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An Imagery-Based Weed Cover Threshold Established Using Expert Knowledge

Louis Longchamps, Bernard Panneton, Marie-Josée Simard, and Gilles D. Leroux*

The implementation of site-specific weed management requires information about weed cover and decision support systems to determine weed cover thresholds and concomitant herbicide rates. Although it is possible to create accurate weed cover maps over large areas, weed cover thresholds have generally been evaluated using tedious weed density counts. To bridge this gap between weed cover obtained by machine vision and the concept of economic threshold, crop advisers specializing in weed scouting were asked to evaluate over 2,500 weed cover images (2 m by 3 m) and determine if a given image would require herbicide application or not. Using the area under the ''receiver operating characteristic'' curve method, an optimal weed cover threshold was established. The derived economic thresholds ranged from 0.06 to 0.31% weed cover contingent on the level of tolerance of the expert adviser. Although this threshold seems low, it is comparable with economic threshold values based on weed density.

Key words: Economic threshold, imagery, receiver operating characteristic, site-specific weed management.

Weeds represent a serious burden for farmers as they are recurrent pests in crops and require yearly control to prevent yield loss (Oerke 2006). In Canada, about 72% of the cropped area is treated with herbicides (Statistics Canada 2006). However, weeds tend to grow spatially aggregated in fields, thus leaving weed-free areas that do not require treatment (Cardina et al. 1997; Clay et al. 2006; Wiles et al. 1992). Site-specific herbicide weed management is a concept based on the aggregation of weeds to reduce the cost of herbicides and their negative impacts on the environment without reducing the yield. Ground-based imagery can be used to estimate weed cover between crop rows (Longchamps et al. 2013). To achieve site-specific weed management, two approaches are possible when the information about weed cover is available. The first is to apply variable herbicide rates on the basis of multiple weed cover threshold values and the second is to apply a single labeled dose only where weed cover is above a certain threshold (Wiles 2005). Registered herbicide doses were set to control multiple weed species (indicated on the label) at selected growth stages (also indicated on the label) for a range of weed densities and environmental conditions. These labeled doses cannot be legally lowered (Zhang et al. 2000). However, a dichotomous single dose/no herbicide weed-management strategy requires a low and carefully evaluated weed threshold as any field section having a weed cover under this threshold would receive no herbicide.

The concept of weed threshold was developed to determine the weed infestation level above which a treatment is required. These thresholds allow the conversion of a weed cover or density map into a herbicide application map. Several parameters can be taken into account to determine the weed threshold, such as weed density, species, or growth stage. Swanton et al. (1999) have done a review of the literature quantifying the level of interference of single- and multispecies weed infestation. The authors concluded that multispecies weed thresholds are complex to implement (e.g., competitiveness with the crop and herbicide efficacy at lower rates vary considerably across weed species), but are necessary since single-species infestations are rare in crop fields. It is recommended that multispecies thresholds be based on the most competitive species present and thus should be based on the lowest threshold, at the risk of overestimating the weed infestation (Dew 1972; Swanton et al. 1999; Swinton et al. 1994). Weed thresholds can be approached as biological thresholds corresponding to the infestation level where a significant negative impact on crop yield is expected or as an economic threshold where implementing weed control returns benefits equal to costs. Usually, the biological threshold is lower than the economic threshold because of the inherent application costs that should

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* First and fourth authors: Graduate Student and Professor, Department de Phytologie, Université Laval, Québec, Canada; second author: Research Scientist, Agriculture and Agri-Food Canada, Horticulture Research and Development Centre, Saint-Jean-sur-Richelieu, Canada; third author: Research Scientist, Agriculture and Agri-Food Canada, Soils and Crops Research and Development Center, Québec, Canada. Corresponding author's E-mail: louis.longchamps@gmail.com

be lower than the yield loss (Coble and Mortensen 1992; Cousens 1987; Swanton et al. 1999). The concept of economic weed threshold is more appealing to farmers that generally implement weed control when benefits equal or exceed costs (Swanton et al. 1999). Economic weed thresholds require information about weed density, yield loss related to weed pressure, yield loss related to crop injury from the herbicide, grain price, and herbicide treatment costs. Cost and benefits of weed management can be challenging to quantify, jeopardizing the reliability of the resulting economic weed threshold (Wiles 2005). This complexity increases when several commercial fields are evaluated, costs can be shared (e.g., joint ownership of machinery), and the relationship between weed density and yield has not been evaluated. Furthermore, the establishment of an economic weed threshold should take into account the impact of the seed production of the residual weeds, further lowering the threshold by a factor that is hard to model (Simard et al. 2009).

