A methodology for the assessment of the potential of precision weed management based on geostatistical and crop growth model simulations

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A methodology for the assessment of the potential of precision weed management based on geostatistical and crop growth model simulations

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Abstract: *The reduction of the use of herbicides is a valuable objective both from economic and environmental perspectives and can be attained by the adoption of precision weed management, i.e. spraying only the areas of the field in which weeds are detected (patch-spraying). The definition of thresholds for spraying, based on agronomic and economic considerations, is needed in order to assess the convenience of patch-spraying. In the present work, a novel methodology, based on the geostatistical simulation of weed spatial patterns coupled with crop growth simulations using the APSIM model (Keating et al., 2003), is illustrated as a tool to identify convenient weed density thresholds. The method is illustrated in an application concerning two weeds species (*Avena sterilis *L. and* Apera spica-venti *L.) in wheat. The proposed methodology can be applied in order to choose the best herbicide spraying strategy among uniform, binary patch-spraying or patch-spraying according to a weed density threshold based on economic criteria.*
Keywords: *Patch-spraying, precision weed management, spatial distribution, APSIM.*

Riassunto: *La riduzione nell'uso degli erbicidi è un obiettivo importante sia in termini economici che ambientali e può essere ottenuto impiegando tecniche di gestione di precisione delle infestanti, cioè l'irrorazione solo nelle aree dove l'infestante è effettivamente presente (patch-spraying). In questo lavoro è illustrata una nuova metodologia per identificare il valore soglia di densità di due infestanti (*Avena sterilis *L. and* Apera spica-venti *L.) nel frumento, in un contesto di agricoltura di precisione. Questa metodologia è basata sulla simulazione geostatistica della distribuzione spaziale dell'infestante unita all'utilizzo di un modello di simulazione di accrescimento delle colture (APSIM). La metodologia proposta può essere applicata per la scelta della strategia di diserbo maggiormente conveniente tra trattamento uniforme, localizzato su tutte le aree infestate o localizzato sulle aree infestate con una densità superiore ad un valore soglia basato su criteri economici.*
Parole chiave: *Irrorazione a tasso variabile, gestione sostenibile delle infestanti, distribuzione spaziale, APSIM.*

1. INTRODUCTION

Intensive agriculture cannot avoid the use of crop protection products to ensure high crop yields, but the excessive use of herbicides has led to serious economic and environmental problems. Herbicides are the most frequent pesticides found in surface water and groundwater in Italy (Ispra, 2014). For these reasons a more rational use of the herbicides is required in order to save production costs and at the same time to safeguard workers safety and consumers health. This necessity has been also dictated by the Directive 2009/128/EC establishing a framework for the sustainable use of pesticides.

The reduction in the use of herbicides is a valuable objective both from economic and environmental perspectives and it can be attained adopting precision weed management (PWM) techniques. Weed distribution is often patchy and this peculiarity offers the opportunity to spray herbicides only in the areas of the field in which weeds are actually detected and exceed a given threshold, avoiding low or non-infested areas (Nordmeyer, 2009). In order to apply a PWM strategy, a detailed knowledge of weed distribution within the field is mandatory. In this context, the use of remote sensing data, in particular by means of optical sensors mounted on unmanned aerial vehicles (UAV), can be a very powerful tool to assist weed management based on patch spraying (Pelosi *et al.*, 2015; Rango *et al.*, 2006). The images acquired by UAV allow to detect the distribution of weeds within the field by means object-based or spectral classification methods (Lopez-Granados, 2009; Pena *et al.*, 2013; Torres-Sanchez *et al.*, 2013; Pelosi *et al.*, 2015). Image classification techniques allows to obtain a weed map from which a herbicide treatment prescription map can be derived, indicating the area of the field in which weed spraying should be carried out.

The knowledge of weed distribution allows to choose different weeding strategies mainly based on level of the infestation:

I) No weeding: if no weeds are present in the field.

II) Uniform weeding: if weed distribution is uniform within the field.

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III) Patch spraying: when the distribution of the weeds is not uniform. This can be subdivided into:

a. Binary patch spraying: herbicide applied only where weeds were detected; in this case the weed map coincides with the prescription maps.
b. Threshold patch spraying: herbicide is applied only where weeds exceed an economic or an agronomic threshold.

