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A model to analyze as-applied reports from variable rate applications

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Abstract During variable rate operations, controller systems report information (as-applied files) about desired rates and real applied rates on georeferenced points along the machine tracks. These reports are useful for operation quality control but they have not been widely used to their potential. The goal of this study was to create a model to help analyzing as-applied files based on quantifying and locating off-rate errors and their probable related sources. The model calculates off-rate error at every point and classifies them as less than target rate, acceptable or over the target rate. Possible error sources are classified regarding three aspects: vehicle path position (inward, middle or outward), high rate change (step up or down) and vehicle acceleration or deceleration. A pulled type applicator (application 1) and a self-propelled applicator (application 2) were analyzed. An average of 30.6 % of the recorded points was considered application errors (10 % off the target rate). 70.5 % of them occurred on high rate change points on application 1 and 69.7 % on acceleration/deceleration points on application 2. The self-propelled applicator performed better during high transition rate than the pulled type which performed poorly when transition rate exceeded 10 %. The model determined the major and minor factors related to application error. It provided means to assess equipment limitations and its impact over the quality of application. The trials demonstrated its flexibility and how it can improve the use of as-applied files.

Keywords Variable rate · As-applied files · Off-rate error · Application error sources · Model

Introduction

Among the site-specific management (SSM) techniques, probably the most marketed and adopted is variable rate technology (VRT). It has become an accepted way to apply crop

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inputs site-specifically. Basically it allows application of inputs at different rates within the field, based on prescription maps or sensor scanning. This technology provides the chance to improve efficiency of inputs, cut costs, generate environmental benefits and result in a more uniform crop, in terms of both yield and quality, all at the same time.

In contrast to conventional methods, VRT meets the modern agriculture needs but, at the same time, it adds complexity to the system. Equipment are sometimes required to perform rapid and intensive rate changes, often following detailed prescription maps generated on a $10 \times 10\ m^2$ pixel scale. Equipment performance has been greatly demanded as pointed out by Schumann et al. (2006) and Cugati et al. (2007). They described single tree prescription fertilization in a citrus orchard, a situation where controller response and rate change should be extremely rapid (4 s is required to pass one tree space, when driving at $1.34\ m\ s^{-1}$). So, often machines cannot follow the prescription maps accurately and off-rate error occurs in the operation. Deficiencies in machine accuracy have been known since the early stages of SSM (Goense 1997).

Application reports ("as-applied files") are available for most variable rate equipment to assess quality of operation, field efficiency and off-rate errors. They register the prescribed rate and the actual applied rate (estimated by the controller) at georeferenced points along the machine paths. Although they contain important information, the as-applied files have been misused by farmers and often taken as simple documentation of operation. This might be due to the lack of user friendly tools that help to analyze reports, leading to poor field trials of equipment and often expectations surrounding VRT cannot be fulfilled.

Authors have presented methods to evaluate quality of variable rate operations based on as-applied files. Fulton et al. (2003), Lawrence and Yule (2007) and Fulton et al. (2013) showed the importance of representing as-applied maps that consider the transversal distribution pattern of spinning disk spreader equipment. These studies are examples of better use of as-applied files, using sophisticated methods to turn raw information into application maps that represent actual deposition and spatial distribution of product in the field. These authors claim that because of poor performance of applicators regarding several aspects (transition rates, overlapping, as well as variation on transversal distribution), the prescription maps are not sufficient to represent field application, so often assumptions regarding VRT are misleading.

A different approach is proposed in this work to improve the use and analysis of as-applied files by practitioners. It focuses not only on verifying application errors, but also to relate them to application situations that might lead to error, which helps understanding of the existing cause/effect relationship in a variable rate application.

Off-rate error occurs when the desired rate is not achieved during the operation. Several aspects might cause these errors. The most common and studied is the rate change. The accuracy at this moment depends on the response or delay time (time gap between rate change signal and actual rate change start) and transition time (time gap between rate change start and finish) of the equipment (Fulton et al. 2005). Another parameter that can be evaluated is the reaction time which indicates the time required by a control system to reach a certain percentage (varies from 50 to 90 %) of the desired application rate (Tumbo et al. 2007). When the application is guided by a prescription map, the "look-ahead" time can be configured based on these parameters. This software device allows the control system to start the rate change before the transition boundary, minimizing off-rate errors.

Vehicle speed changes can also play an important role in application accuracy, once it is a key variable in calculating product dosage. If the equipment changes speed (accelerates or decelerates), the controller must adjust the output flow to achieve the desired dose. Thereby, changing the output flow to correct speed variations also depends on the controller response time. Acceleration or deceleration might occur randomly during the operation due to field slope and systematically when the vehicle approaches headlands and re-enters the field. Error might also occur when the application is turned on or off, because the control system requires a brief time to complete these tasks. So, delays for turning on and off the application when beginning or ending a swath might also lead to off-rate errors. Based on the causes mentioned, it can be stated that the chances of application error are higher whenever there is transition rate in the prescription, changes in vehicle speed or when the application system is turned on or off. These application conditions could all be assessed for every position of the machine in the field if the as-applied file is carefully analyzed.

