Optimum Spatial Resolution for Precision Weed Management

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Abstract. *The occurrence and number of herbicide-resistant weeds in the world has increased in recent years. Controlling these weeds becomes more difficult and raises production costs. Precision spraying technologies have been developed to overcome this challenge. However, these systems still have relatively high acquisition cost, requiring studies of the relation between the spatial distribution of weeds and the economically optimum spatial resolution of the control method. In this context, the objective of this work was to evaluate the best control resolution in simulated scenarios of weed distribution to create guidelines to relate the spatial variability of weed distribution with the optimum resolution of weed control. The methodology uses geostatistical simulations to construct different scenarios of weed distribution, based on real observations from Brazilian crop production fields. The simulations were made in a 0.1 X 0.1 m spatial resolution, considering only presence or absence of weeds to be sprayed in each pixel. We evaluated control resolution starting from 0.2 X 0.2 m to 36 X 3 m, considering section widths and valves on/off timing. In each scenario we calculated the minimum area to be sprayed using each technology, targeting a minimum of 99% of weed control. The economical evaluation was based on the total application cost, considering the herbicide savings and the increase in application cost of each technology. Low incidence levels and random distribution of weeds is favorable for sub meter control resolutions. For section control based applications the range is the more important parameter for predicting herbicide savings, and for nozzle control the nugget effect is more important. The raise in herbicide control costs are likely to be a key driver in the adoption of precision spraying technologies.*

Keywords.

Spatial variability, herbicide resistant weeds, pulse width modulation, precise spraying.

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Introduction

Most of the studies on the spatial variability of weeds are based on traditional sampling methods, and area only able to capture the large scale variations in weed distributions (Rocha et al., 2015). Some studies have focused on better control resolution, but typically the minimum treatment unit considered is 3 by 3 m (Barosso et al., 2004) or 1 by 1 m (Paice et al., 1998). The potential herbicide saving increases with increasing spatial resolution of the weed control. Therefore, the greatest product saving is achieved when the weed seedlings are treated individually, but the cost associated with such technology needs to be evaluated (Franco et al., 2017).

New techniques of weed mapping have been developed, including the use of high resolution aerial and terrestrial images, coupled with advanced computer vision and artificial intelligence models (Peña et al., 2013; Franco et al., 2017; Ferreira et al., 2017, Castro et al., 2018). However, several authors have claimed that real-time weed sensing is a precondition for the adoption of site-specific weed management (Christensen e al., 2009).

The occurrence and number of herbicide-resistant weeds in the world has increased in recent years. Controlling these weeds becomes more difficult and raises production costs. According to the International Survey of Herbicide Resistant Weeds, until 1985 there were 14 cases of resistance to a site of action in the USA, in 2015 that number reached 160. As this problem becomes widespread, localized weed control tools such as the WEEDit® system have gained momentum.

Few farmers, however, have adopted site-specific weed management, although several studies have shown that weed occurrence and density varies significantly within a farm or a field (Rocha et al., 2015; Longchamps et al., 2016). One of the reasons is that these systems still have relatively high acquisition cost, requiring studies of the relation between the spatial distribution of weeds and the economically optimum spatial resolution of the control method. In this context, the objective of this work was to evaluate the best control resolution in simulated scenarios of weed distribution to create guidelines to relate the spatial variability of weed distribution with the optimum resolution of weed control.

Material and methods

Geostatistical simulations were used to construct different scenarios of weed distribution, based on real observations from Brazilian crop production fields. First, we used a sequential Gaussian simulation in a regular grid with 1 X 1 m spatial resolution. Exponential models without nugget effect were used as the model, with piratical range parameters set to 1, 10, 25 and 100 m. The simulated fields represent a random variable normally distributed with zero mean and unit variance. After the initial simulation, each pixel was subdivided by a factor of 10 in each direction, to produce a final map with 0.1 X 0.1 m spatial resolution. In each map, a random set containing 5, 10 or 25% of the pixels had its values reassigned to a random value from the same distribution.

This two step approach to simulate weeds spatial distribution was developed to better represent the process involved in weeds seed dispersion and the field results obtained in other works (Figure 1). A simple approach adding nugget effect to the sequential Gaussian simulation did not produced the same results. This is likely to be due to the additive effects of processes that occur in different spatial resolutions at field level. For example, row and between row differences, straw distribution, machine and wind dispersion, crop canopy closure, all have effects in the spatial distribution of weeds.

