Stability and patterns of topsoil water content in rainfed vineyards, olive groves, and cereal fields under different soil and tillage conditions

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ABSTRACT

Topsoil water content (TSWC) varies at spatial and temporal scales owing to the influence of several factors. In woody crops, few studies have analysed these dynamics under rainfed conditions. The temporal stability of the spatial patterns of TSWC in a Mediterranean rainfed sub-catchment (27 ha; Spain) was analysed during 12 months. Cropland includes four vineyards with cover crops, five cereal fields (fallow / crop rotation), one olive grove under conventional tillage, and one abandoned olive grove. In total, nine land use compartments were distinguished in twelve fields and nine non-cultivated soils. During the test period (May 2016 – April 2017) the monthly TSWC values (mean 13.1% vol. ± 8.0) showed a significant correlation with evapotranspiration. The spatial variability of TSWC increased under dry conditions and more homogeneous patterns appeared in the wet surveys. The vineyards' inter-rows had the wettest (62% > in the rows) conditions owing to the cover crops and their high soil-water holding capacity, and average temporal stability. The vineyards' rows were dry and very stable due to the tillage practices (higher elevation) and the low infiltration rates; and the corridors had wet and stable conditions. The forest presented the driest and stable

temporal conditions associated to the water demand by the trees. Soil in the fallow cereal fields was drier and more stable than in the cereal fields. The abandoned olive grove showed wetter though less stable conditions than the olive grove. The trails had wet but not stable conditions. The different land uses and tillage practices influenced more the TSWC dynamics than the spatial variability of the analysed soil physical properties. However, silty loam and loamy soils presented wetter and more stable conditions than the average values, and the sandy loam and loamy sand soils had drier and less stable conditions.

Keywords: Topsoil water content; vineyard; cover crop; olive grove; temporal stability; soil physical properties

GRAPHICAL ABSTRACT

HIGHLIGHTS

The spatial variability of the topsoil moisture increased under dry conditions

The vineyards' inter-rows had the wettest and stable conditions due to the cover crop

The vineyards' rows were dry and very stable owing to the tillage practices

Fallow cereal fields had drier and more stable conditions than the cereal fields

Silty loam, loamy soils were wetter and more stable than sandy loam, loamy sand soils

1. Introduction

Soil water content (SWC, % vol.) is one of the most limiting factors for crop production and quality by (i) water deficit and excess, (ii) poor synchronisation of the crop growing season to the rain season, (iii) duration of the plant water stress, and (iv) water supply during the ripening period (Qin et al., 2013; Todisco et al., 2013; Saue and Kadaja, 2014; Intrigliolo et al., 2016). This reliance is especially relevant in semi-arid and sub-humid areas where irregular SWC dynamics are frequent (Viola et al., 2012). The SWC in the uppermost layer, the topsoil (TSWC, % vol.), which governs seedling establishment is a more limiting factor for crop yield than total SWC at planting (e.g. sunflower; Aboudrare et al., 2006). Despite Europe is not an arid continent and most temperate countries had humid and sub-humid conditions, water scarcity has become a concern for millions of people. The data indicate trends toward harsher conditions over the past 40 years; droughts have become more frequent (Deitch et al., 2017). Besides, climate models forecast a continuous increase in temperature over the 21st century, and a remarkable decrease of yield in summer crops is expected (Giannakopoulos et al., 2009). Mediterranean areas are subject to dramatic changes in a global change scenario in which SWC will decline and saturation conditions will be increasingly rare and restricted to periods in winter and spring (García-Ruiz et al., 2011). Therefore, soil water studies are demanded and sustainable agriculture and conservation practices are necessary, such as the application of cover crops to increase water infiltration (Gómez et al., 2011; Abazi et al., 2013). To tackle this issue, research on growing freshwater scarcity was included in the priorities of the Water Joint Programming Initiative (JPI) of the European Commission. On the other hand, the antecedent TSWC is a significant factor to predict runoff generation during medium and low intensity storms (Castillo et al., 2003) as well as to explain the soil detachment rates at the first stages of an erosive event (Rodrigo-Comino et al., 2016a).

In most soils, the values of the physical properties vary considerably along the space (Cerdà, 1996; López-Vicente et al., 2008) and TSWC also varies throughout the seasons for a given site (López-Vicente et al., 2009). Besides, the range of the spatial variability of TSWC depends on the climatic conditions (Martínez-Murillo et al., 2017). Overall, distribution of SWC along time and in a site is a complex process characterized by low homogeneity in space and/or time. However, there is a certain long-term temporal stability of this variability (Vachaud et al., 1985; Hu et al., 2013). At catchment scale García-Estringana et al. (2013) found under Mediterranean conditions lower regimes of SWC on hillslopes under forest cover than in downslope areas covered with grasses, though these differences were not persistent through the year. In a fallow cereal field, López-Vicente et al. (2015) found high variability of TSWC at weekly scale but certain stability at yearly scale that allowed identifying wet and dry stable

areas. In rainfed almond orchards, [van Wesemael et al. \(2000\)](#) found that the deeper soils in the valley bottoms produce a more stable moisture regime than shallower soils, which tend to saturate and dry out quickly. And in the same region [van Wesemael et al. \(2003\)](#) demonstrated that the tree-crop disposition and density influence the lateral soil moisture redistribution. [Ruiz-Colmenero et al. \(2011\)](#) revealed that soil moisture was controlled by rainfall at certain times of the year, whereas at other times it depended on the growth, water consumption and transpiration of the vegetation. In croplands, it has long been accepted that the components of a tree/crop mixture can influence total water availability, such as [López-Vicente et al. \(2016\)](#) observed in olive groves where topsoil became saturated 3.3 times faster in the inter-row areas than below the trees.