To encourage better equipment and operation evaluation, the objective of this work was to develop a simple, flexible and user friendly tool that facilitates interpretation of variable rate as-applied files concerning information about off-rate error, application conditions and possible error sources. This would provide means to evaluate equipment performance and quality of operation.

Methodology

A model to analyze application reports was developed in an electronic spreadsheet. It is composed of four main parts: data input, calculation of off-rate error and application conditions (vehicle acceleration and rate change), classification of error and sources and output results (Fig. 1).

The input data is found in any regular as-applied file generated during variable rate application. It contains geographic co-ordinates, time, prescribed rate and the estimated applied rate at each point recorded along the application path, according to the GNSS collecting frequency. Geographic co-ordinates are converted into metric co-ordinates (herein UTM co-ordinates) for further data processing.

Error calculation

Application off-rate errors are calculated based on prescribed rates and estimated applied rates, either as a difference between the two rates and as a percentage of prescribed rates (Eq. 1).

$$E_i = \frac{(AR_i - PR_i)}{PR_i} \times 100 \tag{1}$$

where, E_i is the application off-rate error at point i (%); AR_i is the estimated applied rate at point i (mass/volume area^{-1}); PR_i is the prescribed rate at point i (mass/volume area^{-1}).

The calculated error is classified into three categories: under target rate, over target rate, or considered as an acceptable error. The parameters used for the classification are all adjustable in order to suit each operation specifications.

Error source classification

To analyze possible error sources, the recorded points are classified into situations that might lead to the application error. There are three possible error sources covered by the model: vehicle positioning along the path (inward, middle or outward), high rate change (step up or down) and vehicle acceleration (or deceleration).

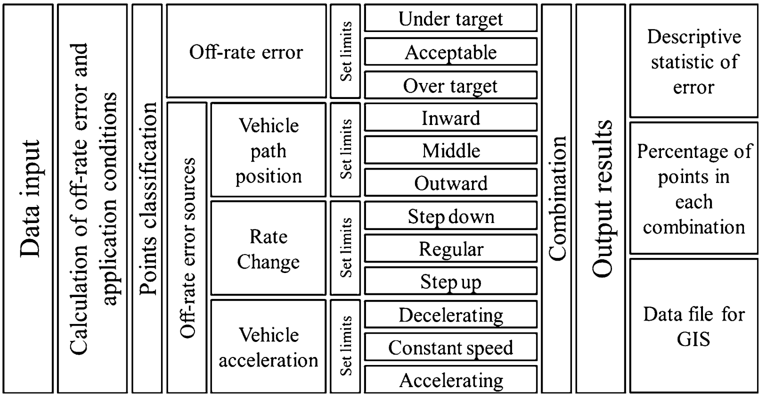

Fig. 1 Model design to analyze as-applied files

The vehicle positioning along the path is determined by first recognizing the first and last point registered in each path (Fig. 2). The angle between two vectors (from three consecutive points) is calculated. If it exceeds a given angle (user defined), it is determined that the machine turned to start a new path and so the model will identify the two extremity points of each path. Later, the distances between every point in the path and the extremity points are calculated (Fig. 2). If the calculated distance is smaller than a given distance (user defined) that point will be considered as "inward" or "outward" point, depending if the vehicle is beginning or ending a path. If the distance is greater than the user-given distance, it is recognized that the vehicle is in the middle of a path and this positioning, per se, should not be related to off-rate error.

High rate change on prescription maps often causes application errors. To identify these occurrences, prescribed rates are verified at recorded points. The rate change at consecutive points is calculated according to Eq. 2. A limit is set to classify rate changes as "step up", "regular" or "step down".

$$RC_i = \frac{(PR_i - PR_{i-1})}{PR_{i-1}} \times 100 \tag{2}$$

where, PR_i is the prescribed rate at point i (mass/volume area^{-1}); RC_i is the rate change at point i (%).

The third error source investigated is vehicle acceleration or deceleration. Machine speed at each co-ordinate is calculated according to the distance from a previous point, and the GNSS collecting frequency (Eq. 3). Based on settable limits, vehicle acceleration (Eq. 4) is classified into three types: "accelerating", "decelerating" or "constant speed".

$$S_i = \frac{D_i}{\Delta t} \tag{3}$$

$$A_i = \frac{(S_i - S_{i-1})}{\Delta t} \tag{4}$$

where, S_i is the vehicle speed at point i (m s^{-1}); D_i is the distance between point i and point i-1 (m); A_i is the vehicle acceleration at point i (m s^{-2}); Δt is the time gap between records (s).

