Precision Agric (2012) 13:337–350
DOI 10.1007/s11119-011-9250-5

Sectioning remote imagery for characterization of *Avena sterilis* infestations. Part B: Efficiency and economics of control

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Published online: 29 October 2011

Abstract *Avena sterilis* weed pressure categories can be discriminated in wheat through remote images taken at late stages of wheat senescence. Site-specific image processing was achieved with SARI®, an add-on software program for ENVI® developed to implement precision agriculture. Using the SARI software and crop-weed competition and economic models, the precision yield losses for each micro-plot can be estimated and herbicide prescription maps obtained. Simulation studies on control indicators and herbicide use efficiency were undertaken using real-time ground data and remote images of two wheat plots infested with *Avena sterilis* at LaFloridaII and Navajas (Southern Spain). The simulation indicated that precision application of herbicides would produce higher overall herbicide savings (OHS) compared to broadcast applications but would vary depending on the level of weed infestation, the decision making criteria (DMC) of applying herbicide above a weed infestation level and the size of the spray grid considered. For example, for areas with low levels of infestation (around 15%), the OHS was 20, 44, 81 and 90% for a DMC of 0, 10, 20 and 30%, respectively. SARI® also estimates the overall herbicide application efficiency (OHAE), a key agro-environmental index to estimate the efficiency of herbicide applications in weedy areas and the lack of herbicide applications in weed-free areas. Ideally, the OHAE is equal to 1 if weed control is complete and herbicide applications in weed-free areas are not necessary. The OHAE index is influenced by the size of the micro-plot and decision-making herbicide application criteria (DMC). The OHAE values increased as the size of the micro-plot decreased, regardless of the intensity of the weed infestation. For example, micro-plots of 20 × 6 m, 5 × 3 m and 1.2 × 1.5 m had OHAE values of 0.27, 0.57 and 0.76, for areas of low infestation, when averaged over the DMC. Generally, the OHAE values increased as the size of the micro-plot decreased regardless of the intensity of weed infestation. Based on actual weed abundance data, competition models and production costs, SARI® estimated wheat yield losses and

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economic net return for each micro-plot and herbicide application strategy. In both locations, weed infestation varied spatially from virtually weed-free micro-plots to 15 and 24% winter wheat yield loss in Navajas and LaFloridaII, respectively. Preliminary calculations indicate that net returns were slightly higher for areas with site-specific adjusted-rate applications than for the overall standard label rate application strategy. Both of these strategies provided considerably higher net returns compared to non-treated areas.

Keywords SARI® add-on software · Control efficiency · Weed control strategies · Economic control

Nomenclature

Wild oat	*Avena sterilis* sp. *sterilis* L
Wheat	*Triticum durum* L

Introduction

In weed science, weed-crop competition has been an important topic and many scientific papers have been produced over the past few decades (Cousens et al. 1987 and Cousens et al. 2003). The implementation of economic thresholds is desirable in site-specific weed management (SSWM) and this is based on models of the competition between weed density and yield loss. Yield losses in response to *Avena sterilis* panicle density were studied in barley (*Hordeum vulgare* L.) (Torner et al. 1991), and in winter wheat (Saavedra et al. 1990). Detection of late-season weed infestations with remote sensing has large possibilities when plants are mature, the soil surface is completely covered and the influence of background soil and crop residue reflectance is minimal (Koger et al. 2003). Most weed competition studies are based on weed density ground sampling. The data from the ground samples are fitted into economic threshold models. However, very few of these studies, if any, have been applied by farmers because the weed-density spatial assessment could not be determined through conventional techniques in an economic and feasible way. Conversely, the use of high spatial resolution remote images and appropriate weed-crop discrimination techniques could be of high utility to determine site-specific weed population. For example, several authors have used remote sensing to map late-season infestations of *Avena sterilis* in wheat (López-Granados et al. 2006), *Ridolfia segetum* Moris in sunflower (*Helianthus annuus* L.) (Peña-Barragán et al. 2007) and weed crucifers in wheat and legumes (deCastro et al. 2009). In addition, weed infestations can be relatively stable from year to year (Wilson and Brain 1991; Barroso et al. 2004), allowing late-season weed detection maps to be used in the design of SSWM for following years.

