Assessment of sunflower yield maps and discrimination of late-season weed patches by using field spectroradiometry and remote sensing: the case of *Ridolfia segetum* Moris

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ABSTRACT
Weed control strategies are commonly applied over the entire agricultural fields, although weeds are spatially distributed in patches. To reduce the consumption of herbicides applying them only where weed patches are present, it is necessary to develop accurate maps of weed patches. These weed maps can be obtained in late-season through high spatial resolution remote sensing and can be used for site-specific control next season. This is especially helpful taken into account that most weeds are stable in time and location. The main objective of this contribution is to describe the remote sensing requirements for predicting yield and mapping weeds, and to outline some results of our group in this research area by explaining the case study of *R. segetum* in sunflower. We have chosen this weed as it is one of the most widely distributed, hard to control and competitive broadleaf weeds in sunflower.

Key words: multitemporal aerial imagery – site-specific weed management – weed patch discrimination.

INTRODUCTION
Sunflower (*Helianthus annuus* L.) is one of the most important crops in Andalusia (southern Spain) with over 240.000 ha grown annually (MAPA, 2006). It is normally grown under dry land conditions; sowing-time is February-March, and harvesting-time late July-mid August. One of the most frequent broadleaf weed species is the umbelliferous *Ridolfia segetum* Moris. It occurs in 25% of the sunflower surface in this region (Peña-Barragán et al., 2007) and two *R. segetum* plants per m^{-2} reduce crop yield by about 32% (Carranza-Cañadas et al., 1995). This weed is hard to control due to it not being controlled by pre-emergence and pre-plant incorporated herbicides used in sunflower, and, consequently post-emergence strategies such as tillage or hand weeding are commonly used, otherwise this weed obstructs the harvester due to it still having a partly green stem during the sunflower harvesting. Uncontrolled *R. segetum* plants also infest other crops included in the rotation, *e.g.* oilseed rape (*Brassica napus* L.) and medicinal-aromatic crops like anisette (*Pimpinela anisum* L.) generating serious contamination problems for oilseed rape oil and the anisette seeds for human consumption. Reduced and no-tillage production have increased in Spain in the last 10 years, and now account for 2.4 million of hectares of the annual crops (AESC/SV, 2005), many of them in Andalusia. So, *R. segetum* has become more troublesome since it cannot be reduced in abundance by repeated tillage or cultivation.

Patchy distribution of broadleaf weeds in sunflower fields is well documented (Jurado-Expósito et al., 2003). However, herbicide or other control strategies are not addressed to the infested zones, but they are usually broadcast over entire fields. The potential for overuse or application and corresponding eco-environmental problems is evident. One aspect of overcoming the possibility of minimizing the impact of herbicide on environmental quality is the development of Site-Specific Weed Management (SSWM). Timmermann et al. (2003) concluded that costs savings were 90% and 60% for broadleaf and grass weeds herbicides, respectively. A key component of SSWM is that accurate and appropriate weeds maps are required to take full advantage of site-specific herbicide applications. Mapping weed patches based on ground survey techniques on field scale is time consuming, expensive and unapproachable in field areas with difficult access. Remote sensing of weed canopies may be more efficient and suitable than field surveys and the majority of studies on discriminating weeds in cultivated systems have involved discrete broadband remote sensing (multispectral sensors) (Brown & Noble, 2005).

To detect and map weeds it is necessary for suitable differences to exist in spectral reflectance between weeds and crop or bare soil. Spectral reflectance differences can be enhanced by using Vegetation Indices, which are mathematical (ratio or linear) combinations between bands. Detection of late-season weed infestation has been demonstrated to have tremendous possibilities when spectral differences between crops and weeds prevail at a certain phenological stage (López-Granados et al., 2006). Taking into account that weed infestations are stable and persistent in location from year to year

(Jurado-Expósito et al., 2004), late-season weed detection maps can be used to design site-specific control methods in the coming 2 to 4 years. Thus, it is crucial to explore the variations in the spectral signatures of crop and weed, indicating suitable wavelengths for species discrimination and classification.