Ngouajio et al. (1999) have demonstrated that leaf cover of undistinguished weed species (i.e., natural weed populations in their paper) had a high predictive capacity for yield loss. They used a relative weed cover value ([weed cover]/[weed cover + corn cover]) computed using the corn cover averaged over the whole field. This value is highly correlated with weed cover alone when corn cover is constant. On the basis of the findings of Ngouajio et al. (1999), Lemieux et al. (2003) decided to (1) verify if these findings apply to commercial fields and (2) develop a weed tolerance threshold on the basis of relative weed cover data. They were able to demonstrate that a relative weed cover threshold of 0.20 presents virtually no risk for reduced yield on the basis of a tolerance threshold of 0.91 in yield, which is equivalent to the inherent variability existing in yield across the field in the absence of weeds. This threshold thus protected the yield of the current year, but did not provide information about the effect of the seed input from the residual weeds and its effect on subsequent weed populations in the spring. This question was addressed by Simard et al. (2009) who demonstrated that applying the relative weed cover threshold of 0.20 on large areas (e.g., 900-m^2 plots) would result in a replenishment of the seed bank that would increase weed infestations above the 0.20 threshold during 3 subsequent years. It is thus believed that using smaller decision units (e.g., 1 m^2 as compared with 900 m^2 used in previously cited studies) and a more conservative threshold would allow fewer weeds to escape control while maintaining fair levels of herbicide savings.

Our goal was to determine a reliable threshold on the basis of expert knowledge (as a surrogate of complex economic calculations) and weed cover obtained by imagery (unbiased by visual estimates). In practice, the decision to apply herbicide or not relies on the judgment of crop advisers that scout the fields regularly at the beginning of the critical period for weed control. This paper relies on the premise that the judgment of crop advisers can be used to establish a reliable weed threshold on the basis of weed cover measured by imagery that ultimately could be used in a decision support system. The specific objectives of the projects were (1) to establish a weed threshold using the judgment of crop advisers and (2) to evaluate the proportion of fields that would be left untreated (no herbicide applied) on the basis of this threshold value.

Material and Methods

Sites. Data were collected in 2008 and 2009 from June to July in 13 commercial corn (*Zea mays* L.) fields. Among the 13 fields, 6 were sampled both in 2008 and 2009, for a total of 19 site-years. The fields were selected according to the following criteria: corn was planted at 75-cm interrow spacing, no mechanical weed control was implemented, no residual herbicides were applied in spring, and conventional tilling was applied (no reduced or zero till). Planters used had four-, six-, or eight-row units. Starter fertilizer containing nitrogen and phosphorus was applied uniformly in each field. Levels and formulations of subsequent uniform fertilizer applications were based on soil analysis and were applied after data acquisition. The composition of the weed flora was evaluated at each site-year. Nine (in 2008) to 16 (in 2009) quadrats (0.5 m by 0.75 m) were systematically distributed throughout the 1-ha plots. All weeds present in the quadrats were identified to the species level except grasses (noted as Poaceae spp.) and counted. This information is reported in Table 1.

Plot Selection. The fields were sampled 1 or 2 d before weed control, corresponding to the two- to four-leaf growth stage of corn. The 13 sites were located along the St-Laurence River, from St-Jean-sur-Richelieu (45.20°N, 73.20°W) to St-Isidore (46.50°N, 71.20°W). At each of the 13 sites, a 1-ha plot was selected for image and weed population sampling. It was positioned away from field margins

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Table 1. Percentages of grasses and broad-leaved weeds along with the three most important weeds (percentage of total count in parentheses) for each site-year.

