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# Site-specific management units in a commercial maize plot delineated using very high resolution remote sensing and soil properties mapping.

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## Abstract

The joint use of satellite imagery and digital soil maps derived from soil sampling is investigated in the present paper with the goal of proposing site-specific management units (SSMU) within a commercial field plot. Very high resolution Quickbird imagery has been used to derive leaf area index (LAI) maps in maize canopies in two different years. Soil properties maps were obtained from the interpolation of ion concentrations (Na, Mg, Ca, K and P) and texture determined in soil samples and also from automatic readings of electromagnetic induction (EMI) readings taken with a mobile sensor.

Links between the image-derived LAI and soil properties were established, making it possible to differentiate units within fields subject to abiotic stress associated with soil sodicity, a small water-holding capacity or flooding constraints. In accordance with the previous findings, the delineation of SSMUs is proposed, describing those field areas susceptible of variable-rate management for agricultural inputs such as water or fertilizing, or soil limitation correctors such as gypsum application in the case of sodicity problems. This demonstrates the suitability of spatial information technologies such as remote sensing and digital soil mapping in the context of precision agriculture.

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# 1 Introduction

The feasibility of modern agriculture requires significant changes in productive systems with regard to traditional production models. These changes are focused on establishing a balance between productivity and environmental conservation. This transformation implies a rational use of agricultural inputs (water, fertilizers, etc...), ensuring the sustainability of resources and avoiding the negative impacts of diffuse off-site pollution.

Traditionally, agricultural plots have been managed as a single, continuous unit, although it has long been known that soil conditions, plant development and grain yield are not homogeneous within them (Smith, 1938). The recognition and analysis of the heterogeneity and spatial distribution of these parameters allows a more adequate use of inputs, but also requires the contribution of spatial information technologies (Moran *et al.*, 1997; Seelan *et al*., 2003) to define site-specific management units (SSMU).

Various approaches to the delineation of SSMUs can be found in the literature. The development of yield monitors (Reyns *et al.*, 2002) brought new opportunities for describing the spatial patterns of final crop yield within fields (Birrell *et al.*, 1996; Pringle *et al.*, 2003; Simbahan *et al.*, 2004). Authors such as Diker et al. (2004) define SSMUs using yield maps drawn by yield monitors. These maps highlight the final effect of abiotic stress on crop yield and the areas which may require differential management. However, this approach lacks a more detailed study of the factors determining the heterogeneous distribution of crop yield.

The development of mobile sensors for soil properties such as resistivity or electrical conductivity provides a great opportunity for describing the distribution of relevant soil parameters (McNeill, 1992; Carter *et al.*, 1993; Freeland *et al.*, 2002). Combining easy readings of soil properties with an accurate spatial location of each measurement, automatic soil mapping proves to be a feasible tool for acquiring information applicable to SSMU delineation. Many studies have used soil maps to propose management units in field plots (Corwin *et al.*, 2006; Kaffka *et al.*, 2005; or Earl *et al.,* 2003) based mainly on empirical relationships between electromagnetic induction (EMI) readings and several soil features that could influence the final yield. Not only salinity, but a wide number of such features have been studied with EMI; some examples are glacial deposits; depth of bedrock surfaces, clay, sand and gravel bodies; and hydrological patterns, as reviewed by Doolittle et al. (1994) or by Robinson et al. (2009). Most research focuses on detecting one or two of these features in field scenarios that have little, if any, variability in other features potentially influencing the EMI readings. Mediterranean landscapes often have the opposite conditions, after thousands of years of human pressure that has resulted in entangled soil patterns, a feature enhanced by the small size of fields with different managements.

Nevertheless, EMI can be still useful for agricultural purposes if a black-box approach is adopted for linking soil properties with vegetation status, a critical point when proposing a plan to differentiate site-specific management.