The presence of permanent features in croplands, such as the trunks of the woody crops, the plantation disposition that usually follow straight lines, and the different tillage practices in the inter-rows and rows influence rainfall-runoff processes, especially in those areas with low and moderate slope gradient ([Biddoccu et al., 2013](#); [Guzmán et al., 2013](#)). Vineyards, almond, olive, orange, coffee, tea and other fruit groves, as well as forest plantations, mean a significant percentage of the total cultivated soils in the world. Perennial crops represent about 16% of the agricultural land in the Mediterranean area ([FAO, 1998](#)) and are of a great economic importance ([Infante-Amate, 2012](#)). Moreover, almonds, olives and vines have expanded rapidly over the last decades and cover important areas in the drier parts of the Mediterranean countries ([van Wesemael et al., 2000, 2006](#)). Although olives and vines are grown under rainfed conditions owing to their adaptation to droughts, soil water availability is the major constraint to their productivity ([Palese et al., 2014](#)).

In Mediterranean countries, grapevines and fruit-trees are spaced and the soil in the inter-row areas is frequently kept bare during most part of the year (mechanical or chemical weeding) to reduce competition for the soil water by weeds and ploughed to increase infiltration rates ([Lasanta and Sobrón, 1988](#)). After long dry periods, high-disturbed soils dry faster, favored by their low water retention capacity. Some practices usually adopted in vineyards' establishment and management (land leveling, deep tillage, and intense tractor traffic along fixed paths) are favoring soil compaction, concentrated and quick runoff, and thus triggering soil erosion and degradation with negative impacts on the soil water holding capacity ([Tropeano, 1984](#); [Ferrero et al., 2005](#); [van Wesemael et al., 2006](#); [Ramos and Martínez-Casasnovas, 2007](#); [Novara et al., 2011](#)).

More conservation-minded soil management practices have also been used in vineyards and olive orchards like cover crops (CC), which eliminate most of the disadvantages of conventional tillage. The use of CC in the inter-rows reduces runoff and soil erosion by intercepting raindrops and speeding infiltration of excess surface water (Tropeano, 1984; Blavet et al., 2009; Novara et al., 2011; Ruiz-Colmenero et al., 2011; Prosdocimi et al., 2016; Biddoccu et al., 2017). Some reports indicated an increase of soil moisture in cover cropped olive groves as a consequence of an augment in the infiltration rate and in the soil organic carbon content, although differences with soil moisture under conventional and no-tillage treatments varied during low, average and high intensity rainfall events (Hernández et al., 2005; Durán-Zuazo et al., 2009; Gómez et al., 2009). The use of CC in the inter-row areas of Mediterranean rainfed vineyards and olive orchards is a common technique of soil management, while weeds under the rows are usually controlled with herbicides in spring (Gómez et al., 2011).

Since the 50's and 60's of the 20th century, some of the old Mediterranean farmed area has been abandoned and now is affected by spontaneous plant colonization processes (Molinillo et al., 1997; López-Vicente et al., 2011). In abandoned farmland, Wang et al. (2011) indicated an increase of the coefficient of variation of SWC (26.7%), indicating the strong spatial heterogeneity of soil moisture in this kind of farmland. The history of cultivation and the structure of the first centimeters of the soil were found also to be major causes in variability of infiltration rates in vineyards (Biddoccu et al., 2016).

In recent years, numerous studies have been carried out across Europe in order to describe the dynamics of SWC in vineyards under different irrigation conditions, such as in Italy (Crescimanno et al., 2012), Portugal (Oliveira et al., 2012) and Spain (Campos et al., 2016). To a lesser extent, the evolution and patterns of SWC in vineyards under rainfed conditions have been analysed: Ruiz-Colmenero et al. (2011) investigated the use of vegetation covers on the inter-rows and their consumption of water, and considered some alternative soil management practices on soil moisture; and Gaudin et al. (2017) developed a new way to estimate the soil water reservoir at local scale, using predawn leaf water potential measurements, where other approaches, such as SWC measurements are not possible. However, these authors largely worked at the hillslope scale, outside the tree canopy projections, and therefore could not quantify the spatial patterns in water availability and their temporal evolution in the different compartments of the cropland. We did not find any study comparing TSWC dynamics between vineyards' rows, inter-rows and corridors. There is still a gap in knowledge about the influence of vineyards' soil conditions on the TSWC. In this study, the dynamics of TSWC were evaluated

in a rainfed cropland with woody crops (27 ha, NE Spain) by means of: (i) assessing the spatial patterns between vineyards with cover crops, olive groves under conventional tillage and abandoned, cereal fields with fallow/crop rotation, and areas with natural vegetation; (ii) evaluating the temporal stability of these patterns over 12 months; and (iii) analysing the correlation of these dynamics with the main soil physical properties. This study contributes to the soil water research in vineyards and other woody crops under rainfed water supply conditions with presence of cover crops.

