Effect of physiographic conditions on the spatial variation of seasonal topsoil moisture in Mediterranean soils

M. López-Vicente[A,B]*, A. Navas*[A]*, and J. Machín*[A]

[A]Department of Soil and Water, Experimental Station of Aula Dei – CSIC. Avda. Montañana 1005, Zaragoza. 50059, Spain.

[B]Corresponding author. Email: mvicente@eead.csic.es

Abstract. This paper studies the spatial variation of topsoil moisture within different soil types in a medium-size catchment at the Spanish Pre-Pyrenees (Estaña catchment, 2.5 km^2) using seasonal data at high spatial resolution. Topsoil moisture was measured with a *Delta-T Theta Probe ML2x* device up to 8 cm of soil depth and at seasonal scale during 2005 and 2006. Measured values were related to the soil water content at field capacity to calculate the relative topsoil moisture (θ_R, %). The highest values of θ_R were obtained in autumn (53.2%) and the lowest in summer (32.1%) showing a positive correlation with seasonal precipitation and an inverse relationship with seasonal solar radiation (*SR*). Steep northern slopes presented the highest values of θ_R in spring, summer and winter and topsoil moisture progressively decreases from steep northern slopes to gentle slopes and from gentle slopes to steep southern slopes, defining a topographical trend. Any topographical trend was observed in autumn when values of θ_R were very high within the whole catchment. No significant correlation was found between values of θ_R and those of topographic wetness index (*TWI*) except in summer. Relative topsoil moisture varied greatly for the different soil types and the highest values were also measured in steep northern slopes in spring, summer and winter. Correlation between θ_R and *SR* was good for the different soil types in winter when *SR* varied the most for the different physiographic units and the range of values of θ_R is the highest. No significant correlation was found in autumn for any soil type due to the very low values of solar radiation. Results of this work draw attention to the importance of considering the slope steepness and aspect conditions for a more precise characterization of moisture-sensitive areas in Mediterranean environments and soils at seasonal scale.

Additional keywords: Topsoil moisture, soil type, slope and aspect, solar radiation, Mediterranean conditions, Spain.

Introduction

Quantification of topsoil moisture is necessary in soil erosion studies, crop production research, water budgeting in watersheds, precision agriculture, environmental monitoring and irrigation planning (López-Vicente *et al.* 2008; Terzoudi *et al.* 2007; Leib *et al.* 2003). Spatially distributed characterization of topsoil moisture at different time scales (seasonal and annual) is necessary to understand fluctuations of soil water content and thus to enhance prediction of hydrological and soil erosion models (Morgan 1995; Govers and Loch 1993). Physically based regional scale hydrologic modelling is gaining importance for planning and management of water resources on different scenarios (Santhi *et al.* 2008). However, soil erosion models do not usually consider the spatial and temporal variations of soil moisture. Thus, using incorrect topsoil moisture values may generate misleading modelling results.

The volumetric water content at initial conditions (θ_0, %Vol) is the residual volume of water retained within the soil profile after a rainfall event. The θ_0 has a substantial influence on time and rainfall to ponding for the different soil types together with the soil infiltration properties (Esteves *et al.* 2005). In gentle slopes, topsoil moisture is one of the dominating controlling factors in the erosive process (Rockström *et al.* 1999) whereas θ_0 is less important in steep slopes where concentrated overland flow takes place.

Antecedent soil moisture depends on climate conditions (amount and temporal pattern of precipitation, temperature, evapotranspiration), topography (solar radiation, areas of overland flow concentration), soil properties (texture, organic matter, saturated and non-saturated hydraulic conductivity), and land uses (water requirement of the different plants and crops). Topography is a major factor controlling both hydrological and soil processes at the landscape scale. However, the assessment and prediction of topsoil moisture at catchment scale is quite difficult to perform due to the high number of variables that control the θ_0 and because of its high spatial and temporal variations (Ramírez-Beltran *et al.* 2008).