Semi-automatic, cost effective, large-scale mapping of weed infestations needs to be developed to take full advantage of SSWM. Software to manage images obtained through remote sensing can play an important role in the fulfilment of this objective. SARI® (Sectioning and Assessment of Remote Images) is a software add-on for ENVI® 4.6 (Visual Information Solution Inc., Boulder, Colorado, USA) that has been developed to implement precision agriculture strategies (García-Torres et al. 2009; Gómez-Candón et al. 2011). SARI® splits field plot images into grids of rectangular “micro-images” or “micro-plots” as multiples of the spatial resolution of the image, assesses diverse indicators for each micro-plot and classifies the micro-plots into arbitrarily defined classes based on these indicators (Gómez-Candón et al. 2011).

Generally, the principles of SSWM are widely accepted for its potential economic and environmental benefits (Timmermann et al. 2003), although not yet applied in practice due to lack of a feasible and cheap technology to determine the weed spatial distribution. Site-specific methodological developments for the management of weed infestation through remote imaging are not common but may be of increasing interest due to the expected development of high spatial resolution imagery in the coming decade. This article intends to contribute to the precision management of *Avena sterilis* in wheat, through the use of remote sensing, a weed-crop competition model and SARI software. Its specific objectives are (1) to evaluate the efficiency of SSWM with varying grid size and decision making criteria and (2) to estimate net economic returns of different herbicide application strategies.

Materials and methods

Airborne photographs of LaFloridaII farm (Utrera, Seville) and of the Navajas farm (StaCruz, Cordoba) in Southern Spain were taken around mid-May 2006 over winter wheat fields. The characteristics of the crop fields, aerial flight and image acquisition and image processing for land use classification were the same as described by Gómez-Candón et al. (2011). Two rectangular portions of LaFloridaII and Navajas images of 1.95 and 2.69 ha, respectively, were selected for the studies and their geographic co-ordinates are shown in Fig. 1. Supervised classification of the grassy weed patches in wheat was previously described by López-Granados et al. (2006), and the use of the NDVI index was recommended due to the high per-class accuracies obtained (0.87–0.94) in all locations.

Classification of weed abundance categories

Each farm was visited during mid-May 2006 to collect ground-truth control points of crop areas of several categories of weed abundance: (a) *Avena sterilis*-free, (b) low (1–30 *Avena sterilis* panicles m^{-2}, average 20 m^{-2}), (c) intermediate (31–80 panicles m^{-2}, average 60 m^{-2}), and (d) high infestation ($>$ 81 panicles m^{-2}, average 140 m^{-2}). Details of ground work for weed abundance assessment and geo-referencing, and for weed abundance categories boundary digital values (BDV) determination were the same as previously described in Gómez-Candón et al. (2011). The overall accuracy and Kappa coefficient of the whole classification process were calculated.

SSWM efficiency versus micro-plot size and herbicide application criteria (DMC)

The NDVI image of LaFloridaII was used to determine the relationship between SSWM efficiency and micro-plot size. Two 0.19 ha wheat crop zones, infested with *Avena sterilis,* were selected. One zone had a low infestation intensity with 14.1% infested pixels (X = 242282, Y = 4124821) and the other zone had an intermediate infestation intensity of 52.8% infested pixels (X = 242264 Y = 4124796). SARI® was used to divide the two selected zones into micro-plots of varying dimensions, from 1.2 × 1.5 m to 80 × 24 m (Table 2). Progressive decision making criteria (DMC) regarding the application of herbicide were considered for each micro-plot and decisions were made based on strict criteria, which included the application of herbicide only if the infestation intensity was