2. Material and methods

2.1. Study area

A Mediterranean rainfed agricultural sub-catchment located in the Ebro River Basin (NE Spain; 42° 02' 00'' N; 0° 04' 12'' E) was selected to perform this study (Fig. 1.a). This study area, so-called 'Los Oncenos', is near Barbastro town and occupies 27.3 ha. The outlet appears in the northern part that drains away in a gully. Topography is hilly with a mean slope steepness of 13% and elevation ranges from 447 to 506 m a.s.l. Land is mainly devoted to agriculture (Fig. 1.b). Four vineyards, one cereal field and one abandoned olive grove appear in the lower part of the hillslope. Four cereal fields and one commercial olive grove (314 trees) occupy the upper part of the sub-catchment. Twelve small and scatter patches of natural vegetation appear throughout the landscape covering 11.8% of the total area. These forest spots are composed by oaks (*Quercus faginea*), holm oaks (*Q. ilex*), Mediterranean shrubs, such as thyme (*Thymus vulgaris*), rosemary (*Rosmarinus officinalis*) and *Genista scorpius*, and grasses. One unpaved road (4 m width) crosses the study area from northwest to southeast separating the upper and the lower parts of the hillslope. Winter cereal (wheat and barley) fields are managed as fallow/crop rotation with conventional tillage. During the test period the cereal fields number 3 and 5 were cultivated, the field number 4 was at fallow conditions, whereas the field number 1 was cultivated during the first months and then remained at fallow conditions and the field number 2 changed from fallow to cultivated. The four commercial vineyards (Bodegas Fábregas, a winery with Certificate of Origin: Somontano) are cultivated with the Spanish variety Grenache (*Vitis vinifera* L. cv. Grenache); three fields with red grapes (planted in 2008) and one field with white grapes (planted in 2007), without any irrigation. The vineyard plantation is composed of 15,039 grapevines arranged in 147 straight lines (espalier system). Soil in the grapevine lines (row hereafter) remain between 8 and 23 cm, 13 cm on average, raised related to the soil in the inter-row area, due to the tillage practices carried out by the

farmer. The inter-row areas of the vineyards are managed with a mixture of plant species as cover crop (CC): i) spontaneous vegetation, and ii) plantation of common sainfoin (*Onobrychis viciifolia*) (Fig. 1.c). Spontaneous vegetation also protect the soil in the corridors between the four vineyards. The maintenance of the inter-rows and corridors includes one mowing pass in spring, usually in May, to avoid water competition between the CC and the grapevines. However, most pruning remains stay on the same place after this practice, thus the soil cover factor (percentage of the soil surface covered with vegetation) keeps high all over the year. The farmer only used herbicides to control weeds in the rows. Conversely, bare soil conditions appear in the inter-tree areas in the commercial olive grove and soil is ploughed twice a year (conventional tillage) to avoid the development of the spontaneous vegetation (Fig. 1.d). During this study, harvest operations were done in the following dates: cereal fields in June, vineyards in September, and olive groves in December.

Soils are Haplic Regosols (calcaric; RGca) in the upper part of the hillslope and surrounding the divides, and Luvic Calcisols (CLI) in the lower part of the hill-slope (Badía-Villas et al., 2006). Climate is continental Mediterranean, with an average annual rainfall, R , of 420 mm year⁻¹ (between the hydrological years 2003/04 and 2015/06), with two rainy periods, in spring and autumn, and a dry summer with occasional thunderstorms (source data: 'Oficina del Regante' of the Regional Government of Aragón). The mean annual temperature, T , and potential evapotranspiration, ET_0 , were 14.1 °C and 1225 mm year⁻¹. During the test period (Test-P: May 2016–April 2017) the values of R , T and ET_0 were 494 mm year⁻¹, 14.2 °C and 1191 mm year⁻¹. During Test-P, rainfall intensity (I_{30}) varied during the year with low average values between November and March, ranging from 1.2 and 2.4 mm h⁻¹; and high values between June and October (from 3.8 and 6.1 mm h⁻¹). The highest peaks of maximum rainfall intensity (I_{30max}) were recorded in September and October when the average I_{30max} were between 50 and 53 mm h⁻¹. Hence, different hydrological response of the soils and runoff depth is expected during the different months of the year. Saturation-excess runoff areas (generated when the soil becomes saturated) were not observed in the study area, and thus infiltration-excess runoff (generated when the rainfall intensity is larger than the infiltration rate) is the predominant overland flow generation process. Several ephemeral gullies (EG) affect the soils in three vineyards, two cereal fields and the olive grove. This process has triggered the development of continuous flow path lines, breaking the topographic thresholds of the rows in some sections; as well as the development of three depositional areas (alluvial fans) at the bottom of two vineyards, and of the cultivated olive grove (López-Vicente and Álvarez, 2018). The largest fan (1480 m²) is near the outlet and within the northern vineyard. Hence, differences in soil

texture and bulk density are expected in the different compartments of the crops and land uses due to the tillage practices, the two soil types and the soil redistribution processes.