Figure 1. Three aerial images from the same field, selected as examples of spatial distribution of weeds. The green plants are *Digitaria insularis*. Left picture can be compared to simulation with 10 m range and 1% random effect; Center picture can be compared to simulation with 25 m range and 10% random effect; Right picture can be compared to simulation with 100 m range and 5% random effect.

The spatial distribution maps were transformed into a probability distribution map, ranging from zero to one. Five levels of infestation were used to finally transform the maps to represent only the presence or absence of weeds to be sprayed in each pixel. All the combinations of these three factors were evaluated, as it is described in Table 1.

Table 1. Description of simulated weed infestation scenarios.

Factor	Levels	Description
Range (m)	1, 10, 25, 100	Spatial distribution of weeds, varying from equally distributed to patchy aggregated weeds
Random (%)	0, 5, 10, 25	Random effect affecting general spatial distribution, varying from none to 25% of randomness
Infestation (%)	1, 5, 10, 25, 50	Percentage area occupied by weeds, varying from rare weeds to half the field infested
Total	80	Combinations of all levels of the three factors above

To simulate herbicide application using different levels of control resolution, a polygonal reticulate with machine specific dimensions was overlaid in the spatial distribution maps. At each polygon, the number of pixels with weeds and the total number of pixels were counted, if at least 1% of pixels represented weeds, all pixels inside the polygon were set as sprayed area, otherwise, all pixels were set as not sprayed. This threshold was set according to general agronomic recommendations for weed control before seeding and is related to the higher costs of controlling this weed in the post-emergence of the crop and the long-term impacts in seedbank. In all scenarios, it is assumed that all the area is infested with weeds that can be controlled using the same product or tank mixture, maintaining a constant application rate.

The boom widths and costs presented are based on the technologies available or under development for sprayers commonly used in large areas of soybean, corn and cotton cultivation. We evaluated control resolution starting from 0.2 X 0.2 m to 36 X 3 m, considering section widths and valves on/off timing (Table 2). All the simulations and data analysis was done in R programming language (R Core Team, 2017), using libraries gstat and raster.

Table 2. Description of precise spraying technologies considered in each simulated scenario of weed infestation.

Sprayer	Width (m)	Length (m)	Cost ($/ha)	Description
1	0.2	0.2	10.00	Real time weed identification and nozzle control
2	0.5	0.5	9.00	Ultra-high resolution map based weed identification and nozzle control
3	1.0	0.5	8.00	Ultra-high resolution map based weed identification and nozzle control
4	4.0	4.0	7.00	High resolution map based weed identification and section control
5	10.0	5.0	6.50	High resolution map based weed identification and section control
6	20.0	5.0	6.00	Map based weed identification and all boom control
7	36.0	5.0	5.50	Map based weed identification and all boom control
8	-	-	5.00	No weed identification and all field application

The application cost was estimated from a survey with service providers in Mato Grosso state, considering the 2017/2018 crop season. All costs are total application costs, including the data acquisition and processing in map based applications, the labor and fuel used. Different herbicide costs were also evaluated, starting from $ 5.00/ha, representing the scenario with easily controlled weeds, up to $ 30.00/ha, which is the cost to control glyphosate resistant *Digitaria insularis*, like the ones in Figure 1. An operational performance gain of half the herbicide savings was also included in the model. To exemplify, if a normal operational performance to apply the whole field is expected to be 40 ha/h, an application with 50% herbicide savings will have an operational performance 25% greater, or 50 ha/h. This is mostly to less time and labor spent to refill the sprayer tank. The total application cost used for economical evaluation considered this performance gain, the herbicide savings and the increase in application cost of each technology.

Results and discussion

Graphical results for all simulations are presented in Figure 3. In general, it can be observed that the range of the spatial variability does not influence the systems with nozzle level of control (0.2, 0.5 and 1 m), but this are sensitive to random distribution at the scales smaller than 1 m. It is also important to note that exists a linear relationship between weed incidence and product savings for these technologies, which makes estimation of herbicide savings more accurate. For the other technologies, with section control, the herbicides savings presents an exponential decay with the increased weed incidence. The larger the section width, the more important is the range of the spatial variability. With 25% of weed incidence, only the section width of 4 m with 100 m range is able to produce savings of at least 50%.

