The effects of four irrigation regimes on vineyard vigour using proximal multi-spectral active sensors

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Abstract

Precision agriculture is a useful tool to assess plant growth and development in vineyards. The present study was focused in the spatial and temporal analysis of vegetation growth variability analysis; considering four irrigation treatments with four replicates. The research was carried out in a vineyard located in the southwest of Spain during 2012 and 2013 growing seasons. Two multispectral sensors mounted on an All-Terrain Vehicle (ATV) were used in the different growing seasons/stages in order to calculate the vineyard Normalized Difference Vegetation Index (NDVI). Soil apparent Electrical Conductivity (ECa) was also measured up to 0.8 m soil depth using a geophysical sensor. All measured data were analysed by means of Principal Component Analysis (PCA). The spatial and temporal NDVI and ECa variations showed relevant differences between irrigation treatments and climatological conditions.

Keywords: Precision agriculture, Vineyard, apparent Electrical Conductivity, NDVI, Irrigation.

1 Introduction

Terroir is a French concept that says - "*there are unique aspects of a place that shape the quality of grapes and wine*". Those aspects that impact on grapes and wine quality are usually associated with topography, soil, climate, plant management and plant genetics (Vaudour, 2002). According to several authors, the study of the plant vegetative vigour is an essential parameter to successfully manage yield and grapes/wines quality because of the fact that plant growth integrates climate, soil, topography, available water and other plant controlling factors (Smart, 1985; Carbonneau, 1995; Cortell et al., 2005; Deloire et al., 2005). Consequently, the appropriate management of soil and the consideration of the main climatic variables are key factors to obtain good yields and, finally, quality wines. Vineyard canopy management such as pruning systems, shoot orientation, shoot thinning or leaf removal, has the capacity to modify climate factors around the plant and therefore, modifying grape and wine quality (Dry, 2000).

Water management in vineyards and their responses have been studied since last decades in a high range of environments and vineyard varieties due to the irrigation implications in yield and final product quality (Smart and Coombe, 1983; Bravdo and Hepner, 1986; Mullins et al., 1992; Williams and Araujo, 2002; Intrigliolo and Castel, 2010). Previous authors also indicate that vine vegetative development is highly influenced by available water, up to the extent that it may become a limiting factor. However, under the same irrigation depth, sometime the response between two closer plants is not the same. This point should be considered when selecting methods to estimate crop water status in order to achieve a better management and the production objectives defined at the beginning of the growing season. On one hand, to cover all the water needs is not recommended because it creates management problems, reduces crop quality and overall unnecessarily increases the cost of cultivation. On the other hand, to increase the water availability to the vineyard, the grape production rises as well, but also the canopy, increasing the cost of pruning, plant protection treatments and usually reduces the quality of the grapes. Thus, water stress had to be controlled to achieve a good yield / quality of grapes and balanced growth while avoiding the problems of excess water. Therefore, it is essential to know the right way to manage this crop.

Some studies related to spectral Vegetation Indices (VI) performed different analysis of vine canopy, shape, size and functional capacity, in order to manage spatially and temporally vegetation and other productions factors such as water. Spectral VI, have the possibility to predict a large number of plant features, such as Leaf Area Index (LAI), vegetation fraction cover, fraction of Absorbed Photosynthetically Active Radiation (fAPAR), chlorophyll pigment concentration, plant stress and other related parameters (Jordan, 1969; Baret and Guyot, 1991; Peñuelas et al., 1993; Rondeaux et al., 1996; Gitelson and Merzlyak, 2004). These spectral vegetation indexes, which are mathematical combinations of two or more electromagnetic bands reflectance, can be used in vine growth site-specific management enabling the optimization of grape yield and grape yield-quality (Lamb and Bramley, 2001).

Nowadays, it is possible to obtain a plant spectral signature with a multispectral proximal sensor (Tardáguila and Diago, 2008), which is relevant to study vine vegetation *terroir*. . The Normalized Difference Vegetation Index (NDVI), developed by Rouse et al. (1973) is one of the most extensively vegetation index used for analysis of vegetation growth. It can be calculated as:

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (1)$$

where *Red* and *NIR* parameters are the reflectance in the Red and NIR electromagnetic radiation bands, respectively. When electromagnetic radiation (natural or man-made) impacts on living green leaves, part of it is absorbed, other part is transmitted and the rest is reflected. The electromagnetic radiation spectral range that can be absorbed by plants is the

Photosynthetically Active Radiation (PAR), being between 0.4 μm to 0.7 μm (similar to the visible range). In this range, chlorophyll is efficient in capturing the Red and Blue ranges and normally reflects the Green, the Infrared (IR) and the Near Infrared (NIR) ranges. Thus, on the basis of NDVI, the greater amount of vegetative cover or canopy, the greater value in the index. However, the ability to absorb and reflect both bands depends not only on the health plant status but also on its size. In this way, a plant with water stress or any other kind of stress (pests, diseases, nutritional deficiencies ...), will have less capacity to absorb the red band by their photosynthetic apparatus and to reflect the NIR band by the cell walls, resulting a lower value of the NDVI. Therefore, the expression of the vineyard vegetative development can be related to NDVI. Several studies have shown the relationship between parameters related to the amount of vegetative canopy vineyard, such as LAI and fAPAR, and physiological factors, such as crop production, quality the grape on harvest or plant water status (Jackson et al., 1983; Smart and Coombe, 1983; Dry, 2000). Furthermore, NDVI is also largely related to the density of vegetative canopy vineyard (Dobrowski et al., 2002; Johnson, 2003; Hall et al., 2008), so that a change in the factors affecting growth and vineyard development could be estimated by the NDVI.

Additionally, *terroir* is affected by physical, chemical and biological soil properties and as a tool to interpret these soil properties variations, soil apparent Electrical Conductivity (ECa) may be used. Soil ECa measurements may characterize the soil spatial variability, mainly the soil physical features and have been used by other authors in order to delineate soil homogeneous management zones (Corwin and Lesch, 2003; Moral et al., 2010; Terrón et al., 2013). Soil ECa measurements can be obtained through geoelectric sensors and this can be an easy and economical way of sampling the soil and guiding soil evaluators in their soil properties analysis (Terrón et al., 2011).

According to Hall et al. (2002) the implementation of vineyard site-specific tools are needed in order to better manage vineyards. Thus, considering the previous, the present work makes use of precision agriculture tools to determine: i) the effects of different irrigation treatments in the vine vegetation growth considering two different climatic seasons; and ii) the soil influence in the vegetation growth expression.

2 Material and methods

2.1 Study area and experimental design

The study was carried out during 2012 and 2013 growing seasons, in a field belonging to the Agrarian Research Institute “La Orden - Valdesequera” , in Extremadura (Spain) (38° 51´ N; 6° 40´ E). Study area is located in a vineyard of 1.8 ha, varietal Tempranillo (*Vitis vinifera* L.) grafted on Richter-110. It was planted in 2001 by vertical trellis in bilateral cordon system, with 60 cm stem height and 12 buds per plant. Cultivar Tempranillo is a vigorous variety adaptable to all types of soils, preferably slightly acid, and oriented towards the sunny noon terrain.

The climate is characterized by mild winters and hot summers, with maximum temperatures reaching 40°C. Rainfall is irregular, with dry summers and often with an annual average below 500 mm. The soil is typical from the Guadiana Valley, with a uniform profile, poorly differentiated. According to the soil survey staff (2006) is into the order Alfisol, suborder Xeralf and the great group is Haploxeralf (Aquic), generally are soils slightly leached, with scarce of calcium and with low sand-adherence value. The upper soil has slight humus content, while the lower soil is poor in it and has weak nitrogen content as well. According to Olsen method, the field content in available phosphorus was satisfactory, while in case of potassium, an essential monovalent cation, was unsatisfactory and sodium content in this soil was low too. It also had lower electrical conductivity and exchangeable cation levels, with a relatively low CEC.

The experimental design was a randomised completely blocks, with 4 replicates (plots) per treatment. Each plot had 108 vines in 6 rows with 18 vines per row, where the distance between plants and rows were 1.20 m and 2.50 m respectively, placed on a trellis with East-West row direction. Watered treatments were dependent on the growing season (Fig. 1): i) 2012 treatments were divided into four levels of irrigation, corresponding to four levels of Crop Evapotranspiration (ETc) rates: a) Fully watered, based on the application of the 100% of the ETc; b) RDI 50-20, based on the regulated deficit irrigation technic, with a 50% of ETc before veraison and 20% of ETc after it; c) RDI 50-0, based on the regulated deficit irrigation technic, with a 50% of ETc before veraison and 0% of ETc after it; d) Non – watered, based on a rainfed treatment; and ii) 2013 treatments were reduced to three levels of irrigation, corresponding to three levels of ETc rates: a) Fully watered, based on the application of the 100% of the ETc; b) RDI 30, based on the regulated deficit irrigation technic, with a 30% of ETc throughout the season; and c) Non – watered, based on a rainfed treatment.