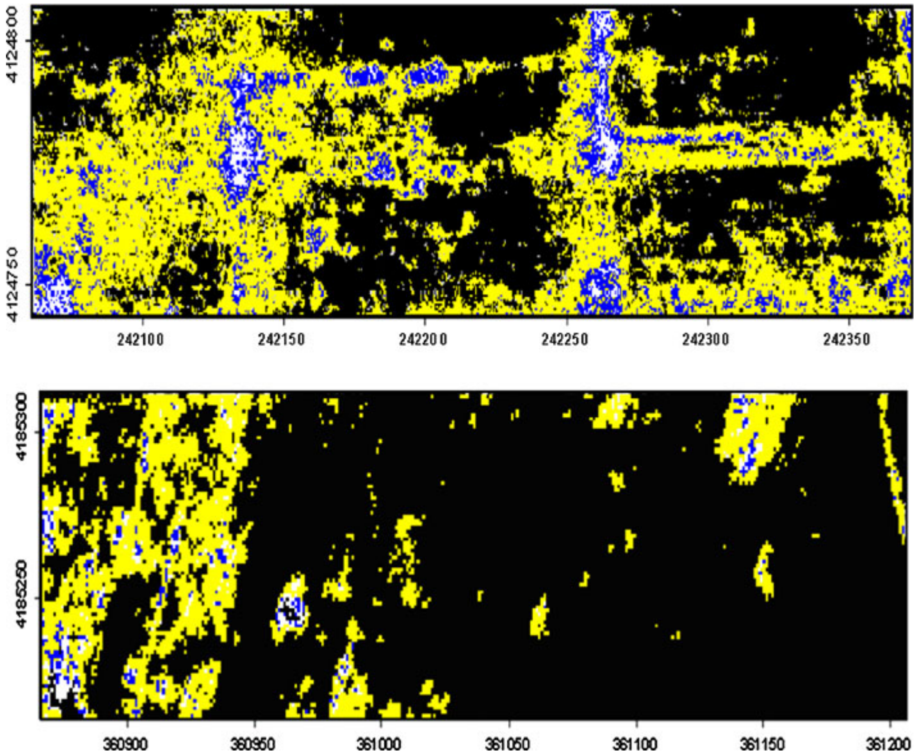


Fig. 1 *Avena sterilis* abundance categories in wheat at LaFlorida (*top*) and Navajas (*bottom*). Weed free area is in *black*, and *Avena sterilis* low, intermediate and high infested areas are in *yellow*, *blue* and *white*, respectively. Overall classification accuracy and Kappa coefficients were 93.6 and 0.89%, and 84.8 and 0.78% for each location, respectively. Wheat weed-free (*black*) and *Avena sterilis* low (*pale grey*), intermediate (*grey*) and high (*white*) weed abundance categories at LaFlorida. Overall classification accuracy and Kappa coefficients were 93.6 and 0.89% (Color figure online)

greater than a given percentage, for example 20% (DMC20%). To estimate the relationship between the efficiency of SSWM and DMC, two agro-environmental indices were used: (a) the Overall Herbicide Saving (OHS), which is the ratio between the area not treated with herbicide compared to the entire plot area and (b) the Overall Herbicide Application Efficiency (OHAE), which estimates the efficiency of herbicide applications in weedy areas and the lack of herbicide applications in weed-free areas, as calculated by the following equation:

$$OHAE = \left(\left(\sum_{i=1}^{n} AITA_i/AI\right) - \left(\sum_{i=1}^{n} AFTA_i/AF\right)\right)/n) \quad (1)$$

where $AITA_i$ and $AFTA_i$ are the *Avena sterilis*-infested and *Avena sterilis*-free herbicide-treated area of each micro-plot, respectively. i is the micro-plot number, n is the number of micro-plots, AI is the *Avena sterilis*-infested area and AF is the *Avena sterilis*-free area of the entire plot. Therefore, the OHAE indicates the efficiency of herbicide applications to weedy areas and the lack of herbicide application to weed-free areas, as affected by the DMC and size of the micro-plot. A value of OHAE near one indicates a high efficiency in herbicide application, while small values indicate poor efficiency. The OHS and OHAE indices, influenced by DMC and micro-plot size, were obtained with SARI® in Excel format.