On the other hand, it is well known that crop yield varies spatially within the field since factors affecting crop growth such as soil properties, water availability, disease, weed and insect pressure, crop management practices, among others, vary spatially. Yield variability estimation during crop development could help farmers to make decisions (*e.g*. fertilization, irrigation, weed control) some time before harvest. Remote sensed imagery has been demonstrated to provide spatial and temporal georeferenced field information related to some field factors to predict yield estimation (Yang et al., 2006). As happens in weed mapping, one of the main challenges of remote imagery analysis in agriculture is to determine how variations in spectral information are related to differences in the crop phenological state, in order to obtain accurate yield maps long before the harvest, so that, crop management can be designed accordingly.

The main objective of this contribution is to describe the remote sensing requirements for predicting yield and mapping weeds and to outline some results of our group in this research area by explaining the case of *R. segetum* in sunflower. Our specific objectives were: 1) to determine the spectral signatures of bare soil, and different phenological stages of sunflower and *R. segetum*; 2) to select bands and Vegetation Indices for multispectral discrimination within-between phenological stages of sunflower and *R. segetum*, 3) to determine the ability to discriminate *R. segetum* patches on sunflower crops using aerial photographs, and 4) to assess the spatial relationship of sunflower yield to *R. segetum* weed presence.

MATERIALS AND METHODS

Study area: The study was conducted on two 40 ha sunflower fields located in Córdoba province (Andalusia, southern Spain), named Matabueyes and Santa Cruz, naturally infested by *R. segetum* and representative of infested areas in Andalusia. Sunflower crop Jalisco *cv*. was seeded at 4 kg ha^{-1} in rows 0.7 m apart in mid-March and harvested in mid-August. The field site was farmer-managed using shallow tillage production methods. Glyphosate was applied at pre-emergence at 0.7 l ha^{-1} for the control of annual weed seedlings. At this rate, this herbicide had no significant activity on *R. segetum*. Spectral reflectance signatures of bare soil, sunflower and *R. segetum* were measured from mid-May to mid-July according to the sunflower and weed phenological stages explained below.

Sunflower and R. segetum phenological stages: Sunflower and weed phenological stages were determined according to those adapted to our field conditions by Peña-Barragán et al. (2006).

A) Sunflower. 1) *mid-May, vegetative phase*: a) vegetative 5-10 leaves (SunV5-10), and b) reproductive head growing (SunHG); 2) *mid-June, reproductive phase*: c) reproductive head flowering (SunHF), and d) initial desiccation of lower leaves and reproductive head turning down (SunID); 3) *mid-July, senescent phase:* e) reproductive head partly desiccated and browning (SunRHPD); and f) plant completely desiccated and darkish/ black (SunPD).

B) R. segetum. 1) *mid-May, vegetative phase*: a) seedling < 5-10 cm, (RidSe); b) vegetative stage without floral stem (RidVe), and c) inflorescence (or umbella) still closed (RidInC); 2) *mid-June, flowering phase*: d) inflorescence yellowing, (RidInY); 3) *mid-July, senescent phase*: e) plant desiccated (RidPD).

Spectroradiometer data measurements and multispectral analysis: In mid-May, mid-June and mid-July, twenty hyperspectral measurements were collected for bare soil and each sunflower and *R. segetum* phenological stage using an ASD Handheld FieldSpec Spectroradiometer (Analytical Spectral Device, Inc., Boulder, USA) placed at 80-100 cm above each plant canopy or soil. Each measurement was georeferenced using the sub-meter differential GPS TRIMBLE PRO-XRS (Trimble, Sunnyvale, USA), to be located in the aerial images later. The spectral data were calibrated with a standard panel (Spectralon®) before each measurement. Measurements were made under sunny conditions between 12 and 14 h, and were collected between 400 and 900 nm (bandwidth of 1.5 nm).