The recent development of very high resolution (< 10 m) remote sensing platforms has enabled the operational use of satellite or aircraft imagery in precision agriculture. Vegetation vigor assessment has been one of the traditional subjects of interest for the remote sensing community (Crist & Cicone, 1984; Rouse *et al.*, 1973). Due to the relationships between plant vigor and reflectance in the visible and near-infrared regions of the solar spectrum, vegetation indices (VI) calculated from multispectral imagery have shown their usefulness in mapping vegetation status (Jackson *et al.*, 1983; Neale *et al.*, 1989; Gallo & Flesch, 1989; Macomber & Woodcock, 1994). VIs have been used to estimate crops' biophysical parameters, such as the Leaf Area Index (LAI) or chlorophyll content (Zarco-Tejada *et al.*, 2005; Haboudane *et al.*, 2004; Baret & Guyot, 1991), which highlights the suitability of remote sensing for obtaining spatial plant information useful in precision agriculture (Seelan *et al.*, 2003). However, the operational implementation of remote sensing techniques in precision agriculture studies is focused on the use of images in pattern recognition from VI (Leon et al., 2003; Vellidis et al., 2004; Yang et al., 2004), and less attention is paid to an agronomical interpretation of reflectance values for the estimation of biophysical parameters.

The aim of this paper is to describe SSMUs in a commercial maize plot by integrating spatial information from different sources: yield maps, soil properties mapping, and LAI maps estimated from remote sensing imagery. Section 2 describes the study area, while Section 3 explains the methods followed to obtain the LAI from Quickbird very high resolution imagery and the acquisition and mapping of physical soil properties. The strategy for delineating SSMUs from the available information will be reported at the end of this section. In Section 4, the agreement between yield, LAI and soil properties maps will be discussed, as well as SSMU delineation. Finally, the conclusions will be presented in Section 5.

# 2 Study area

The present study was conducted during the summers of 2004 and 2005 in a commercial maize field plot within the municipality of Esplús (Spain: 41° 45'N; 0°21'E). The field plot is about 60 ha, with two crops per trial: barley and short-cycle maize. Barley was sown in November and harvested in mid-May. Maize was sown during the first half of June, flowered at the end of August and was harvested in the second week of October in both years.

The climate is Mediterranean-continental with arid conditions. The annual rainfall ranges from 250 to 500 mm, while annual evapotranspiration is about 1050 mm (Government of Aragon, 2009). The study field is irrigated by sprinklers attached to a center pivot. The 2004 and 2005 campaigns brought contrasting climate conditions: during the 2004 hydrological year (October 2003 – September 2004) the accumulated precipitation was 244 mm, while in the 2005 hydrological year the precipitation was 476 mm (Government of Aragon, 2009). Arid climate conditions in the region during 2004 caused severe problems in irrigation water availability, leading to below-optimum crop irrigation. Water shortages are common in this irrigation district.

The irrigated district was set up 100 years ago. Intensive land leveling was needed to produce plots of a suitable size (< 1 ha) for flood irrigation. Within a few years, the lack of drainage ditches produced salinity and water-logging in some areas, with remnants of rice paddies still visible. New earth movements were needed to allow drainage of plots under basin and border flood irrigation. During the 1980s many plots were merged, moving earth again, to produce fields large enough for sprinkling with center pivots or lateral machines. Other areas have been equipped with solid set sprinklers. No soil maps are available.

# 3 Materials and methods

## *3.1 LAI mapping from remote sensing*

### Satellite imagery acquisition and processing

Six Quickbird scenes were acquired during the 2004 and 2005 summer campaigns. Quickbird imagery provides very high resolution (2.4 meters) reflectance data in the blue, green, red and near-infrared wavelengths. In 2004 the acquisition dates were 15 July, 10 August and 25 August, while in 2005 the dates were 18 July, 5 August and 23 August. Thus observations were made during the main phases of maize development, between emergence and flowering. The imagery was acquired on cloudless days with clear skies.

The images were co-registered with digital orthoimages of 0.5 meters spatial resolution to ensure pixel location accuracy. The digital numbers of the image were converted to absolute radiance values by applying transformation coefficients proposed by the image provider (Digital Globe, US). Surface reflectance was retrieved from radiance using the ACORN application (ImSpec, US), which is based on the MODTRAN 4 atmospheric radiative transfer model.