Agro-ecosystems are experiencing environmental changes of a scale and speed without precedent, driven by climate change, human population growth and changing consumption patterns. The importance of conserving soil and water resources has been recognized ever since the dawn of settle agriculture (Lal, 2008). A main threat is soil erosion that has progressively increased in both extent and severity due to the rapid increase of human population (Lal, 2007), dramatically reducing the depth of fertile soil and thus crop yield and food production. Soil erosion and degradation still persists in many countries and some tillage practices and changes in land uses increase the threats of soil loss.

Previous works of soil moisture in Mediterranean environments usually deal with the importance of the antecedent soil moisture in runoff generation, soil erosion and suspended sediment processes (e.g. Murillo and Ruiz Sinoga 2008; Regüés and Gallart

2004; Gallart *et al.* 2002) and some times about the relationships between soil water content and growth quality in trees, seedling establishment and plant status (e.g. Bellot and Ortiz de Urbina 2008; Urbieta *et al.* 2008). Nevertheless, characterization of topsoil moisture content at catchment and seasonal scales on Mediterranean soil surfaces are scarcely reported and few available works are concerning about the effect of physiographic conditions controlling the spatial pattern of topsoil moisture in Mediterranean soils.

The main objective of this work is to characterize the seasonal and spatial variability of topsoil moisture content in a rain-fed agro-ecosystem under Mediterranean conditions. For better characterizing the hydrological processes field measurements are done at catchment scale and obtained values are related to the field capacity of the soil. In order to evaluate the influence of topographic conditions (slope, orientation, upslope contributing area) on the topsoil moisture within each soil type, values of topsoil moisture are statistically analyzed in relation with the values of solar radiation and topographic wetness index at catchment scale. The study of changes in topsoil moisture within each soil type and their analysis at seasonal scale is of interest to improve the quality predictions of hydrological and soil erosion models and fulfill an important research question in Mediterranean environments.

Materials and methods

Study area

The Estaña catchment is a medium-scale endorheic watershed (246 ha) that is located in the External Ranges of the Central Spanish Pre-Pyrenees (Fig. 1). This catchment includes three fresh-water lakes (total area of 17 ha) that are under regional protection since 1997 and are included in the European NATURA 2000 network as Site of

Community Importance (SCI). Elevation ranges between 676 and 896 m a.s.l. and slope steepness means 19.5%. Steep northern slopes occupy 5% of the study area whereas gentle slopes (slope steepness lower than 22.5%) and steep southern slopes cover 67 and 28%, respectively. The different land uses of the study area are representative of the typical Mediterranean agro-ecosystem where natural and anthropogenic areas are heterogeneously distributed. Crops of winter barley are the main land uses and areas with natural vegetation include dense and open Mediterranean forest and scrublands.

The study area yields under Mesozoic gypsiferous marls, dolomites, limestones, and sparse saline deposits. Karstic processes partially lead the evolution of the landscape of the Estaña catchment (López-Vicente *et al.* 2009), and explain the abundance of depressions and sinks where runoff can be concentrated. Machín *et al.* (2008) distinguished six types of soils in the study area being Calcisols, Leptosols and Regosols the main types whereas Gleysols, Gypsisols and Vertisols occupy a small percentage of the catchment (Fig. 1) (Table 1). Calcisols and Leptosols are associated to limestones and Gypsisols, Regosols and Vertisols to clayish materials. Gleysols are developed on clay materials and in areas where the water table is seasonally near the soil surface and appear surrounding the lakes of the Estaña catchment. The different soil types present a complex spatial distribution as a consequence of the intricate geology and topography of the study area. The different soil types of the study area present important differences in soil depth, percentage of coarse fragments and infiltration properties, whereas have similar values of bulk density, and percentage of clay and organic matter and also in the volumetric water content at field capacity (Table 1).