Economic net returns of herbicide application strategies

The images obtained by remote sensing of the LaFloridaII and Navajas farms, the infestation intensity categories and their corresponding NDVI BDV were used to calculate the economic profitability of herbicide application strategies. The original NDVI image of the winter wheat crop infested with *Avena sterilis* was segmented into four images using the BDV thresholds for each farm. These four images included each weed infestation category. Each image was divided into 75 and 112 micro-plots with an area of 20 × 13 m for LaFloridaII and Navajas farms, respectively. The percentage of *Avena sterilis*-infested pixels for each micro-plot was calculated by SARI®. The effect of *Avena sterilis*-infestation on wheat yield for each micro-plot was estimated using the following equation:

$$L = 3.90 \times \sqrt{WOPA} \quad (2)$$

where L is the percentage of wheat yield lost and $WOPA$ is the average *Avena sterilis* abundance for each infestation category. This equation was calculated using data from Saavedra et al. (1990). The percentage of infested surface (%IS, pixels) and grams of wheat yield loss for each micro-plot were calculated using SARI® and obtained in Excel format as described in Gómez-Candón et al. (2011).

Three herbicide application strategies were simulated: (i) no herbicide application, (ii) overall label rate application and (iii) site-specific adjusted rate application. Herbicide treatments in the site-specific adjusted rate strategy were assigned based on the infestation levels present at harvest in the previous season, indicated as a percentage of infested surface area (%IS). Maps of *Avena sterilis* based on the previous year's information can be used for patch spraying in future years (Barroso et al. 2004 and Barroso et al. 2005). In order to match spatial resolutions, the size of the micro-plot was used for the herbicide prescription map. Application maps were based on the following criteria: (a) no herbicide was applied in *Avena sterilis*-free and micro-plots with very low infestation levels (< 10% IS), (b) half the label rate was applied to micro-plots with low infestation levels (11–30% IS) and (c) the label rate was applied to intermediate and highly infested micro-plots (> 30% IS). When the herbicide was applied at the label rate, complete weed control with no yield losses was assumed. At half the label rate, a 10% reduction in wheat yield due to weed competition was assumed. These assumptions were similar to those by Ruiz et al. (2006) and were based on results obtained in previous research (Barroso et al., 2004). The OHS and OHAE indices and the herbicide application strategies were calculated using SARI® and obtained in Excel format.

The economic profitability or net return (NR) for each herbicide application strategy was assessed for each micro-plot by the following equation:

$$NR = \hat{y}\left(1 - \frac{1}{n}\sum_{k=1}^{n} L_k\right)p - \left(C_i + C_a + \mathrm{H}\frac{1}{n}\sum_{k=1}^{n}\delta_k + C_o\right) \quad (3)$$

where $\hat{y}$ is the expected weed-free wheat yield (Y_{max}) and is equal to 4.8 t ha^{-1} and 4.0 t ha^{-1} in LaFloridaII and Navajas, respectively. n is the total number of micro-plots, each of which is 20 × 13 m. k is the micro-plot number, L_k is the yield loss estimate in micro-plot

k according to Eq. 2, p is the price of wheat grain (0.30 € kg^{-1}), C_i is the cost of acquiring and processing the images (€ 2 000 for a 200 ha farm, with an additional 10 € ha^{-1} for site-specific treatments), C_a is the herbicide application cost, 6.6 € ha^{-1} for spraying with a 13-m boom standard sprayer, with a capacity of 3.46 ha h^{-1} and 14.1 € ha^{-1} for precision application using a DGPS-controlled adjusted-dose patch sprayer similarly as achieved by Barroso et al. (2004) and Timmermann et al. (2003). H is the specific herbicide cost at the label rate (40 € ha^{-1}), δ_k is the herbicide rate for micro-plot k according to each strategy (Table 3) and C_o includes all other costs involved in crop production (tillage, seed, fertilisers, harvest, etc., 300 € ha^{-1}). Net returns for the three herbicide application strategies are indicated in € ha^{-1}. Economic parameters were calculated using SARI® and were obtained in Excel format.