Site-year	Grasses	Broad-leaved	Main species (percentage)
	%		
a08	25	75	CHEAL (28), Poaceae spp. (25), TAROF (25)
a09	28	72	Poaceae spp. (28), CAPBP (27), TRFRE (12)
b08	44	56	Poaceae spp. (44), ACCRH (32), POLPE (15)
c09	60	40	Poaceae spp. (60), CHEAL (31), CAPBP (5)
d08	NA[a]	NA	NA
d09	69	31	Poaceae spp. (69), CHYLE (14), CHEAL (9)
e08	90	10	Poaceae spp. (90), CHEAL (6), AMARE (2)
e09	81	19	Poaceae spp. (81), CHEAL (16), VICCR (1)
f08	54	46	Poaceae spp. (54), CHEAL (19), TRFRE (16)
f09	52	48	Poaceae spp. (52), TRFRE (11), PLAMA (10)
g08	62	38	Poaceae spp. (62),AMBEL (19), TRFRE (7)
h09	37	63	CHEAL (47), Poaceae spp. (37), AMARE (6)
i09	74	26	Poaceae spp. (74), CHEAL (9), AMBEL (5)
j08	3	97	CAPBP (86), CHEAL (8), Poaceae spp. (3)
j09	15	85	CAPBP (48), CHEAL (35), Poaceae spp. (15)
k09	8	92	CAPBP (73), CHEAL (8), Poaceae spp. (8)
l08	3	97	CHEAL (66), CAPBP (13), TRFRE (10)
l09	12	88	CAPBP (33), TRFRE (24), CHEAL (20)
m08	41	59	CHEGL (50), Poaceae spp. (41), AMARE (5)

[a] Abbreviations: NA, not applicable; bird vetch, *Vicia cracca* L. VICCR; broadleaf plantain, *Plantago major* L. PLAMA; common lambsquarters, *Chenopodium album* L. CHEAL; common ragweed, *Ambrosia artemisiifolia* L. AMBEL; dandelion, *Taraxacum officinale* G. H. Weber ex Wiggers TAROF; ladysthumb, *Polygonum persicaria* L. POLPE; oakleaf goosefoot, *Chenopodium glaucum* L. CHEGL; oxeye daisy, *Chrysanthemum leucanthemun* L. CHYLE; redroot pigweed, *Amaranthus retroflexus* L. AMARE; rhombic copperleaf, *Acalypha rhomboidea* Raf. ACCRH; shepherd's purse, *Capsella bursa-pastoris* L. Medicus CAPBP; white clover, *Trifolium repens* L. TRFRE.

and common horsetail (*Equisetum arvense* L.) patches. Common horsetail patches were avoided as these perennial weeds form dense patches that are stable from year to year because of poor drainage conditions and tolerance to regular herbicide treatments (Goudy et al. 2001; Marshall et al. 1987). Sites that were sampled both in 2008 and in 2009 were monitored at the same locations. Hereinafter, the 19 1-ha plots will be referred to as site-years.

Ground-Based Imagery and Segmentation of Vegetation. All 19 site-years were exhaustively photographed with a camera (Nikon D100 RGB digital camera) mounted at 2.5 m above the ground on a mobile platform controlling ambient light conditions. The camera was triggered at every 3 m by a sensor on the wheel. Each image covered an area of 2 m by 3 m (resolution of about 1 pixel mm^{-2}) and overlapped four corn rows (three full interrow sections of about 0.35 m by 1.6 m after image processing; Figure 1a). Images thus acquired were analyzed with a custom-built Matlab™ program to segment vegetation pixels from other pixels using principal component analysis (PCA) applied on the whole image (including light-gray tarp flaps on the sides) (Figure 1a). The PCA analysis of image red, green, blue (RGB) channels yielded loadings that had proportions close to the excess green transformation ($r - 2g + b$), but that varied from one image to the other and thus was better tuned to each and every image. The first PC was segregating the gray tarp on the side of the image and the straw (light colors); the second and the third PCs were highlighting the soil and the vegetation (Figure 1b) and were sometimes inverted depending on the vegetation cover (e.g., for images with abundant vegetation, the second PC was segregating the vegetation). Further details about the mobile platform and the image segmentation method can be found in Longchamps et al. (2013). Around 1,100 pictures were taken in each plot.

Extraction of Weed Cover Information. For each image, weed cover was extracted using machine vision. Segmented binary images, from which background was removed and only vegetation remained (Figure 1b), were processed by computing a vertical sum of the pixels. Doing so resulted in bell-shaped curves at the locations of the corn rows. Knowing the location of the center of corn rows in