Patch spraying based on the estimation of an economic threshold should ensure more consistent savings as compared to binary patch spraying, since weed control would not affects all weed patches, but only those that have a plant density higher than a given weed threshold. However, the choice of the spraying threshold using an objective methodology is an issue not completely solved in the context of PWM. The right threshold ensures a yield loss lower or equal to the cost of herbicide treatments in economic terms, while a wrong choice would bring about an economic loss, due to the use of too high or too low weed thresholds. A threshold set too high would entail herbicide saving and environmental benefits, but also lower yields. On the other hand, a too low threshold would cause higher yields but higher herbicide costs and possibly environmental damage. Certainly, the decrease in the herbicide use, also for low reductions, allows to obtain an environmental benefit. On the other hands, the economic advantage is not warranted, taking into account the fixed and variable costs involved when using UAV-assisted patch spraying. Despite the increase in the use of UAVs in the context of precision agriculture, the acquisition and image processing costs are still high, as well as the investment in the equipment required to carry out patch spraying. This includes an on-board computer terminal on the tractor, on which the prescription map can be uploaded, controlling the spraying equipment and linked to a satellite navigation and guidance system. Currently, the allocation of specific incentives (e.g. from the European Common Agricultural Policy) would be necessary in order to warrant the economic feasibility of this type of management. From the agronomic point of view, the issue of how to calculate the right weed threshold for spraying is extremely important, but there is not general agreement on what could be the appropriate methodology for such task. Many empirical models were proposed in the literature, most of them being based on the estimation of the percentage of yield loss as a function of the relative density or relative leaf area of weeds and of specific parameters related to the competition between crop and weeds (Kropff and Spitters, 1991; Christensen *et al.*, 2003; Ali *et al.*, 2013). However the empirical relationships between relative leaf area and crop yield are highly specific, the effect on yield is affected by agronomic management, soil and weather conditions, thus for real situations of patch spraying applications, model parameters would need to be set for every patch according the location and composition of weed species (Ali *et al.*, 2013). Generally, the intensity of weed infestation is not constant over the years, whereas the spatial distribution pattern of a given weed species would persist (e.g patchy or uniform distribution), because it mainly depends on the weed dissemination or vegetative propagation method (Gerhards *et al.*, 1997). Moreover the location of weed patches could be fairly stable within the field over years (Nordmeyer, 2009). The knowledge of the weed spatial pattern, especially for weeds having a stable spatial distribution, is a very important feature in order to apply PWM and consequently to decrease the use of herbicides. Weed species such as *Avena sterilis L.* and *Apera spica-venti L* are common in winter cereal crops and are generally aggregated in patches (Barroso *et al.*, 2004; Nordmayer, 2009). This is due to their dispersal strategy: generally most of the seeds fall at distances lower than the height of the plant prior to crop harvest (O'Toole and Cavers, 1983; Shirtliffe *et al.*, 2002; Blanco-Moreno *et al.*, 2006).

In this present work, a methodology based on the geostatistical simulation of weed spatial patterns was used, in order to produce simulated maps of two common weed species, *Avena sterilis L.* and *Apera spica-venti L*. These maps were obtained using the spatial distribution of the weeds measured in real field conditions (Blanco-Moreno *et al.*, 2006; Nordmeyer, 2009). The weed maps were coupled with a crop/weed growth simulation model, in order to estimate wheat yield, taking into account the competition between crop and weeds. This methodology was applied to identify the convenient weed density thresholds for patch-spraying on wheat crop infested by *A. sterilis* and *A. spica-venti*.

2. MATERIALS AND METHODS

2.1. Geostatistical simulations of weed distribution

In order to simulate the spatial distribution of weeds within a wheat field, a geostatistical technique known as unconditional gaussian simulation (Goovaerts, 1997) was used. This technique allows to generate a gaussian spatial distribution of the weeds (plants m^{-2}) in a field, using a spatial model of the independent variable and simple kriging. Kriging was performed according a regular grid of 2 m on an actual 5.5 ha field located in Vetralla (Central Italy). The dimension of the grid was chosen according to the length of the independent sections of the boom sprayers commonly used for patch

spraying weeding in the context of site specific weed management (Pelosi *et al.*, 2015).
Geostatistical simulations were carried out using the gstat (Pebesma, 2004) R package (R Development Core Team, 2011) using expected values of distribution and spatial model data (type of variogram model, psill and range) retrieved from from the literature. In this work, spatial distribution of *Avena sterilis L.* and *Apera spica-venti L.* was simulated using field experimental data collected by Blanco-Moreno *et al.*, (2006) in Spain for *A. sterilis* and Nordmeyer (2009) in Germany for *A. spica-venti* (Tab. 1). For each weed species, the geostatistical simulation was repeated five times, thus obtaining five weed densities (predicted values) for each grid's node. A map of weed density was then obtained computing the mean predicted value for each node.

2.2. Wheat growth simulations

Simulated weed maps were employed in the APSIM (Agricultural Production Systems sIMulator) crop growth model (Keating *et al.*, 2003). APSIM is modular modelling framework that allows to simulate the main biophysical processes in cropping systems according to input daily weather data, providing predictions of crop production in relation to genotype, soil and management factor and in particular taking into account the crop/weed competition. Modules of APSIM concern climate, plant, soil and management. Soil module takes into account variables (e.g. soil organic matter, nitrogen, pH) and characteristics (e.g. soil depth, horizons, texture, residues) involved in the main soil processes (e.g. water balance, soil erosion, N and P transformations). Plant modules concerns a wide range of crops, pastures and trees, the physiological principles relating to the capture and use of the resources during the growth are the same for all plant, but thresholds and shapes of the response functions are different for each species. Crop modules simulate ontogeny, leaf area production and senescence by observed plant responses to photoperiod and temperature, while the potential crop water uptake is simulated according to root exploration and extraction potential. A complete description of APSIM model is presented by Keating *et al.*, 2003.
In order to obtain results which are not affected by specific climate conditions, crop/weed growth simulations were carried out using daily rainfall, temperature and radiation data collected over 19 years. The meteorological input from 1995 to 2013 (daily rainfall, temperature and solar radiation) were obtained from the agrometeorological station of the University of Tuscia located in Viterbo, Central Italy (lat. 42°43' N, long. 12°07' E, alt. 310 m). Average annual rainfall of the nineteen years were 797 mm, the average annual maximum and minimum temperature were respectively 36°C and -5.7°C. The parameterization of plant and management modules of the APSIM model was set according to typical values for usual agronomic management for wheat growing in Central Italy (Tab. 2). Characteristics of soil module are referred to a generic deep agricultural soil insisting in a flat area, having a good organic matter and nitrogen content in the first 30 cm (Tab. 2). Simulated grain yield maps (t ha^{-1}) were obtained for each growing season from 1995 to 2013, by carrying out simulations for each node of the maps of both weeds, with all APSIM's parameters remaining unchanged except for the weed density (plants m^{-2}). Mean yield values concerning the period from 1995 to 2013 were retrieved from the model output data for each node. All the APSIM simulations were carried out using the apsimr R package.
Four different scenarios were compared using APSIM simulations:

- **I. No weeds**: the field is free of weeds and no herbicide is applied;
- **II. No-spraying**: weeds are present but the herbicide is not applied;
- **III. Uniform spraying**: the herbicide is applied uniformly over the whole field.
- **IV. Precision spraying**: the herbicide is applied according to a weed density threshold, simulating a patch spraying treatment.

