THE TOAS PROJECT: UAV TECHNOLOGY FOR OPTIMIZING HERBICIDE APPLICATIONS IN WEED-CROP SYSTEMS

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ABSTRACT

Site-specific weed management refers to the application of customised control treatments, mainly herbicide, only where weeds are located within the crop-field. In this context, the TOAS project is being developed under the financial support of the European Commission with the main objective of generating georeferenced weed infestation maps of certain herbaceous (corn and sunflower) and permanent woody crops (poplar and olive orchards) by using aerial images collected by an unmanned aerial vehicle (UAV). This article introduces TOAS project and describes the whole research process developed and the main results attained to date. The main tasks are focused on: 1) configuration and use of the UAV and sensors for image acquisition, 2) evaluation of the specifications (sensor type, imagery characteristics, crop-weed phenological stage) required for each type of crop, and 3) development of automatic and robust image analysis procedures for weed mapping and crop assessment by using the captured remote images in order to optimize herbicide applications or other crop-weed management operations. Advances of the TOAS project are regularly updated in http://toasproject.wordpress.com.

Keywords: early season weed mapping, unmanned aerial vehicle, object-based image analysis, herbaceous row crops, woody crops.

INTRODUCTION

Site-specific weed management (SSWM) refers to the application of customised control treatments, mainly herbicides, only where weeds are located within the crop-field. The efficient development of these practices somehow relies on the use of remote sensing technology for collecting and processing spatial data.

This technology has been widely applied in agricultural studies and, in the case of SSWM, relevant results have been obtained in late growth stages (normally at the flowering stage), reporting herbicide savings of more than 50% (Peña-Barragán et al., 2007; de Castro et al., 2012). Nevertheless, in many weed-crop systems, it is impossible to apply treatments in late phases due to the unavailability of herbicides or the toxicity of the existing ones; so that, due to uncontrolled weeds persists in location, the solution is to postpone the treatment to the next year, which could increase the uncertainty of its efficiency. The optimal treatment is usually recommended when the weeds and crop are in the seedling growth stage (early seasons), which is known as "in-season, post-emergence treatment". However, mapping of weed seedlings in early season is a difficult task that has not been possible with conventional aerial or satellite images due to the lack of enough image spatial resolution (Lopez-Granados, 2011).

Nowadays, the new generation of remote platforms known as unmanned aerial vehicles (UAV) can overcome these limitations. The UAVs can operate at low altitudes and, thus, capture images at a very-high spatial resolution (a few centimeters or milimeters), not feasible with conventional planes or satellites. In addition, they can work on demand with great flexibility in critical moments according to each agronomic goal, which is crucial for detecting small weed seedling in the majority of crops. In view of the growing interest in UAV technology and its scarce application to SSWM, the TOAS project (Peña and López-Granados, 2011) is being developed under the financial support of the European Commission with the main objective of generating georeferenced weed infestation maps of certain herbaceous crops and permanent woody crops by using aerial images captured with a quadrocopter.

The successful of this technique goes also associated to the development of advanced algorithms for the management and analysis of the UAV images (Laliberte et al., 2011). Traditionally, the majority of the investigations in remote image classification have been focused on pixel-based analysis. Nevertheless, the pixel-based methods might result unsuccessful for the aims of TOAS project due to spectral similarity between weed and crop pixels and intra-class spectral heterogeneity. To solve these limitations, the TOAS project also involves the development and implementation of the object-based image analysis (OBIA) methodology. OBIA identifies spatially and spectrally homogenous units (objects) created by grouping adjacent pixels according to a procedure known as segmentation and, next, it combines multiple features of localisation, texture, proximity and hierarchical relationships that, with the spectra of each object, drastically increase the success of image classification (Castillejo-González et al., 2009; Blaschke et al., 2014).

Therefore, this article describes the whole process developed in the TOAS project, as well as the main results attained to date. The specific objectives of this project were devoted on: 1) selection, training and evaluation of an unmanned aerial vehicle and the sensors needed for capturing high-quality imagery of each proposed crop-weed system, 2) determining the finest flight configuration (UAV altitude, area covered and image resolution) for each crop, with particular attention to crop evolution (multi-temporal study), 3) optimizing the process of image mosaicking and geo-referencing in order to generate a unique image (ortho-mosaicked) that completely covers the fields of study, and 4) developing and evaluating object-based image analysis procedures for weed mapping and crop monitoring adapted to the specifications of each studied crop (herbaceous or woody crops). The ultimate objective of the project is in agreement with the European policy for the Sustainable Use of Pesticides (Directive 2009128/EC), which promotes reductions in herbicide applications and the utilisation of adequate herbicide according to the weed emergence. Detailed information about this project is regularly updated in http://toasproject.wordpress.com.