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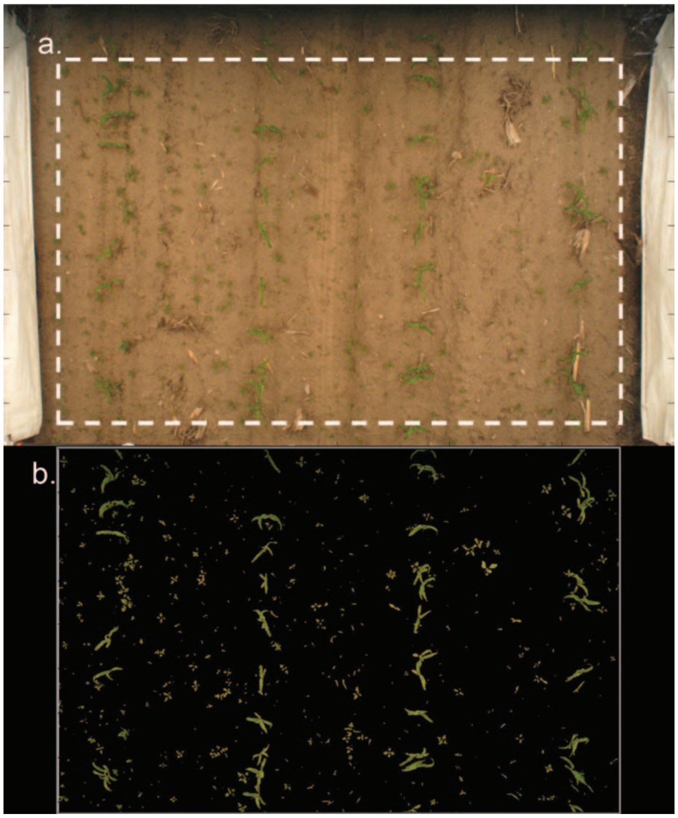

Figure 1. Example of ground image acquired in *a* and image where soil was removed using segmentation in *b*. The white dashed rectangle highlights the region of interest (ROI) of the image.

the image, a fixed distance on each side of the row center was used to delineate the area of the image where corn blobs were located. This process generated three corn-free interrow areas for each image. Weed cover was measured by summing the number of pixels of vegetation in the corn-free interrow areas. The interrow located in the middle of each image was used for comparison with the evaluation of the crop advisers and all three interrows were used independently to create maps of weed presence/absence. More details on image processing to extract weed cover information can be found in Longchamps et al. (2013).

Crop Adviser Input. A sample of images was sent to three crop advisers for the evaluation of weed infestation. The three crop advisers were specialized in corn production and work in three different regions in the province of Quebec. All three are accredited agronomists. A total of 2,795 images was systematically sampled, one every 10 images from the entire data set, corresponding to 10% of all images taken in the 19 site-years. The sampled images were sent to the crop advisers along with a custom-built executable Matlab program with a graphical user interface to process the images (Figure 1). For each image, crop advisers judged if the middle interrow clearly did not require herbicide treatment (infestation level 1), clearly required herbicide treatment (infestation level 3), or was intermediate (infestation level 2). Recommendations were made on the basis of a planned single in-crop herbicide application at the time of image acquisition. The weed cover value (percentage cover of vegetation on interrows on the basis of the percentage of green pixels over black pixels—see above) of all of the images submitted to the crop advisers was added to their output files after their evaluation.

Determination of the Weed Cover Threshold. The threshold was determined by using the receiver operating characteristic (ROC) approach for the performance of binary classifier (Bradley 1997). The advisers' classification was considered as the true value, whereas the classification resulting from a given threshold value (iterated from 0 to 1% by increments of 0.001%) was considered as the predicted value (Table 2). The optimal value was determined from the ROC curve (false-positive rate [FPR] against the true positive rate [TPR]). The optimal value corresponds to the threshold maximizing the area under the ROC curve (AUC). For the special case of a single point in the ROC diagram, the AUC for threshold i is measured as:

$$AUC_i = [(FPR_i \times TPR_i)/2] + \{[(1 - FPR_i)(1 + FPR_i)]/2\} \quad [1]$$

where FPR_i and TPR_i are described in Table 2 (Lundquist and Reich, 2011; R.M. Reich, personal

Table 2. Contingency table between actual and predicted value for threshold *i* describing the components of the area under the ROC curve calculation.

		Classification for threshold *i* (predicted value)		
		Uninfested (0)	Infested (1)	Row total
Adviser' classification (true value)	Uninfested (0)	True negative *a*	False positive *b*	FPR $b/(a + b)$
	Infested (1)	False negative *c*	True positive *d*	TPR $d/(c + d)$

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Table 3. Number of images classified by crop advisers in each category (i.e., uninfested, intermediate, or infested) and threshold resulting from the evaluation of each crop adviser and on average. Average percentage of weed cover for the images within each cell is indicated in parentheses. Each crop adviser observed a total of 2,791 images.

