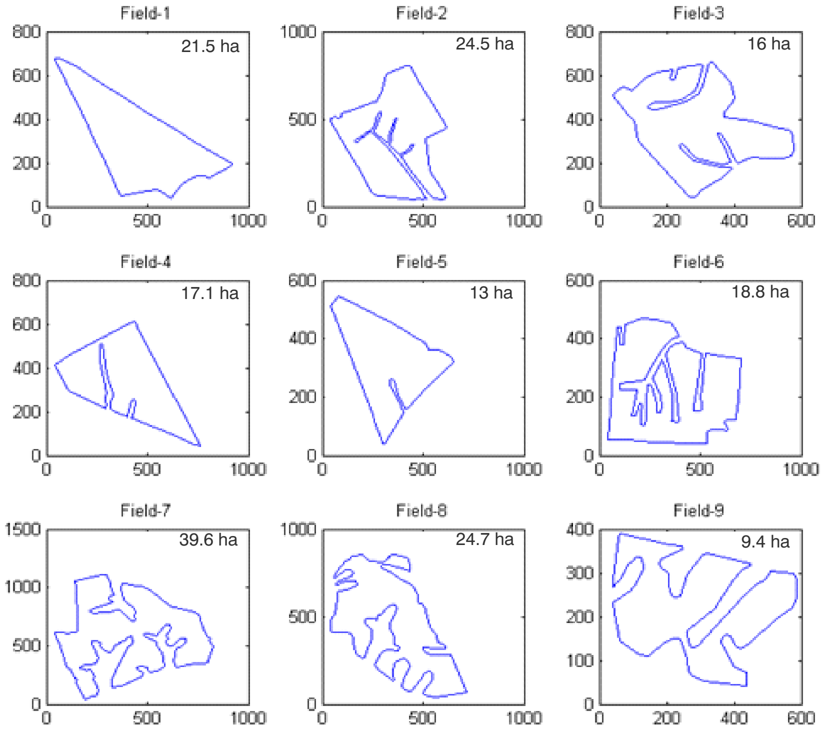


Figure 6. Boundaries of the nine example fields typical of Kentucky farms that were used to test the FieldCAT algorithm.

different section widths were evaluated and each path pattern was rotated from 0° to 175°, there were 288 different coverage patterns evaluated for each field.

Field Data Comparison

For field data comparison, simulation results from FieldCAT were compared to field performance data reported by Luck et al. (2010b). Twenty-one fields ranging in size from 3.1 to 101.0 ha were evaluated. Some of the fields contained grassed waterways and non-navigable obstacles within a unique field boundary, which is typical of agricultural fields in Kentucky. Fields that were comprised of multiple non-connecting polygons were separated into multiple individual fields for coverage simulation purposes, resulting in a total of 25 fields.

The field data were collected with a 24.8 m sprayer, which was equipped with an automatic section control system and an autosteer system utilizing a sub-meter accuracy GPS receiver. The autosteer system was configured to maintain a pass-to-pass overlap of 15 cm. The boom was divided into seven sections. The middle section was 648 cm wide, the next sections out on both sides were 609 cm wide, and the two sections on either end of the boom were 152.5 cm wide. In order to perform an equitable comparison, FieldCAT parameters were adjusted to simulate the same boom configuration and swath spacing used by the sprayer.

Program Test Results

Boundary Filtering Algorithm

The field boundary filtering algorithm proved to be robust and efficient. In the nine example fields evaluated, polygon vertices were reduced by as much as 92% with an area error less than 0.1% (table 1). Even in the most complicated field boundaries, the algorithm was able to reduce the number of vertices by more than 50% without a drastic change to the area (fig. 7).

Controlled Section Width

Because of the number of computation permutations that the software can perform on each field, there are a number of analyses that could be performed using the program output. For example, researchers might be interested in using the data to explore field efficiency and path optimization studies. Producers are particularly interested in the value of automatic section control. The results obtained with Field- CAT by varying the section width clearly showed the advantages of controlling smaller sections, as evidenced by the reduced off-target application area.

Table 1. Results of the polygon filtering operation for the nine fields analyzed.