2.2. Field measurements and soil physical properties

The TSWC was measured in 12 field surveys every 30 days comprising the period May 2016–April 2017. Each survey was performed in the same days of the month, between the days 15 and 19. A frequency-domain probe (*Delta-T SM300*) was used to measure TSWC (θ_v , % vol.) at field conditions (Fig. 2.a). This device has two rods that are inserted in the soil up to 51 mm depth (sample volume is $\sim 55 \times 70$ mm diameter). Measurements are stable regarding salinity (accuracy $\pm 0.025 \text{ m}^3 \text{ m}^{-3}$; 2.5%). Field measurements were done in 74 points of undisturbed soils and three measurements of θ_v were done at each point (222 measurements per month; Fig. 2.b). The average value was estimated as the representative value of each point. A portable device was chosen to measure soil moisture instead of installing permanent devices (sensors, dataloggers and batteries) due to the high number of measurement points and thus the high economic cost of the second option. A total of 48 measurement points were located in the four vineyards. The distance between each measurement point within each vineyard was 40 m covering the three compartments: rows, inter-row areas and corridors. In the other land uses the distance between each measurement point was ca. 50 m. Each survey was performed in less than 6 hours to minimize any temporal change of the soil water content conditions. There was not recorded any rainfall event during each survey and also during the four previous days. Hence, measured values suffered low variation and can be considered as representative of the monthly conditions. The analysis of variance (ANOVA; *statgraphics® centurion XVI*) of the data was done in order to determine statistically significant differences in TSWC between the different land uses and field compartments.

As far as soil physical properties are concerned, 222 topsoil samples were collected (Fig. 2.c). Each sample was collected in the same location where TSWC was measured. Three replicates of 250 cm^3 (*UMS HYPROP* cylinder; 6 cm depth by 5 cm of diameter) were collected at each sampling point. Then, the bulk density (BD, gr cm^{-3}), the content of coarse fragments ($> 2 \text{ mm}$, % weight), clay ($0.04 - 2 \mu\text{m}$), silt ($2 - 63 \mu\text{m}$) and sand ($63 - 2000 \mu\text{m}$) was measured, and the effective volume of the soil (related to the volume occupied by the fine particles, $< 2 \text{ mm}$) and the texture classification were determined. The fine-soil particle size distribution was measured in the laboratory with a laser equipment (*Beckman-Coulter*). Additionally, the infiltration rates (K_f , mm h^{-1}) and the water holding capacity (θ_{-pF} , % vol.) of the soils were

measured in the field. The two most contrasting field compartments were selected to perform these measurements: the rows (7 measurement points) and the inter-row areas (7 measurement points) of the vineyards (Fig. 2.b). The unsaturated hydraulic conductivity was determined by means of a portable tension infiltrometer (*Decagon Mini Disk*) at -2 cm of suction value. Two infiltrometers were located at each measurement point and the average value was considered as representative. The matric water potential at each point was measured in the field with a portable device (*Decagon MPS-6* sensor; Fig. 2.a). This device has an accuracy of $\pm 10\%$ of the reading and has sensitivity from -9 kPa all the way to air dry (-100,000 kPa). For this study, the TSWC at four soil-water tension values we considered: -12, -20, -33 and -1500 KPa that were related to saturated, almost-saturated, field capacity and permanent wilting point conditions, respectively.

2.3. Spatial variability and temporal stability

The spatial pattern of TSWC was calculated for each survey by means of the relative difference, δ_{im} , between the mean value of TSWC in the whole study area at each month 'm', θ_{0m} , and the average value of TSWC at each measurement point 'i', θ_{0im} :

$$\delta_{im} = \frac{\theta_{0im} - \overline{\theta_{0m}}}{\overline{\theta_{0m}}} \quad (1)$$

$$MRD_{iT} = \frac{1}{N_T} \sum_{m=1}^{m=N_T} \delta_{im} \quad (2)$$

where MRD_{iT} is the mean relative difference for the location 'i' and N_T is the number of observation times (12 months). The temporal stability analysis of these differences was done calculating the standard deviation of the set $\delta_{i,m=1}, \delta_{i,m=2}, \dots, \delta_{i,m=T}$ of relative differences at the location 'i' over the test period:

$$SDRD_{iT} = \sqrt{\frac{1}{N_T - 1} \sum_{m=1}^{m=N_T} (\delta_{im} - MRD_{iT})^2} \quad (3)$$

The value of $SDRD_{iT}$ serves as one of the measures of the temporal stability (Vachaud et al., 1985; López-Vicente et al., 2015, 2016) by comparing its magnitude to the spatial variability of MRD_{iT} .

3. Results

3.1. Climatic data and TSWC

The monthly rainfall depth, R , was higher than the ET_0 in October and November 2016 and in February and March 2017. The ET_0 was higher than the R during the other eight months (Fig. 3.a). For all surveys (2,664 measurements), the mean, median, and standard deviation were of 13.1, 13.0 and 8.0% vol. As expected, the driest conditions happened on August, June and July 2016, with mean values of TSWC of 3.0, 3.4 and 3.8% vol., respectively. The wettest conditions appeared on February 2017, December and October 2016 with mean values of TSWC of 24.2 (708% higher than the driest survey), 19.7 and 18.3% vol., respectively. The range of values was minimum for the driest survey, on August-2016 (7.1% vol.), maximum during the wettest survey (February-2017; 36.5% vol.) and the average range during the 12-month period was of 23.1% vol. The greatest values of TSWC were recorded in winter (from December to February; mean 19.3% vol.) and the lowest in summer (from June to August; mean 3.4% vol.). Marked wetting-up conditions appeared in autumn (from September to November; mean 15.9% vol.) and average but drying-up conditions took place in spring (from March to May; mean 13.8% vol.). This seasonal trend was closely related to the temperature, the vapour pressure deficit and the rainfall regime of the study area. As expected, a moderate and positive correlation ($R^2 = 0.3492$) was found between the mean values of monthly TSWC and those of rainfall, and a negative and good correlation between the TSWC and the ET_0 ($R^2 = 0.7094$) and the temperature ($R^2 = 0.5984$).