The procedure applied in this work is summarized in Fig. 1.

Weed species	Expected value (plants m^{-2})	Psill	Range (m)	Reference
Avena sterilis L.	12	20	36.8	Blanco-Moreno *et al.*, 2005
Apera spica-venti L.	30	1541	62.4	Nordmeyer, 2009

Tab. 1 - Expected value of weed density and parameters of spatial models retrieved from experimental data and used for the geostatistical simulations.
Tab.1 - Valore atteso di densità delle infestanti e parametri dei modelli spaziali ottenuti da dati sperimentali ed utilizzati per le simulazioni geostatistiche.

Parameters description	Value
Soil	
Soil depth (cm)	170
Bulk density (g cm^{-3})	1.38
Available water (mm/mm)	0.157
Wilting point (mm/mm)	0.177
Field capacity (mm/mm)	0.287
Saturation water content (mm/mm)	0.341
Organic carbon (%)	0.698
pH	6.46
Initial nitrogen	
NO_3^- (ppm)	0.37
NH_4^+ (ppm)	0.3
Crop management	
Sowing window start	November 1
Sowing window End	December 30
Sowing density (plants m^{-2})	300
Sowing depth (mm)	40
Top dress fertiliser (NH_4NO_3) after 90 days after sowing (kg ha^{-1})	170
Depth of seedbed preparation (mm)	150
Herbicide spraying	December 30

Tab. 2 - Main soil and crop parameters used for APSIM simulations. The soil parameters in the table refer to the mean values along the soil profile.
Tab. 2 - I principali parametri del suolo e della coltura utilizzati per le simulazioni con APSIM. I parametri del suolo nella tabella si riferiscono ai valori medi del profilo del suolo.

2.3. Economic threshold for weed control

In the fourth scenario (precision spraying), different weed density thresholds for patch spraying were tested, starting from 0 plants m^{-2} (binary patch spraying) and increasing the density for both weed species. Plant density threshold indicate the minimum density value above which weeding should be carried out.

In order to compare uniform and precision weeding scenarios, the following data were observed for each threshold value:

a) Grain yield (from APSIM simulations)
b) Gross income from yield considering a grain price of 190 € t^{-1}
c) Missed income derived from the yield difference between uniform and precision weeding
d) Cost of herbicide treatments (60 € ha^{-1})
e) Saving due to different amount of herbicide between uniform and precision weeding

The difference between herbicide saving and missed income expressed in € (balance) was computed for each threshold. A positive value of this difference indicates an advantage to carry out a patch spraying distribution, while when the value is negative the threshold is probably too tolerant, which means that missed income is higher than the saving resulting from the reduction of weeding area.

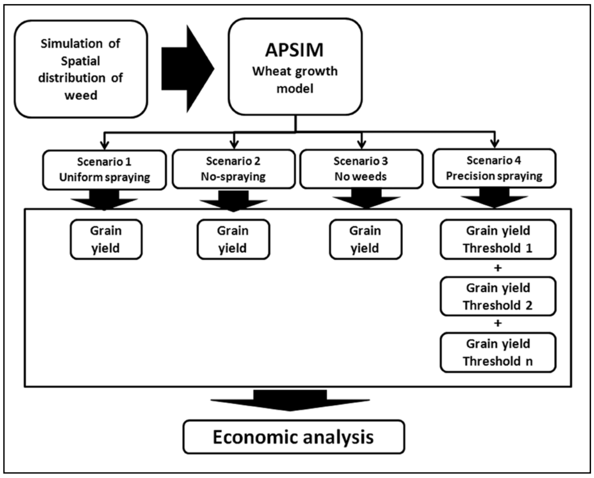

Fig. 1 - Flow chart showing the adopted methodology to estimate the economic thresholds of weed density on wheat crop.
Fig. 1 - Flow chart relativo alla metodologia utilizzata per la stima della soglia di densità delle infestanti nel grano in termini economici.

3. RESULTS

3.1. Spatial distribution of weeds

Mean plant density of *A. sterilis* obtained from unconditional Gaussian simulation is 11.5 plants m^{-2} and it varies between 0 and 25.4 plants m^{-2}. The spatial distribution appears quite patchy, due to the short range (36.8) of the semivariogram (Tab. 1), i.e. two points in the field separated by distances greater than 37 m are not spatially correlated (Fig. 2a). The mean standard deviation of density of *A. sterilis*, over the five simulations was 1.52 plants m^{-2} (Fig. 2b).

The mean density of *A. spica-venti* (30.6 plants m^{-2}) is quite higher than *A. sterilis* and it ranges between 0 and 152 plants m^{-2}. The spatial structure was verified up to distance between samples of 62.4 m. The higher range value of *A. spica-venti* as compared to those measured for *A. sterilis* involves a spatial distribution showing large areas with similar density values, especially at the centre of field, where weed density is very low (Fig. 2c). The mean standard deviation of plant density of *A. spica-venti* is 37.50 plants m^{-2}. Both weeds showed the maximum standard deviation in the field area having high plant density.