Climate is continental Mediterranean with two humid periods, one in spring (April and May) and a second in autumn (September and October) and a dry summer with frequent rainfall events of high intensity (López-Vicente *et al.* 2008) and with an annual precipitation of 595 mm (for the period 1993–2006) (Fig. 1). However, the Estaña catchment is located between the semiarid areas of the Ebro valley to the south and the humid areas of the Pyrenees to the north. As a consequence of this geographical situation the annual precipitation has a strong spatial variability. The average annual rainfall at the weather stations of Benabarre, Camporrélls and Canelles was 619, 536 and 446 mm, respectively, for the period 1997–2006. These weather stations are located NW, SW and SE of the study area at a distance of around 10 km. The average number of annual rainfall events registered at the Canelles weather station is 73 of which only 12 had precipitation above 12.7 mm (0.5 inches). Weather, land uses and tillage practices in the Estaña catchment are representative of rain-fed agricultural areas in Mediterranean mountainous agro-ecosystems.

Soil moisture determination

A frequency-domain probe (*Delta-T Theta Probe ML2x*) was used to measure soil moisture. This device has a portable/handheld reading unit for field measurements and has a configuration of two rods that are inserted in the soil up to 8 cm depth. The *Theta Probe* instrument uses a soil property called apparent dielectric constant of the soil to estimate volumetric water content at initial conditions (θ_0, %Vol). Although soil moisture behavior changes at different soil depths, in this work we only characterized topsoil moisture because processes of runoff generation and soil water storage are mainly controlled by the mechanisms of initially soil surface water repellency, topsoil infiltration and changes in topsoil moisture (Gomi *et al.* 2008), especially in Mediterranean soils where dry conditions are frequent.

Soil moisture was measured in a field campaign and at seasonal scale comprising the years 2005 (February for winter, August for summer and December for autumn) and

2006 (May for spring). A total of 236 measurement points were established following a regular net with a distance of 100 m between points that entirely covers the Estaña catchment (Fig. 1). Measurement points were re-located at during each campaign by using a colour orthophoto of the study area at high spatial resolution. Because of the extension of the study area and the high spatial resolution of the measurements each campaign took five days. There was not recorded any rainfall event during each campaign and thus measured values suffered a low variation due to the lack of rainfall. Three values of θ_0 were measured at each control point and the average value was estimated as the representative value.

The volumetric water content at saturation (θ_S, %Vol) is the maximum amount of water that can be stored within the soil, whereas the volumetric water content at field capacity (θ_{FC}, %Vol) is the amount of water content held in soil after excess water has drained away and the rate of downward movement has materially decreased (Israelsen and Hansen 1965). The relative topsoil moisture or relative volumetric water content of the soil (θ_R, %) is mathematically defined as the ratio between the field measured value of θ_0 and the estimated value of θ_{FC} at each measurement point:

$$\theta_R = \frac{\theta_0}{\theta_{FC}} 100 \tag{1}$$

This relationship was used by Talluto *et al.* (2008) to investigate drying processes on the rootzone in central Sicily and allows a better description of the soil water content. This ratio is of interest to study the spatial distribution and patterns of topsoil moisture at catchment scale as well as to compare the values of θ_R between different soil types.

A field survey was carried out and 236 soil samples were collected in the same points where soil moisture measurements were done. The volumetric water content at field capacity was measured in the laboratory and values were used in Eq. (1). In order to assess the effect of the different topographic conditions on the spatial variation of topsoil moisture, the enhanced digital elevation model (DEM) of the study area obtained by López-Vicente *et al.* (2009) was used to derive the maps of slope, aspect, solar radiation at seasonal scale, and the map of the topographic wetness index (*TWI*) (Fig. 3). Values of solar radiation (*SR*, kWh m^{-2}) summarize the different physiographic conditions of aspect and slope steepness that appear in the study area and are of interest to analyze the role of *SR* on the variation of soil moisture (Bennie *et al.* 2008). The maps of seasonal *SR* were calculated with *SAGA 1.2* (System for Automated Geoscientific Analyses; http://www.saga-gis.org) at daily time step and for a 15-days period. Values of *SR* were calculated without considering water vapour pressure and diffuse insolation due to the lack of the necessary information. The topographic wetness index combines local upslope contributing area (a) and slope (β), and is commonly used to quantify topographic control on hydrological processes (Sørensen *et al.* 2006).

$$TWI = \ln\left(\frac{a}{\tan\beta}\right) \tag{2}$$

Methods of computing this index differ primarily in the way the upslope contributing area is calculated. In this study the upslope contributing area is calculated with the *Sediment Yield Tools 1.03* extension for *ArcView GIS 3.2*. Maps of relative topsoil moisture at catchment scale were done with the *ArcGIS 9.2* application.