The overall evolution in the values of TSWC over the 12 months was mirrored by the values obtained at each land use and field compartment, although clear differences were observed between them. The highest values of TSWC appeared in the inter-row areas of the vineyards (mean 16.2% vol.), the trails (15.6%) and the corridors of the vineyards (15.1%), average values appeared in the abandoned olive orchards (13.5%), the fallow cereal fields (13.4%) and the cereal fields (13.3%), and the lowest values were recorded in the cultivated olive orchard (11.8%), the rows of the vineyards (10.0%) and the patches of natural vegetation (9.0%; Table 1). On average, TSWC in the vineyards was 11.2% higher than in the rest of the land uses. This trend was constant during 11 of the 12 months, except in January 2017, and it was more pronounced in summer (28% higher) and autumn (24% higher), and less marked in winter (5% higher) and spring (4% higher; Fig. 3.b). Thus, the highest differences appeared during the driest and wetting-up conditions whereas minor differences took place during the wettest and drying-up conditions. The wettest conditions over the 12 months appeared in the inter-row

areas of the vineyards, with an average value that was 62% higher than the mean value obtained in the rows. The corridors of the vineyards presented intermediate values of TSWC. The fallow cereal fields had slightly higher values of TSWC than the cultivated cereal fields with lower coefficient of variation. The differences in TSWC between the land uses were statistically significant ($P\text{-value} < 0.05$) and five homogeneous groups were distinguished (Table 1): (i) the rows of the vineyards and the forest; (ii) the olive grove; (iii) the cereal and the fallow cereal fields; (iv) the abandoned olive groves, the corridors of the vineyards and the trails; and (v) the inter-row areas of the vineyards.

3.2. Spatial patterns and temporal evolution

The minimum and maximum relative differences of TSWC, δ_{im} in Eq. (1), were analyzed for each survey (Fig. 4). Decreasing values of the maximum relative differences were found with increasing values of TSWC ($R^2 = 0.8003$). Higher negative values of the relative differences appeared during the driest surveys ($R^2 = 0.3659$). Thus, the spatial variability of TSWC at sub-catchment scale increased under dry conditions and more homogeneous conditions appeared along the study area in the wet surveys.

Regarding the different land uses, the higher mean relative differences (wetter than the average conditions), MRD_{IT} in Eq. (2), appeared in the inter-row areas of the vineyards (0.26), the trails (0.17) and the corridors of the vineyards (0.15), average values appeared in the abandoned olive orchards (0.08), the cereal fields (0.05), and the fallow cereal fields (-0.07), and the lowest values (drier than the average conditions) were recorded in the cultivated olive orchard (-0.14), the rows of the vineyards (-0.24) and the patches of natural vegetation (-0.33; Table 2). As expected, this spatial pattern mirrored the differences observed in the mean values of TSWC between the different land uses, except in the fallow cereal fields that presented a lower MRD (12% drier) than the cereal fields in spite of their similar and slightly higher mean value of TSWC (0.3% higher). The temporal variability of this spatial pattern, assessed by means of the $SDRD_{IT}$ in Eq. (3), clearly changed between the different land uses and field compartments (Table 2). The most stable conditions appeared in the rows of the vineyards, the olive grove, and the fallow cereal fields with $SDRD$ values < 0.25 . The highest temporal variability appeared in the abandoned olive groves, the cereal fields, and the trails, with $SDRD$ values > 0.33 . The inter-rows and corridors of the vineyards, and the forest had average stable conditions.

Humidity areas were defined combining the values of *MRD* and *SDRD* at the following percentiles: very dry conditions below *MRD*-Q10 (-0.325), dry conditions between *MRD*-Q10 and *MRD*-Q33 (-0.168), average conditions between *MRD*-Q33 and *MRD*-Q66 (0.094), wet conditions between *MRD*-Q66 and *MRD*-Q80 (0.245), and very wet conditions above *MRD*-Q80. Related to the temporal variability, very stable conditions were defined below *SDRD*-Q30 (0.203), average stability between *SDRD*-Q30 and *SDRD*-Q80 (0.331), and low stability above *SDRD*-Q80 (Fig. 5). Despite the dispersion of the values of *MRD* and *SDRD* a satisfactory distribution of the values was observed according to the different land uses and field compartments. Besides, a low and positive linear correlation ($R^2 = 0.0986$) appeared between the *MRD* and *SDRD* values indicating that very wet areas tended to present average and/or low temporal stability; whereas dry and very dry areas tended to have average and/or very stable conditions.