Spectroradiometer data were averaged to represent the aerial imagery broad wavebands (blue, B: 400-500 nm; green, G: 500-600 nm; red, R: 600-700 nm; and near-infrared, NIR: 700-900 nm). The following vegetation indices (VI) were also calculated and analysed: Normalized Difference Vegetation Index NDVI = (NIR-R) / (NIR+R) (Rouse et al., 1973), Ratio Vegetation Index RVI = NIR / R (Jordan, 1969), R / B index (Everitt & Villarreal, 1987), VNVI = (NIR-G) / (NIR+G), and ANVI = (NIR-B) / (NIR+B). Multispectral data were subjected to analysis of variance, and means were separated at the 5% level of significance by LSD test using the SPSS software.

Aerial photographs: Conventional-colour (400–700 nm) and colour-infrared (500–900 nm) aerial photographs of the fields studied were taken in mid-May, mid-June and mid-July. Average flight height was 1525 m to obtain photographs at a scale of 1:10000. Selected photographs were digitised using the AGFA Horizon A3 scanner (635 dpi corresponding to pixels of 40 x 40 cm) and georeferenced (using 40 ground control points). ENVI 4.3 software was used to process images.

Image analysis: Two methods widely explained in Peña-Barragán et al. (2007) were applied to classify the images and to discriminate between the *R. segetum*-infested and the non-infested zones:
A) Class Separation Method: This was used in the four wavebands and the five Vegetation Indices previously described. Each image was classified by grouping the digital values according to the value ranges that characterized *R. segetum* training patches. Boundary digital values were established according to the statistical value obtained from 220 *R. segetum* training pixels, adding and reducing the standard deviation to the average.
B) Spectral Angle Mapper (SAM) Method: used for multispectral band images. It is based on an n-dimensional angle to match pixels to reference spectra made up of the digital signature of each training zone. The algorithm determines the similarity between two digital signatures by comparing their angles, treating them as vectors in a space with dimensionality equal to the number of bands. Smaller angles represent closer matches to the reference signature. The photo-interpreter has to specify the Maximum Angle Threshold in radians that set each land-use, so no pixels outside this threshold were classified.

During the field visits, 550 ground-truth pixels (infested and non-infested zones) were used to create the ground-truth images for every classification method. A numerical analysis called *Confusion Matrix* was then performed to quantify the accuracy of the coincidence between classification images and real patches for each classification method. The confusion matrix was used to obtain the overall accuracy (OA), which is the percentage obtained by dividing the pixels correctly classified among all ground-truth images. OA has been standardized in at least 85% for minimum accepted values (Thomlison et al., 1999).

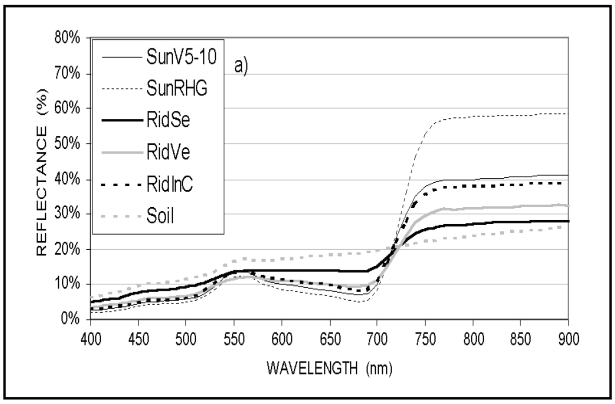
Sunflower Yield Data: The fields were harvested on 8th August using the farm´s MF34 combine harvester equipped with a differentially-corrected global positioning system (DGPS) receiver and a yield monitor with the Fieldstar® system (Massey Ferguson®, AGCO Corporation, Duluth, GA, USA). The yield data set used was of 2541 points, ranging from 0.30 to 2.30 t ha$^{-1.}$ A contour yield map of the complete field was then generated using the SURFER software (Golden software, Inc., Golden, Colorado, USA). Yield data set and yield map were grouped to six yield intervals (Very-Low=[0.30-0.60], Low=[0.61-0.95], Medium-Low=[0.96-1.30], Medium-High=[1.31-1.65], High=[1.66-2.00], and Very-High=[2.01-2.30] t ha^{-1}), to perform the statistical analysis. The four wavebands B, G, R, and NIR, and two vegetation indices (NDVI and NDYI) were considered to predict the yield map. Vegetation indices were calculated as follows: NDVI = (NIR - R) / (NIR + R); NDYI = (R - G) / (NIR + G).