Field	Total Points on Non-Navigable Boundary	Points Removed (%)	Area Error (%)
1	442	91.6	0.07
2	498	82.7	0.07
3	348	64.4	0.07
4	379	88.1	0.09
5	173	71.1	0.09
6	1038	77.7	0.03
7	378	58.7	0.06
8	307	67.4	0.04
9	220	59.5	0.06

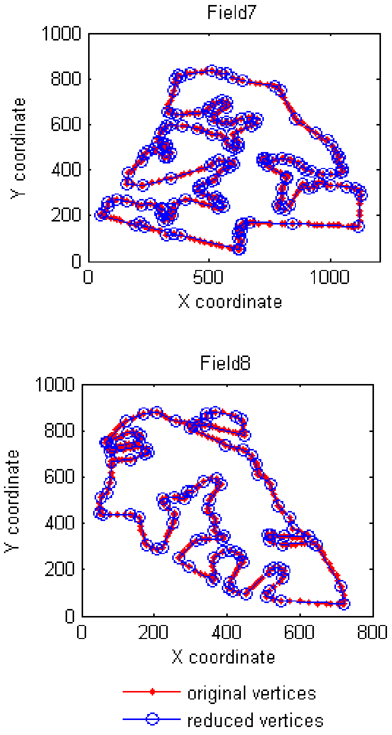


Figure 7. Results of the polygon filtering operation for two example fields.

For fields 1, 2, 4, and 5, it was possible to determine the predominant orientation of the travel paths in current practice by interpreting the GPS coordinates collected during field operations. For the other fields, approximations of row orien–

Table 2. Percentage off-target application resulting from four different section widths in the nine test fields.

Field	Area (ha)	Controlled Section Width 27 m	13.5 m	1 m	0.5 m
1	21.5	9.1	6	0.5	0.2
2	24.5	13.7	7.2	0.6	0.3
3	16	15.5	9	0.7	0.3
4	17.1	15.4	8.1	0.6	0.3
5	13	12.5	7.2	0.5	0.3
6	18.8	17.3	9.7	0.7	0.4
7	39.6	16.8	8.1	0.6	0.3
8	24.7	16.5	8.4	0.6	0.3
9	9.4	27	13.1	1	0.5

Table 3. Maximum and minimum off-target coverage for 27 and 0.5 m section widths, along with the path orientation at which each value occurred in the nine test fields.

Field	Area (ha)	27 m Section Width Maximum (%)	27 m Section Width Minimum (%)	0.5 m Section Width Maximum (%)	0.5 m Section Width Minimum (%)
1	21.5	12.5, 125°	5.0, 30°	0.2, 115°	0.1, 30°
2	24.5	15.4, 175°	7.9, 60°	0.5, 135°	0.2, 60°
3	16.0	17.0, 150°	12.6, 75°	0.4, 135°	0.3, 70°
4	17.1	15.9, 125°	7.5, 65°	0.3, 135°	0.2, 65°
5	13.0	15.4, 150°	7.3, 55°	0.4, 135°	0.2, 55°
6	18.8	20.6, 40°	14.7, 90°	0.4, 35°	0.3, 95°
7	39.6	17.3, 10°	9.7, 85°	0.3, 0°	0.2, 85°
8	24.7	17.3, 140°	13.2, 90°	0.9, 135°	0.3, 90°
9	9.4	29.8, 50°	17.8, 180°	1.0, 135°	0.4, 145°

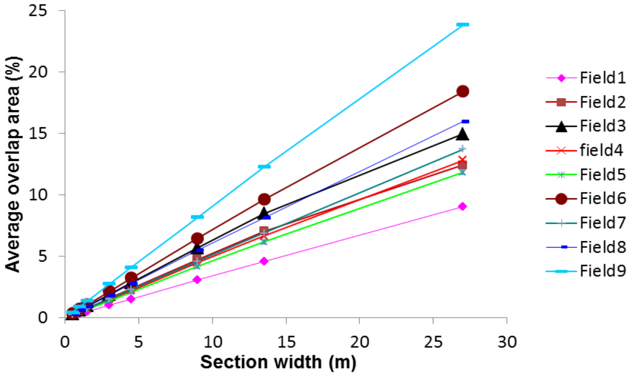


Figure 8. Percent of the field area classified as off-target application area with different section widths for the nine test fields at a path orientation typically used in each field.