The irrigation system is characterized by drip irrigation with one emitter of 4 l h^{-1} every 0.6 m (two emitters per vine) attached to a wire suspended 0.4 m above the ground. Full ETc was calculated by means of the weight differences recorded in a weighing lysimeter installed in the centre of the assay, corresponding to a fully watered treatment plot (Yrissarry and Naveso, 1999). Two grapevine plants were planted into the lysimeter container in order to provide the water balance along their canopy development. Precipitation was collected by an agro-meteorological station located over a reference prairie nearby the vineyard.

Soil management was characterized by two annual cultivator treatments, one in winter dormancy and another in bud break phenological stage. Later on, spontaneous vegetation was controlled by herbicide treatments. Furthermore, it is added to soil 250-350 kg/ha. of NPK fertilization (9-18-27). Figure 2 shows the spatial distribution of some soil physicochemical parameters analyzed by official laboratory procedures. Regarding to the canopy management, a spring pruning was realized to adjust the potential yield to the 12 initial shoots. Subsequently, before veraison stage, growing shoots are introduced into the trellis to facilitate passage of agricultural machinery. From veraison to harvest, plant protect treatments were done against cryptogamic diseases in cycles of 15 to 20 days.

2.2 Vegetation index and soil apparent electrical conductivity

The NDVI estimation was performed with two active proximal multi-spectral sensors mounted on All – Terrain Vehicle (ATV). These sensors (OptRx ACS–430, Ag Leader Technology, USA) report directly the vineyard canopy NDVI calculated with Red (0.67 µm) and NIR (0.78 µm) wavelengths. Datasets were collected using a PDA data logger connected to the sensors with the TopView software (Betop Topografía SL, Seville - Spain). Geographical coordinates were obtained by a dual frequency GPS (GGD Maxor JAVAD Javad GNSS Inc., U.S.A.) with Real – Time Kinematic (RTK) differential corrections that reached a planimetric accuracy lower than 0.03 m. To obtain the vineyard canopy reflectance the active multi-spectral sensors were placed at nadir position and at a distance, from the top of the grapevines rows, of 0.80 m (± 0.20 m, depending on the vineyard height) (Fig. 3). The number of intra-year spectral datasets was fixed to 5 and, according to the season: i) in 2012, they were started on 29 May and ended on 6 September; and ii) in 2013, they were started on 30 May and ended on 2 September.

To validate the NDVI with the LAI, several measurements of the latter was carried out throughout the ripening stage of the crop in both years. Measurements was recorded by a Plant Canopy Analyser LAI-2000 (LI-COR, Inc, U.S.A.), following the procedure of Mabrouk and Carbonneau (1996).

ECa measurements were conducted on 18 February 2011, with a VERIS 3150 Surveyor sensor (Fig 4.), obtaining simultaneously in two different soil levels: i) Shallow or ECs **–** in to a depth of 0.30 m from the soil surface and, ii) Deep or ECd **–** in to a depth of 0.80 m from the surface. Sampling details can be consulted at Moral et al. (2010).

2.3 Geostatistical and statistical data processing

The samplings showed in this work, corresponding to each dataset of both growing seasons, were statistically analyzed by means of some tools contained in the ArcGIS v.10.1 software (ESRI, U.S.A), for those geostatistically analyses, and SPSS v.17 software (SPSS Inc., U.S.A.), for inferential statistics analyses.

The geostatistical analysis of the multi – temporal NDVI samplings included the followings phases: i) Voronoi map – it was performed a previous exploratory analysis of the samplings to take out outliers; ii) Ordinary Kriging interpolation – the parameters used in the semivariograms of each sampling to generate the corresponding maps are showed in Table 1. Once obtained these maps, they were rasterized using a pixel size of 2 m; iii) Principal Component Analysis (PCA) – at this work, a PCA process was established separately for each of the years of study. At each analysis, input raster dataset included the five NDVI sampling of the growing seasons, and the output data were distributed in 5 principal components.

Thus, results of PCA analyses obtained were were composed of five principal components for each year, where the first principal component shows the spatial variability of NDVI for the whole of all mapping dates of each year.

Meanwhile, the samplings belonging to the ECa were also geostatisically analized. In this case, only ordinary kriging interpolation tool was used, from which it was obtained the ECs and ECd maps of 2011. The parameters used to interpolate the samplings of ECa are shown in Table 1.

Furthermore, NDVI samplings of both growing seasons and samplings of ECa of both depths acquired by kriging were statistically analyzed in two phases: i) On the one hand, it was acquired descriptive parameters of each water treatment in each sampling date to get a global knowledge of the behavior of each component that make up the statistical design; ii) On the other hand, it was done variance analyses of each treatment in each sampling date too. These analyses let compare the behavior the spatial and temporal behavior previously mentioned.

In addition, with the aim of determine the importance of the local soil characteristics over the vegetative expression of the vineyard, given by the ECa and NDVI parameters respectively, it was used the Geographically Weighted Regression tool (GWR), included in the ArcGIS v.10.1 software (ESRI, U.S.A.). The relationship between both variables resulted in maps of coefficient of determination (R^2) of each water treatment, growing season and depth. The chosen geometric resolution was of 4 m of spatial resolution, which led the goodness of fit in the influence of soil characteristics on the vegetative growth of vines in each of the irrigation treatments of the assay.

3 Results and Discussions

Climatic variables logged by the weather station sited in a reference prairie nearby the tested vineyard, recorded a diverse behaviour during the two – years test, with drier conditions in the first growing season. Figures 5a and 5b show the cumulative annual rainfall, the cumulative annual ETc, temperature parameters and growing degree days (GDD) on both years. Focusing in the accumulation of precipitation, the total amount on the second year trial (2013) was more than double when compared with the first year trial, where only in its first quarter had the same amount of rainfall that the whole previous season. However, during final stages of vegetative development and within the whole ripening phenologic stages, both years had a similar low accumulation of precipitation. On the contrary, temperature was not very different between both years. The observed climatological differences on both seasons influenced differentially the vineyard vegetative development when considering the different irrigation treatments analysed on this study.

On the other hand, in spite of the large differences in precipitations between the two growing seasons, it is observed how, being the wettest, the second year of the test presented a similar hydric demand that the previous year. This result allowed to compare the vegetative response of two consecutive years that were very different on their climatology. Furthermore, if this premise is constant over the years, it could be possible to know the total needs of the culture of vineyards at any annual climatological quality and make appropriate reductions in ETc for a watering schedule based on precipitation occurred in every moment of the campaign. Obviously, and according to Wample and Smithyman (2002), it must be taken into account the increases of hydric necessities of each phenological stage, which are showed in the slope changes of the accumulation curve of ETc (Fig. 5a), paying more attention in dry seasons to not producing unwanted water stresses to the vineyard.

In this study, Figure 6 shows the relationship between LAI estimations and NDVI measurements, which measurements of LAI recorded throughout the period ripening of the crop in both years confirm that they are well related (R^2 = 0.81), indicating the ability to estimate the degree of development of the vineyard crops by NDVI determinations obtained by proximal active sensors. These results are coincident with several authors, which has been stated a good relationship NDVI – LAI (Johnson, 2003).

Regarding to the temporal variability, Fig. 7 shows the obtained results in the first principal component (PC1) of each PCA made to the different mapping dates in each growing season. According to the results, there were differences in plant development even when the same doses of irrigation and cultural practices were received into the different plots of each type of treatment of irrigated. In this way, it was estimated the spatial variability of the soil properties by means of laboratory analyses (Fig. 2) and the geographical determination of ECa, shallow and deep, which are represented in Fig 8. There seems to be a pattern consisted in a variation of ECa from the northern and southern boundaries of the assay up to its centre and, on the other hand, from east to west, coincident with some physicochemical parameters of soil. Then, exist a pattern in the soil characteristics variability due to the good relationship that ECa keeps with some of them, mainly with the clay content, and soil pH (Moral et al., 2010). The spatial variability of ECa, shallow and deep, also had shown significant differences among the locations of the plots of the different irrigation treatments (Table 2), designating different values in the soil properties that influenced the vegetative growth of grapevines. It is observed how the plots of each treatment shown, in general, the spatial variability pattern above discussed, presenting higher values of ECs or ECd in plots near to the northern and southern boundaries of the vineyard test site. Because of this spatial variability, even within plots of the same treatment, it was necessary the geostatistical analysis between NDVI and ECa to know how much influence the soil properties on the vegetative growth of the vineyard in each irrigation treatments and their respective plots.