The Normalized Difference Vegetation Index (NDVI) was calculated from reflectance images in accordance with the expression:

$$NDVI = \frac{\rho_{QB4} - \rho_{QB3}}{\rho_{QB4} + \rho_{QB3}}$$

where $\rho_{QB4}$ and $\rho_{QB3}$ are, respectively, the surface reflectance in near-infrared and red bands of the Quickbird sensor. NDVI is widely used in remote sensing to estimate vegetation development and LAI (Ganguly *et al.*, 2008; Xiao *et al.*, 2005; Wulder *et al.*, 1998). Different VIs were tested to retrieve the LAI (not shown here for the sake of brevity), but NDVI is the one which provided the best results.

### Field measurements

Indirect LAI measurements were taken in the study field plot. Twenty points were selected in each field campaign in 2004 and 2005 via a random-stratified sampling using NDVI maps of ancillary Landsat 5 imagery of the area. The purpose of the stratification was to select sample points of high, medium and low maize development. Each of the sample points was revisited with a maximum delay of 2-3 days after the image acquisition, and the LAI was retrieved using a SunScan ceptometer (Delta-T Devices Ltd., Cambridge, UK) attached to a beam fraction sensor that allows simultaneous acquisition of photosynthetically active radiation (PAR) above and below the canopy. The SunScan optical device is well suited for LAI determination in maize (Wilhelm *et al.*, 2001). At each measurement point, 5 SunScan readings were taken within a square of 3 m × 3 m and the central measurement was geo-referenced using the eTrex Vista (Garmin International Inc., Olathe, KS) GPS unit. The expected accuracy in geo-location is to within 2 meters. The LAI was retrieved from the transmitted PAR using SunScan software (Delta-T, 1997), and then the 5 estimations per sample point were averaged. Thus a total of 118 field measurements were available during the 2004 and 2005 campaigns for producing and validating LAI maps.

**LAI estimation and validation**

The total amount of indirect LAI measurements was randomly divided into 2 independent groups of 59 measurements. The first group was used to describe LAI-NDVI empirical relationships (Fig. 1).

A strong exponential relationship was found between the two parameters ($r^2$=0.92) and described as:

$$LAI = 0.1176e^{4.1861NDVI} \quad [1]$$

This function was applied to NDVI images to retrieve LAI maps, which were validated with the second group of measurements. The coordinates of the sampled points were located on LAI maps, and values within a 5-meter buffer area at each point were averaged and compared with the observed LAI (Fig. 2). The local averaging within the 5 m buffer (twice the resolution of the imagery) enhances the representativeness of the LAI value selected, as well as avoiding errors associated with the geometric correction of the imagery. The results show a general agreement between estimated and observed LAI data, with an RMSE of 0.49, which can be considered satisfactory. It can be seen that one point is highly underestimated due to the presence of weeds, which contaminates the reflectance values in the image, thus producing deviant results.

***Fig. 1.***

***Fig. 2.***

## *3.2 Grain yield mapping*

In the 2004 season, a grain yield map was provided by the plot's owner. The data were taken with the aid of a GREENSTAR (John Deere, USA) yield monitor. The yield monitor used a real-time differential GPS (RTK GPS), providing a position accuracy to within a few centimeters. The yield measurements registered by the yield monitor were treated with dedicated software to produce a continuous yield map. Blank values were recorded by the yield monitor in several areas due to data overwriting when the combined traversed areas that were already harvested.

## *3.3 Soil properties mapping*

**EMI readings and soil sample acquisitions**

Electromagnetic induction (EMI) readings were carried out automatically on 22 June 2006, using a mobile platform. This platform consists of a vehicle towing a sleigh equipped with a DUALEM 1S (DualEM, Inc., Milton, ON) electromagnetic sensor, which registers EMI signals simultaneously in the horizontal and vertical orientation of the receiver dipole, achieving 70% of the cumulative response up to depths of 0.5 m and 1.5 m, respectively (Abdu et al., 2007). Data from the DUALEM and from an eTrex Vista GPS unit mounted on the vehicle were stored jointly on an Allegro SX portable computer (Juniper Systems, Inc., Logan, UT) running an HGIS application (Starpal, Inc., Fort Collins, CO) to record the absolute position of the EMI readings.

