SOIL Discuss., 1, 947–979, 2014
www.soil-discuss.net/1/947/2014/
doi:10.5194/soild-1-947-2014

SOIL Discussions Open Access

Precision agriculture suitability to improve vineyard terroir management

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Received: 15 October 2014 – Accepted: 21 October 2014 – Published: 25 November 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Precision agriculture is a useful tool to assess plant growth and development in vineyards. Current study was focused in the spatial and temporal vegetation growth variability analysis; considering four irrigation treatments with four replicates; carried out in a vineyard located in the southwest of Spain during 2012 and 2013 growing seasons. Two multispectral sensors mounted on 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 measured up to 0.8 m soil depth using a geophysical sensor. All measured data was statistically analysed by means of Principal Component Analysis (PCA). The spatial and temporal NDVI and ECa variations showed relevant differences between irrigation treatments and climatological years.

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 normally associated with topography, soil, climate, plant management and plant genetics (Vaudour, 2002). The study of the plant vegetative vigour, according certain authors, is an essential parameter to manage successfully yield and grapes/wines quality due to the fact that plant vegetative vigour integrates climate, soil, topography, available water and other plant controlling factors (Smart, 1985; Carbonneau, 1995; Cortell et al., 2005; Deloire et al., 2005). 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

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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, the response between two closer plants could not be the same. This point must 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.

Several spectral Vegetation Indices (VI) studies tried to analyse 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) and this is relevant to study vine vegetation *terroir*. One of the vegetation indexes most extensively used in the literature for vegetation growth analysis is the Normalized Difference Vegetation Index (NDVI), developed by Rouse et al. (1973), and is expressed as Eq. (1):

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{Red}}{\mathrm{NIR} + \mathrm{Red}}, \tag{1}$$

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

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is the Photosynthetically Active Radiation (PAR) and it is normally comprised between 0.4 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 performance, the greater amount of vegetative cover or canopy, the greater value in the index. However, the ability to absorb and reflect both bands depends also on the health plant status and not only on its size. In this way, considering a plant with water stress or any other kind of stress (pests, diseases, nutritional deficiencies . . .), it will has less capacity to, on the one hand, absorb the red band by their photosynthetic apparatus and, on the other hand, to reflect the NIR band by the cell walls. The result will be a lower value of this index. Therefore, the expression of the vegetative development of the vineyard, both its size and its health status, can be given as a function of 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.

On the other hand, 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). 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 vine terroir. Thus, considering the previous, the

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present work makes use of precision agriculture tools to determine: (i) the impact of different irrigation treatments in the vine vegetation growth considering two different climatic seasons; (ii) the soil influence in the vegetation growth expression; and (iii) the "vegetative growth vs. soil quality importance" in the terroir management.

2 Material and methods

3 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). 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 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 and 2.50 m respectively. 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. Other vine cultural practices were consistent with commercially accepted techniques.

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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.

3.1 Vegetation index and soil apparent electrical conductivity

The NDVI estimation was performed with two active proximal multispectral 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., USA) 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 multispectral 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. 2). 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.

ECa measurements were conducted on 18 February 2011, with a VERIS 3150 Surveyor sensor (Fig. 3), 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).

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3.2 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, USA), for those geostatistically analyses, and SPSS v.17 software (SPSS Inc., USA), 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 (ACP) – at this work, it was established two input features, coinciding each one with the whole sampling of each growing seasons. The output features were distributed in 5 principal components to each one.

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, USA). The relationship between both variables resulted in maps of coefficient of determination (R^2) of each water treatment, growing season and depth. The pixel size chosen in this case it was 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.

4 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. Figure 4 shows the cumulative annual rainfall and the cumulative annual ETc on both years trial. 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. 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

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curve of ETc (Fig. 4), paying more attention in dry seasons to not producing unwanted water stresses to the vineyard.

4.1 Intra-year NDVI variability

4.1.1 2012 growing season

Figure 5 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 2). 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

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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. 5 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 existed an associated factor to the geographical location that provided some influence over the vegetative growth. The *terroir* effect, in which are included the physic – chemical 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).

4.1.2 2013 growing season

Figure 6 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 2). 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

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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 2): (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. 6.

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4.2 Between-year NDVI variability

The results of each mapping date of NDVI of both growing seasons, in Figs. 5 and 6, 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 3 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.