Results and discussion

Antecedent (θ_0, % Vol) and relative (θ_R, %) topsoil moisture presented the highest mean, minimum and maximum values in autumn (December) (average values of 17.7% Vol and 53.2%, respectively) and the lowest in summer (August) (10.7% Vol and 32.1%) for the whole catchment (Table 2). However, variability of θ_0 and θ_R was higher in spring (May) and winter (February) than in summer and autumn. These values show a positive and direct correlation with values of seasonal precipitation (r-Pearson = 0.62) and an inverse relationship with those of solar radiation (r-Pearson = 0.53) (Table 2). These correlations agree with field measurements and rain gauge records reported by several authors under different climate conditions (e.g. Keefer *et al.* 2008).

Relative topsoil moisture presents a high spatial variation within the catchment and during the four seasons as can be seen in the corresponding maps of θ_R (Fig. 2). Estimated values of θ_R vary for the different topographic conditions and the highest values occur in spring, summer and winter in steep northern slopes (Fig. 4). Moreover, soil moisture progressively decreases from steep northern slopes to gentle slopes and from gentle slopes to steep southern slopes (Fig. 4). A similar and inverse topographical trend was also observed in the calculated values of solar radiation (*SR*) for the four seasons obtaining the highest values in steep southern slopes and the lowest insolation was estimated in steep northern slopes (Table 3). The maximum annual variation of θ_R took place in steep northern orientated soils (149%). In gentle northern slopes the average maximum annual variation was 139%, whereas in gentle and steep southern slopes the variation was 130 and 119%, respectively. Hence, values of relative topsoil moisture and of the maximum annual variation of θ_R decreases with increasing solar radiation. These results agree with the measurements of incoming solar radiation flux and soil moisture performed by Bennie *et al.* (2008) in grassland field sites of the United Kingdom and under different conditions of slope and aspect.

In order to analyze other topographic parameters controlling the spatial variation of the relative topsoil moisture, values of θ_R were related to the topographic wetness index (*TWI*). The relationship between the *TWI* and the topsoil moisture has been used by several authors to analyze the influence of topography in hydrological and soil processes (e.g. Seibert *et al.* 2007). However, no significant correlation was found, though in summer a positive trend was observed. The topographical complexity of the study area that is divided into fifteen sub-catchments and presents numerous sinkholes could explain this lack of correlation. The solar radiation factor appears to be the most significant physiographic factor controlling the spatial variability of topsoil moisture at catchment scale and more important than others such as the topographic wetness index.

Values of relative topsoil moisture in autumn are not in accordance with the described physiographic-moisture trend observed in spring, summer and winter. In autumn the maximum values of relative topsoil moisture (56.2%) appear in gentle southern orientated soils. This unexpected spatial pattern can be explained by changes in the infiltration properties of the different soil types in this season when the heaviest storm events take place (López-Vicente *et al.* 2008). Soil water repellency has been observed at the end of the dry season in other Mediterranean soils (Cerdà and Doerr 2008; Murillo and Ruiz Sinoga 2008) and can explain the irregular pattern of soil moisture registered during the autumn field campaign in the Estaña catchment.

Relative soil moisture varied greatly for the different soil types. The highest values at annual scale were measured in Gleysols (mean equals 55%) and Vertisols (49%) and the lowest in Leptosols (40%) and Gypsisols (35%) (Fig. 5). The differences of θ_R between the six soil types of the study area were also observed at seasonal escale, e.g., Leptosols and Regosols always presented lower values of θ_R than Calcisols. The statistical analysis (ANOVA) performed with the values of θ_R for the main soil types and for the four seasons in the Estaña catchment indicates that there were significant differences between the soil types in spring and winter and no significant differences in summer and autumn (Table 4).