3.2. APSIM simulations and economic analysis

The APSIM simulation in absence of weeds provided a mean grain yield of 4.06 t ha^{-1} (Tab. 3). The productivity sharply decreases introducing weeds in the model without herbicide treatment. In this case, grain yield was 2.72 and 2.24 t ha^{-1}, respectively for *A. sterilis* and *A. spica-venti* infestation (Tab. 3). Obviously, lowest yield values were detected in the field areas showing the highest weed density (Fig. 3a and 4a). This significant decrease of yield caused by the presence of weeds confirms the need to carry out an appropriate weed management in order to ensure a profitable wheat crop. In fact, using an uniform weeding, the grain yield values obtained from model simulations were very similar to those obtainable in absence of weeds (Tab. 3), and a more uniform spatial distribution of yield was noticed (3.88 – 4.05 t ha^{-1}; Fig. 3c and 4c). However the spatial distribution of both weeds

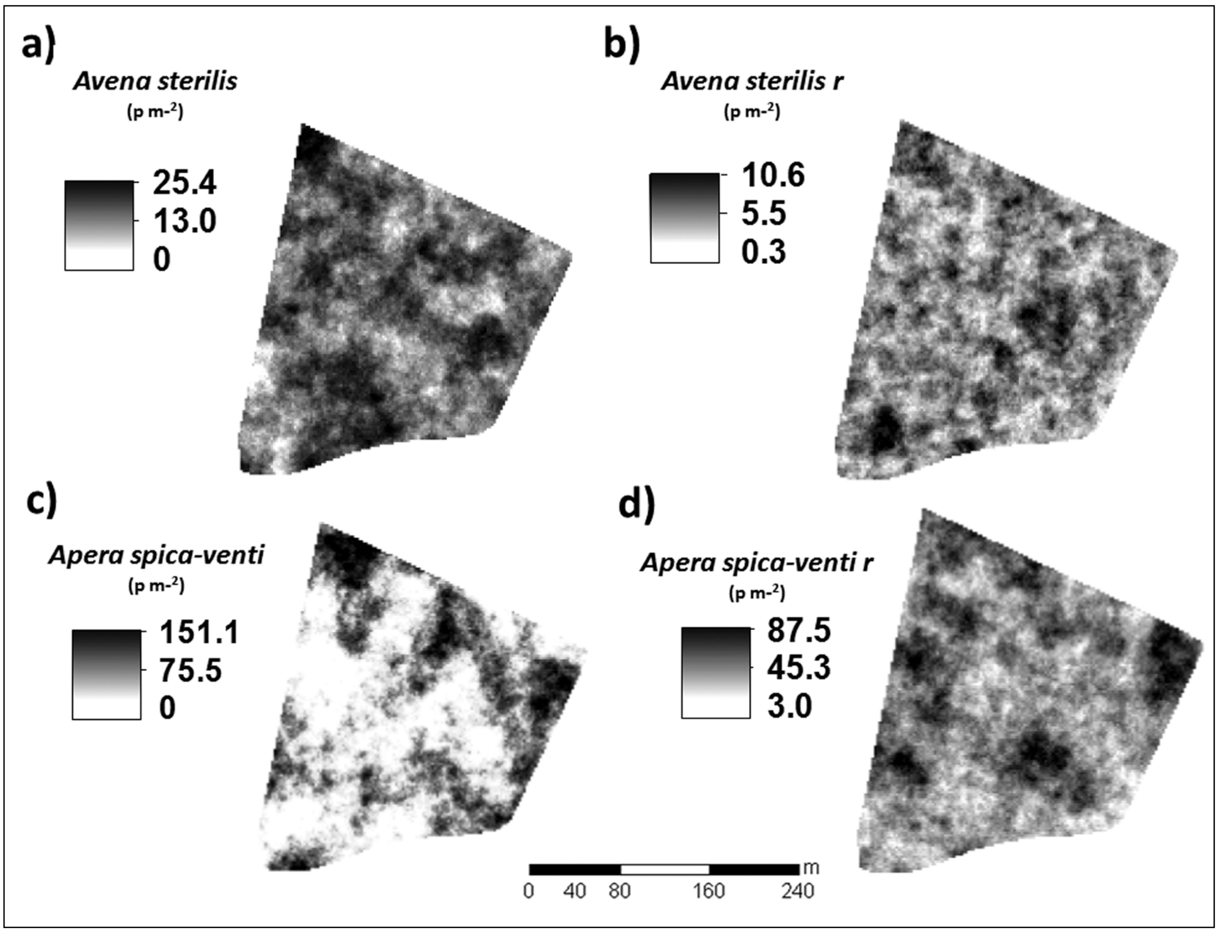

Fig. 2 - Maps of weeds density and standard deviation (*r*) retrieved by geostatistical simulations.
Fig. 2 - Mappe della densità delle infestanti e deviazione standard (r) ottenute dalle simulazioni geostatistiche.