MATERIALS AND METHODS

Selection of the UAV and the sensors: Technical specifications

A survey of commercial UAV and sensors (optical and multispectral cameras) was done in order to select the devices for the TOAS project. A quadrocopter platform with vertical take-off and landing, model md4-1000 (microdrones GmbH, Siegen, Germany), and two sensors with different spectral and spatial resolutions, a visible camera, model Olympus PEN E-PM1 (Olympus Corporation, Tokyo, Japan), and a six-band multispectral camera, model mini-MCA-6 (Tetracam Inc., Chatsworth, CA, USA), were finally selected (Figure 1). The visible camera acquires 12-megapixel images in true colour (Red, R; Green, G; and Blue, B, bands) and is equipped with a 14–42 mm zoom lens. The camera's sensor is 4,032×3,024 pixels. The mini-MCA-6 is a lightweight (700 g) multispectral sensor composed of six individual digital channels arranged in a 2×3 array. Each channel has a focal length of 9.6 mm and a 1.3 megapixel (1,280×1,024 pixels) CMOS sensor. The multispectral camera has user configurable band pass filters (Andover Corporation, Salem, NH, USA) of 10-nm full-width at half-maximum and centre wavelengths at B (450 nm), G (530 nm), R (670 and 700 nm), R edge (740 nm) and near-infrared (NIR, 780 nm). These spatial and spectral resolutions could meet the specifications required for early weed seedling detection. Additional information about technical specifications of the UAV and the sensors were described in (Torres-Sánchez et al., 2013).

Figure 1. Quadrocopter platform with the multispectral camera embedded under its belly.

Description of crops and study sites: Experimental field campaigns

Two herbaceous crops (sunflower and corn) and two woody crops (olive and poplar) were selected to develop the system. A standard area of 1 hectare was defined in each experimental field to perform the flights and capture the UAV images. The fields were located at two different places: 1) the sunflower field (Figure 2a), corn field (Figure 2b) and olive orchard (Figure 2c) in the experimental farm Alameda del Obispo in Cordoba (Spain, coordinates 37.856 N, 4.806 W), and 2) the poplar orchard (Figure 2d) at a private farm in Arganda del Rey (Madrid, Spain, coordinates 40.320 N, 3.477 W).

The remote images of the sunflower and corn fields were collected on May 29th (34 days after sowing, DAS), June 4th (41 DAS) and June 12th (49 DAS), 2013, with the main objective of performing a multi-temporal evaluation of the image analysis procedure according to the crop development. The remote images of the poplar and the olive orchards were collected on June 20th and on August 21th, 2013, respectively, with the main objective of testing the whole system in both woody crops.