3.3. Soil physical properties

In the 222 soil samples, the values of bulk density (BD; mean 1.438 gr cm^{-3}) ranged between 0.456 and 2.011 gr cm^{-3} appearing the highest densities in the trails (mean 1.633 gr cm^{-3}) and vineyard corridors and inter-row areas (mean 1.582 gr cm^{-3}), whereas the lowest densities appeared in the forest and the fallow cereal fields (mean $< 1.25 \text{ gr cm}^{-3}$; Table 3). The effective volume of the soil (Vol_{eff} ; mean 89.6%) ranged between 66.3% and 98.9% with the minimum values in the forest and cereal fields (mean $< 87\%$) and the maximum values in the vineyard rows and inter-row areas (mean 91%). As expected, the commercial olive grove under conventional tillage had an average bulk density 10% higher than the abandoned grove despite its lower rock fragments' content (21% lower). Four soil textures were identified: silt loam (24% of the total soil samples), loam (24%), sandy loam (45%) and loamy sand (7%). On average, the three vineyards compartments have loamy soils whereas the remaining land uses present sandy loam soils. A positive and moderate correlation was observed between the mean values of TSWC and those of clay (Pearson's $r = 0.327$), silt ($r = 0.401$) and bulk density ($r = 0.513$), whereas the correlation with the values of Vol_{eff} was weak ($r = 0.300$). These coefficients of correlation were similar during the wettest survey but clearly declined during the driest survey. The correlations between the values of these soil physical properties and those of the *MRD* were quite similar to those obtained with the values of TSWC. However, very weak correlations ($r < 0.1$) were observed between the values of the soil physical properties and those of the *SDRD*. Concerning the four soil textures a clear evolution in the values of

TSWC, MRD, SDRD, BD and Vol_{eff} was obtained (Table 4). Silt loam and loam soils presented wetter and more stable conditions than the average scenario, as well as lower values of BD and higher of Vol_{eff} , whereas the sandy loam and loamy sand soils had drier and less stable conditions, higher values of BD and lower of Vol_{eff} .

The unsaturated hydraulic conductivity, K_f , and the soil-water holding capacity, $\theta-pF$, in the inter-row areas of the vineyards were much higher than in the vineyards' rows. The mean (15 mm h⁻¹) and median (17 mm h⁻¹) K_f values in the vineyards' inter-rows were 134% and 268% higher than the K_f values in the vineyards' rows. The mean values of $\theta-pF$ in the vineyards' rows were 21%, 15%, 11% and 7% vol. at -12, -20, -33 and -1500 KPa, respectively; whereas the $\theta-pF$ values in the vineyards' inter-row areas at the same soil-water tension values were 27% (32% higher), 24% (63% higher), 21% (92% higher) and 9% vol. (30% higher), respectively.

4. Discussion

4.1. Topsoil water content dynamics

The very wet and stable conditions observed in the vineyards' inter-row areas were explained by the soil-water conservation role played by the cover crops (CC) and the presence of plant debris all over the year. These results concurred with other studies done in Mediterranean vineyards and olive groves: (i) Blavet et al. (2009) observed lower runoff yields in French vineyards when the prunings were left on the soil after mechanical inter-row weeding; (ii) Gómez et al. (2011) obtained reductions in average annual runoff coefficients in plantations with CC in Andalusia (Southern Spain), Portugal, and France compared with the coefficients under conventional tillage (CT) conditions; (iii) Gómez et al. (2018) found benefits in reducing runoff and soil losses up to one order of magnitude in olive orchards with CC compared to management based on bare soil; and (iv) Biddoccu et al. (2017) recently reported the positive and stable effect of grass cover on the soil water content (SWC) and the soil-water holding capacity in vineyards' inter-rows in north-west Italy, during both the dry and the wet seasons. These results agreed with the temporal stability of the TSWC observed in the vineyards' inter-rows of our study area. On the other hand, our results partially disagreed with those reported by López-Vicente et al. (2016) who found similar values of SWC in olive groves with CC and CT during the wet months, and lower values of SWC with CC during the dry months. These differences can be explained because the CC plants of the olive groves were chemically killed in late winter or early spring, and thus the soil-water conservation effect of the CC was limited to the wet period. However, none of these authors compared the TSWC

dynamics of the different woody crops' compartments: rows, inter-rows and corridors. Vomocil (1986) obtained no significant difference comparing moisture contents in the rows with those between the rows with CC in vineyards in Oregon (USA). This disagreement highlighted the key role played by the higher elevation and bare conditions of the soil in the rows in our study area that explain the dry and very stable conditions observed in this field compartment.

The high temporal variability observed in the cereal fields can be explained by the significant changes in the soil cover factor during the year, with high values in spring, low values in summer after harvesting and bare soil conditions in autumn owing to ploughing and seeding. The fallow cereal fields presented drier and more stable conditions than the cereal fields that can be explained by the similar values of the soil cover factor all over the year and the water demand by the natural vegetation. The drier and more stable conditions observed in the soil of the commercial olive grove than in the soil of the abandoned olive grove can be explained by two reasons: (i) the tillage practices (bare soil, ploughed conditions and tractor traffic) of the commercial plantation that triggered soil compaction; and (ii) the higher clay content (25% higher) in the abandoned olive grove despite both groves had the same soil texture (sandy loam). Similar results were observed by van Wesemael et al. (2006) in Spanish almond groves where bare topsoils managed with conventional tillage presented lower soil-water holding capacity than topsoils with vegetation cover. Durán-Zuazo et al. (2009) also observed higher SWC in rainfed olive orchards with permanent plant strips in the inter-tree areas than in the fields without plant cover between the trees, despite the lack of tillage operations.