The three technologies with best spatial resolution provided the same savings when only 1% of less of the weeds were randomly located on the fields. With 10% of randomness and 25% of weed incidence, which can be common in production fields in intensive crop systems in tropical areas, independently of the range of the spatial dependence, the use of 0.2 m control resolution proportioned 13% more savings than 0.5 m and 26% more savings than 1.0 m control resolutions.

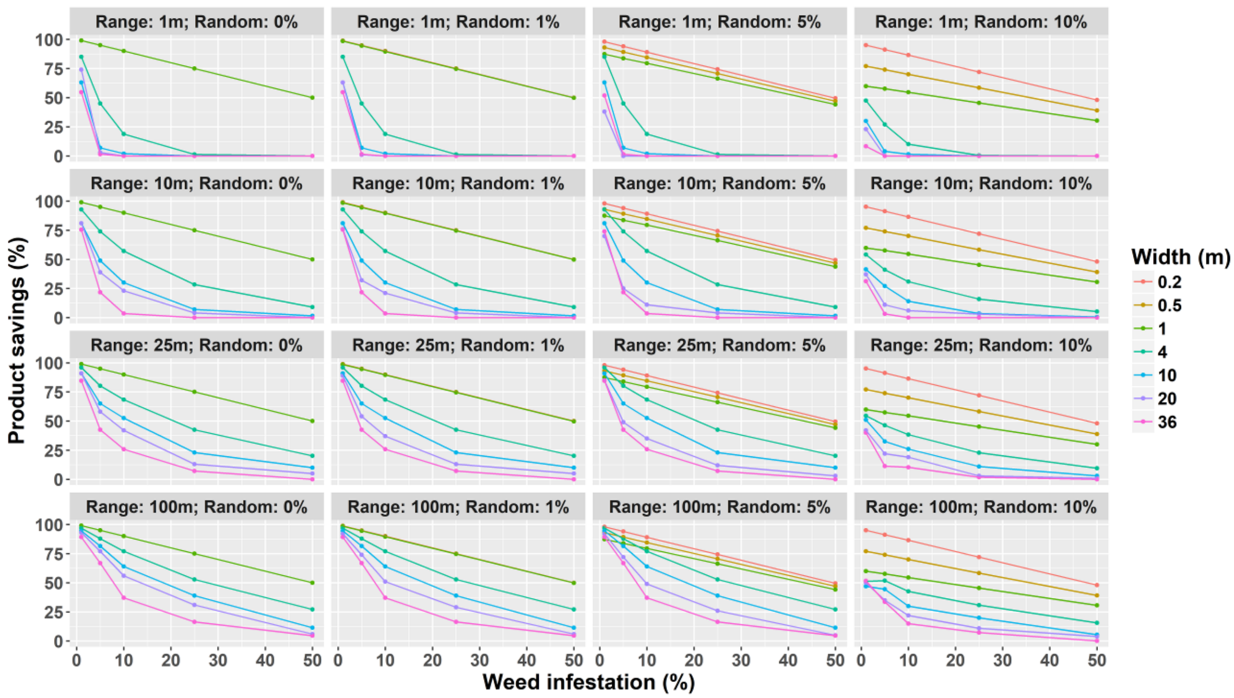

Figure 2. The relation of weed infestation and product savings for each width of control and its interaction with the spatial distribution of weeds for the simulated fields.

Some maps of sprayings simulations where choose to illustrate the numerical results obtained (Figure 4). With an infestation of 5%, a range of 100 m and no random effect, all the technologies provide good results, there is no difference between the 0.2 or 1 m widths and even the 36 m boom control can produce savings of 70%, although some very isolated weeds will not be sprayed. When the range is decreased to 25m and 5% random effect is added to the map, the 0.2 m width can maintain 94% savings, while the 1 m control produces only 80% savings. In this scenario, the 4 m section will apply the same amount of herbicide as the 1 m system, but with poorer results because many individual plants were not sprayed. The 36 m still produces 50% savings, but only the large patches of weeds are sprayed. When the range goes down to 10 m and the random effect is increased to 10%, all the systems produces different results. The savings with the 0.2 m system are still greater than 80%, while the 1 m system is spraying half of the total area, even with only 5% of area really infested.