Results

Classification of weed abundance categories

At LaFloridaII, the selected NDVI BDV values for weed free, low, intermediate and high weed pressure categories were < 0.56, 0.56–0.66, 0.67–0.72 and 0.73–0.80 (Table 1), respectively, assessed with an overall classification accuracy of 93.6% and Kappa coefficients of 0.89. At Navajas, for the same categories the defined BDV were < 0.16, 0.16–0.39, 0.40–0.46 and 0.47–0.59 for Navajas (Table 1), with an overall accuracy 84.8% and Kappa coefficient of 0.78. For both locations, the infested surface for each weed abundance category is indicated in Table 1 and shown in Fig. 1.

SSWM efficiency versus micro-plot size and herbicide application criteria

Site-specific overall herbicide saving (OHS) varied considerably with the degree of infestation, decision making criteria (DMC) and the size of the micro-plots (Table 2). Generally, the OHS was considerably lower in intermediately infested areas (52.8% infested pixels) than in areas of low infestation (14.8%), when averaged across the size of the micro-plot and DMC. The OHS increased as DMC increased when averaged across the size of the micro-plot. Strict decision making criteria (DMC0% to DMC30%), when averaged across the size of the micro-plot, were more efficient at reducing OHS in areas of low infestation (20–90%) than in areas with intermediate infestations (5–30%).

At DMC0% criterion, the herbicide was applied only to each *Avena sterilis* infested micro-plot regardless of its density and, at low infestation intensities, micro-plots that were 5 × 3 m or larger provided an OHS of zero, but smaller micro-plots gave greater values 40–65% of the total area (Table 2). DMC0% criterion at an intermediate infestation level resulted in OHS values ranging from 5 to 18% for the four smallest micro-plot sizes. The use of DMC10% in low infestation areas resulted in OHS of about 37% for micro-plot sizes of 20 × 12 m, and the OHS increased as micro-plot size decreased, up to 71% (Table 2). Generally, SSWM produced consistent herbicide savings. For example, in areas with low levels of infestation, the OHS was 20, 44, 81 and 90% for DMC0, DMC10, DMC20 and DMC30%, when averaged over micro-plot size, respectively (Table 2). However, very permissive decision-making application criteria such as DMC40%, DMC50 and DMC60% (data not shown for abbreviation) indicated a predisposition for the lack of a herbicide application or to apply herbicide only at very high infestations. This would be unusual in highly productive farming systems.

Table 1 Ground-truth *Avena sterilis* infestation categories, remote sensing boundaries digital values (BDV) and wheat yield losses at LaFloridaII and Navajas fields using SARI® software

Weed pressure[b]		Location[a]													
		LaFloridaII							Navajas						
Category	No. of panicles m^{-2}	Remote image BDV	Average		Minimum		Maximum		Remote image BDV	Average		Minimum		Maximum	
			%IS[c]	kg ha^{-1}	%IS	kg ha^{-1}	%IS	kg ha^{-1}		%IS	kg ha^{-1}	%IS	kg ha^{-1}	%IS	kg ha^{-1}
Low	1–30	0.56–0.66	41.1 ± 13	164 ± 101	1.2	5.5	33	277	0.16–0.39	16.4 ± 9	8 ± 5	0	0	60	14.5
Intermediate	31–80	0.67–0.72	5.5 ± 8	80 ± 114	0	0	24	549	0.4–0.46	1.0 ± 2.1	1 ± 3	0	0	5	6
High	81–300	0.73–0.80	0.7 ± 0.1	17 ± 51	0	0	13	281	0.47–0.55	0.9 ± 2.9	2 ± 6	0	0	13	24
Overall		0.56–0.80	47.3 ± 27	261 ± 254	1.2	5.5	70	1107	0.16–0.55	18.3 ± 22	11 ± 14	0	0	78	44.5

[a] The study area of each location was made of 75 and 112 micro-plots each 20 × 13 m for LaFlorida and Navajas, respectively

[b] %IS is the percentage of infested surface and yield losses in wheat kg ha^{-1}

[c] Mean ± standard deviation

Table 2 Overall herbicide saving (*OHS*) and overall herbicide application efficiency (*OHAE*) for low and intermediate infestation intensities as a result of the size of the micro-plot and decision-making herbicide-application criteria (*DMC*)