	Infestation level		
	1 Uninfested	2 Intermediate	3 Infested
Adviser 1	705 (0.052)	325 (0.245)	1,761 (2.041)
Adviser 2	801 (0.089)	505 (0.322)	1,485 (2.341)
Adviser 3	352 (0.021)	532 (0.142)	1,907 (1.902)
Average	619.3 (0.054)	454.0 (0.236)	1,717.7 (2.095)

communication). The AUC will be 1 if the TPR is 1 and the FPR is 0, it will be 0.5 if TPR is equal to FPR, and it will be 0 if TPR is 0 while FPR is 1. The higher the AUC, the higher the discrimination accuracy of the threshold. The optimal threshold value was determined when the AUC, FPR against the TPR, was maximal. This approach works with binary data, whereas the output from the crop advisers' classification had three possible values (i.e., uninfested, intermediate, infested). To obtain a binary input, four different scenarios were used: (1) intermediate values were excluded; (2) intermediate values were randomly converted into uninfested or infested values; (3) all intermediate values were converted into uninfested values, and (4) all intermediate values were converted into infested values. This process yielded 12 different threshold values (three crop advisers by four scenarios).

Weed cover maps were converted into herbicide treated/untreated maps on the basis of the resulting threshold values. The visual aspects (e.g., patchiness or spatial segregation) of the weed maps were described as well as the proportion of mapped area that would be left untreated (no herbicide applied) on the basis of the different threshold values. The regression between the threshold value (in x) from 0 to 0.35% and the corresponding proportion of the field requiring control (in y) was calculated and averaged over all site-years. The slope of this regression was used as an indicator of sensitivity at each threshold value. A higher slope indicates a higher difference in the resulting proportion of the field requiring weed control at a given threshold value and an increment of 0.001%.

Results and Discussion

Weed Infestation Level Based on Crop Advisers. The advisers did not have the same level of tolerance for weeds (Table 3). Adviser 3 showed the lowest tolerance; he selected infestation level 1 for 352 images compared with 705 and 801 for advisers 1 and 2 respectively. The average percentage of weed cover for the images classified as uninfested was also the lowest (0.021%) (Table 3). This translated into the lowest average threshold value of 0.120% for adviser 3 (Table 4). On the other hand, adviser 2 showed the highest tolerance to weed infestation, with the highest number of uninfested images and the lowest number of infested images. The average percentage of weed cover for the images classified as uninfested was the highest (0.089%) (Table 3). This translated into the highest average threshold for adviser 2 (0.207%) (Table 4). Adviser 1 selected infestation level 2 for only 325 images compared with 505 and 532 for advisers 2 and 3 respectively, showing a higher desire or skill at classifying as infested and uninfested images. The average threshold value over the three crop advisers (0.159%) was close to the average threshold value resulting from the evaluation of adviser 1 (0.150%) (Table 3).

Weed Cover Threshold. Thresholds obtained from the AUC method resulted in values ranging from 0.060 to 0.312%, with a median of 0.186% and an average of 0.159% (Figure 2). The average threshold obtained with the first scenario (intermediate values removed) was lower than the threshold obtained from the second scenario (intermediate values randomly converted into uninfested or infested values), which indicates that the intermediate images

Table 4. Threshold values resulting from the different scenarios for each adviser and on average as measured by the area under the receiver operating characteristic curve method.

	Scenario to convert intermediate values				
	Excluded	Random[a]	To uninfested	To infested	Average
Adviser 1	0.128	0.145	0.204	0.121	0.150
Adviser 2	0.176	0.216	0.312	0.125	0.207
Adviser 3	0.084	0.129	0.205	0.060	0.120
Average	0.129	0.163	0.240	0.102	0.159[b]

[a] Average threshold value obtained over 100 randomizations.
[b] Overall average of the four scenarios.