Given the geometry of the study field (a center pivot), the EMI readings were taken describing concentric circles from the outer limits of the circle to the center of the pivot, with a distance between circles of 25 m, and 2-4 m between consecutive reading points along the line of measurement. After data acquisition, the relative position of the GPS antenna with respect to the DUALEM sensor was corrected. Finally the EMI readings were converted to a reference temperature of 25°C, and designated EMh and EMv for the horizontal and vertical orientation of the receiver coil, respectively.

Two different soil samplings were carried out in the field plot, focused on determining soil properties that would affect maize development. The first (7 April 2005) was conducted in an orthogonal grid with points placed at a distance of 70 m from each other (henceforth referred to as 'orthogonal sampling'). A total of 150 soil samples were collected to a depth of 30 cm. The locations were registered using an eTrex Vista GPS unit, and the soil samples were placed in aluminum cans and transported to the laboratory. The second sampling (9 June 2005) was conducted on ten sites selected according to maize development observed in the LAI maps (Section 3.1). Sites with high, medium and low maize development were chosen, and soil samples collected by hand auger at two points 12 m apart in each site at depth intervals of 25 cm up to a maximum depth of 150 cm (henceforth referred to as 'deep sampling') where soil conditions allowed it. The coordinates of the auger holes were also registered with an eTrex Vista GPS unit. The soil samples, placed in plastic bags, were transported to the laboratory for analyses of the fine earth. The percentage of coarse fragments (> 2 mm Ø) was measured on a weight to weight basis.

## Lab determination of soil properties

The two different soil samplings were analyzed separately, and different soil properties were determined in each case.

The soil texture was determined in the orthogonal sampling, as well as the electrical conductivity in 1:5 water to soil extracts. Concentrations of P, K, Mg, Ca and Na were determined in the same extracts. The analyses were carried out in accordance with the official methods of the Spanish Ministry of Agriculture (MAPA, 1994).

In the deep sampling, the concentrations of Ca, Na, and Mg were determined at each depth in saturated paste soil extracts. Then the sodium adsorption ratio (SAR) in the saturated soil extract was calculated as:

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+} + Mg^{2-}}{2}}} \qquad [2]$$

where $Na^{+}$, $Ca^{2+}$ and $Mg^{2-}$ are, respectively, Na, Ca and Mg concentrations (meq/L) in the saturation extract.

The saturated soil extract is an attempt to approach the conditions of soil under irrigation and is the standard method for assessing soil and plant response to salinity (United States Salinity Laboratory Staff, 1954). The main drawback is that preparation is tedious and time-consuming, and is inappropriate for a large number of soil samples as in the case of the orthogonal sampling.

Both soil samplings were needed to complement each other. Orthogonal sampling describes the spatial patterns of ion concentrations within the field plot, since an appropriate spatial resolution is required to describe SSMU. Deep sampling complements superficial sampling, helping to determine the soil limitations for crop development.

**Altitude**

Altitude measurements were also acquired with a spatial resolution of 2 meters using the real-time differential GPS (RTK GPS) – vertical error < 10 cm – used by the yield monitor in parallel to grain yield measurements. The stored coordinates were then used to build a digital elevation model (DEM). Although moderate and high slopes are not expected in agricultural field plots, the range of the recorded altitudes was 19.5 meters.

**Spatial interpolation of soil properties**

Each soil spatial dataset was interpolated using the kriging technique, which is widely used for these purposes (Delin & Soderstrom, 2003; Schumann & Zaman, 2003). A spherical model was selected for the variogram in the kriging process, which was accomplished using ArcGIS 9.2 (ESRI, USA).

In the case of the orthogonal sampling and elevation measurements, all the points were used to perform the kriging, taking into account that the spatial distribution of points in the field was homogeneous. However, in the case of the EMI readings, a marked spatial pattern was observed as a consequence of sampling in concentric rings. To avoid possible mapping artifacts resulting from the sampling pattern, the whole EMI reading dataset was divided into five subsets, selecting one of each five consecutive points, in the order of acquisition, for each group. As a result, each subset constituted an almost regular sampling of EMI. Each subset was interpolated using the above-mentioned technique, and the five resulting maps were averaged to produce the final EMI map.