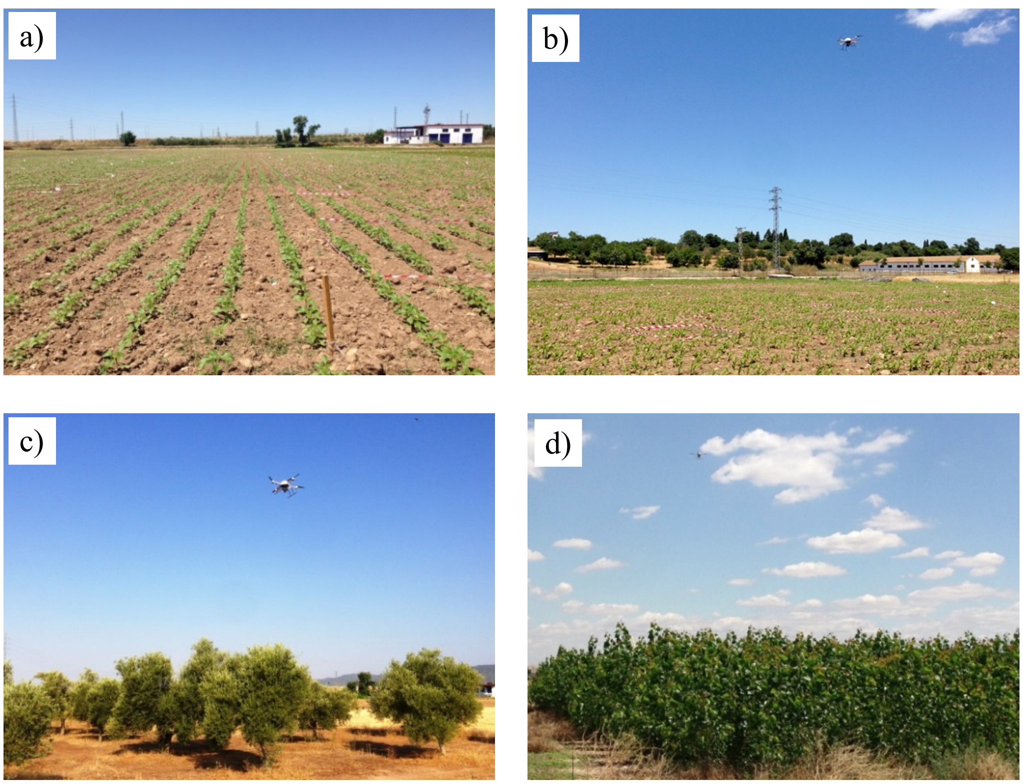

Figure 2. Views of the crop-fields studied in the TOAS project: a) sunflower, b) corn, c) olive orchard, and d) poplar orchard.

In the herbaceous crops, a systematic on-ground sampling procedure was designed and carried out the day of the UAV flights. Fieldwork consisted of placing 96 square frames of three different areas (16, 4 and 1 m) distributed regularly throughout the studied surface. For validation purposes, a flight at 10 m altitude was performed in these crops to collect vertical pictures of the sampling frames. Proximity to the frame images made it possible to detect individual plants and visually classify ground-truth weed infestation in every frame.

Mission planning and tests on flight altitude

Flight altitude affects image spatial resolution and the number of individual images needed to cover the whole crop-field. Therefore, several independent flight routes were programmed for each type of camera at 30, 60 and 100 m altitude above ground level in the case of sunflower and corn, and at 50, 100 and 150 m in the case of olive and poplar, with the objective of evaluating the optimal spectral and spatial resolutions needed in each scenario. The flight mission was planned with the Waypoint Editor module of the support software installed at the ground station. The flight route was designed over the orthoimages and the digital elevation model (DEM) of the flight area previously imported from the application Google Earth™ (Keyhole Inc., Mountain View, CA, USA). Three different parameters were needed to plan the route: flight area, camera specifications and UAV tasks. Once the flight route was designed, it was transferred to the UAV memory card via a standard serial link.

Image acquisition, mosaicking and geo-referencing

The UAV performed the flight and acquired the images in the automatic mode, although take-off and landing were manually controlled by the pilot. At the moment of capturing each remote image, the on-board computer system recorded a timestamp, the GPS location, the flight altitude, and vehicle principal axes (pitch, roll and heading).

A sequence of images was collected with 60% forward and 30% side overlapping in each flight mission to cover the whole experimental crop-field. An important task prior to image analysis was the combination of all these individual and overlapped images by applying a mosaicking process. The Agisoft Photoscan Professional Edition (Agisoft LLC, St. Petersburg, Russia) software was employed in this task. Coordinates from several artificial terrestrial targets (ATT) located on ground were added to assign geographical coordinates to the image. Then, the software automatically performed the orthorectification and mosaicking of the imagery set into a single image of the whole experimental field. The resulted orthophoto should have the high-quality landscape metric, minimum georeference errors and accurate correlation matching, which must guarantee imagery inter-operability from consecutive flights executed over the same field (Honkavaara et al., 2009).

Object-based image analysis (OBIA) procedure for weed mapping and crop monitoring

The OBIA methodology, developed with the commercial software eCognition Developer (Trimble GeoSpatial, Munich, Germany), was applied and evaluated into the series of UAV images captured with both cameras and adapted to each experimental field. In general, the OBIA procedures consisted of the next phases:

1) Image segmentation: This is a pixel-merging process in which the image was divided into homogeneous objects according to several parameters (band weights, scale, colour, shape, smoothness and compactness) defined by the operator. The new objects incorporated a large number of new features related to localization, texture, shape, neighbourhood and hierarchical relationships that, in combination to spectral features, provided a relevant increase of the algorithm power for image classification.