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4.3 NDVI and ECa relationship

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 the geographical determination of ECa, shallow and deep, which are represented in Fig. 8. Those determinations shown a similar pattern in the analysis of both depths but with higher values of ECd due to the large volume of the profile soil analyzed. This pattern consisted in a positive 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. 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, cation exchange capacity (CEC) and soil pH (Moral et al., 2010). Furthermore, according to Terrón et al. (2013), if that surface was no modified by deep agricultural practices and/or nutrient intakes, those variations must be maintained at short to medium term. Thus, the knowledge of the existence of a spatial variability over the crop field temporally stable, will allow compare it with spatial and temporal variabilities of successive growing seasons.

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 4), designating different values in the soil properties that influenced the vegetative growth of grapevines. It is observed how the different 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.

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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 5), and relatively high when it is considered a large section of soil (ECd, Table 5). 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 a influent factor but not a limiting one over the vegetative expression, and it does the availability of water resources.

Figure 9 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).

5 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 precision agriculture to the vineyard crop, through NDVI index 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 terroir characteristics are different. The irrigation schedule as function of the real time results of NDVI, and the knowledge of the variability of the terroir characteristics could be the basis to improve the vineyard management.

Acknowledgements. This work was carried out with funding the RITECA Project, Transboundary Research Network Extremadura, Center and Alentejo, co-financed by the European Regional Development Fund (ERDF) by the Spain-Portugal Border Cooperation Operational Programme (POCTEP) 2007–2013 and by the Government of Extremadura.

This research was also co-financed by the Government of Extremadura and the European Regional Development Fund (ERDF) through the project GR10038 (Research Group TIC008).

The vineyard irrigation project with which has complemented this work is INIA RTA2009-00026-C02-02 and it was co-financed by the European Regional Development Fund (ERDF).

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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 NDVI interpolated datasets for 2012 and 2013 growing seasons (dimensionless).

Dataset	Treatment	Mean*	SD	Minimum	Maximum	Range	Skewness
29 May 2012	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
	RDI 50-0	0.597c	0.046	0.472	0.706	0.233	−0.265
	Non-watered	0.572d	0.044	0.446	0.677	0.231	−0.302
6 July 2012	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
	RDI 50-0	0.714b	0.054	0.569	0.817	0.249	−0.311
	Non-watered	0.624c	0.060	0.453	0.766	0.313	−0.210
24 July 2012	Fully Watered	0.750a	0.041	0.597	0.813	0.215	−0.998
	RDI 50-20	0.718b	0.046	0.452	0.789	0.337	−1.300
	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
14 August 2012	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
	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
6 September 2012	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
	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
30 May 2013	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
	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
8 July 2013	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
	RDI 30b (previous 50-0)	0.754bc	0.069	0.555	0.832	0.276	−1.138
	Non-watered	0.761c	0.050	0.614	0.823	0.209	−0.808
22 July 2013	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
	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	0.174	−0.659
12 August 2013	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	0.228	−0.986
	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
2 September 2013	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
	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

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

		2012				
Treatment	Dataset	29 May	6 July	24 July	14 August	6 September
Fully watered	29 May	1				
	6 July	0.47	1			
	24 July	0.33	0.65	1		
	14 August	0.42	0.35	0.47	1	
	6 September	0.28	0.57	0.59	0.57	1
RDI 50-20	29 May	1				
	6 July	0.74	1			
	24 July	0.61	0.72	1		
	14 August	0.69	0.79	0.70	1	
	6 September	0.70	0.81	0.66	0.84	1
RDI 50-0	29 May	1				
	6 July	0.59	1			
	24 July	0.69	0.86	1		
	14 August	0.69	0.89	0.86	1	
	6 September	0.68	0.86	0.83	0.95	1
Non-watered	29 May	1				
	6 July	0.70	1			
	24 July	0.68	0.83	1		
	14 August	0.66	0.83	0.81	1	
	6 September	0.65	0.82	0.79	0.90	1
		2013				
		30 May	8 July	22 July	12 August	2 September
Fully watered	30 May	1				
	8 July	0.76	1			
	22 July	0.61	0.61	1		
	12 August	0.58	0.66	0.67	1	
	2 September	0.64	0.79	0.63	0.76	1
RDI 30a	30 May	1				
	8 July	0.85	1			
	22 July	0.82	0.86	1		
	12 August	0.83	0.85	0.93	1	
	2 September	0.83	0.87	0.91	0.90	1
RDI 30b	30 May	1				
	8 July	0.90	1			
	22 July	0.87	0.93	1		
	12 August	0.88	0.94	0.95	1	
	2 September	0.89	0.95	0.95	0.96	1
Non-watered	30 May	1				
	8 July	0.80	1			
	22 July	0.77	0.88	1		
	12 August	0.84	0.89	0.88	1	
	2 September	0.73	0.83	0.85	0.86	1