The measurements from the deep sampling were not interpolated since the number of points sampled is too small to allow map production.

## 3.4 Delineation of SSMU

The LAI maps retrieved from remote sensing images for the 2004 and 2005 campaigns were analyzed to describe crop development dynamics. Only the LAI maps calculated for 10 and 25 August 2004 and 5 and 23 August 2005 were considered, since in earlier images maize development was too low to show significant differences in LAI within the field plot.

Three different classes of maize development were established from the LAI values on each of the LAI maps. For the maps of 5 August 2005 and 10 August 2004 the first class ranged from 0-0.75 and represents areas with a severe degree of stress; in the second class the LAI ranged from 0.75-2 and refers to areas with a moderate degree of stress; finally the third class comprises areas with a LAI greater than 2 and apparently no abiotic stress. In the case of the maps of 23 and 25 August, LAI intervals of 0-1.5, 1.5-3.5 and > 3.5 were selected to describe, respectively, the areas with severe, moderate and no abiotic stress.

These intervals were chosen according to the relation observed between the LAI maps and grain yield maps in the year 2004, which will be covered in section 4.1. The grain yield increases with the LAI, starting from a minimum LAI of 0.75 and 1.5 in early and late August respectively. This associated increment ends at values of about 2 and 3.5, on 10 and 25 August respectively, where the grain yield stands at a value of about 9.5 tons per hectare, after which LAI increments are not associated with significant yield increments.

Superimposing the resulting maps for 2004 and 2005, two final LAI class maps were obtained – for early and late August – with five different categories according to crop development in the two years: areas with recurrent severe abiotic stress (class A), areas with recurrent moderate abiotic stress (class B), areas with moderate stress in year 2004 and no stress in 2005 (class C), areas with moderate stress in 2005 and no stress in 2004 (class D), and areas with no stress in either of the years (class E). Finally, a map from late August is selected for subsequent analyses since LAI maps from 23-25 August appear more closely related with the final yield (see section 4.1).

This classified map from late August will be analyzed in conjunction with the spatial information on soil properties collected in order to evaluate the contribution of each of the soil properties to the crop development. A specific analysis was performed on class C, because this class occupies a large surface in the field, grouping areas with different soil properties. We applied an unsupervised classification – cluster analysis – only to class C, using soil maps (Na, Mg, Ca, P, K, soil texture and elevation) as input parameters for the ISODATA algorithm implemented in the unsupervised classification utility in the ERDAS 9.1 (Leica Geosystems, USA) commercial package.

The interpretation of this analysis in terms of crop development and soil properties yielded the delineation of SSMUs, each one with specific crop conditions, soil properties and management proposals, which will be explained in section 4.3.

# 4 Results and discussion

## *4.1 Relationships between image-based LAI and yield*

The LAI maps derived from high-resolution satellite imagery were compared with the grain yield maps obtained in 2004 to evaluate the ability of image-based LAI maps to predict maize production. Fig. 3 shows the average grain yield of 2004 for each LAI interval, derived from LAI maps. Only the results of 10 and 25 August are shown, since no significant relations were found between yield and LAI in the image of 18 July.

The results show that LAI maps are able to describe the spatial patterns of yield production. In the image of 10 August the grain yield starts to increase in parallel to the LAI until a plateau of LAI at about 2-2.5, above which the grain yield stands at around 10 tons per hectare. The LAI map of 25 August shows a similar trend: production starts at 5 tons per hectare for low LAI values (< 2), whereas above this value LAI and grain yield show positive trends until a plateau of 3.5-4, at which production stabilizes at 10 tons per hectare. However, it can be noted that for the highest LAI class the grain yield decreases slightly due to the existence of small weed patches, estimated as high LAI areas in satellite images. The sensitivity of LAI to yield production on this date (Fig. 3) is higher than in the previous image, since at the end of August leaf area development is completed, resulting in a more stable LAI-yield relation.