The standard deviation (s.d.) of the values of relative soil moisture and of the maximum annual variation decreased with decreasing means of topsoil moisture. In addition, changes in soil moisture at annual scale are lower in Gypsisols (s.d. 12%), Leptosols and Regosols than in Calcisols, Gleysols and Vertisols (s.d. 21%). The range of estimated values of θ_R for the soils at the Estaña catchment is of the same magnitude than other ranges observed in similar soil types, such as in Gypsisols in Central Ebro Valley in Spain (between 14 and 31%) (Navas *et al.* 1998) or in Regosols in Germany (Kuzyakova and Stahr 2006).

The lowest values of relative topsoil moisture appear in summer for all soil types, except in Vertisols that has the lowest values in winter with a mean value of 27.5%. Moreover, this value of θ_R is the lowest for all soil types and for the four seasons. This low value of θ_R can be explained by the high content of ice observed in the soil profile of Vertisols that can affect the measurements of soil moisture (Fig. 1).

The physiographic trend of relative topsoil moisture observed at seasonal and catchment scales also appear in the main soil types of the study area. Calcisols and Leptosols present the highest values of θ_R in steep northern slopes in spring, summer and winter and Regosols also in spring and winter (Table 5). Moreover, values of the maximum annual variation have the same trend in Leptosols and Regosols. This trend is not observed in any soil type in autumn when the maximum values of θ_R were measured.

The values of relative topsoil moisture are negatively correlated with those of solar radiation (Table 6). Correlation was good in winter for the different soil types when solar radiation varied the most for the different physiographic units (standard deviation of SR = 11 kWh m^{-2} for a 15-days period) and the range of values of relative topsoil moisture is the highest registered during the four season campaigns (standard deviation of θ_R = 19.1%). The best correlation was found in Vertisols in winter (r-Pearson equals 0.85). Correlation was poor in spring (s.d. of SR = 4 kWh m^{-2}) and summer (s.d. of SR =

5 kWh m^{-2}) when the lowest range of values of *SR* were calculated and medium and low values of relative topsoil moisture were measured. No significant correlation was found in autumn for any soil type. The lack of correlation in autumn could be due to the combined effect of low values of solar radiation estimated during this field campaign as it was close to the solstice (mean SR = 30 kWh m^{-2} for a 15-days period) together with the high values of relative topsoil moisture that are close to the values of field capacity of the soil in many control points.

These results draw attention to the importance of considering the spatial and seasonal variation of the solar radiation factor that is strongly dependant on the slope steepness and aspect conditions for a more precise estimation of the topsoil moisture content within the catchment scale and for different soil types. In Mediterranean environments, where significant changes of topsoil moisture are frequent, the consideration of the results of this work is of interest to enhance the characterization of topsoil moisture at catchment and seasonal scales. This better assessment of topsoil moisture will help improving the performance of hydrological models to predict the peak of runoff at catchment and event scales (von Peter and Zepp 2008) and of soil erosion models in the calculation procedures of soil erodibility for concentrated runoff (Knapen *et al.* 2008). Moreover, the ease of mapping the different physiographic units with GIS applications and available DEMs makes the estimation of solar radiation a low time-consuming tool to discriminate moisture-sensitive areas within each soil type that results of interest in agronomic and forest studies and management planning.

Conclusions

Relative topsoil moisture (θ_R) significantly varies within the catchment and during the four seasons, reaching the highest values in autumn (December) and the lowest in summer (August). Variation of θ_R increases with increasing their measured values. The seasonal variation of θ_R has a positive correlation with the seasonal values of rainfall and a negative correlation with those of solar radiation (*SR*).

A physiographic trend has been identifying between values of θ_R and the slope steepness and aspect factors. Steep northern slopes present the highest values of topsoil moisture whereas topsoil moisture progressively decreases in gentle areas and the lowest values are measured in steep southern slopes. This trend was observed in spring, summer and winter and is associated to the spatial variability of *SR* for the different physiographic units during the different seasons. Topsoil moisture in autumn reach high values and no physiographical trend is observed. Moreover, *SR* is very low in this season and can not explain the spatial variations of θ_R within the catchment. The topographical complexity of the study area explains the low correlation observed between the values of θ_R and those of the topographic wetness index.