		OHS					OHAE				
Infestation intensity	Micro-plot size (m)	DMC0%[a]	DMC10%	DMC20%	DMC30%	Mean[c]	DMC0%[a]	DMC10%	DMC20%	DMC30%	Mean[d]
Low[b]	80 × 24	0	0	100	100	50	0	0	0	0	0
	40 × 24	0	0	100	100	50	0	0.03	0	0	0
	40 × 12	0	25	75	100	50	0	0.14	0.18	0	0.08
	20 × 12	0	37	87	87	53	0	0.28	0.25	0.25	0.19
	20 × 6	0	38	69	87	50	0.07	0.37	0.38	0.24	0.27
	20 × 3	0	62	78	91	58	0.10	0.49	0.47	0.34	0.35
	10 × 3	0	47	73	84	51	0.29	0.57	0.55	0.44	0.46
	5 × 3	40	66	73	85	66	0.45	0.66	0.65	0.52	0.57
	5 × 1.5	50	68	78	83	70	0.58	0.71	0.70	0.65	0.66
	2.5 × 1.5	58	71	78	83	72	0.58	0.72	0.73	0.68	0.68
	1.2 × 1.5	65	71	81	90	70	0.74	0.79	0.78	0.74	0.76
	Mean[e]	20 ± 27	44 ± 26	81 ± 10	90 ± 6		0.25 ± 0.2	0.43 ± 0.2	0.42 ± 0.3	0.35 ± 0.2	
Intermediate[b]	80 × 24	0	0	0	0	0.0	0	0	0	0	0
	40 × 24	0	0	0	0	0.0	0	0	0	0	0
	40 × 12	0	0	0	25	6.3	0	0	0	0.23	0.05
	20 × 12	0	0	12	37	12	0	0	0.17	0.4	0.14
	20 × 6	0	12	18	31	15	0	0.21	0.3	0.42	0.23
	20 × 3	0	18	25	34	19	0	0.32	0.41	0.50	0.31
	10 × 3	1	21	26	35	21	0.03	0.38	0.44	0.53	0.34
	5 × 3	5	21	30	38	23	0.1	0.37	0.5	0.57	0.39
	5 × 1.5	12	27	36	41	29	0.24	0.5	0.61	0.66	0.5
	2.5 × 1.5	17	29	35	42	31	0.38	0.57	0.66	0.71	0.58

Table 2 continued

		OHS					OHAE				
Infestation intensity	Micro-plot size (m)	DMC0%[a]	DMC10%	DMC20%	DMC30%	Mean[c]	DMC0%[a]	DMC10%	DMC20%	DMC30%	Mean[d]
	1.2 × 1.5	18	32	37	44	26	0.32	0.49	0.60	0.68	0.52
	Mean[e]	5 ± 7	15 ± 12	20 ± 15	30 ± 15		0.09 ± 0.1	0.26 ± 0.2	0.33 ± 0.2	0.42 ± 0.2	

[a] DMC % = % of micro-plots treated with herbicide

[b] The average infestation intensity was 14.1 and 52.8% infested pixels for the low and intermediate infested area, respectively

[c] OHS and [d] OHAE means for each micro-plot size averaged over DMC

[e] Means of DMC averaged over micro-plot sizes and standard deviation

The OHAE index was influenced by micro-plot size and decision-making criteria (Table 2). Ideally, if the OHAE was equal to 1, this would indicate complete weed control and no herbicide application was necessary in weed-free areas. The OHAE values increased as the size of the micro-plot decreased, regardless of the intensity of weed infestation. For example, micro-plots of 20 × 6, 5 × 3 and 1.2 × 1.5 m had OHAE values of 0.27, 0.57 and 0.76, for areas with low infestation and 0.23, 0.39 and 0.52 for areas with intermediate infestation, respectively, when averaged over DMC. Averaging over the size of the micro-plot, the OHAE for areas of low infestation (14.1% infested surface) was higher for DMC10% (0.43) and DMC20% (0.42), than for the other DMCs. In areas with intermediate infestation levels (52.8% infested surface), the OHAE was 0.09, 0.26, 0.33 and 0.42 for DMC0%, DMC10, DMC20 and DMC30%, respectively. Thus, when averaging the size of a micro-plot, a DMC that approximates the overall infestation level is optimal for obtaining high OHAE values.