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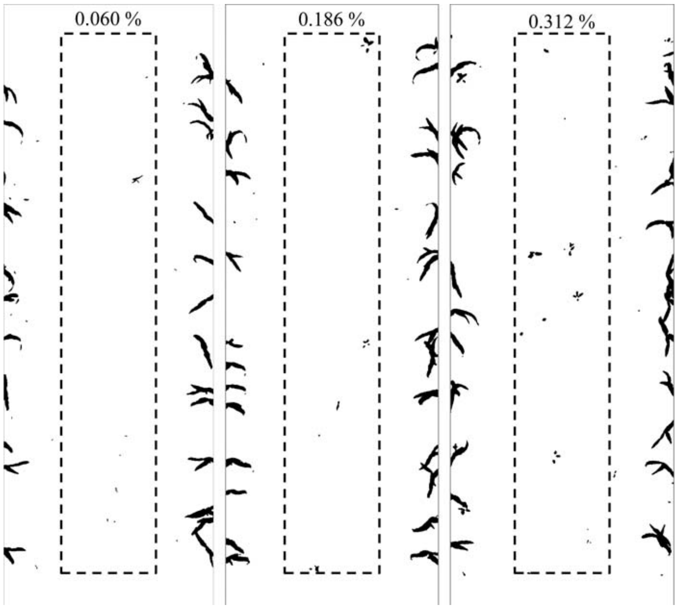

Figure 2. Illustration of the minimum (0.060%), median (0.186%), and maximum (0.312%) threshold values on actual ground imagery at the three-leaf stage of corn. Dashed rectangle is 0.35 m wide by 1.5 m long.

had a weed cover that was generally higher than the median between uninfested and infested images. As expected, considering all intermediate images as uninfested (third scenario) resulted in the highest average threshold of 0.204%. Consistently, considering all intermediate images as infested (fourth scenario) resulted in the lowest average threshold of 0.102% (Table 4).

All crop advisers had higher proportions of infested (level 3) images compared with other classifications (Table 3). This is consistent with the rather low tolerance that farmers have for weeds and is comparable with density-based thresholds described in the literature. When corn is at the two- to four-leaf stage, the area covered by about four broad-leaved weed seedlings m^{-2} or seven to eight grass seedlings m^{-2} corresponds to a weed cover of about 0.2% (Figure 2). A review of the literature reported that in general, the economic threshold in corn (weed densities that result in a 5 to 10% yield loss) for broad-leaved weeds is below five plants m^{-2}, whereas 10 to 40 grass weeds m^{-2} can be tolerated (Swanton et al. 1999). As discussed in Thornton et al. (1990), weed thresholds should be higher if the spatial variability of weed distribution is taken into account. Consistently, Weis et al. (2008) have demonstrated that in corn, the economic weed threshold based on an average over the whole field area was three grass seedlings m^{-2}, whereas the economic weed threshold adapted to spatial variability was eight grass seedlings m^{-2}. Also, Lemieux et al. (2003) have reported that in corn, a weed cover that is approximately 20% or less of the total vegetation cover (weed plus corn) would have no statistically significant impact on yield for the current growing season. For 1 m^2 that would include a corn row on one side, a threshold of 0.186% (i.e., the median value between 0.060 and 0.312% obtained using the AUC method) represents a weed cover of 18.6 cm^2 m^{-2}. On the basis of a 20% relative weed cover this would translate into a corn cover of 74.4 cm^2 m^{-2} (e.g., about four corn plants of 1.5 cm by 12 cm), which is far below a realistic corn cover at the two- to four-leaf stage. Therefore, it is considered that the threshold values obtained using our methodology were lower than what is needed to preserve the current year's crop yields. However, preserving the yield of the current year is not enough since residual weeds can produce seeds, replenish the seed bank, and increase seedling recruitment to the point where infestation during subsequent years is above threshold (Simard et al. 2009; Wallinga and van Oijen 1997). It is considered that expert crop advisers judge the weed infestation with the aim of preserving not only yields, but also subsequent infestations, and this may potentially explain why threshold values measured from their evaluation were much lower than the 0.2 relative weed cover of Lemieux et al. (2003). Williams et al. (2000) used a threshold on the basis of weed density for site-specific weed management on a 15-m by 15-m grid. They used a density of 12 seedlings m^{-2} for grasses and 25 seedlings m^{-2} for broad-leaved weeds and found no evidence that using reduced herbicide rates in below-threshold quadrats compromised weed management in the subsequent years. Ritter (2008) also observed consistent herbicide savings over 6 yr using 7.5-m by 15-m plots and on the basis of three herbicide rates.