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Table 4. 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 ($mS\,m^{-1}$)**	SD ($mS\,m^{-1}$)	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.

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Table 5. 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

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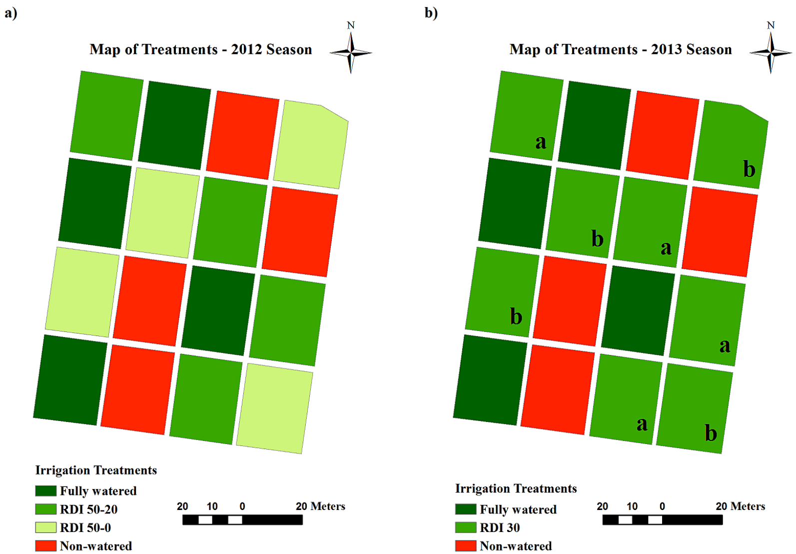

Figure 1. Maps of treatments and respective plots: **(a)** Map of treatments of 2012 growing season; **(b)** Map of treatment of 2013 growing season, where "a" and "b" replicates of RDI 30 are in the same emplacement of the respective replicates of RDI 50-20 and RDI 50-0 of the previous season.

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Figure 2. ATV with two multi-spectral sensors for NDVI mapping of vineyard canopy.

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Figure 3. Mobile sensor platform Veris 3150 for ECa mapping.

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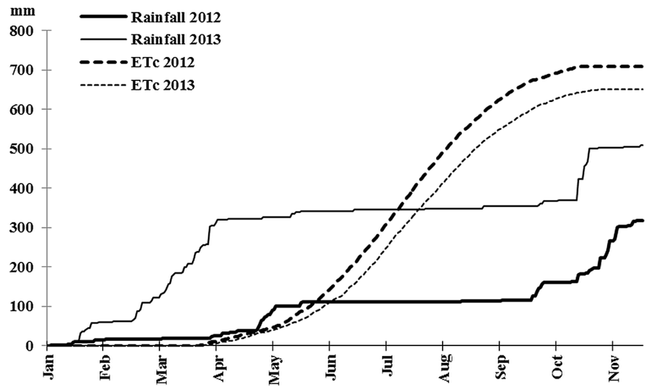

Figure 4. Accumulation of rainfall and ETc of 2012 and 2013 growing seasons.