Topsoil moisture varies for the different soil types appearing the highest values in Gleysols and Vertisols and the lowest in Gypsisols though Calcisols, Leptosols and Regosols are the main soil types. This pattern of values of θ_R for the different soil types remains constant for the four seasons. In most control points, topsoil moisture spatially varies within each soil type following the same physiographic trend observed for the whole catchment.

The correlation between values of *SR* and θ_R improves with increasing the range of values of both properties and thus, correlation is best in winter. Hence, the different physiographic conditions add considerable variability to the values of topsoil moisture within each soil type and must be considered in detailed hydrological studies. This work underlines the usefulness of considering spatial and temporal variations of *SR* – an ease and low time-consuming property to assess – at catchment and soil type scales to enhance the characterization of topsoil moisture in Mediterranean environments.

Acknowledgements

This research was financially supported by the following project: “Soil erosion and carbon dynamic in Mediterranean agroecosystems: radioisotopic modelling at different spatial and temporal scales” (MEDEROCAR, CGL2008-00831/BTE) funded by the Spanish Ministry of Science and Innovation.

References

Bellot J, Ortiz de Urbina JM (2008) Soil water content at the catchment level and plant water status relationships in a Mediterranean Quercus ilex forest. *Journal of Hydrology* **357**(1-2), 67–75.

Bennie J, Huntley B, Wiltshire A, Hill MO, Baxter R (2008) Slope, aspect and climate: Spatially explicit and implicit models of topographic microclimate in chalk grassland. *Ecological Modelling* **216**(1), 47–59.

Cerdà A, Doerr SH (2007) Soil wettability, runoff and erodibility of major dry-Mediterranean land use types on calcareous soils. *Hydrological Processes* **21**(17), 2325–2336.

Esteves M, Descroix L, Mathys N, Lapetite JM (2005) Soil hydraulic properties in a marly gully catchment (Draix, France). *Catena* **63**(2–3), 282–298.

Gallart F, Llorens P, Latron J, Regüés D (2002) Hydrological processes and their seasonal controls in a small Mediterranean mountain catchment in the Pyrenees. *Hydrology and Earth System Sciences* **6**(3), 527–537.

Gomi T, Sidle RC, Ueno M, Miyata S, Kosugi K (2008) Characteristics of overland flow generation on steep forested hillslopes of central Japan. *Journal of Hydrology* **361**(3–4), 275–290.

Govers G, Loch RJ (1993) Effects of initial water content and soil mechanical strength on the runoff erosion resistance of clay soils. *Australian Journal of Soil Research* **31**(5), 549–566.

Israelsen OW, Hansen VE (1965) 'Principios y aplicaciones del riego. 2a. ed.' (Editorial Reverté: Barcelona, Spain)

Keefer TO, Moran MS, Paige GB (2008) Long-term meteorological and soil hydrology database, Walnut Gulch Experimental Watershed, Arizona, United States. *Water Resources Research* **44**, W05S07.

Knapen A, Poesen J, Govers G, De Baets S (2008) The effect of conservation tillage on runoff erosivity and soil erodibility during concentrated flow. *Hydrological Processes* **22**, 1497–1508.

Kuzyakova IF, Stahr K (2006) Use of time series analysis and mixed models in studying the long-term dynamics of soil temperature and moisture in a catena on loess deposits. *Eurasian Soil Science* **39**(2), 176–186.

Lal R (2007) Anthropogenic Influences on World Soils and Implications to Global Food Security. *Advances in Agronomy* **93**, 69–93.

Lal R (2008) The urgency of conserving soil and water to address 21st century issues including global warming. *Journal of Soil and Water Conservation* **63**(5), 140A–141A.

Leib BG, Jabro JD, Matthews GR (2003) Field evaluation and performance comparison of soil moisture sensors. *Soil Science* **168**(6), 396–408.