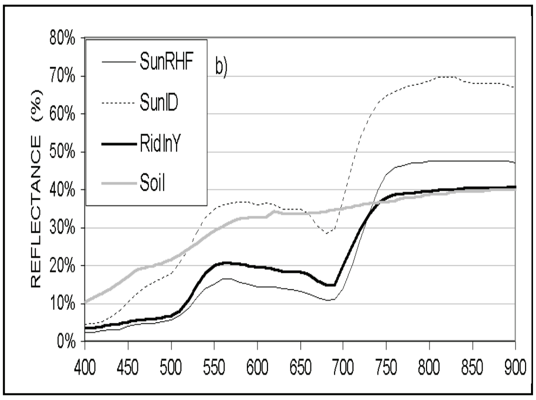
RESULTS AND DISCUSSION

Hyperspectral signatures of bare soil and phenological stages of sunflower and R. segetum: Reflectance curves of bare soil, and sunflower and *R. segetum* phenological stages corresponding to Mid-May (vegetative phase), mid- June (flowering phase) and mid-July (senescent phase) are indicated in Fig. 1. Phenological stages of crop and weed consistently affected the magnitude and amplitude of spectral reflectance values. Vegetative and flowering phases showed their characteristic higher reflectance in G (Green peak, 550 nm) and NIR (from 700 to 900 nm) parts of the spectrum. Senescent phase and bare soil presented their typical spectral signatures, *i.e.* reflectance values increased as wavelengths increased.

Multispectral analysis of bands and Vegetation indices: Results from analysis of variance and corresponding LSD test are shown in Table 1. B, NIR, NDVI, RVI, VNVI and ANVI values were statistically different between bare soil, and *R. segetum* and at least one of the sunflower phenological stages, suggesting that there is a potential for a successful discrimination between bare soil, sunflower and *R. segetum* using remote sensing.

Image classification method and weed map: OAs calculated throughout the confusion matrix for every classification method in mid-June (flowering phase) are listed in Table 2. Most classification methods studied, such as B, G, R, R/B, ANVI and SAM, discriminated *R. segetum* patches from bare soil and sunflower with OAs ≥ 85%. In particular, the best classifications of weed patches were obtained using SAM and R/B vegetation index, resulting in OAs of 95% and 98% in Matabueyes and Santa Cruz, respectively. Results obtained in mid-May and mid-July are not shown because they were generally poor (lower than 80%) and did not reach the commonly accepted requirement of at least an 85% classification of the overall accuracy. Therefore, it is not recommended to take any image in phenological stages corresponding to these dates to discriminate *R. segetum* patches.





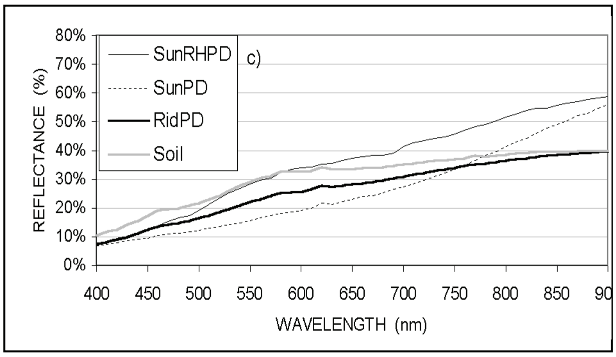


Fig. 1. Mean reflectance curves of bare soil and different phenological stages (*) of sunflower and *R. segetum* corresponding to three dates: a) mid-May (vegetative phase); b) mid-June (flowering phase), and c) mid-July (senescent phase).
(*See acronyms in Materials and Methods section).

Table 1. Mean reflectance values of bare soil, and sunflower and *R. segetum* phenological stages on three dates for multispectral bands and vegetation indices. (Best results are shaded in grey).