According to the classification method developed, the model provides 54 combinations of error and possible error sources, each one labeled with an ID number (Table 1). It

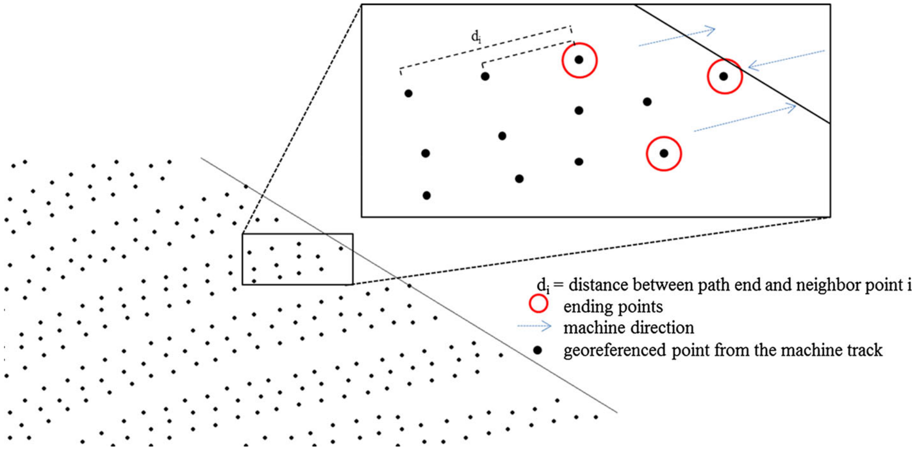

Fig. 2 Recognition of path endings to determine vehicle position along the paths

includes combinations that do not explain the error (classification ID's 14 and 41), which is when the machine is in the middle of a path, performing a regular rate change, traveling at constant speed and still the application was not accurate. Error under or over target rate that occurs in this condition are labeled as a "random error".

Output data

The output result includes descriptive statistics of error, percentage of points in each classification of error and sources and a ranking of the most frequent error and possible error source combinations. The model also composes files ready for geographic information system (GIS) software, containing data about a point's classification and its specific combination of error and sources allowing users to access geographic information and application error diagnostic through maps.

Implementation example

The model was run using as-applied files from two fertilization scenarios. The first application was carried out on an orange orchard using a pulled type fertilizer spreader (Fig. 3a) with conveyor belt and pneumatic assisted delivery mechanism. The dosage mechanism acts on the fertilizer conveyor belt speed and on the gate opening height. An airflow produced by a centrifugal blower, carries the product along two pipes to dispose it under the tree canopies. The second application occurred on a corn field using a self-propelled machine with conveyor belt and pneumatic assisted delivery mechanism (Fig. 3b). Applicators both had similar dosage and distribution mechanisms, but the latter had nine dispersal tubes for individual crop rows. They were equipped with the same variable rate instrumentation and positioning system. The control systems in these machines estimate the applied rate by assessing the conveyor belt speed and gate opening height at each georeferenced point. These two parameters are converted into applied rate (kg ha^{-1}) based on previous calibration. The calibration consists of weighing the applied product using different configurations of conveyor belt speed and gate opening height. Applicators reproduced prescription maps on raster format with 100 m^2 area pixels. The

Table 1 Combinations of error and sources given by the user defined classification

Classification ID	Off-rate error	Vehicle path position	Rate change	Vehicle acceleration	Classification ID	Off-rate error	Vehicle path position	Rate change	Vehicle acceleration
1	Under target	Inward	Step down	Decelerating	28	Over target	Inward	Step down	Decelerating
2	Under target	Inward	Step down	Constant speed	29	Over target	Inward	Step down	Constant speed
3	Under target	Inward	Step down	Accelerating	30	Over target	Inward	Step down	Accelerating
4	Under target	Inward	Regular	Decelerating	31	Over target	Inward	Regular	Decelerating
5	Under target	Inward	Regular	Constant speed	32	Over target	Inward	Regular	Constant speed
6	Under target	Inward	Regular	Accelerating	33	Over target	Inward	Regular	Accelerating
7	Under target	Inward	Step up	Decelerating	34	Over target	Inward	Step up	Decelerating
8	Under target	Inward	Step up	Constant speed	35	Over target	Inward	Step up	Constant speed
9	Under target	Inward	Step up	Accelerating	36	Over target	Inward	Step up	Accelerating
10	Under target	Middle	Step down	Decelerating	37	Over target	Middle	Step down	Decelerating
11	Under target	Middle	Step down	Constant speed	38	Over target	Middle	Step down	Constant speed
12	Under target	Middle	Step down	Accelerating	39	Over target	Middle	Step down	Accelerating
13	Under target	Middle	Regular	Decelerating	40	Over target	Middle	Regular	Decelerating
14[a]	Under target	Middle	Regular	Constant speed	41[a]	Over target	Middle	Regular	Constant speed
15	Under target	Middle	Regular	Accelerating	42	Over target	Middle	Regular	Accelerating
16	Under target	Middle	Step up	Decelerating	43	Over target	Middle	Step up	Decelerating
17	Under target	Middle	Step up	Constant speed	44	Over target	Middle	Step up	Constant speed
18	Under target	Middle	Step up	Accelerating	45	Over target	Middle	Step up	Accelerating
19	Under target	Outward	Step down	Decelerating	46	Over target	Outward	Step down	Decelerating
20	Under target	Outward	Step down	Constant speed	47	Over target	Outward	Step down	Constant speed
21	Under target	Outward	Step down	Accelerating	48	Over target	Outward	Step down	Accelerating
22	Under target	Outward	Regular	Decelerating	49	Over target	Outward	Regular	Decelerating
23	Under target	Outward	Regular	Constant speed	50	Over target	Outward	Regular	Constant speed
24	Under target	Outward	Regular	Accelerating	51	Over target	Outward	Regular	Accelerating