2) Image classification: The new objects were the minimum basic elements to perform the image classification. Several approaches were tested and compared, and the parameters that increased discrimination between weed, crop and bare-soil objects were selected in the OBIA algorithm. In the herbaceous crops, particular attention was paid to the relative position between the weed seedling plants and the crop rows.

3) Mapping evaluation: The accuracy and reliability of the OBIA algorithms developed for each crop were quantified by comparing between weed coverage estimated in the UAV images and weed coverage observed in the on-ground sampling frames. As a result of this evaluation, the potential of each sensor for weed detection and the optimal image spatial resolution were determined for each crop and agronomic objective previously described.

RESULTS AND DISCUSSION

Optimal flight mission

Flight area and flight altitude were the primary factors required to configure the flight mission. Flight area was easily determined from the field crop size (in our case, 1 hectare) and flight altitude was calculated according to the image spatial resolution needed (for every objective) and the type of sensor (Figure 3a). In addition, image spatial resolution was derived from the size of the smaller object to be discriminated in the images, which in our investigation depended on the crop type (herbaceous or woody) and its growth stage and on the agronomic objective (weed seedling detection, crop monitoring, tree assessment, etc.) of the flight mission. The figure 3a illustrates two cases. In herbaceous crops, remote images of about 3 cm/pixel (with a variability of ±2 cm) are targeted in order to detect weed plants in early-season, which resulted from flight altitudes of 55 and 79 m with the multispectral and the visible cameras, respectively. Alternatively, remote images of 6 cm/pixel or higher are proper in woody crops, which resulted from flight altitudes of 111 and 158 m with the multispectral and the visible cameras, respectively. At these altitudes, the area covered by each image of the multispectral camera increased from 0.11 ha (38×30 m) to 0.48 ha (77×62 m) and of the visible camera from 1.10 (121×90 m) to 4.41 ha (242×182 m), respectively (Figure 3b).

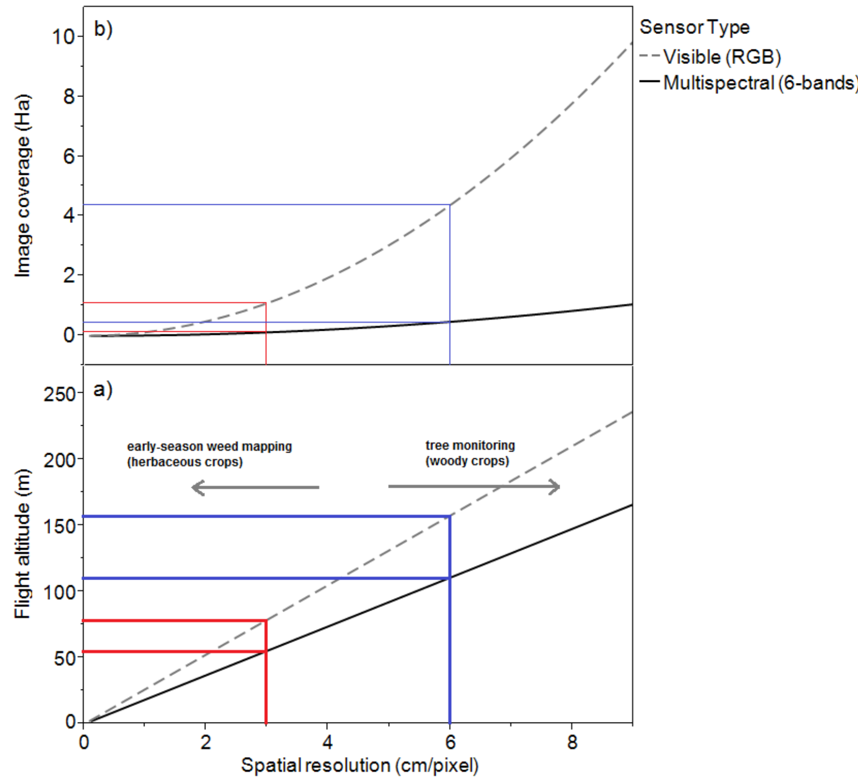

Figure 3. Flight altitude (a) and area covered by each individual image (b) according to image spatial resolution and type of sensor.