The wet and not stable conditions observed in the trails can be associated to several factors: (i) Biddoccu et al. (2016) evaluated the effect of the passage of tractor wheels in vineyards and found an increase in the TSWC values in track position owing to the soil compaction that seals the topsoil surface; and (ii) the most likely short-distance lateral subsurface flow from adjacent land uses with higher infiltration rates to the trails, such as Grayson et al. (1997) observed in semi-arid environments in Australia. The very dry and average stable conditions of the forest soils agreed with the temporal dynamics of SWC observed by James et al. (2003) after comparing the soil moisture regimes in natural grassland, shrubland and forest. Despite our results showed clear differences in the topsoil water content dynamics between the different land uses and field compartments, a long-term database (more than two years) of soil water content measured at different soil depths (most kind of plant roots, both natural and crops, are concentrated within top 60 cm) is necessary to confirm

the observed spatial and temporal patterns as well as to better appreciate the soil water conservation role played by the cover crops.

4.2. Influence of the soil physical properties

The differences in the values of the soil physical properties observed between the different land uses and field compartments were explained by the different tillage practices that predominated in each field compartment. The man-made accumulation of soil in the vineyards' rows explained their low bulk density values despite presenting similar values of coarse fragments and soil texture as the vineyards' inter-rows and corridors. The higher infiltration rates observed in the vineyards' inter-rows compared with the values in the rows agreed with the results by Lasanta and Sobrón (1988) in other Spanish vineyards (La Rioja Certificate of Origin) where the root system of the fields with vegetation cover favoured the quick vertical soil-water flow. This process (much higher K_f values) mainly explained the very wet conditions observed in the inter-rows instead of the cover crop evapotranspiration (ET_{cc}) was expected to be higher than the soil evaporation (E_s) (Centinari et al., 2013).

The mean values of TSWC measured in the winter months, from December to February, in the vineyards' rows (15.0% vol.) and inter-rows (22.9% vol.) were quite similar to the soil-water content at -20 KPa of soil-water tension in the two field compartments, and thus in between field capacity and saturation conditions. The mean values of TSWC in summer, from June to August, in the vineyards' rows (2.7% vol.) and inter-rows (4.5% vol.) were similar to the soil-water content at permanent wilting point conditions. Therefore, the range of observed TSWC values in the vineyards was very broad over the test-period and close to the maximum range of topsoil-water holding capacity. López-Vicente et al. (2009) observed a similar temporal variability in cultivated and non-cultivated Calcisols, Leptosols and Regosols with higher values of TSWC than the soil-water content at field capacity in autumn and winter and very low relative values of moisture during the summer.

In rainfed almond orchards, van Wesemael et al. (2000) observed that deeper soils produced a more stable moisture regime than shallower soils, which tend to saturate and dry out quickly. And Palese et al. (2014) observed more homogeneous distribution of soil macroporosity and thus of the vertical water movement down to deeper horizons in rainfed olive orchards with CC compared with CT. Therefore, the assessment of soil depth and the SWC dynamics at deeper horizons along our study area, and the analysis of the correlations between these factors will be considered in further research. On the other hand, Rodrigo-

Comino et al. (2016b) observed higher temporal stability in the spatial patterns of soil moisture, infiltration rates and soil organic content in old vineyards than the stability obtained in young vineyards in a German plantation. Thus, further research will study the influence of plantation age on the TSWC dynamics in rainfed Mediterranean vineyards. The assessment of the infiltration rates and the soil-water holding capacity in the remaining land uses and field compartments are included in the ongoing research activities in the study area. These results will be analysed in relation to the observed TSWC dynamics and humidity areas, and will be of interest to refine the soil-water balance at sub-catchment scale and during the different seasons and tillage practices.

5. Conclusions

As expected the evolution of the values of topsoil water content (TSWC) during the test period showed a good agreement with the values of total rainfall depth, and potential evapotranspiration. Dry conditions favoured higher relative differences of TSWC along the study area while more homogeneous spatial patterns appeared during the wet surveys. The higher infiltration rates observed in the vineyards' inter-rows mainly explained the very wet and stable temporal conditions of this field compartment. The permanent presence of the cover crops and the plant debris (from the mowing pass) all over the year supported the soil-water conservation role played by this soil management practice. The traditional tillage practices in the vineyards' rows that placed the soil in a higher elevation under bare conditions triggered low infiltration rates and thus dry and very stable conditions. The vineyards' corridors had average spatio-temporal dynamics between the rows and inter-rows.

The forest presented the driest and average stable temporal conditions associated to the water demand by the trees. The fallow cereal fields presented drier and more stable conditions than the cereal fields that can be explained by the similar values of the soil cover factor all over the year and the water demand by the natural vegetation. Conversely, the bare soil conditions of the commercial olive grove explained the drier and more stable conditions observed in this field compared with the soil moisture conditions of the abandoned olive grove. The trails had wet but not stable conditions owing to the soil compaction that seals the topsoil surface, and the most likely short-distance lateral subsurface flow. A longer database is necessary to verify these patterns and dynamics with values of soil water content at different soil depths.

The contrasted climatic conditions in the study area explained the observed range of soil moisture in the vineyards' rows and inter-rows between wetter conditions than field capacity in winter to permanent wilting point conditions in summer. The different land uses and tillage practices influenced more the TSWC dynamics than the spatial variability of the analysed soil physical properties. However, silty loam and loamy soils presented wetter and more stable conditions than the average dynamic at sub-catchment scale, and the sandy loam and loamy sand soils had drier and less stable conditions. The results of this study can be of interest to enhance the management of water in rainfed agricultural systems with woody crops and different tillage practices and edaphic conditions.