Table 1 continued

Classification ID	Off-rate error	Vehicle path position	Rate change	Vehicle acceleration	Classification ID	Off-rate error	Vehicle path position	Rate change	Vehicle acceleration
25	Under target	Outward	Step up	Decelerating	52	Over target	Outward	Step up	Decelerating
26	Under target	Outward	Step up	Constant speed	53	Over target	Outward	Step up	Constant speed
27	Under target	Outward	Step up	Accelerating	54	Over target	Outward	Step up	Accelerating

[a] Random error

as-applied files contained 2715 points in the first scenario and 1783 in the second. This type of equipment (with fixed application width) generally gives better distribution uniformity than spinner box applicators. Therefore, errors due to uneven distribution—as studied by Fulton et al. (2013) and Lawrence and Yule (2007)—were not considered in these case examples.

Results and discussion

The model was used to evaluate two application files, from a pulled type fertilizer applicator and from a self-propelled fertilizer applicator. The parameters set to run the model are presented in Table 2. Some of the parameter limits are different between applications, and they were chosen based on the characteristics of each application. That demonstrates the flexibility of the developed tool. Off-rate error values are uncertain since both prescription and the actual applied rate are given under certain assumptions. Classifying error points rather than analyzing only the off-rate error itself seems to minimize misinterpretation of the results.

The descriptive statistics data and classification of points from the model output showed important information that helps in understanding the application errors and their possible sources. The absolute error averages found in each analysis were 12.2 and 9.7 % respectively (Table 3). Unacceptable error (higher than 10 %) occurred on 38.2 and 23.1 % of all recorded points from the first and second applications, respectively (Table 3).

Table 4 shows the descriptive statistics of the prescribed rate, transition rate, speed and acceleration of the two applications. It is noticed that although the prescribed rate variation (CV) was similar between applications, the average transition rate in consecutive points was notably higher in the first application (8.3 %). Vehicle speed was fairly low in the first application as it was carried out by a pulled type applicator. Variation in speed (CV) and acceleration was higher in the self-propelled applicator (application 2). This information is reflected in the classification results shown in Table 5. High transition rates (up or down) happened more frequently in the first application, on ~30 % of the points (Table 5). Vehicle acceleration occurred more often on the self-propelled machine than on the pulled-type, which agrees with the machines characteristics. Classification of points, concerning their position within paths, was similar in both applications. Approximately 87 % of the points were recorded in the middle of paths (Table 5) and the remaining points were recorded either at an inward or outward position.

After separate evaluation of error and possible sources, they are then combined and their relationship is investigated. All 54 combinations of error and error sources can be assessed from the model output result. The ten most significant combinations for the two applications are presented in Tables 6 and 7. For the pulled-type applicator, the high rate change happened on approximately 60 % of error points and it appears alone on the first two ranking positions (Table 6). At the third and fourth positions, a random error was found, which is an error point that did not fit to any type of error source indicated in this paper. The following combinations are errors that occurred during either machine inward or outward path position, transition rate or both at the same time. Vehicle acceleration or deceleration did not occur on any of the ten most frequent combinations and it was not considered an important possible error source in this application.

Vehicle acceleration was significantly related to off-rate error in the second application. As seen in Table 4, speed varied significantly in this application. This factor appears alone on the first, second, fourth and fifth combinations, which represent 37.4 % of error points

Fig. 3 Machines evaluated in two example case studies

Table 2 Parameters set to run the implementation examples

Parameter	Classification	Limits configuration	
		Application 1	Application 2
Off-rate error	Under target	<−10 %	<−10 %
	Acceptable	−10 ↔ 10 %	−10 ↔ 10 %
	Over target	>10 %	>10 %
Vehicle path position	Inward	<10 m[a]	<10 m[a]
	Middle	>10 m[a]	>10 m[a]
	Outward	<10 m[a]	<10 m[a]
Rate change	Step down	<−0 %	<−5 %
	Regular	−10 ↔ 10 %	−5 ↔ 5 %
	Step up	>10 %	>5 %
Vehicle acceleration	Decelerating	<0 m s^{-2}	<−0.05 m s^{-2}
	Constant speed	0 m s^{-2}	−0.05 ↔ 0.05 m s^{-2}
	Accelerating	>0 m s^{-2}	>0.05 m s^{-2}

[a] Distance to the extremity point of the path

Table 3 Descriptive statistics and classification of application error

Application	Application off-rate error[a]				Off-rate error classification		
	Average (%)	CV (%)	Min (%)	Max (%)	Under target (% of points)	Acceptable (% of points)	Over target (% of points)
1	12.2	146.0	0.0	214.2	20.6	61.7	17.6
2	9.7	185.5	0.0	100.0	13.5	76.7	9.6

[a] Descriptive statistics were carried over data in module

(Table 7). 16.1 % of error points remained unexplained by the model when ran with the stated settings. They are shown in the third and sixth ranking position (Table 7). The last four positions represent transition rate and acceleration acting together as possible error sources.