Economic returns of herbicide application strategies

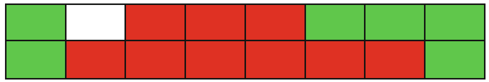
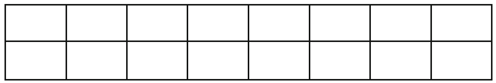
The yield losses and economic return of each micro-plot can be estimated through SARI software output, and subsequently a prescription herbicide map can be obtained based on these parameters, as shown in Table 3 for the upper left 16 micro-plots of each location. In addition, the overall economic net returns were estimated based on infestation categories defined by ground-truth control points at the selected plots at LaFloridaII and Navajas and their corresponding NDVI BDV in the images (Table 1). At LaFloridaII, the observed infestation categories were estimated as low, intermediate and high with 40, 5 and 0.7% *Avena sterilis*-infested pixels and with yield losses of 253 79 and 16 kg ha^{-1} (6 598, 2 072 and 422 g micro-$plot^{-1}$) for each category, respectively. The presence of weeds on micro-plots varied from 1.2% of infested surface and yield losses of 5.4 kg ha^{-1} (143 g micro-$plot^{-1}$), to a maximum of 83% of infested surface and 1.1 kg ha^{-1} (30.2 g micro-$plot^{-1}$) of yield loss (Table 4). At Navajas, the average percent of surface infestation for the low, intermediate and high infestation categories were 16.4, 1.0 and 0.9%, with corresponding yield losses of 200, 32 and 45 g micro-$plot^{-1}$, respectively.

Across the three herbicide application strategies, yield losses were 351 0 and 27 kg ha^{-1}, while overall costs were 273 319 and 296 € ha^{-1} at LaFloridaII for non-treated areas, standard overall label rate application and site-specific adjusted rate application strategies, respectively (Table 4). Economic net returns were slightly higher for areas with site-specific adjusted-rate applications (1 137 € ha^{-1}) than for the overall standard label rate application strategy (1 121 € ha^{-1}). Both of these strategies provided considerably higher net return compared to non-treated areas (1 062 € ha^{-1}). Additionally, the OHS was 21%. The *Avena sterilis*-infested non-treated areas were only 0.45% in the site-specific adjusted-rate strategy compared to the overall standard label rate strategy. At Navajas, the results showed the agronomic advantages of site-specific adjusted-rate applications over the other two strategies evaluated.

Discussion

Agro-environmental indices, such as the OHS and the OHAE, provide important insight into the advantages of using SSWM and can be estimated through remote sensing and SARI® software. Generally, the data show that SSWM can be used to save unnecessary

Table 3 Expected yield losses of the 16 upper left micro-'plots (20 × 13 m) at the LaFloridaII and Navajas study sites, and corresponding herbicide prescription map, as follows: white (no herbicide application), green (intermediate herbicide rate) and red (high herbicide rate)

Location	Expected yield losses (Kg ha^{-1})								Prescription map
LaFloridaII	49	39	222	428	281	111	122	141	
	141	335	396	999	686	456	480	124	
Navajas	30	10	23	26	6	3	1	5	
	21	15	28	24	0	0	0	0	

Further indication of the decision herbicide taking is indicated in the text

Table 4 Agronomic parameters and economic net returns as a result of herbicide application strategies