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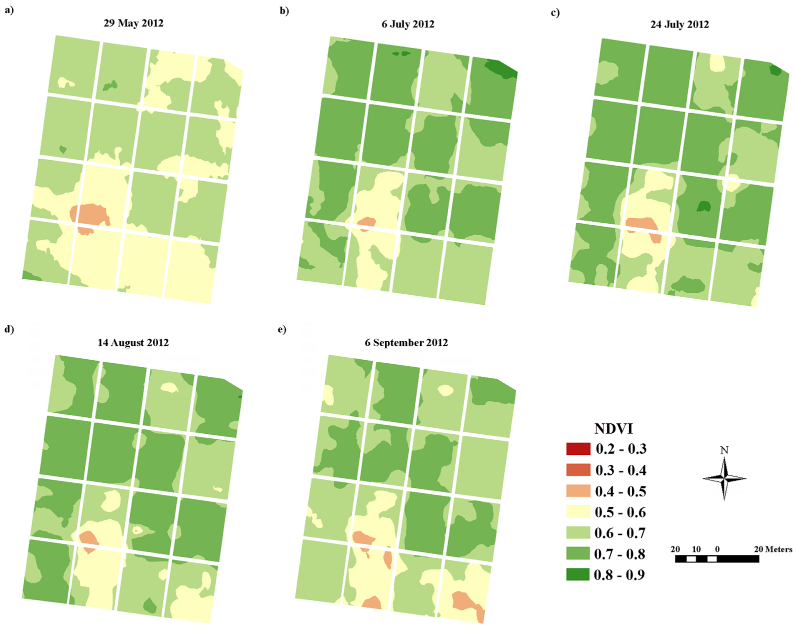

Figure 5. Interpolated NVDI maps of 2012 growing season: **(a)** 29 May; **(b)** 6 July; **(c)** 24 July; **(d)** 14 August; and **(e)** 6 September.

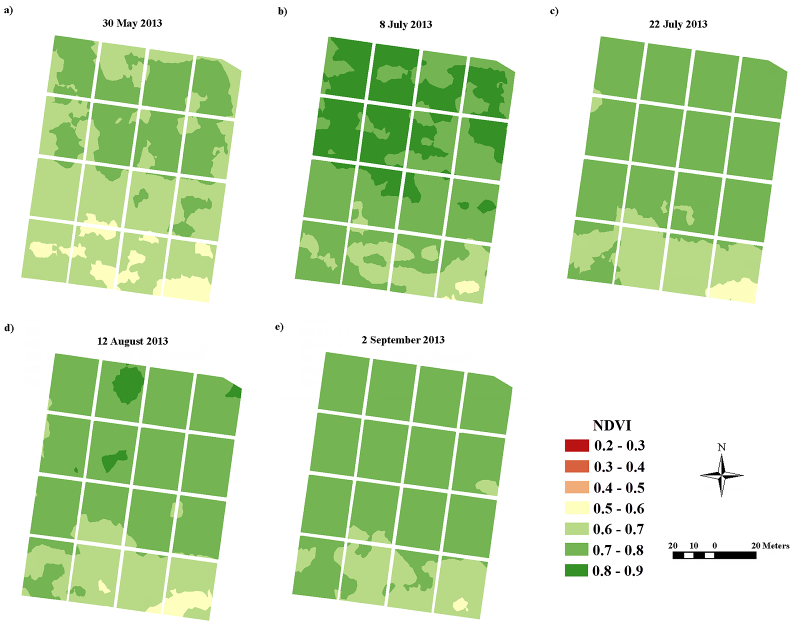

Figure 6. NVDI maps year 2013: **(a)** 30 May; **(b)** 8 July; **(c)** 22 July; **(d)** 12 August; and **(e)** 2 September.

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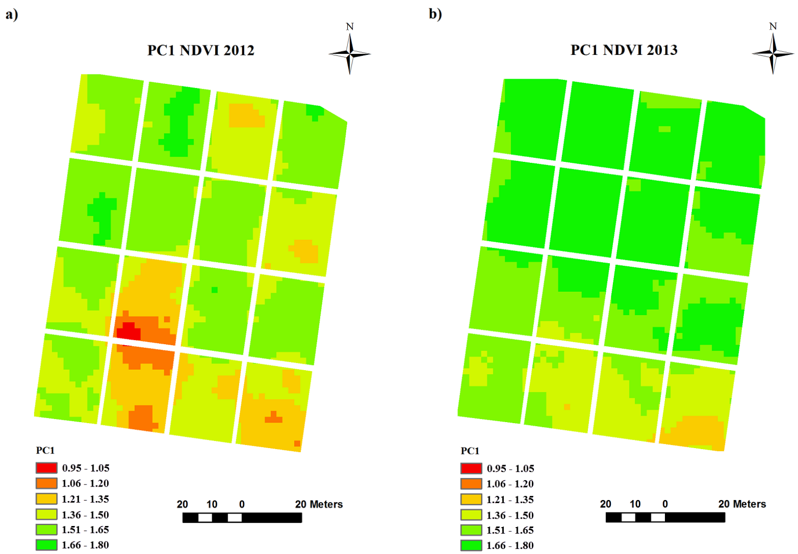

Figure 7. NDVI First principal component of: **(a)** 2012; and **(b)** 2013.