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Table 1

Values of TSWC (θ_o , % vol.) in the different land uses and field compartments, and over the 12-month test period (2,664 measurements). The number of measurement points (n; three measurements per point) is also indicated. Within column, values followed by the same letter are not significantly different between them at $P < 0.05$ (using Fisher's least significant difference procedure).

Land use and field compartment	θ_o (% vol.)				
	n (x3x12)	min	mean	max	sd
Vineyard (4 fields)	48	0.2	13.6*	38.0	8.0
Vineyards: rows	20	0.2	10.0a	28.1	5.9
Vineyards: inter-row areas	25	0.9	16.2c	38.0	8.4
Vineyards: corridors	3	0.7	15.1bc	33.2	8.4
Cereal-cultivated	6-8**	0.7	13.3b	36.0	8.2
Cereal-fallow	4-6**	0.5	13.4b	32.4	7.6
Olive grove	3	0.7	11.8ab	31.7	7.5
Abandoned olive grove	2	1.8	13.5bc	29.1	7.2
Forest	7	0.3	9.0a	26.3	6.1
Trail	2	0.8	15.6bc	40.7	9.6

* The combined values of the vineyards were excluded of the analysis of variance; ** The fields under fallow conditions changed over the test-period.

Table 2

Mean relative differences (*MRD*, spatial variability) of the TSWC and standard deviation of the relative differences (*SDRD*, temporal stability) at each land use and compartment over the test period. Average humidity conditions of each land use are presented.

Land use	MRD	SDRD	Conditions
Vineyard (4 fields)	0.047	0.226	Average & Stable
Vineyards: rows	-0.235	0.193	Dry & Very stable
Vineyards: inter-rows	0.261	0.250	Very wet & Stable
Vineyards: corridors	0.146	0.251	Wet & Stable
Cereal-cultivated	0.047	0.354	Average & Not stable
Cereal-fallow	-0.074	0.248	Average & Stable
Olive grove	-0.140	0.245	Average & Stable
Abandoned olive grove	0.079	0.373	Average & Not stable
Forest	-0.332	0.280	Very dry & Stable
Trail	0.167	0.331	Wet & Not stable

Table 3

Mean values of bulk density (BD), content of coarse fragments (CF), clay, silt and sand, of the effective volume of the soil (Vol_{eff}), and of the texture classification in the different land uses and field compartments. The number of soil samples is also indicated.

Land use	Samples	BD	CF	Vol_{eff}	Clay	Silt	Sand	Texture
	<i>n</i>	gr cm ⁻³	% weight	% vol.	%	%	%	Type
Vineyard (4 fields)	144	1.482	15.8	90.7	8.8	42.9	48.3	Loam
Vine: row	60	1.343	16.7	90.9	9.3	43.4	47.3	Loam
Vine: inter-row	75	1.582	14.7	90.8	8.4	42.3	49.3	Loam
Vine: corridor	9	1.582	18.0	88.6	8.3	44.6	47.1	Loam
Cereal	24*	1.564	21.9	86.3	6.2	37.0	56.8	Sandy loam
Cereal-fallow	12*	1.224	19.7	90.0	6.7	40.2	53.1	Sandy loam
Olive grove	9	1.413	18.9	89.2	6.1	39.5	54.4	Sandy loam
Abandoned olive grove	6	1.288	24.0	87.7	7.6	38.2	54.2	Sandy loam
Forest	21	1.108	33.2	86.4	4.7	29.3	66.0	Sandy loam
Trail	6	1.633	17.2	90.0	6.5	42.8	50.7	Sandy loam

* Soil samples were collected in April 2016, one month before the test-period.

Table 4

Mean values of topsoil water content (TSWC), mean relative differences of TSWC (MRD), standard deviation of the MRD (SDRD), bulk density (BD), and effective volume of the soil (Vol_{eff}) in the four soil textures of the study area.

Soil texture	Samples	TSWC	MRD	SDRD	BD	Vol_{eff}
	$n (x3)$	% vol.			$gr\ cm^{-3}$	%
Silt loam	16	14.2	0.073	0.270	1.361	92.5
Loam	19	13.9	0.057	0.235	1.460	91.2
Sandy loam	36	12.3	-0.064	0.258	1.452	87.6
Loamy sand	3	11.1	-0.118	0.288	1.534	88.7

Fig. 1. Location of the study area in the Ebro River Basin (NE Spain; a), map of land uses (b), and pictures of the vineyard plantation with cover crop (c) and of the olive grove under conventional tillage (d).

Fig. 2. Field measurements of TSWC with the *Delta-T SM300* device and of the soil water potential with the *Decagon MPS-6* device (a). Location of the measurement points on the study area, and of the ephemeral gullies and alluvial fans (b). Soil sample collected with the *UMS HYPROP* cylinder (c).

Fig. 3. Monthly values of rainfall depth (R, mm), potential evapotranspiration (ET_0 , mm), mean temperature (T, °C) and topsoil water content (TSWC, % vol.) during the test period (a). Monthly mean values of TSWC in the different land use compartments (b).

Fig. 4. Correlation between the maximum (a) and minimum (b) relative differences (δ_{it}) of TSWC during each month, and the average value of monthly TSWC (θ_0 , % vol.).

Fig. 5. Humidity areas defined with the values of the mean relative differences (MRD) of the TSWC and those of the standard deviation of the relative differences (SDRD).

Supplementary content

Google Earth file "Barbastro - Los Oncenos SOIL MOISTURE.kml"