Location	Parameters		Herbicide application strategy		
			None	Standard overall label rate	Site-specific adjusted rate
LaFloridaII	Agronomic	Wheat yield (kg ha^{-1})	4 449	4 800	4 773
		Yield losses (kg ha^{-1})	351	0	27
		Overall herbicide saving (%)	100	0	21
		Avena-infested non treated area (%)[a]	46.5	0	0.45
		Avena-infested herbicide treated area (%) [b]	0	100	46.1
		Avena-free herbicide treated area (%)[a]	0	53.5	53.8
	Economic	C_i all remote sensing costs	–	–	10
		C_a standard herbicide application cost (€ ha^{-1})	–	6.5	–
		C_{ss} site-specific herbicide application cost (€ ha^{-1})	–	–	14.2
		H herbicidecost (€ ha^{-1})	–	38.5	8.1
		C_0 all other production costs (€ ha^{-1})	273	273	273
		C_{OH} overall cost (€ ha^{-1})	273	319	296
		Net economic return (€ ha^{-1})	1062	1 121	1 137
Navajas	Agronomic	Wheat yield (kg ha^{-1})	3 893	4 000	3 988
		Yield losses (kg ha^{-1})	107	0	12
		Overall herbicide saving (%)	100	0	37
		Avena-infested non treated area (%)[a]	18.8	0	0.7
		Avena-infested herbicide treated area (%)[b]	0	100	18
		Avena-free herbicide treated area (%)[a]	0	81.3	26.7
	Economic	C_i all remote sensing costs (€ ha^{-1})	–	–	10
		C_a standard herbicide application cost (€ ha^{-1})	–	6.6	–
		C_{ss} site-specific herbicide application cost (€ ha^{-1})	–	–	14.2
		H herbicidecost (€ ha^{-1})	–	40.0	14.2
		C_0 all other production costs (€ ha^{-1})	273	273	273
		C_{OH} overall cost (€ ha^{-1})	273	319	311
		Net economic return (€ ha^{-1})	895	881	885

[a] Over whole area

[b] Over whole infested area

herbicide applications on *Avena sterilis*-free areas or zones with very low infestations, which is in agreement with the findings of other authors (Timmermann et al. 2003).

To implement any SSWM strategy, it is necessary to decide the size of the micro-plot and the criteria for the application of herbicide (DMC). OHS and OHAE indices vary with the size of the micro-plot and the DMC used. Both indices are important in the analysis of the efficacy of SSWM strategies. Generally, higher values of OHS and OHAE indicate a superior SSWM strategy. Ideally, the OHAE should be equal to 1, where a value of 1 can be interpreted as complete weed control and avoidance of herbicide applications in weed-free areas. It should be pointed out that the OHS and OHAE can only be calculated by processing remote images through SARI® software, and conversely the estimation of these indices through conventional ground or image processing techniques would simply hardly be feasible.

Agricultural, environmental and economic objectives should be balanced in the final decision regarding the application of herbicides. From the objective of agricultural production, increasing the proportion of the field that is treated with herbicides will improve production, assuming that this practice leads to the maximum yield. From an environmental viewpoint, the goal would be to reduce the area treated with herbicide. Finally, the economic objective is to get the maximum benefit, taking into account weed-crop competition losses, input production costs and the crop sale price. Through the use of SARI® software, it has been shown that these three objectives can be studied if basic information is available.

Conclusions

Avena sterilis weed pressure categories can be discriminated in wheat through remote images taken at late stages of wheat senescence. Furthermore, using SARI software and weed-crop competition and economic models, the yield losses for each micro-plot can be estimated and a herbicide prescription map designed. In addition, key agri-environmental indices such as OHS and OHAE can be determined through SARI®. They vary with the size of the micro-plot and the DMC used and are important in the analysis of the efficacy of SSWM strategies. An original method for the implementation of weed-crop competition models under site-specific conditions has been shown. As previously described, the method requires images obtained through remote sensing, appropriate models, ground-truth data and SARI® software. An additional limitation to this method is that weeds, or other biotic or abiotic factors, have to be detected in the images. The computerised decision making method has the important advantage of using images obtained through remote sensing and the ability to adapt these images to site-specific actions, which potentially reduced the costs of mapping biotic or abiotic factors across a field. SARI® has been shown in two fields to be effective software for sectioning images, the assessment of agro-environmental indicators and the implementation of weed control strategies in each micro-plot.

Acknowledgments This research was partially financed by the Spanish Commission of Science and Technology through the projects AGL2007-60926 and AGL2010-15506.

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