3.1 Intra-year variability

3.1.1 2012 growing season

Figure 9 shows both temporal a spatial evolution of NDVI index of the irrigation treatments and their respective plots in the 2012 growing season. At first glance, the results of NDVI mapping of this year show how all the treatments had a temporal evolution similar to Gaussian function, increasing the mean value of the index as the campaign went, reaching a maximum value around the phonological stage of veraison, from which the index went lower up to the harvest. In spite of this sigmoidal evolution, a positive relationship between the NDVI and the water dose was produced, in which the Fully watered treatment kept the mean value of NDVI higher for all the mapping dates, and the Non-watered treatment the lower mean value being this differences, furthermore, significant (Table 3). These results indicate that the more quantity of water in vineyard the more vegetative development of its canopy.

The intermediate RDI 50-20 and RDI 50-0 irrigation treatments also had significant differences between the NDVI values regarding to the previous ones, positioning itself at intermediate values. Both RDI treatments kept similar their NDVI values up to January and then they were differentiated because of the change on the water dose of the experimental design. At that moment, the RDI 50-0 treatment had a higher decreasing in the NDVI mean value and, consequently, in the vegetative expression of the vineyard. Taking into account these aspects, and knowing the existing relationship between the vegetative growth of the vines and the NDVI value, it can be considered that the last one increase its value when the water doses are higher and variations on that dose will result in changes on the vegetative expression of the vineyard.

On the other hand, despite the relationship given among the water doses applied in the assay and the vegetative development of the vines, significant differences were given among the several plot of each one of them (data not shown), indicating that exist a spatial variability of the NDVI index, thus the vegetative growth too, that is dependent of other factors, but the characteristics of the management were identical. At this way, it is observed in Fig. 9 how the vegetative expression was not homogeneous at the whole of plots within a specific water treatment, but it was found variations in the NDVI value dependent on the geographical location of each one of those plots. Thus, for a specific mapping date, some plots of different water treatments had similar mean values of NDVI, even among plots of Fully watered and Non-watered treatments. Then, it was occurred an associated factor to the geographical location that provided some influence over the vegetative growth. The *terroir* effect, in which are included the physicochemical parameters of soil, could be one of the factors that caused a certain influence on the vegetative development, as indicated by Van Leeween and Seguin (2006).

A priori, the global results about the relationship between NDVI and ECa indicated a low association if it is compared the first 0.3 m of soil depth (ECs, Table 4), and relatively high when it is considered a large section of soil (ECd, Table 4). This results suggest that the soil surface layer in not very much influent over the vegetative expression of the vineyard, which a pivoting conformation of the roots cause no effect substantially to their development, but it does in other crops with shallow roots (Fortes et al., 2014). Furthermore, in the year where the climatic quality involves drought

(2012), ECa and NDVI values were lower, suggesting that the soil properties seem to be an influent factor but not a limiting one over the vegetative expression and it does the availability of water resources.

3.1.2 2013 growing season

Figure 10 shows the spatial and temporal evolution of NDVI in the watered treatments and their respective plots in the 2013 growing season. At the same way the previous year, an increase in the water doses applied to the vineyard still being associated to a higher mean value of NDVI index. However, in this season, the differences occurred in this mean value were closer, being no higher than 0.1 points of index value. The intense precipitations given between post-harvest of 2012 and flowering of 2013 decreased the possibility of water stress in the vines, so its vegetative development it was presented very similar at the beginning of the NDVI mappings, differing only the RDI 30 treatment that coming from the RDI 50-20 of the previous growing season (Table 3). On the other hand, at this 2013 season, the temporal evolution of mean value of NDVI of the whole treatments was more homogeneous during most of the season. Generally speaking, it was an initial increment of the NDVI value in all treatments up to the phenological stage of veraison, from which that value was constant up to the harvest. Both results, higher and constant values of NDVI than the previous season could be caused by the high groundwater recharge, which could provide water available to plants almost without limitations during the early stages of vineyard growth.

Related to the temporal behavior of the NDVI among water treatments, the mean value of the index resulted in significant differences slightly higher according as the season went, establishing around the veraison two different groups of treatments (Table 3): i) Fully watered and RDI 30a, and; ii) Non-watered and RD 30b. Since that moment, and up to harvest, the irrigation treatments of the first group shown significant differences in the mean value of NDVI, while treatments of the second one had a similar value. In general, at the same way that the previous season, there were some factors, in this case climatological ones, that modified the expected trend of a vineyard managed under specific water conditions.

The irrigation treatments of 2013 growing season also had spatial significant differences in mean value of NDVI among their respective plots (data not shown), following a reduction pattern of its value from north to south of the vineyard test area. Thus, for the same water treatment and mapping date, the mean value of NDVI of each plot decreased the further south was located that plot, existing in addition, significant differences among them. This result was already shown by Blanco et al. (2012), indicating that vegetative growth of the vines under the same management had different behaviors due to spatial changes in some influent factor, such us the spatial variability of the physic – chemical properties of soil. On the other hand, the influence of *terroir*, taken into account its climatic and edaphic factors, was so high in the 2013 season that caused that closed plots of different irrigation treatments had similar mean values of NDVI, with some exceptions. Thus, for example, northern plots of Fully watered and Non-watered treatments had shown a similar value of NDVI, at the same way the southern plots, but being statistically different between both geographical locations. This behavior can be observed in Fig. 10.

Figure 11 shows the local relationship between the PC1 of NDVI of each growing season and ECa of 2011, shallow and deep, along the test area, which it is given the level of influence of the soil features over the vegetative development in each water treatment. The highest ratios prevailed, again, in the northern and southern limits of the test area, agreeing with those zones where ECa reached the lower values. Thus, the maximum values in the relationship between soil properties and vegetative growth were given during the 2013 season, with values of R^2 in the relationship between soil properties and vegetative growth were given during the 2013 season, with values of R^2 of 0.55 and 0.64 points of ECs and ECd respectively, compared to the 0.56 and 0.47 points reached in 2012. Nevertheless, this latter growing season shows high relationship in a large area of the assay, suggesting that, in drier seasons with lower amount of available groundwater, the variability of soil were influent over a great vegetation surface, but soils with limits on water in zones where ECa has low values, and lower clay content expected (Sudduth et al., 2005; Terrón et al., 2011), tend to have higher availability to the plant of the water that contain versus soils or zones with higher clay content (higher values of ECa).

3.2 Between-year variability

The results of each mapping date of NDVI of both growing seasons, in Figs. 9 and 10, shown the behavior of the vegetative development of the whole treatments established in the experimental designs. As said before, NDVI values and, accordingly, the vegetative growth of the vineyard were influenced by means of the soil properties (included the level of waterground), in its spatial component, and climatic features, in its temporal ones.

Regarding to the temporal variability, Fig. 7 shows the obtained results in the first principal component (PC1) of each PCA made to the different mapping dates in each growing season. This PC1 shows the spatial variability of NDVI for the whole of NDVI mapping dates of each year. Thus, each PC1 map of 2012 explains an 80.57% of the temporal variability of each geographical location within the assay area, and an 85.92% for the 2013 growing season. Thus, PC1 of each year shows more than an 80% of the mean variability of the NDVI values throughout both seasons in each irrigation treatments and their respective plots. In general, PC1 map of 2013 shows higher and homogeneous values than the 2012 one, indicating a higher and homogeneous vegetative growth of grapevines.

On the other hand, Table 5 shows the level of relationship of NDVI values among the different mapping dates for each irrigation treatment. Generally speaking, both 2012 and 2013 got an increase of the correlation coefficient (R) given by the NDVI values as the season went, indicating that the continuous development of the vineyard canopy it was slowing, i.e., the development rate or evolution of that canopy was increasingly smaller up to reach the harvest stage. However, the behavior of the different irrigation treatments did not equally evolve neither intra-year nor inter year ways. So, in 2012, the treatment with higher water doses (Fully watered), had low values of correlation (R lower than 0.65) in all NDVI mapping dates due to a higher development rate versus the rest of water and rainfed treatments during the later phenological stages of the vineyard, indicating higher change rates. On the other side, Non-watered treatment had correlation coefficients above 0.65 points, suggesting a low development rate due to the lower hydric availability, as limiting factor. Meanwhile, the 2013 season had shown a similar behavior pattern in the extremes water treatments. Obviously, the correlation coefficients were shown higher and homogeneous than the previous season among the different mapping dates due to the intense precipitations, being $R < 0.77$ for Fully watered and $R > 0.73$ for Non-watered treatments. These results point out a lower canopy development than 2012 and, within the 2013 season, the differences among treatments were less pronounced.