	Avena sterilis L.		*Apera spica-venti L.*	
Scenario	Mean (t ha^{-1})	*sd* (t ha^{-1})	Mean (t ha^{-1})	*sd* (t ha^{-1})
No weeds	4.06	1.56	4.06	1.56
No weeding	2.72	1.04	2.24	1.19
Uniform weeding	4.05	1.57	4.02	1.57

Tab. 3 - Mean and standard deviation (*sd*) of wheat yield values obtained by APSIM simulations for three scenarios.
Tab. 3 - Media e deviazione standard (sd) dei valori di resa del grano ottenuti mediante le simulazioni APSIM per tre differenti scenari.

showed large areas where density is very low or zero (Fig. 2), suggesting the opportunity for a site-specific weed management according to weed density. The use of precision weeding allows the saving of herbicide amount and therefore a reduction of the environmental impact, but might also bring about a decrease of yield and income. Weed maps and wheat growth simulations allowed to simulate precision weeding using different weed density thresholds.
The starting simulation was carried out using a null threshold, i.e. the herbicide was applied in all the areas where weeds were present. The total absence of *A. sterilis* is not very frequent (only 0.3% of the field area), this involved a very low difference between uniform weeding and precision weeding using this threshold (Tab. 4), both in terms of weed area and yield. The difference between saving and missed income (balance) is still positive up to a threshold for spraying of 2 plants m^{-2} (Fig. 5). Increasing the spraying threshold up to 4 plants m^{-2} the slope of the missed

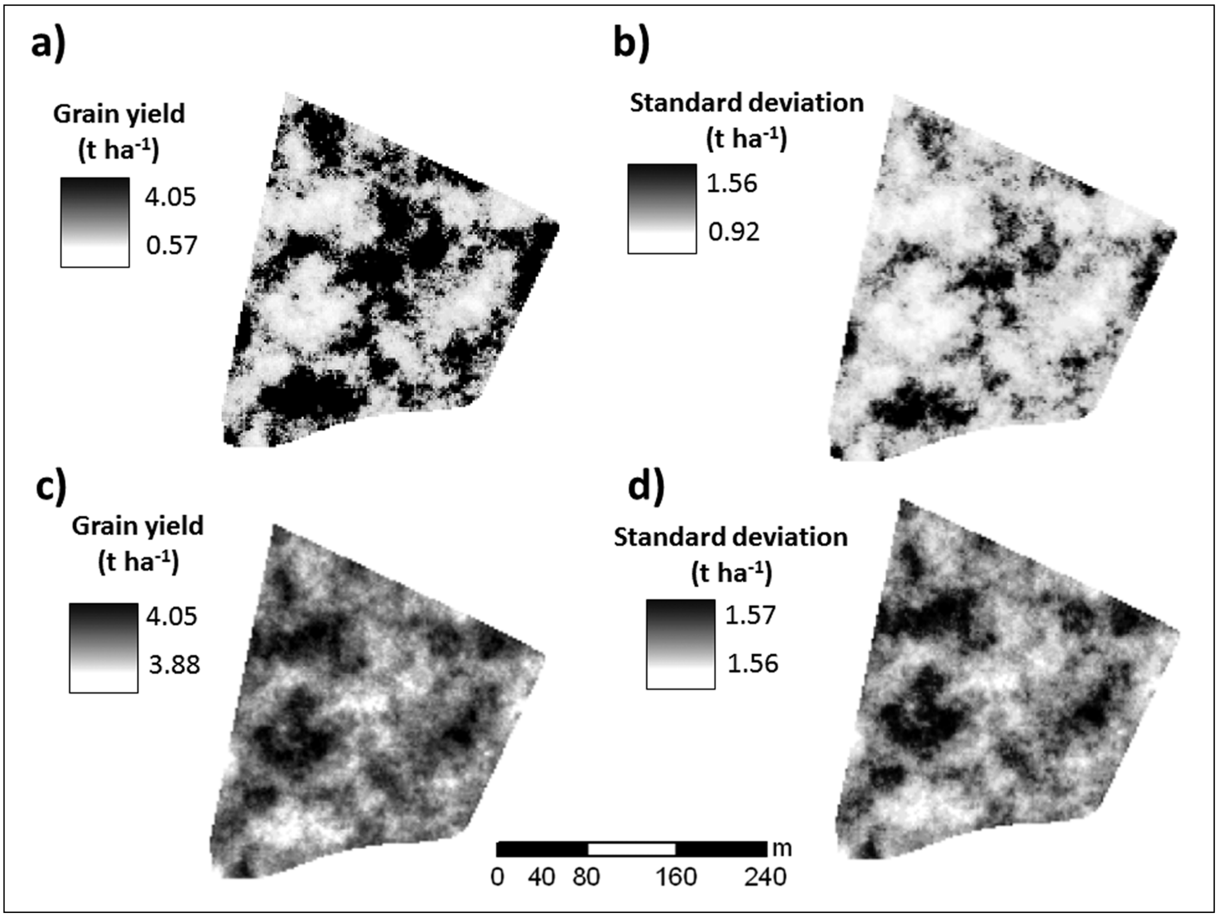

Fig. 3 - Maps of wheat grain yield and standard deviation values obtained by APSIM simulations for a wheat crop infested by *A. sterilis*. Maps refer to no-weeding (a and b) and uniform weeding (c and d) scenarios.
Fig. 3 - Mappe della resa in granella e della deviazione standard ottenute dalle simulazioni APSIM per il grano infestato da A. sterilis. Le mappe si riferisco a due differenti scenari: nessun diserbo (a, b) e diserbo uniforme (c, d).