Threshold Values Applied to a Field Area. The threshold value has a direct effect on the proportion of area to be treated with herbicides. The lower the threshold the higher the proportion of the field considered as infested and vice versa. The 19 site-years were used to evaluate the effect of the threshold value on the proportion of area requiring herbicide treatment. The area requiring herbicide treatment varied from over 90%, regardless of the threshold (3 site-years) to less than 30% or 10% (based on the thresholds) (2 site-years) (Figure 3a). The sensitivity (variation in area requiring herbicide treatment) to the threshold was higher for site-years

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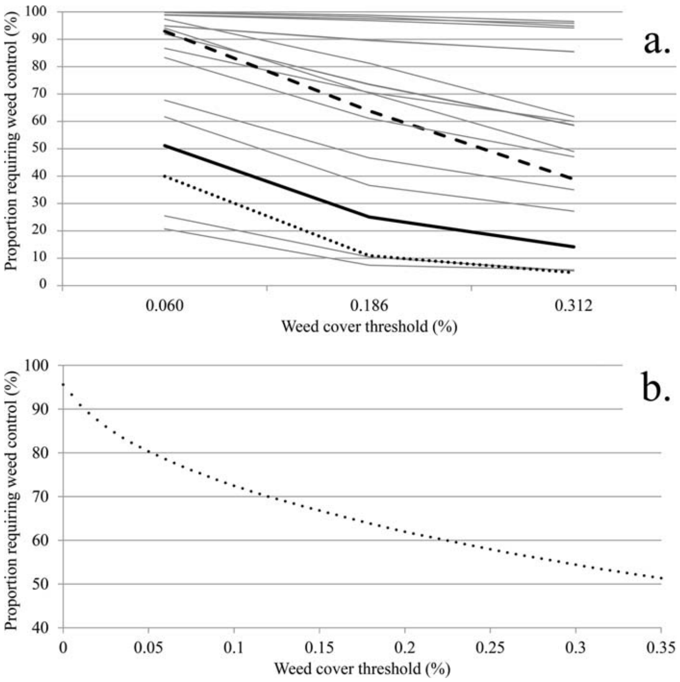

Figure 3. In *a*, proportion of field area requiring herbicide treatment on the basis of weed cover thresholds. Lines represent 19 fields (site-years). The site-years for which the sensitivity to the threshold was the highest are highlighted by a solid (site a_{08}), dashed (site e_{09}), and pointed (site i_{09}) black line (see also Figure 5). In b, proportion of field area requiring herbicide treatment on the basis of weed cover thresholds averaged for all 19 site-years.