Respecting to differences on the spatial variability of the vegetative growth between years tested, the 2013 season shown a higher homogeneity, where the higher rise was given in the northern half of the test area, independently of the water dose applied. On the other hand, this vegetative development was lower the further south, where the southern plot of Non-watered treatment had not the lower vegetative growth, but responded to a spatial pattern. Thus, the response of vegetation in 2012 was more dependent of the irrigation treatments, meanwhile in 2013 it was more dependent of the soil characteristics or other edaphic – climatic variables. In 2013, RDI 50-20 and RDI 50-0 treatments became RDI 30a and RDI 30b respectively, with water dose of 30% of ETc during the whole irrigation period. At the same way that the rest of the treatments had higher values of NDVI in 2013, RDI 30 also shown higher values of NDVI than the RDI treatments of the previous season. However, despite to have the same water dose, RDI 30b resulted in lower values than RDI 30a during most of the season (data not shown), suggesting one more time that the water dose must be redefined considering the climate and the soil properties.

According to Howell (2001), there must be an optimal method of management of a crop at any situation, with the goal to obtain yields and qualities searched and, but the intra – year and between – year management must be performed depending on the *terroir* features of each year or a group of them.

4 Conclusions

Water level and vegetative growth are clearly related, where a higher availability of water resources gave way to a higher vegetative development of the vineyard. However, changes spatio – temporal in the climatic quality or in the soil properties also affect to its vegetative expression. At the already estimated differences in the vegetative growth of grapevines among different water doses, it must be applied the effects that the climate and soil properties perform over the plants. Due to that, the application of the same cultural practices in each growing season makes unfeasible the attainment of stable goals during them, i.e., the same level of quality in grapes and wines or similar yields every season. The application of some precision agriculture techniques to the vineyard crop, through real-time measurements of the NDVI and ECa, makes possible the determination of homogeneous zones of growth and development of the vineyard as function of the climatic and soil characteristics for a specific irrigation treatment. Thus, according to the results of this study: i) in global terms, the higher water doses the higher values of NDVI and, hence, the higher vegetative growth of the vineyard; ii) nevertheless, the vegetative development is not homogeneous, even when the same cultural practices are being used, but it is shown a spatial and temporal variability as function of the climatic and soil characteristics, and the interaction among them; iii) so, it is necessary that the crop management fits to the variability of the agronomic factors to reach an homogeneous vegetative growth even in zones where the soil characteristics are different. The irrigation schedule as function of the real-time results of the NDVI, and the knowledge of the variability of the soil characteristics could be the basis to improve the vineyard management.

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431 # Tables

Table 1. Parameters corresponding to the theoretical semivariograms for NDVI samplings in 2012 and 2013 growing seasons.

Dataset	Variable	Model	Lag size (m)	Nugget	Range (m)	Partial Sill	RMSE
29 May 2012	NDVI	Spherical	6	0.009	36.5	0.003	0.098
6 July 2012	NDVI	Spherical	6	0.007	32.7	0.005	0.091
24 July 2012	NDVI	Spherical	6	0.005	31.0	0.007	0.083
14 August 2012	NDVI	Spherical	6	0.005	28.7	0.007	0.078
6 September 2012	NDVI	Spherical	6	0.003	33.2	0.005	0.063
30 May 2013	NDVI	Spherical	6	0.008	72.0	0.003	0.092
8 July 2013	NDVI	Spherical	6	0.004	72.0	0.003	0.068
22 July 2013	NDVI	Spherical	6	0.006	72.0	0.002	0.083
12 August 2013	NDVI	Spherical	6	0.005	72.0	0.003	0.074
2 September 2013	NDVI	Spherical	6	0.002	72.0	0.002	0.051
18 February 2011	ECs	Spherical	7	0.321	70.6	0.808	0.601
18 February 2011	ECd	Spherical	7	0.594	67.3	2.264	0.943

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Table 2. Statistic descriptive analyses of shallow and deep soil apparent electrical conductivity interpolated data; sampling was carried out on 18 February 2011.

Dataset	Treatment	Plot*	Mean ($mS\ m^{-1}$)**	Std. Deviation ($mS\ m^{-1}$)	Minimum ($mS\ m^{-1}$)	Maximum ($mS\ m^{-1}$)	Range ($mS\ m^{-1}$)	Skewness
ECs	**Fully watered**	**1**	5.57cd	0.29	4.95	6.30	1.35	0.32
	Fully watered	**2**	5.49d	0.33	4.84	6.21	1.37	0.01
	Fully watered	**3**	6.63a	0.55	5.54	7.69	2.15	-0.02
	Fully watered	**4**	5.94b	0.48	5.05	6.83	1.78	0.16
	RDI 50-20 - RDI 30a	**1**	4.55h	0.17	4.23	5.06	0.83	0.40
	RDI 50-20 - RDI 30a	**2**	5.52d	0.42	4.60	6.75	2.15	-0.08
	RDI 50-20 - RDI 30a	**3**	6.59a	0.30	5.82	7.39	1.57	0.14
	RDI 50-20 - RDI 30a	**4**	5.61de	0.43	4.81	6.51	1.70	0.24
	RDI 50-0 – RDI 30b	**1**	5.29ef	0.49	4.50	6.26	1.76	0.27
	RDI 50-0 – RDI 30b	**2**	5.25f	0.23	4.72	5.63	0.91	-0.52
	RDI 50-0 – RDI 30b	**3**	5.14f	0.49	4.31	6.40	2.09	0.51
	RDI 50-0 – RDI 30b	**4**	5.72c	0.74	4.33	7.10	2.77	-0.16
	Non Watered	**1**	4.80g	0.30	4.39	5.71	1.32	0.66
	Non Watered	**2**	5.4de	0.45	4.27	6.45	2.18	-0.29
	Non Watered	**3**	5.60cd	0.51	4.61	6.50	1.89	0.19
	Non Watered	**4**	5.49d	0.30	5.03	6.60	1.57	0.76
ECd	**Fully watered**	**1**	9.90cd	0.77	8.79	13.81	5.02	2.69
	Fully watered	**2**	10.01c	0.39	9.06	10.83	1.77	0.21
	Fully watered	**3**	10.96b	0.77	8.95	12.49	3.54	-0.03
	Fully watered	**4**	9.96c	0.64	8.76	12.06	3.30	0.51
	RDI 50-20 - RDI 30a	**1**	8.62gh	0.33	8.07	9.62	1.55	0.76
	RDI 50-20 - RDI 30a	**2**	9.97c	0.49	9.00	11.23	2.23	0.15
	RDI 50-20 - RDI 30a	**3**	11.37a	0.36	9.62	12.00	2.38	-1.38
	RDI 50-20 - RDI 30a	**4**	8.82fg	1.05	7.11	10.82	3.71	0.23
	RDI 50-0 – RDI 30b	**1**	8.91f	0.48	7.75	10.15	2.40	0.35
	RDI 50-0 – RDI 30b	**2**	9.68d	0.37	9.01	10.33	1.32	-0.21
	RDI 50-0 – RDI 30b	**3**	9.76cd	0.48	8.73	10.55	1.82	-0.43
	RDI 50-0 – RDI 30b	**4**	8.88fg	1.51	6.08	11.50	5.42	-0.04
	Non Watered	**1**	8.53h	0.37	7.82	9.47	1.65	0.27
	Non Watered	**2**	9.40e	0.77	7.41	11.14	3.73	-0.20
	Non Watered	**3**	9.77cd	0.28	9.11	10.49	1.38	0.35
	Non Watered	**4**	8.72fgh	0.57	7.90	10.53	2.63	0.99

* Plots are numbered in a North – South orientation.

** Variance analyses among treatments are made for each dataset independently; a, b, c, d means significant difference at p-value ≤ 0.05 in Tukey post-hoc analysis.

Table 3. Statistic descriptive analyses of NDVI interpolated datasets for 2012 and 2013 growing seasons (dimensionless).