The third part of the model output is GIS-ready data to create maps of classification of error, error sources and their combinations. For these examples, the software SSToolbox®

Table 4 Descriptive statistics of application parameters

Application	Parameter	Unit	Average	CV (%)	Min.	Max.
1	Prescribed rate	kg ha^{-1}	95.2	21.6	28.0	172.0
1	Rate change[a]	%	8.3	160.5	0.0	214.3
1	Speed	km h^{-1}	5.9	7.5	1.0	7.0
1	Aceleration[a]	m s^{-2}	0.0	615.8	0.0	0.2
2	Prescribed rate	kg ha^{-1}	199.1	20.8	93.0	265.0
2	Rate change[a]	%	1.8	177.9	0.0	62.4
2	Speed	km h^{-1}	11.0	35.3	0.0	21.1
2	Aceleration[a]	m s^{-2}	0.1	126.0	0.0	1.6

[a] Descriptive statistics were carried over data in module

Table 5 Percentage of points in each classification of error sources

Error source	Classification	Percent of points	
		Application 1 (%)	Application 2 (%)
Vehicle path position	Inward	5.2	7.5
	Middle	86.8	87.1
	Outward	7.9	5.2
Rate Change	Step down	14.2	5.3
	Regular	70.6	89.6
	Step up	15.1	5.1
Vehicle Acceleration	Decelerating	2.2	30.7
	Constant speed	95.6	34.2
	Accelerating	2.1	35

(SST Development Group, Stillwater, OK, USA) was used to create the maps. Figures 4 and 5 show the maps generated from the point's classification with reference to off-rate error and the three possible error sources. They demonstrate an efficient diagnostic tool, once users are able to visualize where off-rate error occurs and the possible reasons. On the orange orchard fertilization, clearly transition rate points are fairly more frequent than vehicle acceleration or boundary points; also, they are visually more related to the distribution of off-rate error points (Fig. 4).

Maps from the corn field fertilization carried out by the self-propelled applicator (Fig. 5) show predominance of vehicle acceleration points rather than transition rate points or boundary points. Although not as frequent as acceleration, the high transition rate points seem to have a distribution highly correlated to the off-rate error.

The method for identification of inward and outward machine positions was successful once points close to the field boundary and path ending points within the field were identified on both fields.

Besides off-rate error and error sources maps, each of the 54 combinations can be seen through maps and investigated spatially as exemplified in Figs. 6 and 7.

Results from error source classification, ranking and mapping outlined important information about the application itself and what happened at every recorded point regarding error and possible error sources. The machine performance is now approached

Table 6 Ten most frequent combinations of error and sources for application 1

Ranking	Classification ID	Off-rate error	Vehicle path position	Rate change	Acceleration	Percent of error points
1th	17	Under target	Middle	Step up	Constant speed	31.1
2th	38	Over target	Middle	Step down	Constant speed	29.2
3th	14	Under target	Middle	Regular	Constant speed	11.6
4th	41	Over target	Middle	Regular	Constant speed	9.1
5th	5	Under target	Inward	Regular	Constant speed	3.5
6th	47	Over target	Outward	Step down	Constant speed	2.7
7th	26	Under target	Outward	Step up	Constant speed	2.3
8th	23	Under target	Outward	Regular	Constant speed	1.2
9th	50	Over target	Outward	Regular	Constant speed	1.2
10th	32	Over target	Inward	Regular	Constant speed	1.0

Table 7 Ten most frequent combinations of error and error for application 2

Ranking	Classification ID	Off-rate error	Vehicle path position	Rate change	Acceleration	Percent of error points
1th	15	Under target	Middle	Regular	Acceleration	12.0
2th	13	Under target	Middle	Regular	Deceleration	9.6
3th	14	Under target	Middle	Regular	Constant speed	8.6
4th	40	Over target	Middle	Regular	Deceleration	8.2
5th	42	Over target	Middle	Regular	Acceleration	7.7
6th	41	Over target	Middle	Regular	Constant speed	7.4
7th	6	Under target	Inward	Regular	Acceleration	7.2
8th	39	Over target	Middle	Step down	Acceleration	5.8
9th	16	Under target	Middle	Step up	Deceleration	4.6
10th	15	Under target	Middle	Step up	Acceleration	4.3

by assessing separately all points where a single source of error occurred and counting the percentage of unacceptable error points (Fig. 8). It demonstrates the machine capability to perform the application during specific situations. For the pulled-type applicator, it underperformed for high rate changes with an off-rate error over 10 % in ~90 % of points on step up or down. Naturally, error under-target occurred in step up transitions while error over-target occurred in step down transitions. The second poorest performance of this equipment was during the extremity points, especially when re-entering the field after maneuvering (inward). This type of error is related to the same sources as the errors during transition rates, which is the delay and reaction times of the control systems. Because extremity points are not as frequent as transition rate points in this operation, the poor equipment performance during inward positions did not affect overall quality of application. Regarding the performance during vehicle speed changing, the machine was more accurate when decelerating than accelerating. This type of error is also related to the reaction time of the control system.