The remote images were acquired with 60% forward lap and 30% side lap. At this overlapping, the multispectral camera needs 38 images to capture the whole experimental field (1 ha) at 3 cm/pixel as well as 12 min approximately of UAV operating time (55 m flight altitude), whereas the visible camera only needs 9 images and 5 min approximately (79 m flight altitude). These variables have also strong implications in the configuration of the optimum flight mission, since a very large number of images can limit the mosaicking process and the operation timing is limited by the UAV battery duration. Therefore, configuration of flight mission involved two main conditions: 1) to provide remote images with a fine spatial resolution to guarantee success on image analysis, and 2) to minimise the operating time and the number of images to reduce the limitation of flight duration and image mosaicking, respectively.

UAV images in herbaceous crops

The figure 4 shows a sequence of remote images collected with the visible camera at 30 m altitude at three different dates with an interval of 7-8 days throughout the earliest stages of corn. The images showed the rapid growth of this crop in early-season, which was very similar to the evolution observed in the sunflower field. In addition, the figure 5 shows the remote images captured with the visible and the multi-spectral (color-infrared composition) cameras over the sunflower field (41 DAS) at 30, 60 and 100 m altitude. At these altitudes, the visible camera provided images at 1.14, 2.28 and 3.81 cm/pixel of spatial resolution and the multi-spectral camera at 1.62, 3.25 and 5.41 cm/pixel, respectively. The figure 5 also illustrates the different area covered in each case.

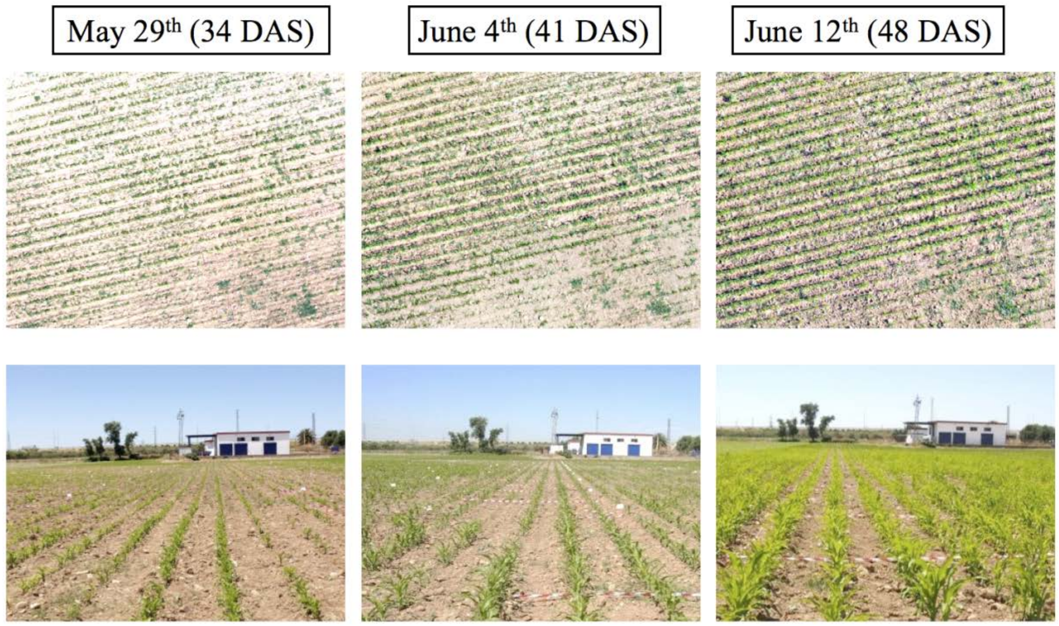

Figure 4. UAV images collected over the corn field at 30 m altitude in three different dates in early-season (top) and associated on-ground photograph (bottom).