This suggests the prediction capability of remote-sensing-derived LAI maps. Grain yield maps delineated by yield monitors are often not suitable for a pixel by pixel comparison with imagery data, since they are subject to errors due to speed changes, overlapping passes and operational errors such as unequal harvesting in two adjacent passes (Dobermann & Ping, 2004; Simbahan et al., 2004). However, grain yield maps provide an adequate description of the spatial patterns of grain production and make it possible to highlight those areas subject to stress that produce significantly lower yields.

***Fig. 3.***

## *4.2 Relation between LAI and soil properties maps*

### LAI spatial variability in 2004 and 2005 campaigns

The LAI maps obtained for 2004 and 2005 are shown in Fig. 4. The spatial patterns of crop development describe important differences between the two years, especially remarkable in the late August maps. There are areas – classified as A and B in Fig. 5 – that presented a sub-optimal development in both years, with two different degrees of stress: severe and moderate respectively according to LAI. These areas have a fragmented distribution in the field plot, with several small patches. The sum of both classes is about 20% of the total field surface area (Fig. 5).

The zones that presented good development in 2004 and moderate stress in 2005 are about 34% of the plot (classified as C in Fig. 5). The differences between the two years can be explained by the drought events in 2005 (see Section 2), with low rainfall and a shortage of irrigation water resulting in plant stress.

The opposite behavior is observed in class D. This LAI class presents areas with normal maize development in 2005 – despite the water shortage in the field – and moderate stress in 2004, when no limitations on irrigation water availability were experienced. This LAI class is only 17% of the field and mainly constitutes a single patch in the north-west part of the field plot.

Finally, class E – comprising areas with no abiotic stress either in 2004 or 2005 – is located towards the center pivot, where water supplies are more continuous in time, and in several small patches of the field plot. These non-stressed areas occupy 19% of the field.

Although both LAI class maps provide close distributions of the LAI classes described, the one obtained from the late August images (Fig. 5) will be used in subsequent treatments for SSMU delimitation, since they appear to be more sensitive to final yield (section 4.1).

***Fig. 4.***

### Relationships between LAI and soil properties maps

The colinearity between EMI readings in horizontal (EMh) and vertical (EMv) modes was noticeable ($EMh = 6.43 + 0.735 \times EMv$; $R^2 = 86.8$). On the other hand, of the 8373 EMI reading points, 6303 have $EMv \geq EMh$, showing the influence of deep soil layers (Rhoades et al., 1999, page 44) below the rooting depth of most crops and not reached by our augering. These deep layers undergo irregular changes in water content depending on the management of the plot itself but also the surrounding irrigated plots. Another characteristic of the plot is the lateral variability of the shallow soil, illustrated by the coarse fragments content at the first 50 cm, ranging from 0% to 29% in our soil samples, with a bi-modal distribution, probably due to the several episodes of earth movement required to build the present plot. The high spatial variability of soil properties influencing the EMI readings precluded calibration against electrical conductivity, in spite of the good results obtained in nearby areas, both at a plot scale (Díaz and Herrero, 1992; Herrero et al., 2003) and an irrigation-district scale (Nogués et al., 2006).

The spatial distribution of soluble ions (Fig. 6) is similar to that of the LAI class maps. In Fig. 6 the relation between high values of EMv and high Na and Mg concentrations can be seen. Roughly speaking, the areas that show high Na, Mg and EMv are associated with LAI classes A and B (severe and moderate stress in both years). Texture data also suggest similar trends, mainly in sand and clay contents, with a NE-SW strip in the field plot where fine materials appear to be linked to higher Na concentrations (Fig. 7). Conversely, sandy areas in the south-east of the field plot (which correspond to the higher elevation areas) present low values of EMv and Na and Mg concentrations. In these areas EMv ≈ EMh, probably suggesting a lower influence from deep soil layers.

***Fig. 5.***

***Fig. 6.***

Fig. 8 depicts the average values of ion concentrations in each LAI class. The results show that the problems of A and B classes may be associated with soil sodicity, since both present much higher Na concentrations than the other classes. Moreover, the SAR of saturated extract from these small patches ranges between 5-10, and is higher than 10 at some points in samples deeper than 0.50 m. Sodicity has two main effects in crop development: the first is toxicity, which limits crop development at high concentrations (Sümer *et al.*, 2004); second, it induces a lack of soil structure that can result in crust formation on the top soil layer (United States Salinity Laboratory Staff, 1954; Agassi *et al.*, 1981; Rengasamy & Olsson, 1991; Sumner & Naidu, 1998), limiting water infiltration and plant emergence. This could explain the low values (close to 0) of LAI maps in those areas with recurrent abiotic stress, even in the late August images. Relevant differences in texture were not found between LAI classes (results not shown).