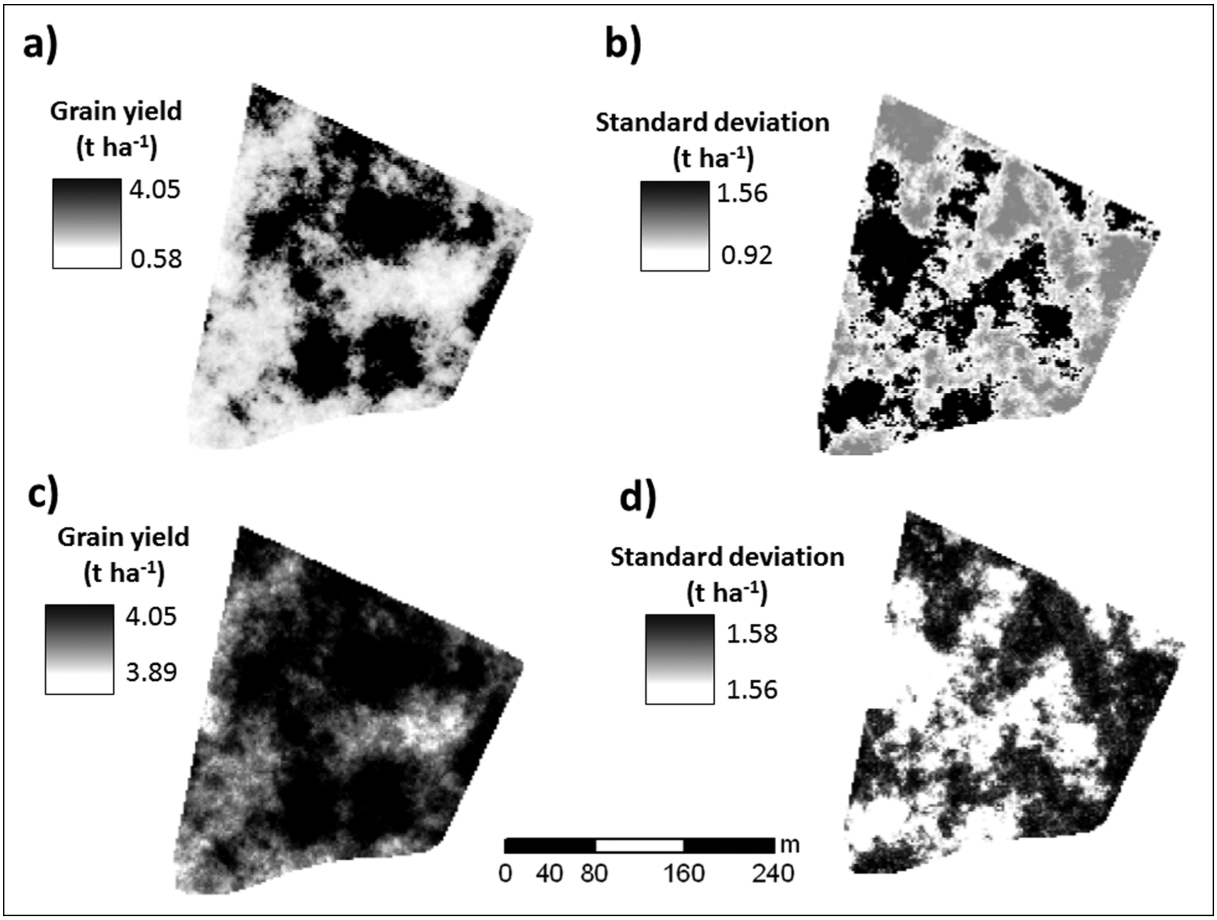

Fig. 4 - Maps of wheat grain yield and standard deviation values obtained by APSIM simulations for wheat crop infested by *A. spica-venti*. Maps refer to no-weeding (a and b) and uniform weeding (c and d) scenarios.
Fig. 4 - Mappe della resa in granella e della deviazione standard ottenute dalle simulazioni APSIM per il grano infestato da A. spica-venti. Le mappe si riferisco a due differenti scenari: nessun diserbo (a, b) e diserbo uniforme (c, d).

Threshold (plants m^{-2})	Grain yield ($t\ ha^{-1}$) Mean	sd	Weeded area (ha)	Non-weeded area (ha)	Income (€)	Missed income (€)	Weeding cost (€)	Herbicide saving (€)	Balance[a] (€)
Uniform weeding	4.05	1.57	5.55	0.0	4266.4	0	333.0		
0	4.05	1.57	5.53	0.0164	4266.4	0.0	332.0	0.98	0.98
2	4.04	1.57	5.46	0.0924	4262.2	4.2	327.4	5.54	1.39
4	4.02	1.56	5.26	0.2892	4240.9	25.5	315.6	17.35	-8.17
6	3.96	1.54	4.85	0.7016	4175.0	91.4	290.9	42.10	-49.30
8	3.83	1.48	4.16	1.3936	4035.2	231.2	249.4	83.62	-147.61

[a] Difference between herbicide saving and missed income

Tab. 4 - Mean and standard deviation values (*sd*) of grain yield, weeded and no-weeded area and economic data (for the 5.5. ha field) obtained for each density threshold values of *A. sterilis*.
*Tab. 4 - Valori medi e deviazione standard (*sd*) della resa in granella, superficie diserbata e non diserbata e dati economi (per il campo di 5.5. ha) ottenuti ad ogni valore soglia di densità di* A. sterilis.