The self-propelled applicator had a better performance because columns representing the percentage of error points at each condition are generally shorter than in the first

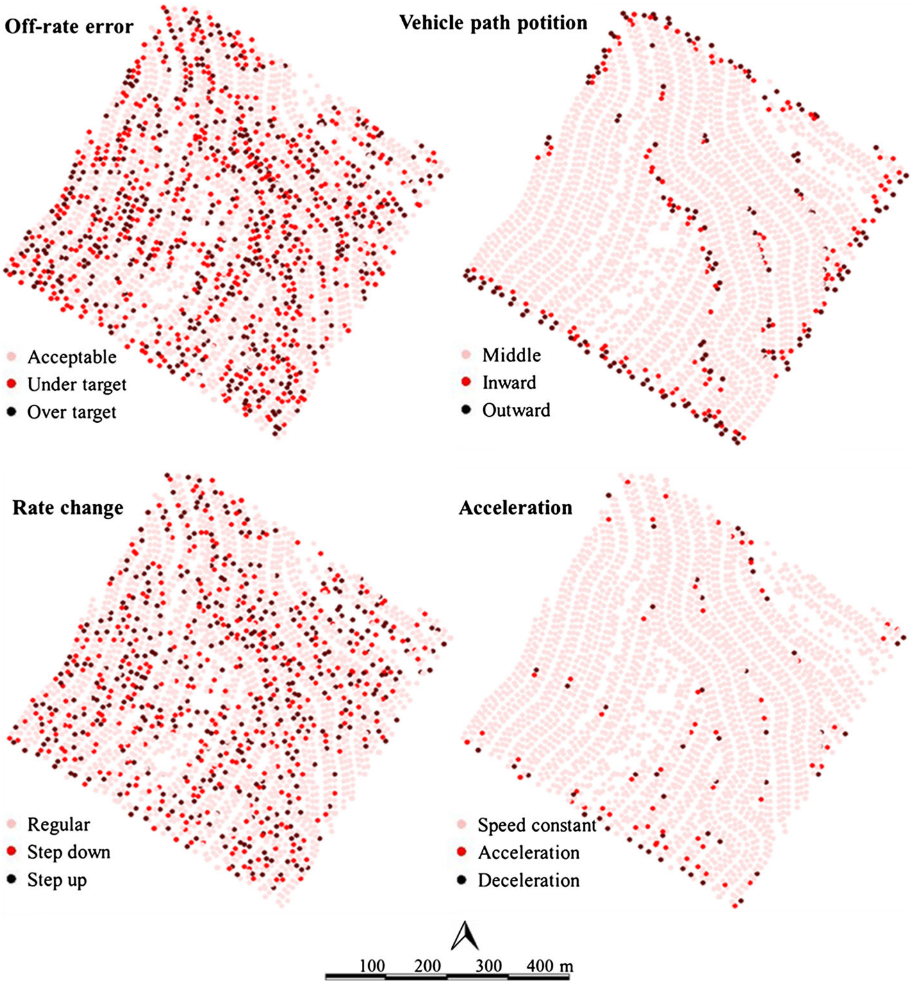

Fig. 4 Maps of off-rate error and possible error source classification on an orange orchard fertilization

application. Nevertheless, transition rate (step up or down) was also the main weakness of this equipment. Vehicle accelerating was a constant situation in this application and was often related to error (Table 7) but in the majority of the acceleration points, the application was still accurate, as shown in Fig. 7. Application during inward and outward points was not accurate in ~40 % of points, which is close to the number observed during transition rate points. As in the first application, because extremity points are usually not a predominant situation in the operation, it does not affect overall quality of application, although it might compromise application accuracy at these locations.

In general, it is possible to understand how the final quality of application relies on two factors: (1) the machine performance and its capability to be accurate under specific situations and (2) the conditions that the machine is subjected to, which might intensify its weaknesses or not. The model provided information to assess these two factors separately helping users to understand their equipment limitations and how they can minimize error

Fig. 5 Maps of off-rate error and possible error source classification on a corn field fertilization

by controlling application conditions. Although it compares values with a level of uncertainty (prescribed and applied rate), it gives reliable information about machine performance under different application conditions as well as an overview about quality of application.

Not all application errors can be assessed using the methodology presented here, e.g. GNSS positioning error (Chan et al. 2004) and uneven transversal distribution (Fulton et al.