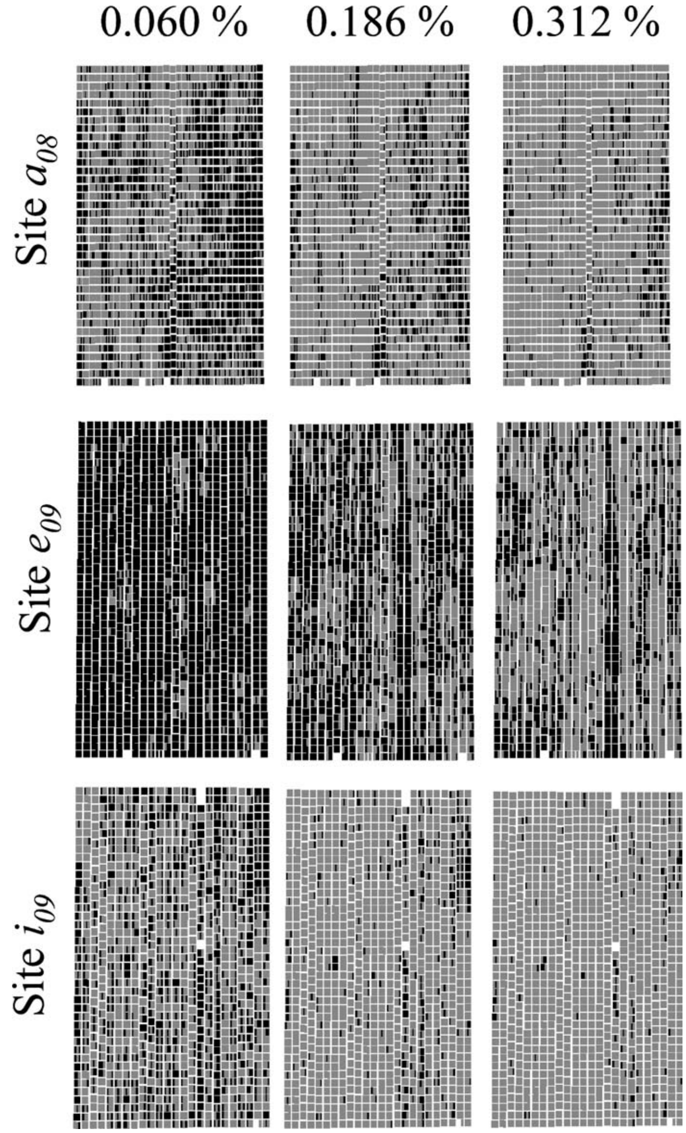

Figure 4. Maps showing the herbicide application area of the 3 site-years (sites a_{08}, e_{09}, and i_{09}) that showed the highest sensitivity to the weed cover thresholds depending on the threshold applied (left to right). Black rectangles represent interrow sections (each measuring 0.35 m by 1.6 m) and delineate herbicide-treated areas and gray rectangles represent interrow sections delineating untreated areas. Threshold values correspond to minimum (0.060%), median (0.186%), and maximum (0.312%) weed cover values.

with low weed covers than for highly infested ones (Figure 3a). In general, there was a more important decrease in infested proportion between the minimum (0.060%) and the median (0.186%) threshold values (average 15% decrease) than between the median and the maximum (0.312%) threshold value (average 10% decrease), indicating a higher sensitivity of the threshold at lower values. This was consistent with the observations of Tian et al. (1999) in which changing the weed cover threshold from 0 to 0.5% resulted in an increase of 225% nonspray area, whereas changing the weed cover threshold from 0.5 to 1% resulted in an increase of 114% nonspray area. The average slope of the regression beween the percentage of the field requiring weed control and the threshold value crossed the value of -1 around a threshold of 0.15% and crossed -0.5 around a threshold of 0.4% (Figure 3b). This demonstrated that even though the threshold values appear fairly low (e.g., less than 0.5%) the choice of the threshold had an important impact on the infested proportion and thus on the resulting weed map.

Figure 4 illustrates maps of the herbicide application area for the 3 site-years (sites a_{08}, e_{09}, and i_{09}) that showed the highest sensitivity to the weed cover thresholds depending on the threshold applied (left to right). For these site-years, increasing the threshold value resulted in higher apparent segregation between treated and untreated, thus forming more uniform patches and gaps. For the 3 site-years that were the most affected by the threshold value, certain patches were distinct at threshold values of 0.186 and 0.312% but were somewhat indistinct at 0.060% weed cover (Figure 4). It is anticipated that at lower threshold values, the spatial structure would

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be even less discernible because the proportion of treated area would increase drastically. The area treated as well as its spatial structure are key components of the decision process for the implementation of site-specific weed management. Therefore, below a certain weed cover tolerance, site-specific weed management may be impractical. In general, growers have a relatively low tolerance toward weeds for practical reasons such as crop competition, harvesting problems, and seed bank replenishment or less practical reasons such as field appearance (Czapar et al. 1997). Schröder et al. (2000) refers to the use of high rates of nitrogen fertilizer in corn as "insurance rates" for farmers, meaning that applying more nitrogen than needed acts as insurance for high yield. This statement probably also applies to blanket herbicide applications considering that weeds are not present above the economic threshold at every location of the field. Moreover, farmers often account for a certain yield loss due to crop injury when they use herbicides, which also relates to the concept of insurance. However, if crop value does not increase at the same rate as increasing cost of farm inputs and the incentives for the adoption of environment conservation practices, the price of this insurance might become too expensive. This might increase the tolerance of farmers for the presence of weeds.

Weed cover threshold values should reflect the level of tolerance toward weed presence. The scenario considering all "intermediate" images as "uninfested" reflects a more tolerant approach (i.e., threshold value of 0.240%), whereas the scenario converting these to "infested" reflects a more conservative approach (i.e., threshold value of 0.102%). Tian et al. (1999) evaluated weed cover threshold values from 0 to 3.0%, which seems high as compared with the threshold values obtained in the present study and would have been more realistic to evaluate threshold values from 0 to 0.5%. It is believed that using a more conservative threshold has more chances to allow site-specific weed management in the long term as compared with a more tolerant weed threshold, as demonstrated by Simard et al. (2009). One practical approach could be to experiment with site-specific weed management using a conservative threshold (e.g., 0.1%) and increase toward more tolerant threshold values (e.g., 0.2 or 0.25%), as suggested by Thornton et al. (1990) for site-specific weed management, when the farmer gains confidence in site-specific weed management strategy and no increase in weed infestation occurs in the long term.

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