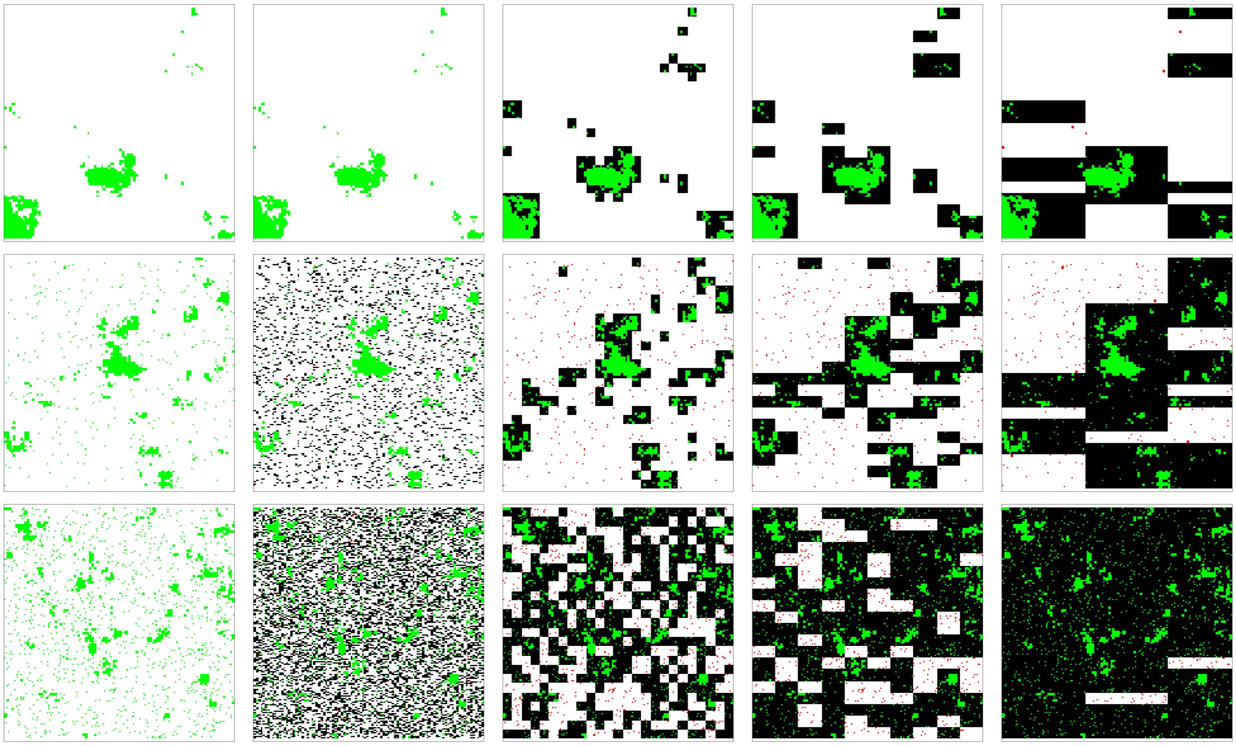

Figure 3. As applied maps for fields with 5% weed infestation following three spatial distributions: 100 m range (A), 25 m range with 5% random (B) and 10 m range with 10% random (C); considering five control widths: 0.2 m (a), 1 m (b), 4 m (c), 10 m (d) and 36 m (e). Weeds correctly sprayed in green, areas correctly not applied in white, areas unnecessarily sprayed in black and missed weeds in red.

Considering the costs presented on Table 2, the minimum herbicide savings to compensate for increased operational cost of each technology was calculated (Table 3). This table is already considering the gain in operational performance due to optimized use of tank mixture and less time spent on displacement and refilling. Instead of considering the cost of each technology, the table is based on the cost difference between any two scenarios. In this away, it can be applied to compare not only a specific technology with the traditional blanket application, but also any pair of technologies (Figure 4). For low cost herbicides, great savings are necessary to justify the increased operational costs. If the herbicide cost is $ 10.00/ha, about 10% of herbicide savings are needed for each more dollar spent on the operation. Comparing the 1 m and the 0.2 m resolution systems, the later must provide 19% more savings than the first to be economically optimum, and this is only observed in the maps with less than 30% infestation and 10% of randomly distributed weeds. When the herbicide costs go up to $ 20.00/ha, due to glyphosate resistance, for example, an increased savings of 9% is enough to justify the use of the fine resolution technology.