Dataset	Treatment	Mean*	Std. Deviation	Minimum	Maximum	Range**	Skewness
	Fully Watered	0.643a	0.036	0.502	0.713	0.211	-0.319
	RDI 50-20	0.608b	0.039	0.507	0.691	0.184	-0.548
29 May 2012	**RDI 50-0**	0.597c	0.046	0.472	0.706	0.234	-0.265
	Non-watered	0.572d	0.044	0.446	0.677	0.231	-0.302
	MEAN	**0.605**	**0.041**	**0.482**	**0.697**	**0.215**	
	Fully Watered	0.729a	0.050	0.586	0.807	0.221	-0.535
	RDI 50-20	0.708b	0.042	0.579	0.780	0.201	-0.591
06 July 2012	**RDI 50-0**	0.714b	0.054	0.569	0.817	0.248	-0.311
	Non-watered	0.624c	0.060	0.453	0.766	0.313	-0.210
	MEAN	**0.694**	**0.052**	**0.547**	**0.793**	**0.246**	
	Fully Watered	0.750a	0.041	0.597	0.813	0.216	-0.998
	RDI 50-20	0.718b	0.046	0.452	0.789	0.337	-1.300
24 July 2012	**RDI 50-0**	0.721b	0.055	0.554	0.803	0.249	-0.767
	Non-watered	0.618c	0.064	0.430	0.730	0.300	-0.448
	MEAN	**0.702**	**0.052**	**0.508**	**0.784**	**0.276**	
	Fully Watered	0.742a	0.039	0.483	0.803	0.320	-1.853
	RDI 50-20	0.712b	0.048	0.577	0.794	0.217	-0.475
14 August 2012	**RDI 50-0**	0.696c	0.070	0.512	0.800	0.288	-0.828
	Non-watered	0.613d	0.054	0.404	0.731	0.327	-0.568
	MEAN	**0.691**	**0.053**	**0.494**	**0.782**	**0.288**	
	Fully Watered	0.701a	0.032	0.575	0.761	0.186	-0.825
	RDI 50-20	0.673b	0.045	0.534	0.740	0.206	-0.681
06 September 2012	**RDI 50-0**	0.647c	0.070	0.445	0.750	0.305	-0.917
	Non-watered	0.600d	0.056	0.417	0.707	0.290	-0.647
	MEAN	**0.655**	**0.051**	**0.493**	**0.740**	**0.247**	
	Fully Watered	0.671b	0.039	0.570	0.749	0.179	-0.454
	RDI 30a (previous 50-20)	0.680a	0.045	0.570	0.749	0.179	-0.728
30 May 2013	**RDI 30b (previous 50-0)**	0.665b	0.053	0.518	0.747	0.229	-0.573
	Non-watered	0.671b	0.050	0.528	0.761	0.233	-0.547
	MEAN	**0.672**	**0.047**	**0.547**	**0.752**	**0.205**	
	Fully Watered	0.779a	0.040	0.655	0.831	0.176	-0.827
	RDI 30a (previous 50-20)	0.766b	0.052	0.597	0.833	0.236	-1.000
08 July 2013	**RDI 30b (previous 50-0)**	0.754bc	0.069	0.555	0.832	0.277	-1.138
	Non-watered	0.761c	0.050	0.614	0.823	0.209	-0.808
	MEAN	**0.769**	**0.053**	**0.605**	**0.830**	**0.225**	
	Fully Watered	0.737a	0.034	0.646	0.794	0.148	-0.429
	RDI 30a (previous 50-20)	0.738a	0.049	0.607	0.792	0.185	-1.200
22 July 2013	**RDI 30b (previous 50-0)**	0.724b	0.063	0.547	0.802	0.255	-1.238
	Non-watered	0.728b	0.043	0.617	0.792	0.175	-0.659
	MEAN	**0.732**	**0.047**	**0.604**	**0.795**	**0.191**	
	Fully Watered	0.749a	0.042	0.632	0.822	0.190	-0.366
	RDI 30a (previous 50-20)	0.734b	0.053	0.570	0.797	0.227	-0.986
12 August 2013	**RDI 30b (previous 50-0)**	0.721c	0.071	0.542	0.810	0.268	-0.989
	Non-watered	0.718c	0.050	0.583	0.796	0.213	-0.735
	MEAN	**0.731**	**0.054**	**0.582**	**0.806**	**0.225**	
	Fully Watered	0.753a	0.030	0.656	0.795	0.139	-0.766
	RDI 30a (previous 50-20)	0.742b	0.035	0.624	0.790	0.166	-1.076
02 September 2013	**RDI 30b (previous 50-0)**	0.731c	0.054	0.564	0.791	0.227	-1.133
	Non-watered	0.725d	0.037	0.609	0.781	0.172	-0.543
	MEAN	**0.738**	**0.039**	**0.613**	**0.789**	**0.176**	

* Variance analyses among treatments are made for each dataset independently; a, b, c, d means significant difference at p-value ≤ 0.05 in Tukey post-hoc analysis.

** Statistical range of NDVI values (max – min)

Table 4. Correlation matrix (R) between 1st principal components of 2012 and 2013 growing seasons and apparent electrical conductivities, shallow and deep, interpolated data of 2011.

Variable	1st PC NDVI 2012	1st PC NDVI 2013	ECs 2011	ECd 2011
1st PC NDVI 2012	1.00			
1st PC NDVI 2013	0.58	1.00		
ECs 2011	0.18	0.16	1.00	
ECd 2011	0.59	0.70	0.83	1.00

Table 5. Correlation matrices among 2012 and 2013 NDVI surfaces of each irrigation treatment.

		2012				
Treatment	**Dataset**	**29 May**	**6 July**	**24 July**	**14 August**	**6 Sept.**
	29 May	1				
	6 July	0.47	1			
Fully watered	**24 July**	0.33	0.65	1		
	14 August	0.42	0.35	0.47	1	
	6 Sept.	0.28	0.57	0.59	0.57	1
	29 May	1				
	6 July	0.74	1			
RDI 50-20	**24 July**	0.61	0.72	1		
	14 August	0.69	0.79	0.70	1	
	6 Sept.	0.70	0.81	0.66	0.84	1
	29 May	1				
	6 July	0.59	1			
RDI 50-0	**24 July**	0.69	0.86	1		
	14 August	0.69	0.89	0.86	1	
	6 Sept.	0.68	0.86	0.83	0.95	1
	29 May	1				
	6 July	0.70	1			
Non-watered	**24 July**	0.68	0.83	1		
	14 August	0.66	0.83	0.81	1	
	6 Sept.	0.65	0.82	0.79	0.90	1

		2013				
		30 May	**8 July**	**22 July**	**12 August**	**2 Sept.**
	30 May	1				
	8 July	0.76	1			
Fully watered	**22 July**	0.61	0.61	1		
	12 August	0.58	0.66	0.67	1	
	2 Sept.	0.64	0.79	0.63	0.76	1
	30 May	1				
	8 July	0.85	1			
RDI 30a	**22 July**	0.82	0.86	1		
	12 August	0.83	0.85	0.93	1	
	2 Sept.	0.83	0.87	0.91	0.90	1
	30 May	1				
	8 July	0.90	1			
RDI 30b	**22 July**	0.87	0.93	1		
	12 August	0.88	0.94	0.95	1	
	2 Sept.	0.89	0.95	0.95	0.96	1
	30 May	1				
	8 July	0.80	1			
Non-watered	**22 July**	0.77	0.88	1		
	12 August	0.84	0.89	0.88	1	
	2 Sept.	0.73	0.83	0.85	0.86	1

Figures

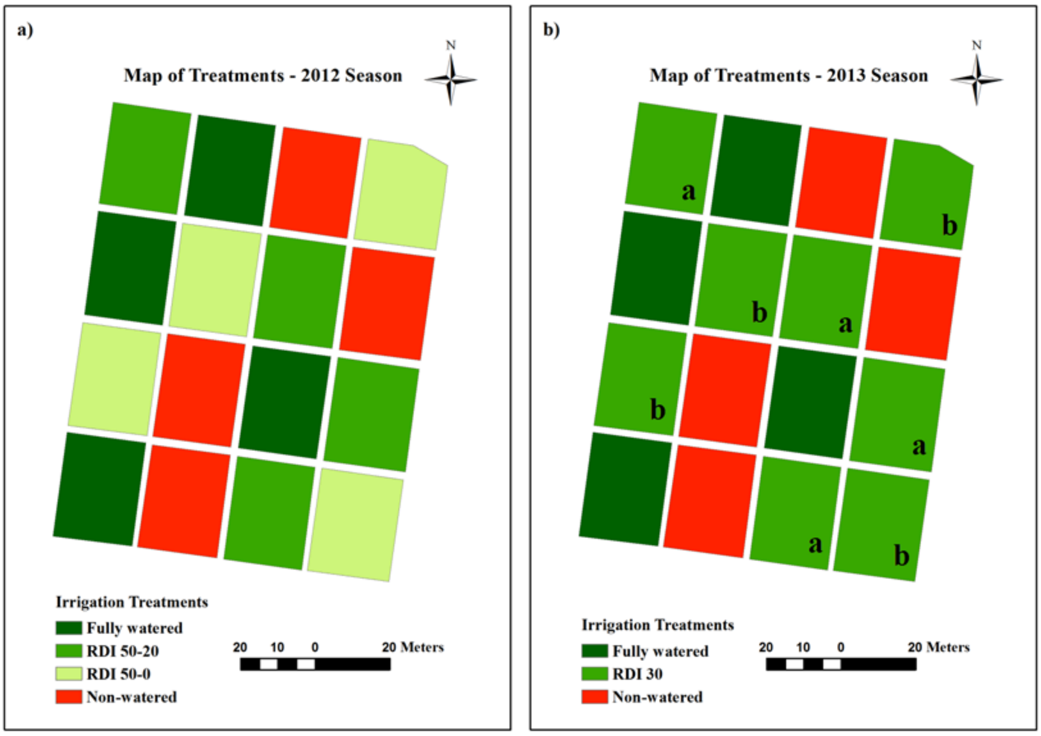


Figure 1. Maps of treatments and respective plots: a) Map of treatments of 2012 growing season; b) Map of treatment of 2013 growing season, where “a” and “b” replicates of RDI 30 are in the same emplacement of the respective replicates of RDI 50-20 and RDI 50-0 of the previous season.