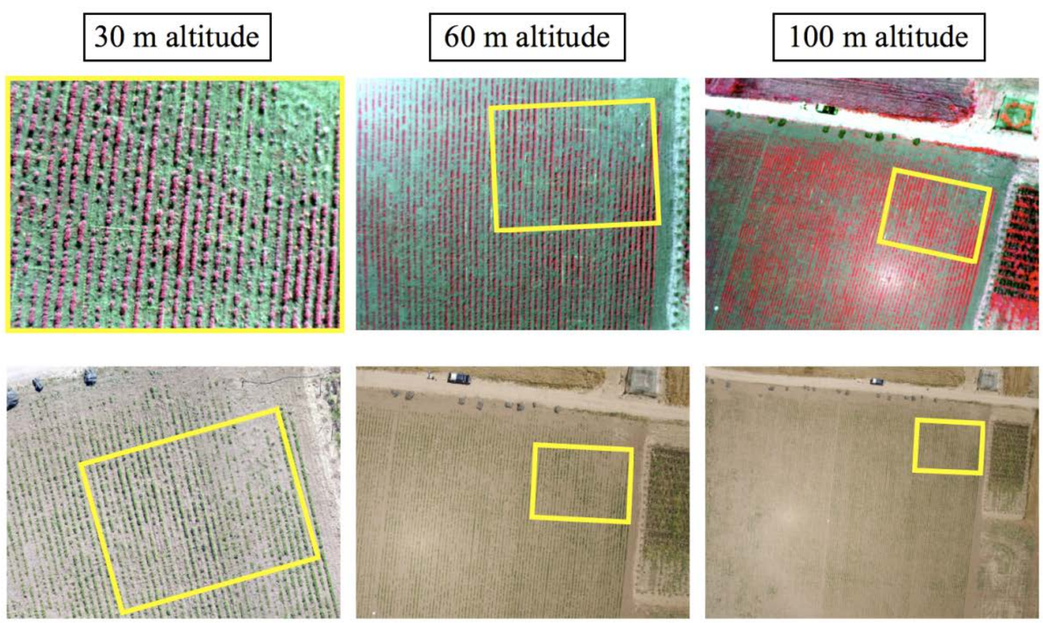

Figure 5. UAV images collected over the sunflower field at 30, 60 and 100 m altitude with the multi-spectral (color-infrared images in the top) and the visible (conventional-color images in the bottom) cameras in early-season (41 DAS). The yellow squares compare the area covered by each camera at different flight altitudes.

Different spatial and spectral information provided by the UAV images, in addition to the rapid development of the herbaceous crops, suggest three aims: 1) developing a robust image analysis method adapted to different crop scenarios, 2) determining the best moment for crop-weed discrimination in early-season, and 3) determining optimum spatial and spectral resolutions in agreement with flight length and UAV battery duration.

In this research context, an entirely automatic OBIA procedure for weep mapping was developed with the multispectral images captured at 30 m altitude over a corn field (Peña-Barragán et al., 2012; Peña et al., 2013). The OBIA procedure consisted of four consecutive phases: 1) image segmentation, 2) detection of crop rows by application of a dynamic and auto-adaptive classification approach, 3) discrimination of crop and weed plants on the basis of their relative positions with reference to the crop rows, and 4) generation of a weed infestation map in a grid structure (figure 5). The estimation of weed coverage from the image analysis yielded satisfactory results. The relationship of estimated versus observed weed coverage had a coefficient of determination of R =0.89 and a root mean square error of 2%. A map of three categories of weed coverage was produced with 86% of overall accuracy. The OBIA procedure computed multiple data and statistics derived from the classification outputs (figure 6), which allowed calculation of herbicide requirements and estimation of the overall cost of weed management operations in advance.

Evaluation of this procedure in the UAV images captured at higher altitude and in the images captured in the sunflower field is currently in progress.