Threshold (plants m^{-2})	Grain yield (t ha-1) Mean	sd	Weeded area (ha)	Non-weeded area (ha)	Income (€)	Missed income (€)	Weeding cost (€)	Herbicide Saving (€)	Balancea (€)
Uniform weeding	4.02	1.57	5.55		4240.4		332.98		
0	4.02	1.57	4.07	1.48	4240.4	0.0	244.37	88.6	88.61
5	4.00	1.56	3.83	1.72	4217.9	22.6	229.50	103.5	80.90
10	3.95	1.54	3.58	1.97	4166.6	73.8	214.61	118.4	44.53
15	3.89	1.52	3.33	2.22	4098.0	142.4	199.94	133.0	-9.41
20	3.81	1.49	3.10	2.45	4022.0	218.4	186.14	146.8	-71.61

[a] Difference between herbicide saving and missed income

Tab. 5 - Mean and standard deviation values (*sd*) of grain yield, weeded and no-weeded area and economic data (for the 5.5. ha field) obtained for each density threshold values of *A. spica-venti.*
Tab. 5 - Valori medi e deviazione standard (sd) della resa in granella, superficie diserbata e non diserbata e dati economi ottenuti ad ogni valore soglia di densità di A. spica-venti.

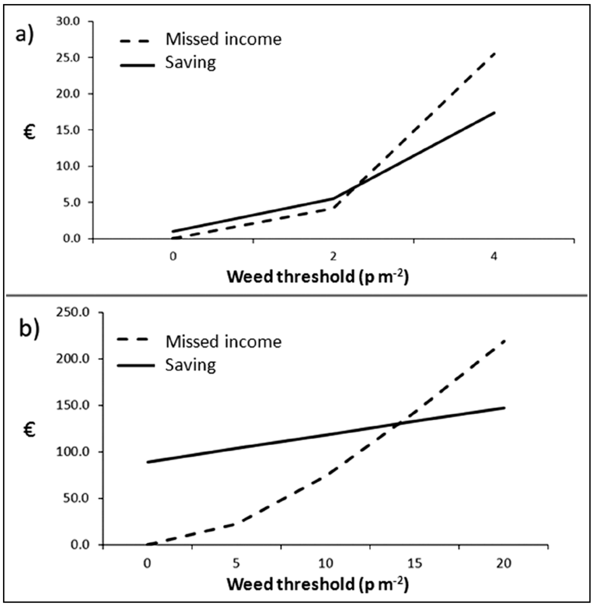

Fig. 5 - Plots of saving and missed earnings (euros) obtained at each weed thresholds applied to A. sterilis (a) and A. spica venti (b).
Fig. 5 - Grafici relativi ai mancati ricavi e al risparmio (€) per ciascuno soglia di diserbo applicata a A, sterilis (a) and A. spica venti (b).

income curve sharply increases, surpassing the saving curve. The economic threshold detected, i.e. 2 plants m^{-2}, ensures a high productivity, showing mean values and spatial distribution of the yield (Fig. 6a) very similar to those obtained with a uniform weeding. Since the density threshold is located in the first decile of weed distribution, there are very few areas not interested by weeding (1.7%). Consequently, the saving of herbicide would not be very relevant (5.54 €). The economic saving and no-weeded area are quite low to justify the implementation of PWM, both in economic and environmental terms. In this case a uniform weeding would be advisable in order to ensure a good crop yield. The area showing a zero density of *A. spica-venti* is 1.48 ha (26.6% of the field), therefore a precision weeding with a density threshold fixed to 0 plants m^{-2} (binary patch-spraying) would allow a consistent reduction of weeded area and a saving of 88.6 € (Tab. 5). For this weed species, an increase of density threshold is economically admissible up to 10 plants m^{-2} (Fig. 5). A precision weeding done according the detected threshold would allow to decrease the weeded area and the cost of herbicide treatment of the 35.5%, causing a very low yield loss (-1.7%). The yield map obtained from threshold patch-spraying is characterized from a reduced variability over the most of field area, where the yield is higher, while in the North area, in correspondence of the high density of *A. spica-venti*, the production showed a sensible decreasing up to 2.76 t ha^{-1} (Fig. 6c). Although the weeding would be economically convenient at weed density of 10 plants m-^{2}, the balance value obtained using a binary patch-spraying is double as compared to that gained with threshold patch-spraying. However, the choice between binary and threshold patch-spraying should take into account the environmental impact of weeding, in this case a threshold of 10 plants m-^{2} allows to decrease the weeding area of half a hectare.

4. DISCUSSION

Differences in economic threshold for spraying within the same weed species are mainly due to agronomic management practices and soil and weather conditions. Zanin *et al.*, (1993) found a much higher economic threshold than ours for *A. sterilis* density in a wheat