***Fig. 7.***

Two new classes, called C1 and C2, were generated as a result of the cluster analysis performed on class C (section 3.4). The two classes differ both in ion concentrations and texture. Class C1 includes the areas with higher EMI, Na, and Mg concentration within class C, and a texture with a predominance of fine materials (clay and fine silt), while C2 presents the opposite conditions, low ion concentrations and coarser materials (sand), and is located in the higher parts of the field plot.

***Fig. 8.***

## SSMU delineations and differential management proposals

The delineation of SSMUs is shown in Fig. 9. Classes A and B are grouped in a single management unit, designated 'areas with recurrent abiotic stress linked to soil sodicity' (S). These areas presented low maize development in both 2004 and 2005, and soil with high relative concentrations of Na and Mg, high EMI readings (Fig. 10), and SAR values close to 10 in some patches. This suggests problems associated with a lack of soil structure and crusts, which could explain the very low LAI values (0-2) in the August images. Sodic soils are prone to develop surface seal under rain or the impact of sprinkler drips and further drying, this kind of sealing being well known in the area as hampering the emergence of maize plantlets.

Class C1 constitutes a single management unit designated 'areas with stress under dry conditions associated with soil sodicity' (SDS). The Na and Mg concentrations in these areas (Fig. 10) are also higher than in areas without stress. Roughly speaking, it comprises the NE-SW strip which presented high values of EMI and ion concentrations in the soil maps (Fig. 7). The moderate sodicity problems in this SSMU are exacerbated when water application is low, as happened in 2005. Moreover, the differences in altitude in the field plot shown in Fig. 7 (20 meters in 60 Ha) could generate runoff from this unit to lower areas, limiting water infiltration and re-distributing the applied agrochemicals, since this SSMU is located on the slope between the upper and lower areas of the field.

***Fig. 9.***

Class C2 comprises the SSMU called 'areas with stress under dry conditions linked to low water retention' (SDW). These areas are characterized by low concentrations of Na, which excludes problems related to soil sodicity, and a predominance of coarse materials in the soil (47% sand) and a very low standard deviation (Fig. 10). The low water-holding capacity of sandy soil, as a limiting factor for plant development under water scarcity, may explain LAI differences in 2004 and 2005.

The SSMU designated 'areas with stress under wet conditions associated with flooding' (SW) corresponds to LAI class D. This management unit is located mainly in a single, large patch in the north-west part of the field plot. This unit doesn't present problems associated with soil sodicity, as shown by the low concentrations of Na in the soil (Fig. 10). The low plant development in 2004 suggests that water flooding occurs in these areas. Fig. 10 shows low proportions of fine materials (clays) in the first 30 cm of soil of this management unit, but clay layers could well occur at lower depths, causing water flooding. Moreover, the low altitude (Fig. 8) of this area suggests that water accumulation from higher parts of the field could happen, with flooding affecting crop development.

Finally, the areas with high development in both 2004 and 2005 (LAI class E) comprise the SSMU 'areas with no stress' (NS).

The proposed delimitation of management units highlights the importance of a variable-rate application of several inputs. Agricultural inputs such as irrigation water or agrochemicals can be managed by engineering the pivot, installing a system of programmable valves (King *et al*., 2009; Dukes & Perry, 2006; Coates *et al*., 2006). Crown sectors (Fig. 9b) centered on the pivot are convenient SSMUs not only for these devices, but also for tractors and combines that already work in circular paths. Assuming that the field is irrigated using a variable-rate center pivot with sprinklers 25 m apart and that changes the water flow they apply each 5° along the track, a division of the selected field plot is proposed (Fig. 9b) based on the original SSMU delineation. This is just one possibility for a derived map adapted to the actual infrastructure of the studied field plots. Merging or splitting map units, crown sectors or other units, could be required for easier management. All derived maps should attain a compromise with the type and amount of map impurities incorporated. Both geo-referenced crop weight measurements by the grower and high-resolution space or airborne images will help, in an iterative process, to refine the maps to be used for the different inputs.