Dates	Phenological stages[2]	Mean values[1]								
		Multispectral Bands				Vegetation indices[2]				
		Blue	Green	Red	NIR	NDVI	RVI	RB	VNVI	ANVI
Mid-May	SunV5-10	0.04 b	0.10 ab	0.09 b	0.36 d	0.62 e	4.36 d	1.96 a	0.55 e	0.78 d
	SunRHG	0.03 a	0.09 a	0.07 a	0.50 e	0.76 f	7.61 e	1.93 a	0.69 f	0.87 e
	RidSe	0.07 d	0.13 c	0.14 d	0.26 a	0.30 b	1.86 a	1.93 a	0.34 b	0.56 b
	RidVe	0.05 c	0.10 ab	0.10 c	0.29 b	0.49 c	3.05 b	1.89 a	0.48 c	0.69 c
	RidInC	0.04 b	0.11 b	0.10 c	0.34 c	0.56 d	3.69 c	2.11 b	0.52 d	0.76 d
	Bare soil	0.09 e	0.15 d	0.18 e	0.23 a	0.13 a	1.30 a	2.01 ab	0.22 a	0.45 a
Mid-June	SunRHF	0.04 a	0.13 a	0.13 a	0.43 a	0.53 c	3.49 c	3.65bc	0.54 c	0.84 c
	SunID	0.10 a	0.31 b	0.33 b	0.64 b	0.36 b	2.40 b	3.14 b	0.37 b	0.74 b
	RidInO	0.05 b	0.16 a	0.18 a	0.37 c	0.36 b	2.16 b	3.86 c	0.39 b	0.76 b
	Bare soil	0.16 c	0.28 b	0.34 b	0.38 a	0.06 a	1.13 a	2.06 a	0.15 a	0.40 a
Mid-July	SunRHPD	0.12 b	0.27 c	0.37 c	0.51 b	0.17 c	1.40 c	3.01 c	0.31 c	0.61 c
	SunPD	0.10 a	0.16 a	0.23 a	0.41 a	0.29 d	1.80 d	2.42 b	0.45 d	0.62 c
	RidPD	0.12 b	0.22 b	0.28 b	0.36 a	0.13 b	1.30 b	2.40 b	0.26 b	0.51 b
	Bare soil	0.16 c	0.28 b	0.34 b	0.38 a	0.06 a	1.13 a	2.06 a	0.15 a	0.40 a

[1]Mean values followed by the same letter within a column for a single date do not differ significantly at the P [0.05%] according to LSD test.
[2]See Vegetation Indices and Phenological stages in Materials and Methods section.

Remote imagery vs. yield: Data presented are only from Matabueyes due to Santa Cruz's analysis still being in progress. The averaged wavebands and vegetation index data as affected by sunflower yield intervals and crop development stage are shown in Table 3. R waveband digital values and the NDVI index at the vegetative crop stage (mid-May) showed significant differences in all yield intervals. Furthermore, the NDVI mean value was negative for the three lowest yield intervals and positive for the three highest ones, and their values increased as the yield intervals increased. Mean values for the 6-sunflower yield interval map for NDVI index in mid-May are shown in Fig. 2a.

Table 2. Overall accuracy values (%) of every classification method in mid-June (Flowering phase). (Best results are shaded in grey).

Locations	Classification methods									
	SAM*	Blue	Green	Red	NIR*	NDVI§	RVI§	R/B§	VNVI§	ANVI§
Matabueyes	95	79	88	84	--	--*	--*	86	--*	--*
Santa Cruz	83	85	88	87	777	83	79	99	80	84

(*) SAM, Spectral Angle Mapper; NIR: Near-infrared band of Matabueyes field in mid-June could not be obtained due to technical problems and, thus, Vegetation Indices with NIR were not calculated .
(§) See Vegetation Indices in Materials and Methods section.

The NDYI index was only significantly different in the four highest yield intervals, and their mean values were positive and very similar for the three lowest yield intervals and negative for the three highest ones. In the flowering crop stage (mid-June), there were significant differences in B and G wavebands and in NDYI index (Table 3). On this date, NDYI mean values were negative in all yield intervals and inversely correlative with the increase in the yield intervals, ranging from -0.02 to -0.17. Higher NDYI values were found in mid-June than in mid-May due to greater differences between R and G values being obtained in mid-June. In mid-July (senescent stage), data are not shown because no significant differences were found between yield intervals and any bands or vegetation indices.