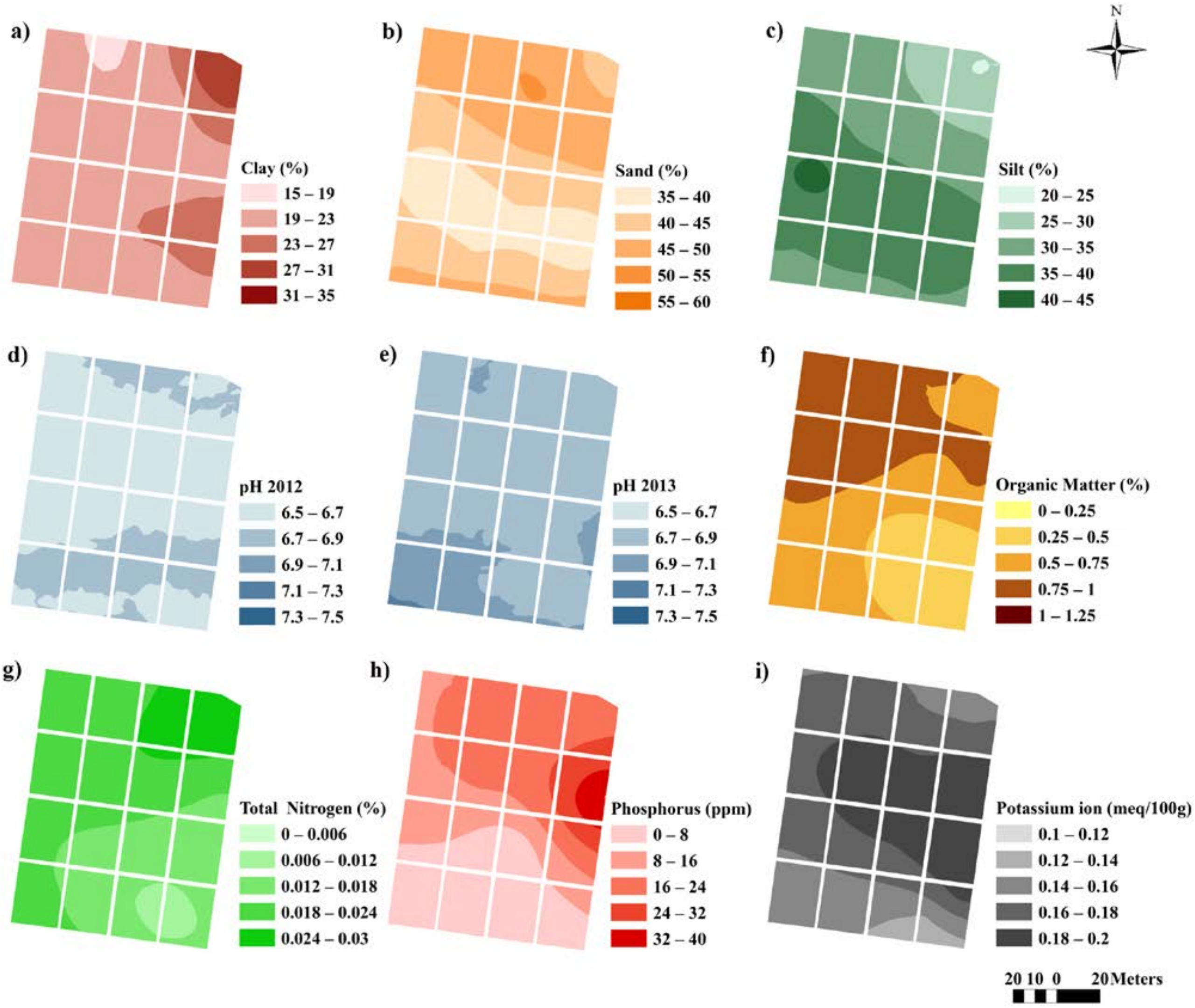


Figure 2. Maps of spatial distribution of some soil components in the vineyard site: a) Clay; b) Sand; c) Silt; d) pH of 2012 growing season; e) pH of 2013 growing season; f) Organic matter; g) Total Nitrogen; h) Assimilable phosphorus; i) Potassium ion (K).

Figure 3. ATV with two multi-spectral sensors for NDVI mapping of vineyard canopy

Figure 4. Mobile sensor platform Veris 3150 for ECa mapping.

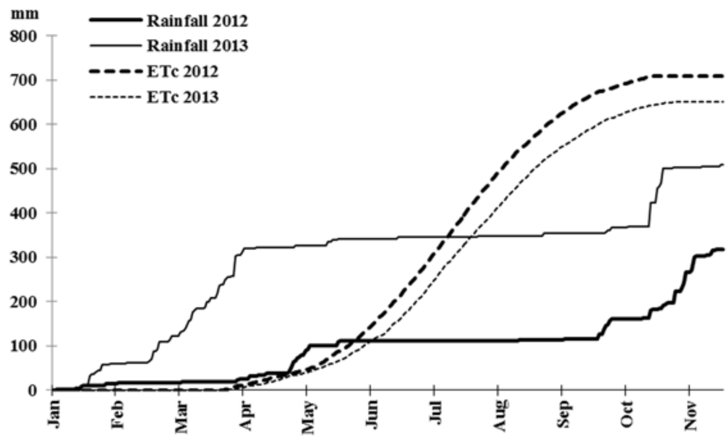


Figure 5a. Accumulation of rainfall and ETc of 2012 and 2013 growing seasons.

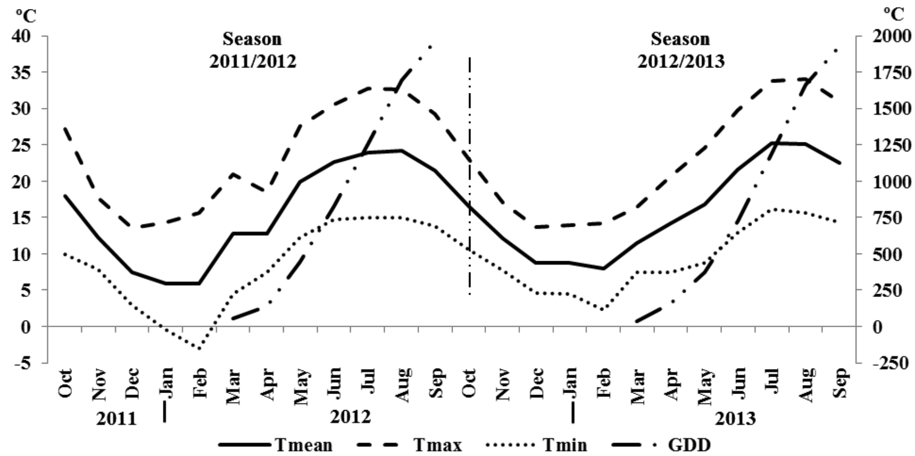
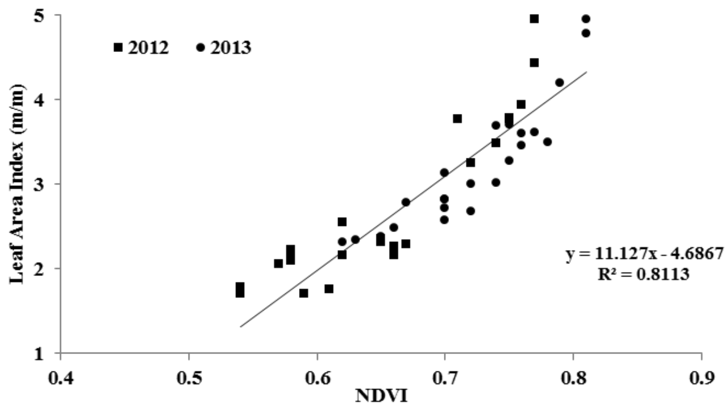


Figure 5b. Temperature components recorded on both 2012 and 2013 growing seasons: Tmean, Tmax and Tmin are the monthly average, maximum and minimum temperature respectively; GDD is the growing degree day reached the last day of the month.