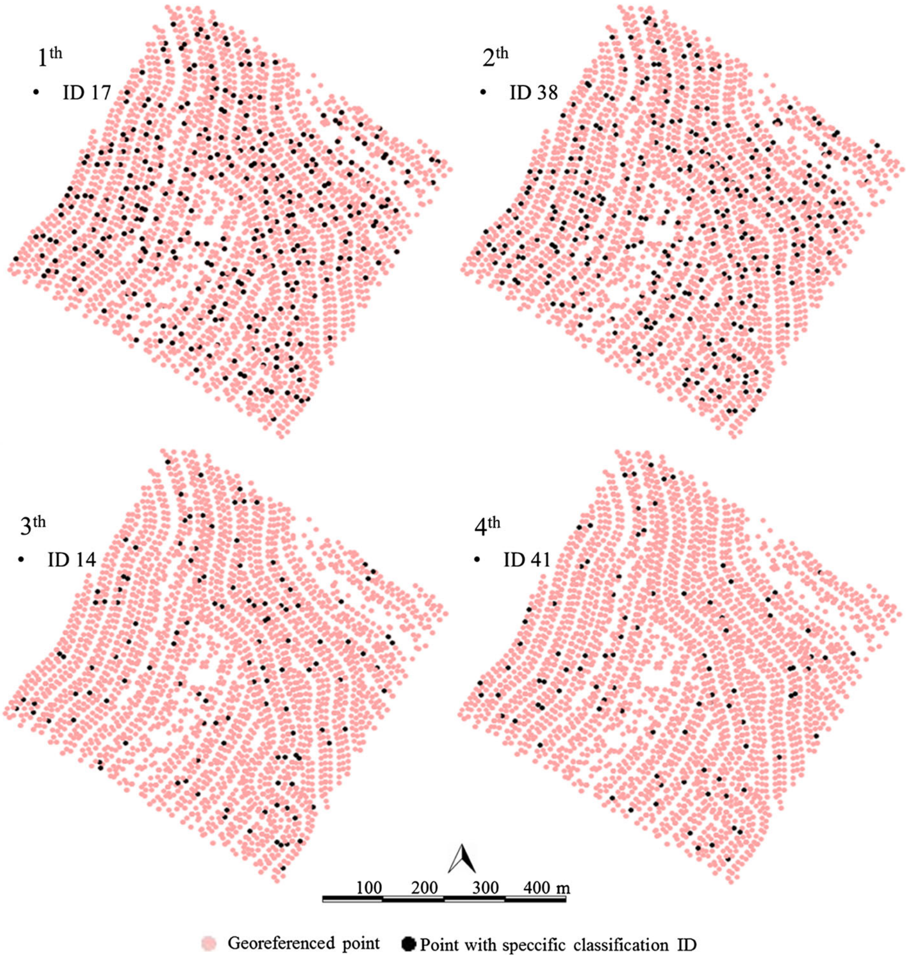

Fig. 6 Visualization of points of a specific classification ID in the orange orchard

2013; Lawrence and Yule 2007), but important information can still be extracted from raw as-applied files.

Summary and conclusion

A model was developed to help interpret as-applied reports from VRT operations. The analyses cover quantification and classification of off-rate error and possible related sources. It presents several adjustable parameters to better suit different files and application characteristics. After the classification process at each point, error is then related to possible sources (vehicle position in the application path, rate change or vehicle acceleration) allowing diagnostics about what factor might be limiting quality of application. The output result includes statistics of error and application conditions as well as the percentage of points in each class of error and possible error sources. All combinations of error and