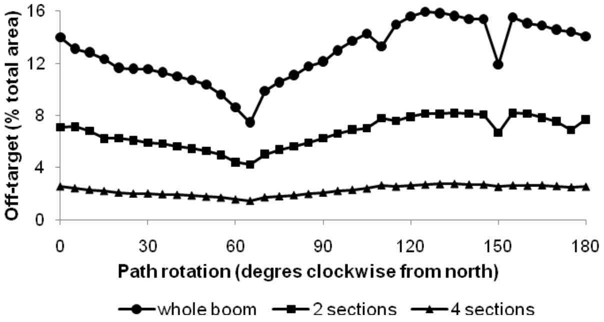


Figure 9. Percent of the field area that would receive off-target application at different path orientations in field 4 as a function of the number of sections controlled. This field is typically managed at a path orientation of 150°.

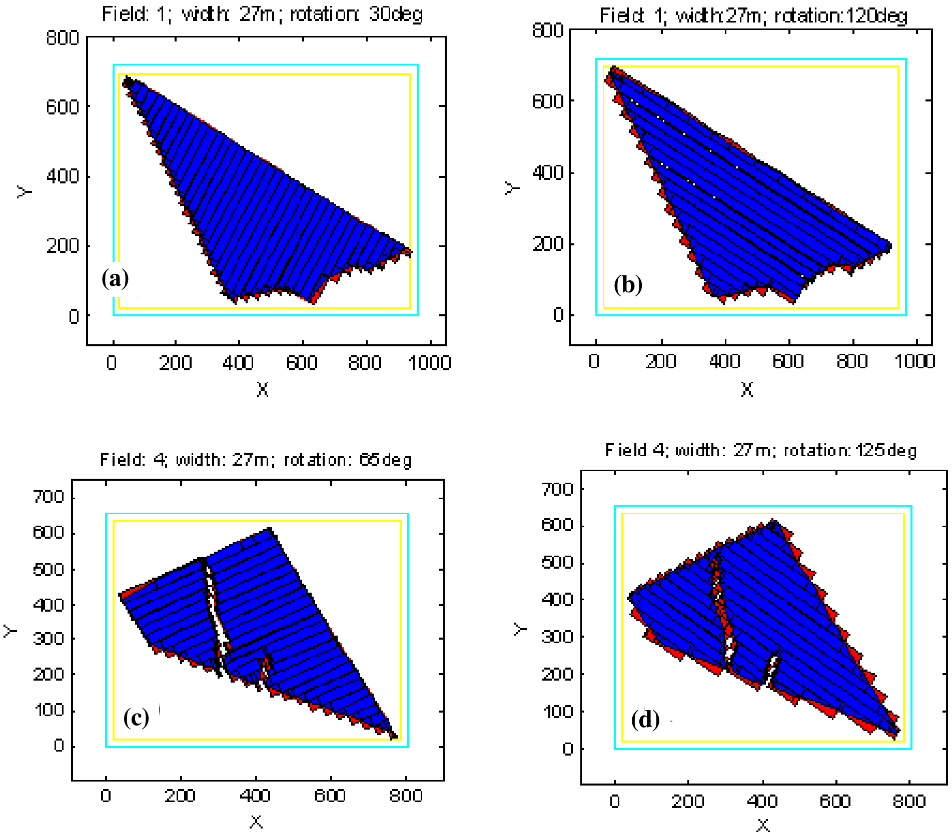


Figure 10. Path orientations causing (a) minimum and (b) maximum double coverage for field 1 and (c) minimum and (d) maximum double coverage for field 4.

tations were determined by inspection of aerial photography (KDGI, 2006). FieldCAT was used to determine the potential impact of different resolutions of automatic section control applied to machinery operated at the current practice orientation (fig. 8, table 2). A producer could use these data to compare the savings that would result from different numbers of controlled sections to the cost of implementing the automatic control at those resolutions to determine the best equipment for a particular field or set of fields.

The results revealed that even for less complex field boundaries (e.g., fields 4 and 5), reduction of the double coverage area was notable. Reductions of this magnitude when applied to multiple field operations (e.g. spraying, planting, or nitrogen application) performed throughout the season could yield substantial cost reductions.