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469 **Figure 6.** NDVI – LAI relationship of both 2012 and 2013 years.

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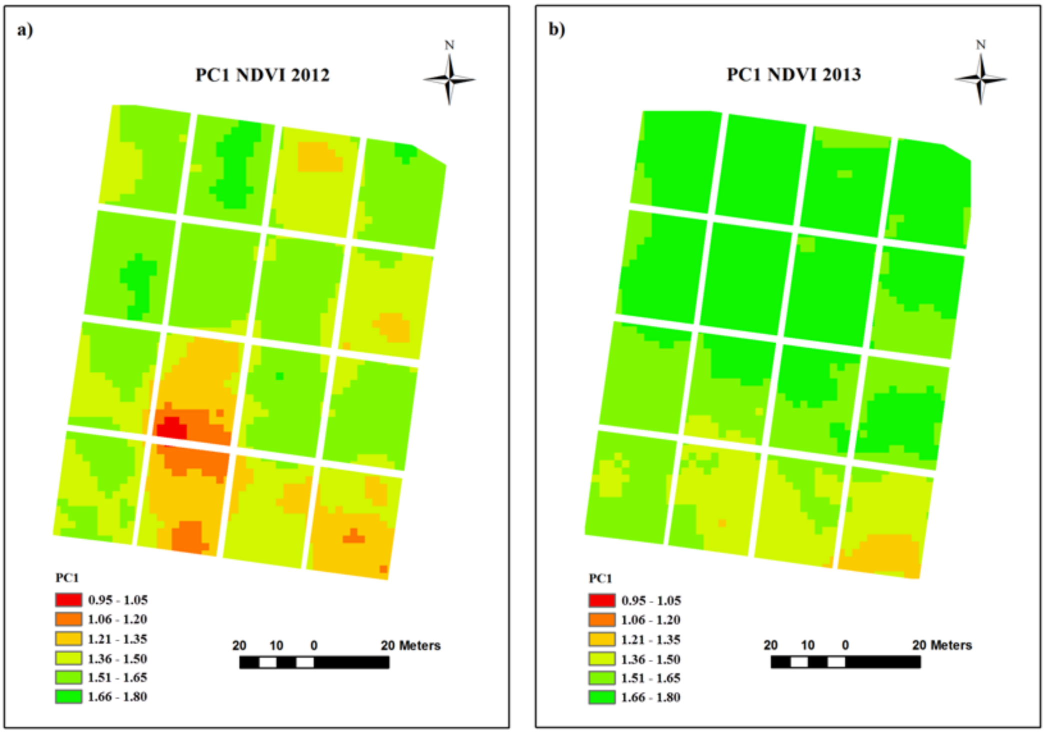

Figure 7. NDVI First principal component of: a) 2012; and b) 2013

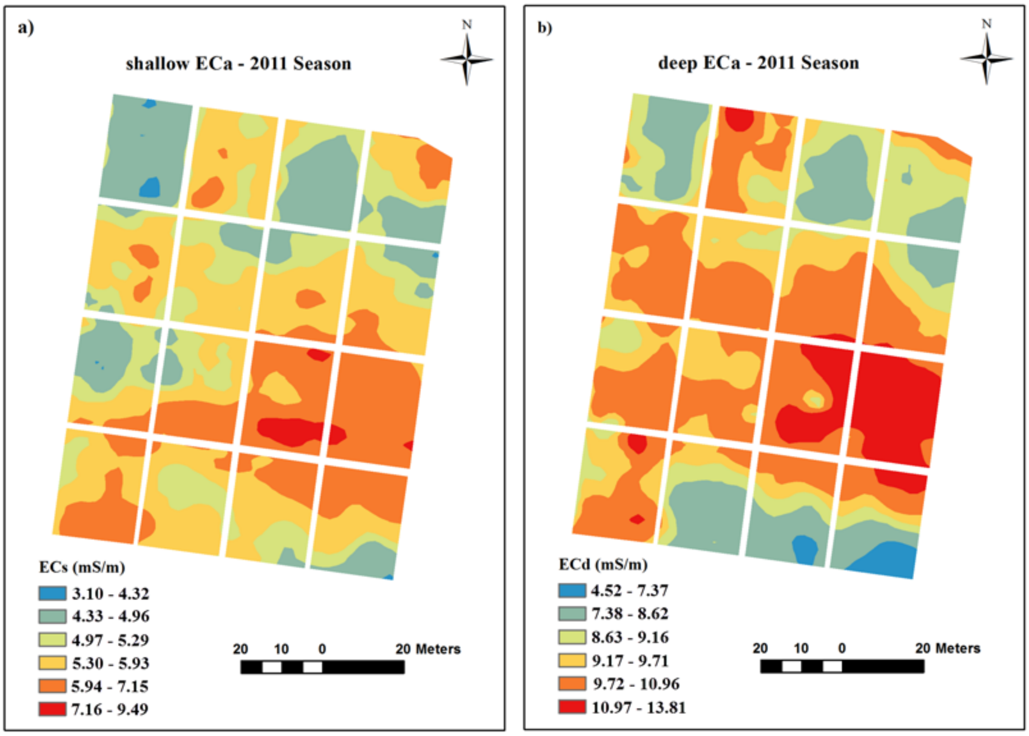

Figure 8. Interpolated apparent electrical conductivity maps of 2011 growing season: a) shallow ECa map; b) deep ECa map.

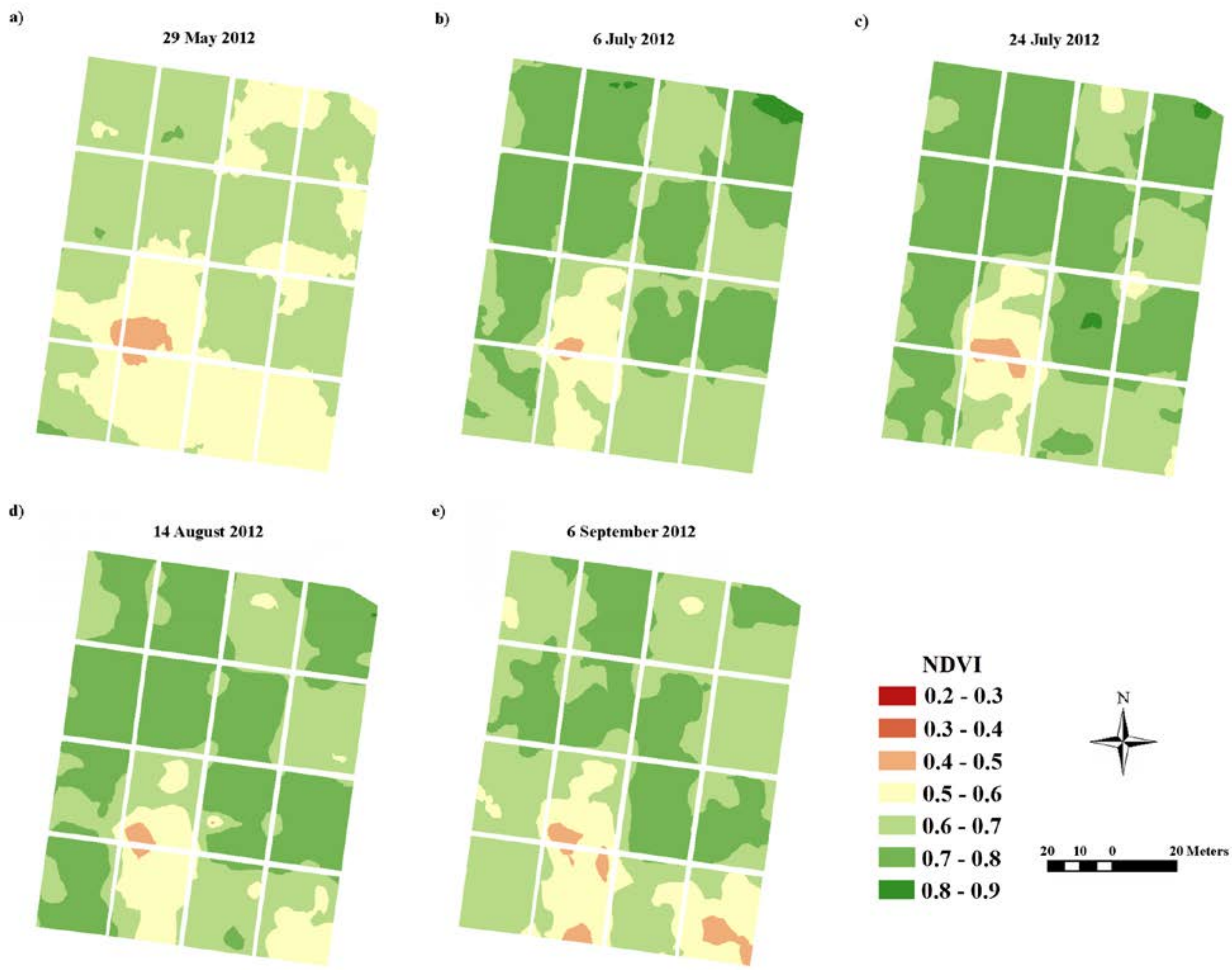

Figure 9. Interpolated NVDI maps of 2012 growing season: a) 29 May; b) 6 July; c) 24 July; d) 14 August; and e) 6 September.