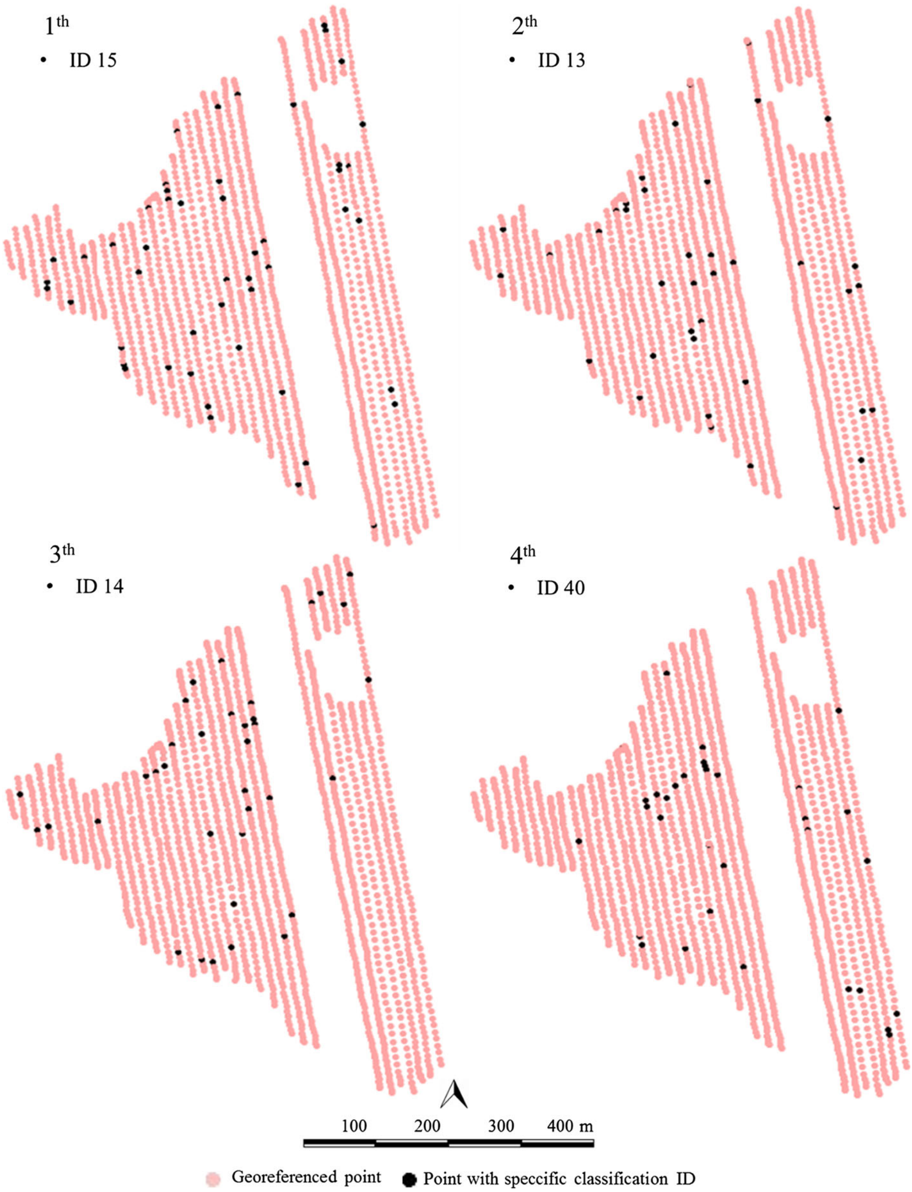

Fig. 7 Visualization of points of a specific classification ID in the corn field

sources can be assessed separately and ranked from the most to the least frequent. Results are also shown through maps to allow interpretation about spatial distribution. The user can also assess machine performance under a specific situation of interest.

Analyzing two as-applied files, the model showed that high transition rate was the main condition related to off-rate error in the first application by a pulled type applicator. In the second application, by a self-propelled machine, the main condition related to error was

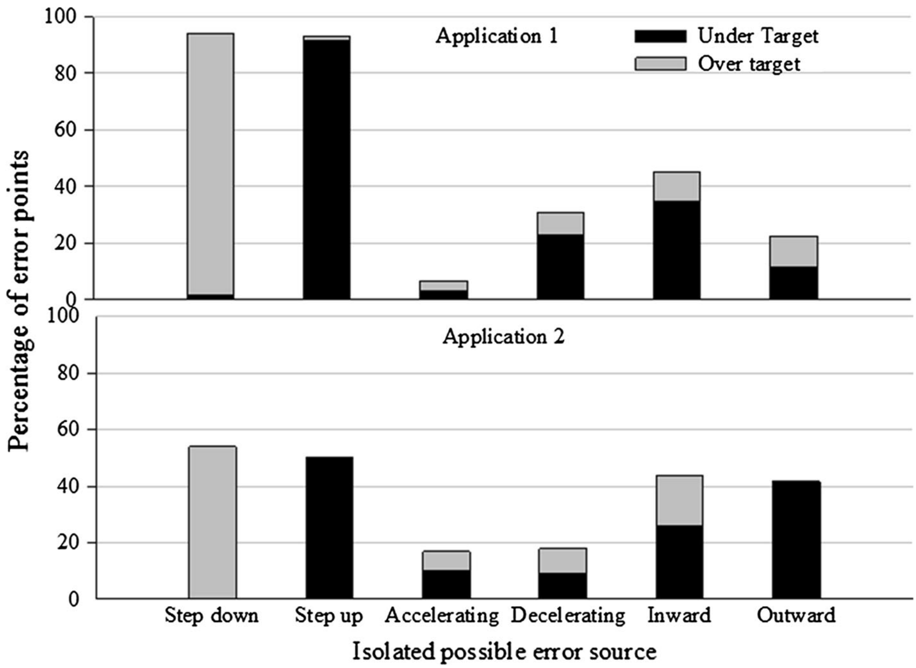

Fig. 8 Percentage of error points in each error source classification

vehicle acceleration or deceleration. Using the maps of distribution of error and possible sources, it is possible to identify the impact of high transition rate on error occurrence once they were visually related on both applications. Regarding machine performance, the main weakness of the applicators was the rate change, especially for the pulled type.

Overall, the model gives information about quality of application and possible error sources related to equipment limitations or inadequate application conditions. It represents a better use of as-applied files, extracting important information for PA practitioners.

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