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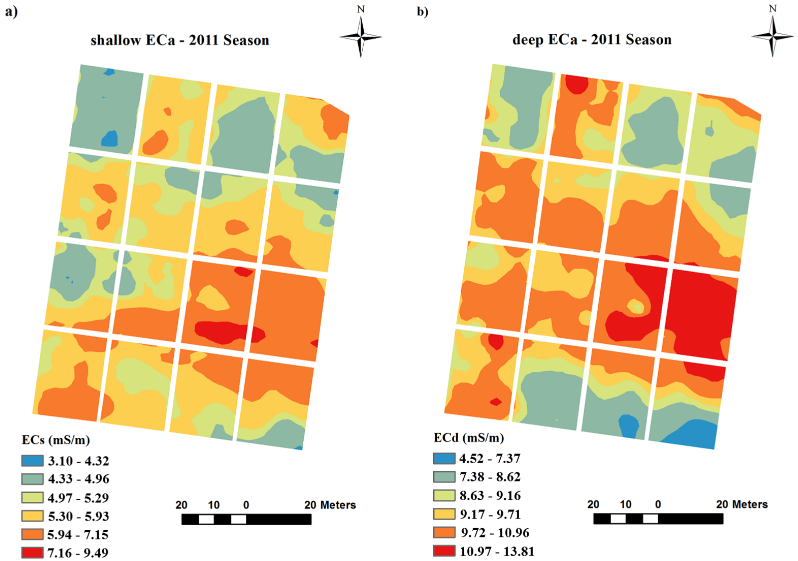

Figure 8. Interpolated apparent electrical conductivity maps of 2011 growing season: **(a)** shallow ECa map; **(b)** deep ECa map.

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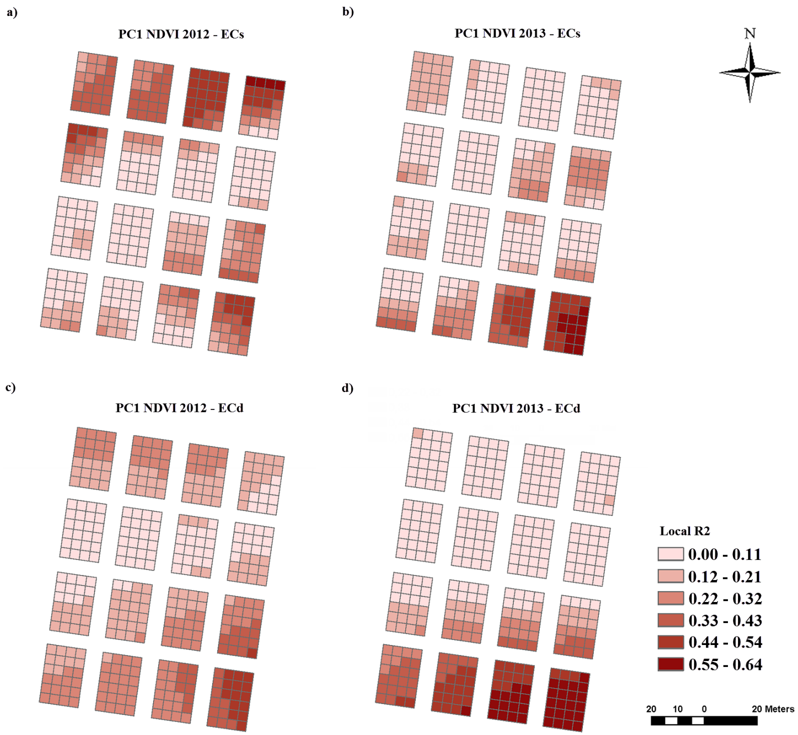

Figure 9. Local R^2 of GWR analyses: **(a)** 1st principal component of NDVI in 2012 and ECs of 2011; **(b)** 1st principal component of NDVI in 2013 and ECs of 2011; **(c)** 1st principal component of NDVI in 2012 and ECd of 2011; **(d)** 1st principal component of NDVI in 2013 and ECd 2011.

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