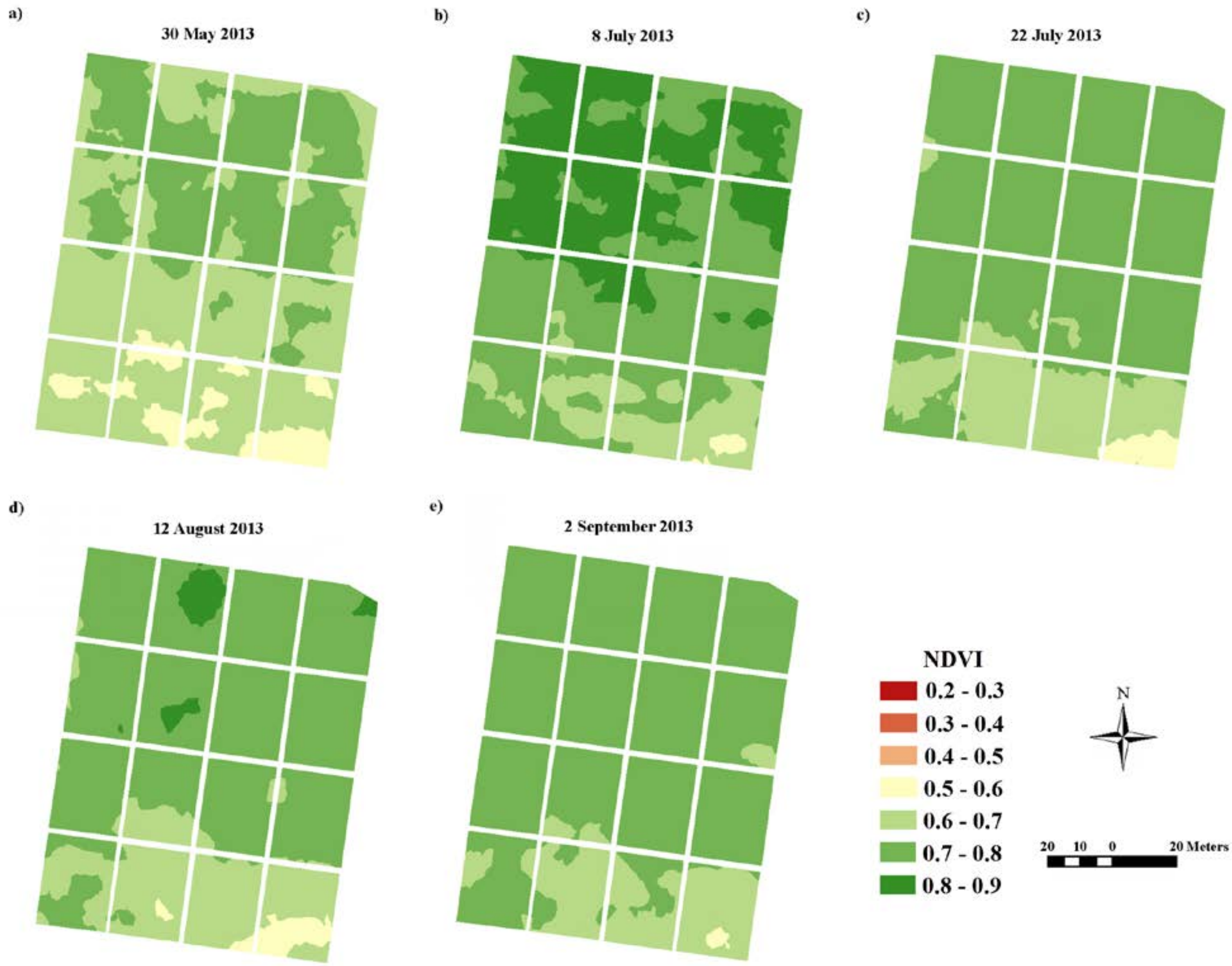

Figure 10. NVDI maps year 2013: a) May 30th; b) July 8th; c) July 22nd; d) August 12th; and e) September 2nd.

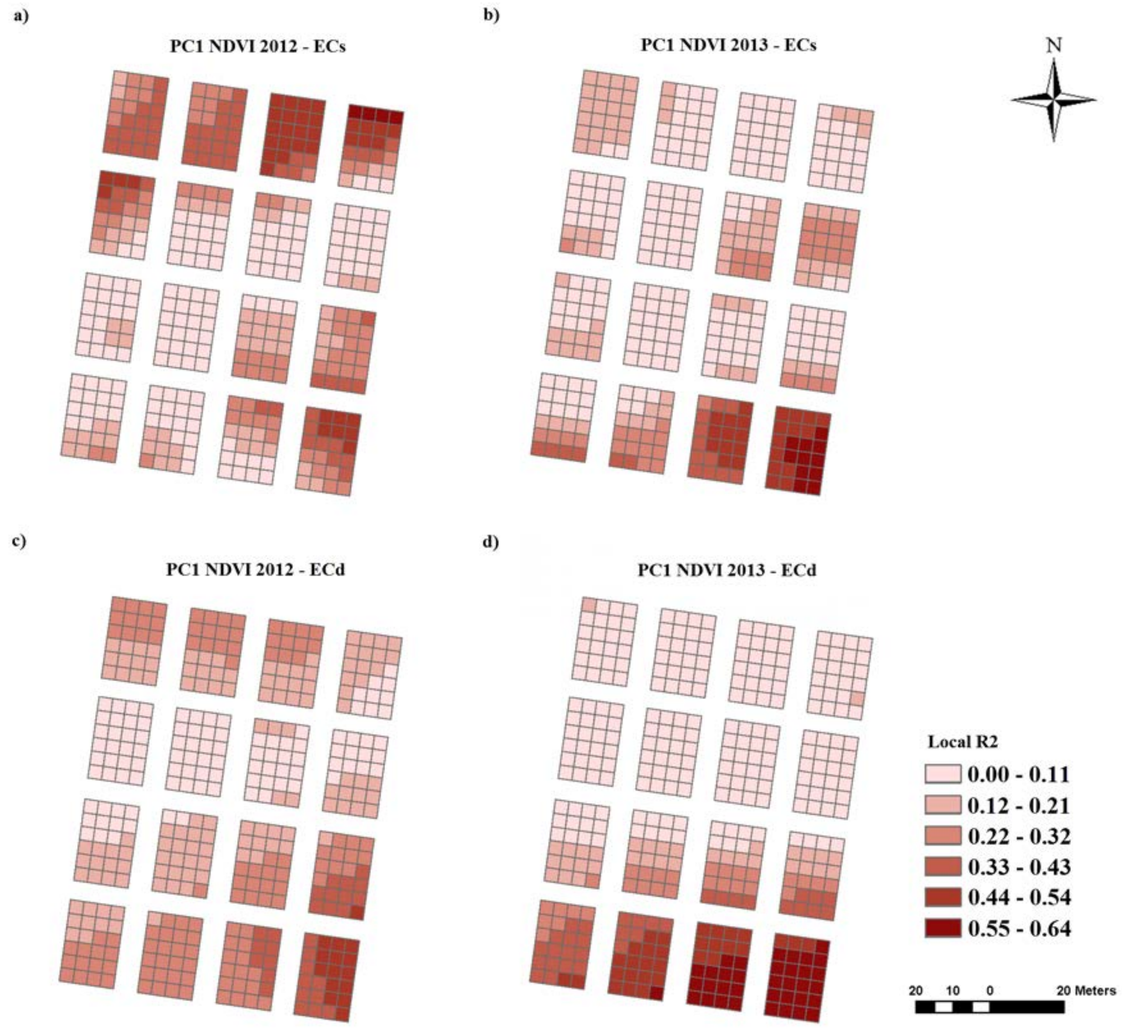

Figure 11. Local R^2 of GWR analyses: a) 1st principal component of NDVI in 2012 and ECs of 2011; b) 1st principal component of NDVI in 2013 and ECs of 2011; c) 1st principal component of NDVI in 2012 and ECd of 2011; d) 1st principal component of NDVI in 2013 and ECd 2011.