PATH ORIENTATION

Off-target application coverage analyses were performed on each of the nine fields at different path orientations and different section widths. At first glance, the results showed that the software tool could be useful for producers to determine the best path orientation for their equipment set because, as expected, the results clearly showed that path orientation has an effect on the percentage of the field that receives off-target coverage (table 3, fig. 9). For less complex boundaries, such as fields 1, 4, and 5, path orientations that resulted in minimum and maximum off-target application tended to be similar across the different section widths, whereas for more complicated shapes, the path orientation varied to a greater extent depending on the section width.

An interesting finding regarding the simpler field boundaries was that the minimum double coverage path orientation did not always coincide with the most intuitive path orientation that would often be chosen to cover the field. This was particularly noticeable in fields 1 and 4, where the minimum double coverage path orientation was not the typical orientation (fig. 10). An important point to note is that the number of turn maneuvers required for the minimum off-target path orientation was much higher than for the maximum off-target path orientation. For instance, 25 swaths were needed to cover field 1 with the 30° orientation, whereas 17 swaths were sufficient with the 125° pattern (fig. 10). This issue results in an optimization problem to evaluate the tradeoff between machine field efficiency and application error.

FIELD DATA COMPARISON RESULTS

Actual field performance data from an automatic section control system (Luck et al., 2010b) were compared to simulation results obtained using FieldCAT (fig. 11). Note that the simulated off-target application area was always less than the actual off-target area observed from the field dataset. Although at least part of this discrepancy may be attributed to less than ideal performance of the automatic section control system, the automatic steering system employed on the sprayer was also a major contributing factor, especially considering that it relied on sub-meter accuracy GPS rather than a more precise RTK-GPS. Luck et al. (2010a) discussed the contribution of DGPS to overlap errors. Position accuracy would not significantly affect the off-target computation since the section control is based on the perceived position of the vehicle, as indicated by the GPS data. Similarly, the automatic steering system performance is based on perceived position; however, increased noise in position data would make it more difficult for the steering control to follow the desired path, thus decreasing the perceived steering accuracy along the paths. In addition, there was some deviation from the desired path on headlands, through curves, and near the ends of swaths as the machine steering was converging to the desired path. The off-target application estimates reported by Luck et al. (2010b) included this lateral deviation as well as the headland encroachment overlap. FieldCAT assumes perfect guidance and thus no lateral overlaps or skips between adjacent passes. Unexpected maneuvers in the middle of the field were also observed in the field datasets, which caused additional overlapped areas that were not replicated by the simulation algorithm.

On initial inspection, the larger fields as well as fields with greater numbers of internal obstacles appeared to have more off-target application area and more discrepancy between the simulated and the field-observed off-target areas. Fields 1, 17, and 20 were the largest fields of the dataset. As expected, they exhibited the largest overall off-target application area, but they also exhibited the largest difference between the simulated and field-observed data. Field 9, although slightly smaller, also exhibited a large discrepancy, which was probably due to the high number of non-navigable obstacles encountered in that field that required irregular maneuvering by the operator.

Although the simulation underestimated the off-target area, it presented a strong relationship (coefficient of determination of 0.77 and coefficient of correlation of 0.87) with the field-observed data (fig. 12a), indicating the validity of the method. A simple compensation factor could be applied to the model if the error was systematic or constant; however, the errors were proportional to the field size, as previously explained. The difference between the simulated and observed off-target areas was found to be a factor 0.04 times the field area (fig. 12b). Thus, these data could be used, for example, to quantify the effectiveness of a guidance system combined with operator skill in maneuvering on headlands passes and in headland turns. To further validate the model results, a 4%