Considering the three dates, NDVI and NDYI corresponding to vegetative and flowering stages (mid-May and mid-June images) produced the best results, and their mean values correlatively increased as the yield increased, and decreased as the yield increased, respectively.

Table 3. ANOVA analysis of means for sunflower yield map, elevation, and bands and vegetation index data according to airborne imagery collected in mid-May and mid-June.

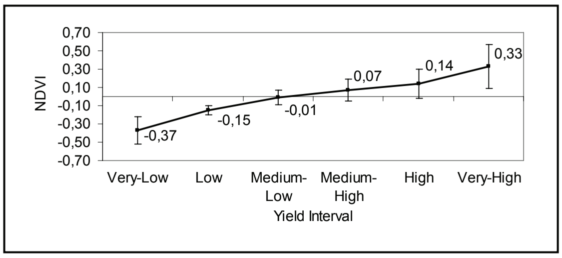
Yield Interval	Airborne image in mid-May						Airborne image in mid-June			
	Blue	Green	Red	NIR	NDYI	NDVI	Blue	Green	Red	NDYI
Very-Low	179 e	191 e	204 f	112 a	0.03 d	- 0.37 a	68 a	82 a	81 b	-0.02 f
Low	178 e	191 e	198 e	162 b	0.02 d	- 0.15 b	80 d	98 d	94 e	-0.04 e
Medium-Low	159 d	175 d	179 d	179 c	0.02 d	- 0.01 c	76 c	93 c	84 c	-0.08 d
Medium-High	142 c	157 c	155 c	180 cd	- 0.01 c	0.07 d	74 b	88 b	77 a	-0.10 c
High	129 a	135 b	130 b	181 d	- 0.03 b	0.14 e	96 e	102 e	89 d	-0.12 b
Very-High	136 b	123 a	116 a	206 e	- 0.08 a	0.33 f	107 f	105 f	89 d	-0.17 a

R. segetum pressure vs. sunflower yield intervals: The presence of *R. segetum* according to each yield interval and the weed influence on the reduction in the total yield are shown in Fig. 2b. This figure shows that weed presence diminished where yield increased. At the lowest yield intervals, R. segetum infested between 15 to 20 % of the total surface, but from medium-high yield to up upwards, the infestation was reduced from 14 to 3 %, suggesting that the zones within the high sunflower yield were sensitive to the absence of weed infestation.

CONCLUSIONS

Our results demonstrated that remote sensing images taken in mid-June can be a useful tool for both: 1) to estimate sunflower yield variability that can be used to generate a yield map for within-season identification of problematic or stressed areas for further site-specific management some time before harvest, and 2) to estimate late-season *R. segetum* patch maps that can be used in subsequent years for site-specific control strategies due to uncontrolled weeds being stable in location over the years in the field. The key question in predicting yield maps and mapping weed patches in crops is related to the time interval in which weed patches and crops show consistent and significant spectral differences. This paper concluded that aerial images taken in mid-June, which corresponds to the flowering phase of *R. segetum* and sunflower plants in our climate conditions, is the appropriate time to take aerial images for successfully completing the map of *R. segetum* patches and the expected sunflower yield.

a)



b)

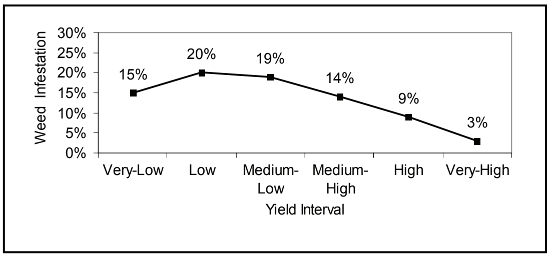


Fig. 2. a) Mean values of the 6-yield interval map for NDVI index in mid-May; b) Percentage of field surface infested by *R. segetum* according to 6-sunflower yield intervals.

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