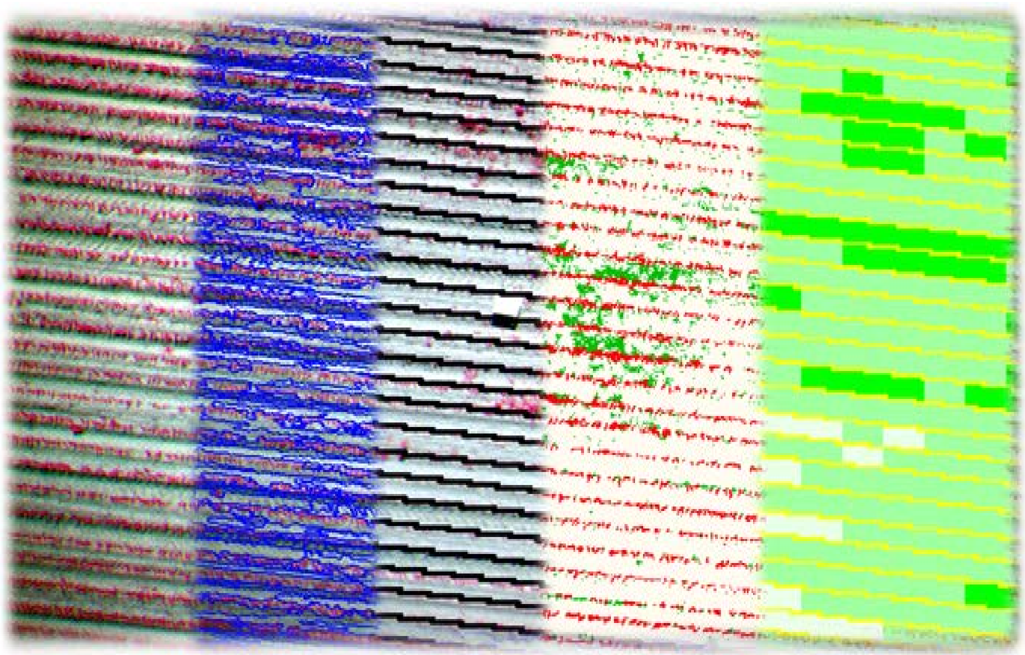

Figure 5. Visual simulation of the OBIA outputs applied to a multispectral image with the objective of mapping weed emergences in a corn field in early-season.

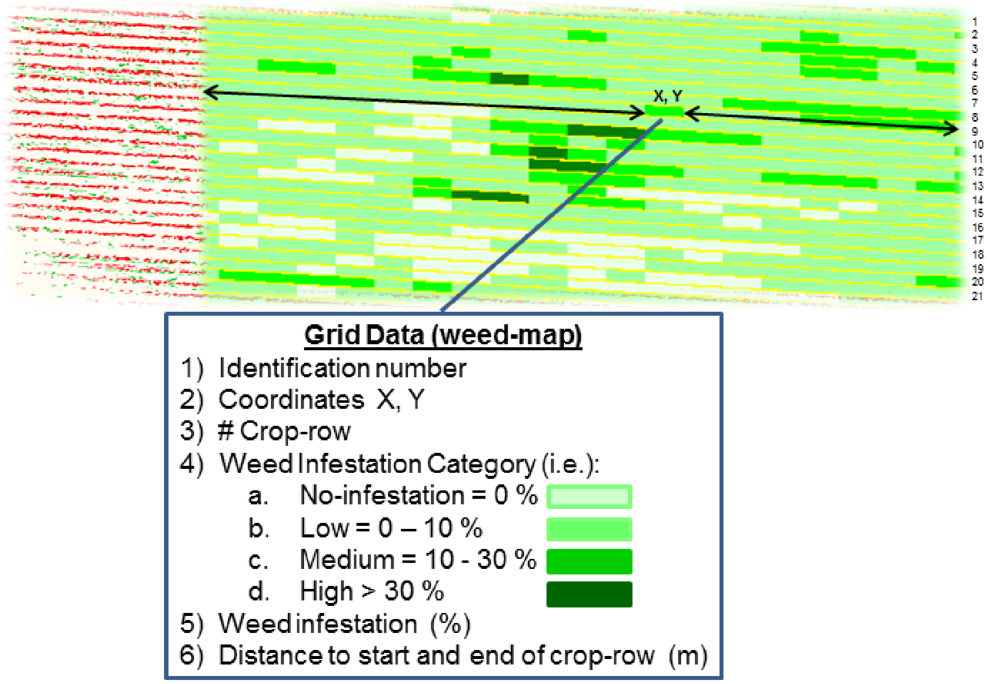

Figure 6. Data and statistics derived from the output weed-map generated by the OBIA procedure.