First, precision irrigation would mitigate the differences observed between the areas SDW and SW. As these SSMUs present different soil textures and have shown opposite problems related with flooding and low water retention, an optimal irrigation strategy comprises lower application rates in SW, avoiding water excess and flood problems. Conversely, higher application rates could be applied to SDW, since this management unit presented high crop development when sufficient irrigation had been applied. Moreover, it doesn't present soil sodicity problems, as shown by soil sample analysis, so irrigation water hypothetically saved in the SW unit could be applied to SDW, where it would presumably produce a grain yield increment.

***Fig. 10.***

S and SDS units present different problems. In the S unit, abiotic stress observed both in the presence and absence of water highlights the role of soil sodicity as a limiting factor in crop development. The effect of sodicity could be mitigated with gypsum application (Sawhney & Baddesha, 1989), so the delimitation of unit S could be used as a gypsum application map. Alternatively, very low grain yield is expected in these areas, so if the sodicity cannot be fixed, no input application to these areas is proposed. Similarly, gypsum application in SDS could be considered as a way of reducing the observed effects of soil sodicity. Although adequate crop development was observed in 2004, the application of gypsum could help to mitigate the problems associated with sodicity at low irrigation rates.

# 5 Conclusions

In the present article, spatial information technologies have been jointly used in the determination of site-specific management units in a commercial maize center pivot field in a study involving two field campaigns (2004 and 2005). The simultaneous use of image-based LAI maps and soil maps obtained from soil sampling has been proposed as an operational method for delineating homogeneous areas within a field so as to apply differential management over the field.

Image-based LAI maps have provided a diagnostic tool of crop development and yield. The observed relationship between LAI values collected from LAI maps and the yield measured by a yield monitor in the 2004 campaign has shown the suitability of remote-sensing techniques for predicting areas where lower yield is expected. Moreover, LAI maps have made it possible to study the changes in maize development in the two field campaigns, thus delineating the areas with different maize development in the two years, which is necessarily associated with non-optimal management.

The soil maps produced from superficial and deep soil sampling have helped to identify the soil parameters associated with the LAI classes derived from LAI maps. Our work portrays the agricultural value of EMI readings in themselves even when their pedological meaning is left at the black-box stage. EMI readings appear to be a comprehensive measure of soil characteristics related to maize development.

The EMI, Na, Mg and Ca maps, together with information on SAR values from several sampling points, made it possible to correlate sodicity problems with areas with recurrent low maize development. At the same time, soil texture maps provided a basis to relate low plant development during 2004 – when no water constraints occurred – with possible flooding episodes in the lowest parts of the field plot and, conversely, to relate low development in 2005 to the small water-holding capacity of sandy soils in the higher areas. The division of SSMU maps into sectors makes it possible to engineer the water distribution through the pivot for precision sprinkling.

The proposed SSMU maps summarized the analyses carried out using the available spatial information. Five different management units have been described, with two main factors that can be managed to compensate for the differences observed in the field: sodicity, which can be treated with gypsum application; and different soil textures, which can cause unequal soil water content and can be managed with precision irrigation, adapting water inputs to the specific soil properties.

The present article is an example of how spatial information on soil and plant data from different sources can be integrated to provide the basis for differential management within a context of precision agriculture.

We have presented the results of only two field campaigns (2004 and 2005), which are intended as representative of wet and dry years in the local climate. A longer period of observation might be necessary to validate some of the conclusions reported here, especially those related with the proposal of precision irrigation or the correction of soil sodicity.

The relationship between soil properties, climate and plant response has been established in an empirical and descriptive way. In this respect, the use of crop-functioning models in precision agriculture could open an avenue in decision-making support, since they could provide the basis for linking soil properties, crop development and climate parameters, thus allowing more detailed management recommendations and helping to understand the plant response to the different management strategies.

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