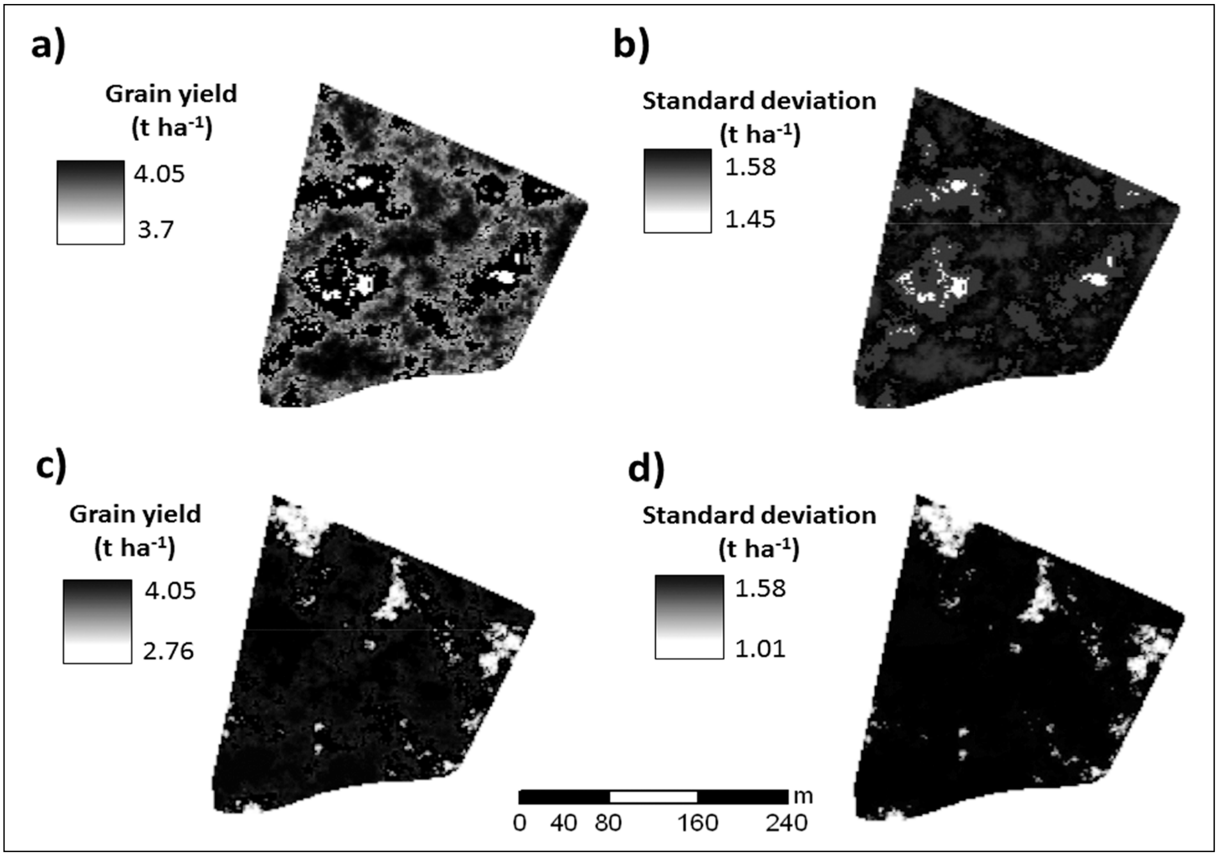

Fig. 6 - Maps of grain yield and standard deviation values obtained by APSIM simulations for wheat crop infested by A. sterilis (a and b) and A. spica-venti (c and d) applying threshold patch-spraying based on economic analysis.
Fig. 6 - Mappe delle rese in granella e deviazione standard ottenute dalle simulazioni APSIM per il grano infestato da A. sterilis (a and b) and A. spica-venti (c and d), diserbando solo le aree del campo aventi densità delle infestanti maggiore del valore soglia individuato dall'analisi economica.

crop (7 – 12 plants m^{-2}) in North-Eastern Italy, however their results were obtained using experimental plots of few square meters, where weed seeds were sown to obtain the desired final densities. The field trials of Zanin *et al.*, (1993) did not take into account the actual spatial distribution of *A. sterilis*, moreover they were replicated only for two years and thus the results were probably affected by a particular level of crop/weed competition caused by weather conditions of these two years. The competition level between crop and weed affects the differences in economic threshold among weeds species. The economic threshold of weed density within wheat crops found in literature varies widely: low thresholds (0.5 – 2 plants m^{-2}) were detected for *Galium aparine* L., *Fallopia convolvulus* L, and *Vicia* ssp. (Gerhards *et al.,* 1997), medium densities (4 – 7 plants m^{-2}) were found for *Secale cereale* L. (Pester *et al.,* 2000) and *Phalaris minor* Retz. (Hussain *et al.,* 2015), while high thresholds (18 – 20 plants m^{-2}) were obtained for *Raphanus raphanistrum* L. (Boz *et al.*, 2005) and *A. spica-venti* (Gerhards *et al.*, 1997). This high variability of threshold values confirms the need of specific calibrations for each weed species and for each climate and soil characteristics in order to retrieve reliable economic thresholds.

5. CONCLUSIONS

The present work proposes a methodology to evaluate the economic weed threshold for specific weed species or weed mixtures, independent from crop and weed sampling, but using geostatistical and crop growing simulation. The knowledge of spatial distribution pattern of the weed species, soil characteristics and at least ten-year climate data within a specific area could be used as inputs to carry out crop/weed growth simulations. The yield values obtained by simulations can be used to estimate average economic thresholds to apply in a field crop. Obviously this methodology must be tested and calibrated on real field conditions.
The proposed methodology allowed to estimate the weed density above which is convenient to spray herbicides within a wheat field. The methodology provides a useful decision tool in order to choose the best weeding strategy among uniform, binary patch-

spraying or patch-spraying according to a weed density threshold based on economic criteria. The geostatistical simulations confirmed the typical patchy distribution of both weed species (*A. sterilis* and *A. spica-venti*). The presence of large areas without *A. spica-venti* within the field suggested an opportunity for the implementation of a PWM strategy. In this case the use a of a weed threshold involved a consistent decrease of weeded area as compared to binary patch-spraying, but also a decrease of income. The simulations concerning *A. sterilis* did not show evident advantages of using PWM instead of classic uniform weeding, both in economic and environmental terms.

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