UAV images in woody crops

The figures 7 and 8 show a partial view of the remote images collected with both cameras at 50 m altitude over the olive and the poplar orchards, respectively, as well as the NDVI image derived from the multi-spectral camera. Similar images were captured at 100 and 150 m altitudes (data not shown). At these altitudes, the visible camera provided images at 1.90, 3.81 and 5.71 cm/pixel of spatial resolution and the multi-spectral camera at 2.71, 5.41 and 8.12 cm/pixel, respectively. This high spatial resolution allowed the identification and assessment of each individual olive tree and of each poplar row by applying OBIA classification techniques after image segmentation. As a preliminary result, the OBIA procedure automatically extracted position, shape, size and vegetation index values of every olive tree and poplar row in the studied parcel, as well as plot-based parameters such as total area, number of trees and relationships between neighbouring trees. Next, remaining vegetation out of the tree surface was classified as weed patches, cover crops or other classes according to several spectral and object-based features.

At this point, the development of the complete OBIA procedure and evaluation of the output maps are currently under development, aiming to adapt the analysis to each particular orchard pattern and cropping system.

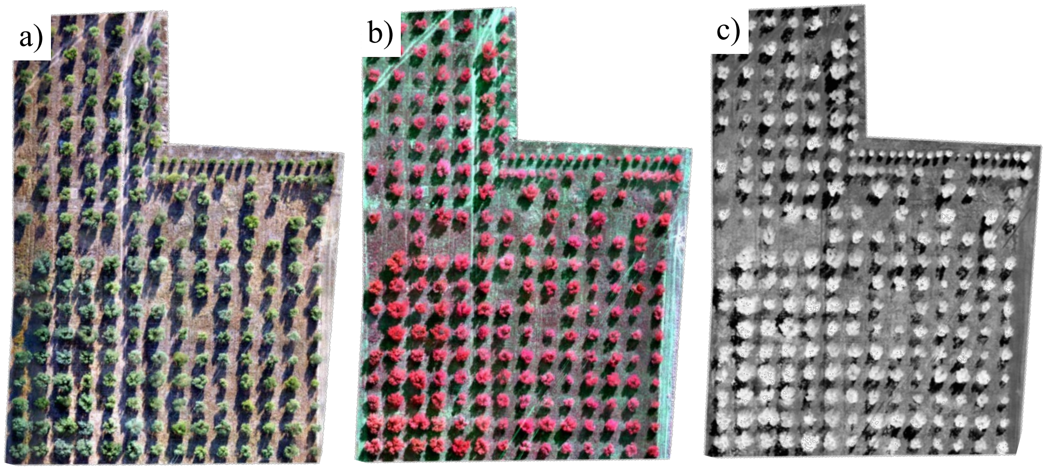

Figure 7. UAV images collected over the olive orchard at 50 m altitude with the visible (a) and the multi-spectral (b) cameras, as well as the NDVI image (c) calculated from the multi-spectral image.

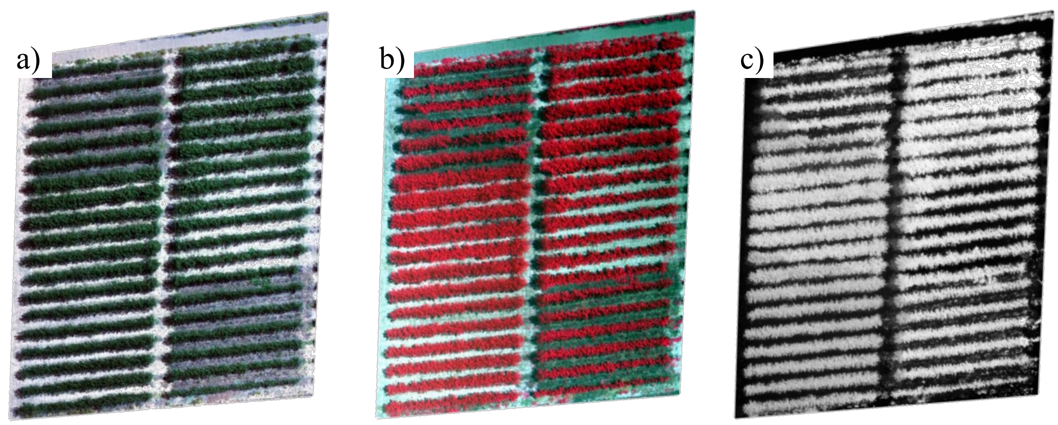

Figure 8. UAV images collected over the poplar orchard at 50 m altitude with the visible (a) and the multi-spectral (b) cameras, as well as the NDVI image (c) calculated from the multi-spectral image.

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