Table 3. Minimum increase in product savings to account for increased operational costs of using precision spraying technologies as related to the product costs.

Herbicide Cost ($/ha)	Increase in operational cost ($/ha)					
	0.50	1.00	2.00	3.00	4.00	5.00
5.00	9%	19%	37%	56%	73%	91%
10.00	5%	10%	19%	28%	38%	47%
15.00	3%	6%	13%	19%	26%	32%
20.00	2%	5%	10%	15%	19%	24%
25.00	2%	4%	8%	12%	16%	19%
30.00	2%	3%	7%	10%	13%	16%

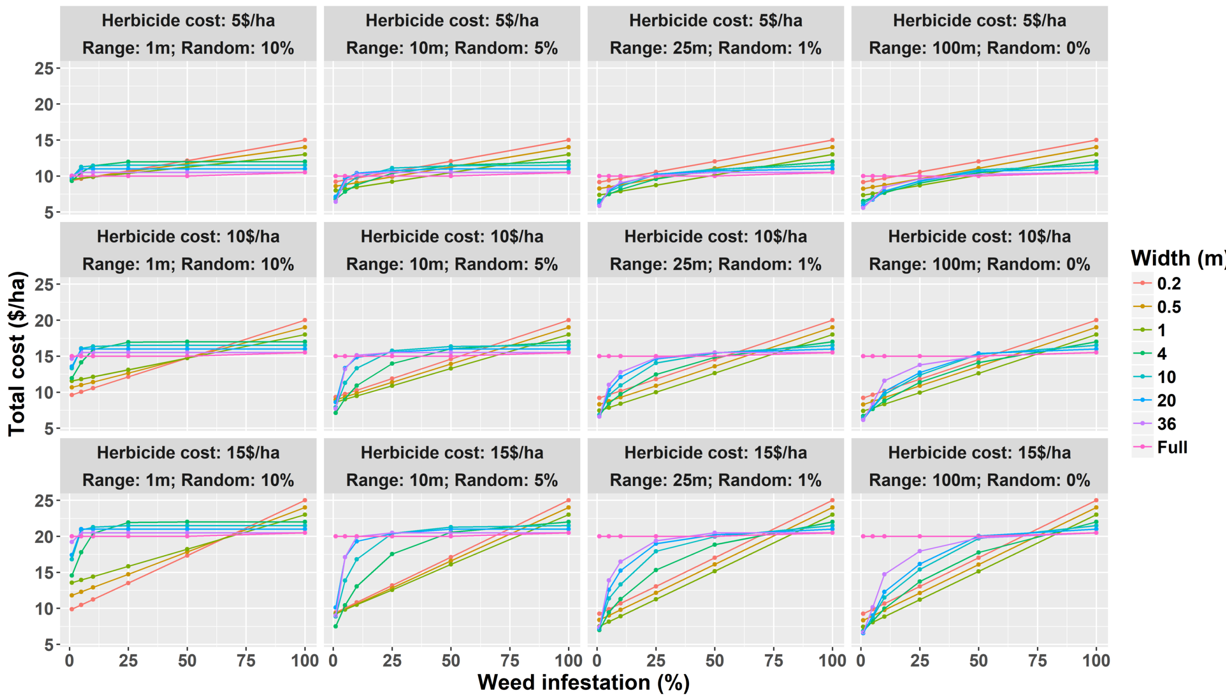

Figure 4. Total costs of precision spraying technologies as related to the herbicide costs, weed infestation and spatial distribution.

The results obtained through the simulations and analysis presented in this research shows that there is a close relation between spatial distribution of weeds and the optimal spatial resolution of control systems. The conclusion found in Franco et al. (2017), indicating that the potential gains and marginal cost reductions of herbicides decrease significantly with increased precision in spraying, are valid under the assumption that the weed distribution in one field presents spatial dependence. The more random this distribution is, more value can be extracted with precision spraying in increased levels of resolution.

Conclusion

Low incidence levels and random distribution of weeds is favorable for sub meter control resolutions. For section control based applications the range spatial dependence is the more important parameter for predicting herbicide savings, and for nozzle control the nugget effect is more important. The raise in herbicide control costs are likely to be a key driver in the adoption of precision spraying technologies.

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