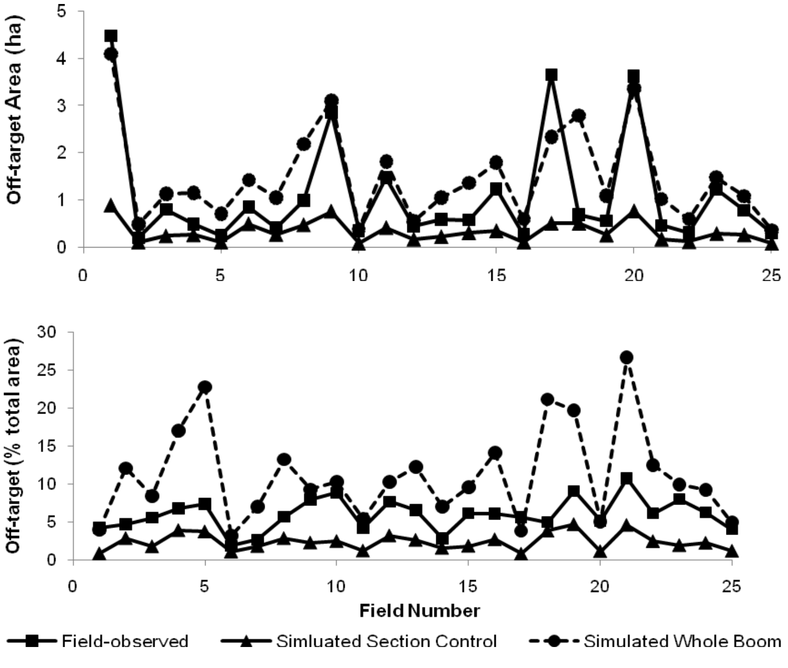


Figure 11. Off-target application computed from field-observed section control data and from the simulation tool for each of the 25 fields analyzed.

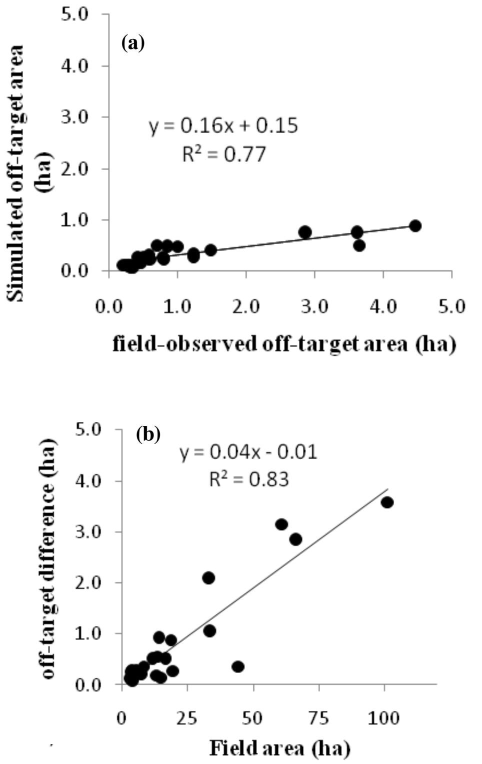


Figure 12. (a) Simulated off-target application versus observed off-target application, and (b) difference between the off-target application area as simulated and as measured from field performance versus the field area.

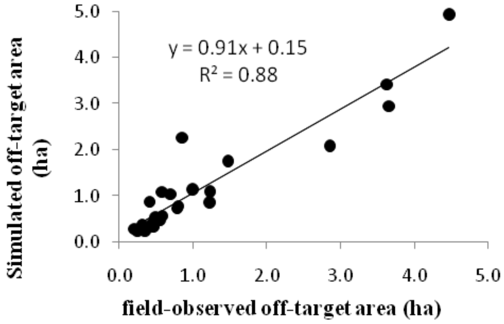


Figure 13. Simulated off-target application considering 4.0% off-target due to pass-to-pass overlap versus observed off-target application.

area-proportional factor was applied to the program output, and the resulting simulated data were very close to the field-observed data (fig. 13).

CONCLUSIONS

A software tool (FieldCAT) developed and described herein was able to provide a quantitative estimate of off-target application of inputs that would occur because of the limited resolution of machine-controlled section width and the path orientation for different field shapes. Results clearly showed that potential savings could be achieved with the implementation of automatic section control technology. FieldCAT was also used to illustrate that path orientation can have a significant impact on input errors due to point rows and headland encroachment. Additionally, use of the tool elucidated the conflict between the optimum path orientation for minimizing application errors and the optimum path for maximizing machine field efficiency.

Comparison of FieldCAT output with field data confirmed the validity of using the tool to evaluate off-target application area. The field data comparison also indicated that a complete analysis of off-target coverage during application of field inputs must consider guidance errors.

ACKNOWLEDGEMENTS

This material is based upon work supported by the USDA Cooperative State Research, Education and Extension Service under Agreement No. 2008-34628-19532. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the view of the USDA. The information reported in this article (No. 10-05-102) is part of a project of the Kentucky Agricultural Experiment Station and is published with the approval of the Director. Mention of trade names is for informational purposes only and does not necessarily imply endorsement by the Kentucky Agricultural Experiment Station.

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