López-Vicente M, Navas A, Machín J (2008) Identifying erosive periods by using RUSLE factors in mountain fields of the Central Spanish Pyrenees. *Hydrology and Earth System Sciences* **12**(2), 523–535.

López-Vicente M, Navas A, Machín J (2009) Geomorphic mapping in endorheic subcatchments in the Spanish Pyrenees: an integrated GIS analysis of topographic-karstic features. *Geomorphology* **111**(1-2): 38–47.

Machín J, López-Vicente M, Navas A (2008) Cartografía digital de suelos de la Cuenca de Estaña (Prepirineo Central). In "Trabajos de Geomorfología en España, 2006-2008". (Eds J Benavente, FJ Gracia) (In Spanish) pp. 481–484. (SEG: Cádiz, Spain)

Morgan RPC (1995) Soil Erosion and Conservation. Second Edition. (Longman Group Limited: Harlow, United Kingdom)

Murillo JFM, Ruiz Sinoga JD (2008) La humedad antecedente del suelo como factor de la estacionalidad de la escorrentía y la movilización de sedimentos en los ambientes eco-geomorfológicos de una ladera mediterránea (Montes de Málaga). In "Trabajos de Geomorfología en España, 2006-2008". (Eds J Benavente, FJ Gracia) (In Spanish) pp. 105–108. (SEG: Cádiz, Spain)

Navas A, Bermúdez F, Machín J (1998) Influence of sewage sludge application on physical and chemical properties of Gypsisols. *Geoderma* **87**(1-2), 123–135.

Ramírez-Beltran ND, Castro JM, Harmsen E, Vásquez R (2008) Stochastic transfer function model and neural networks to estimate soil moisture. *Journal of the American Water Resources Association* **44**(4), 847–865.

Regüés D, Gallart F (2004) Seasonal patterns of runoff and erosion responses to simulated rainfall in a badland area in Mediterranean mountain conditions (Vallcebre, Southeastern Pyrenees). *Earth Surface Processes and Landforms* **29**(6), 755–767.

Rockström J, Barron J, Brouwer J, Galle S, de Rouw A (1999) On-Farm Spatial and Temporal Variability of Soil and Water in Pearl Millet Cultivation. *Soil Science Society of America Journal* **63**, 1308–1319.

Santhi C, Kannan N, Arnold JG, Di Luzio M (2008) Spatial calibration and temporal validation of flow for regional scale hydrologic modeling. *Journal of the American Water Resources Association* **44**(4), 829–846.

Seibert J, Stendahl J, Sørensen R (2007) Topographical influences on soil properties in boreal forests. *Geoderma* **141**(1-2), 139–148.

Sørensen R, Zinko U, Seibert J (2006) On the calculation of the topographic wetness index: evaluation of different methods based on field observations. *Hydrology and Earth System Sciences* **10**(1), 101–112.

Talluto G, Farina V, Volpe G, Lo Bianco R (2008) Effects of partial rootzone drying and rootstock vigour on growth and fruit quality of 'Pink Lady' apple trees in Mediterranean environments. *Australian Journal of Agricultural Research* **59**(9), 785–794.

Terzoudi ChrB, Gemtos TA, Danalatos NG, Argyrokastritis I (2007) Applicability of an empirical runoff estimation method in central Greece. *Soil & Tillage Research* **92**(1-2), 198-212.

Urbieta IR, Pérez-Ramos IM, Zavala MA, Marañón T, Kobe RK (2008) Soil water content and emergence time control seedling establishment in three co-occurring Mediterranean oak species. *Canadian Journal of Forest Research* **38**(9), 2382–2393.

von Peter C, Zepp H (2008) Detection of the temporal variability of the catchment runoff tendency based on soil-moisture measurements. *Hydrologie und Wasserbewirtschaftung* **52**(3), 98–109.

Table 1. Surface area, mean soil depth, bulk density (*BD*), percentage of coarse fragments, clay and organic matter (*OM*), volumetric water content at field capacity (θ_{FC}), saturated hydraulic conductivity (K_{fs}), and matrix flux potential (ϕ) for the different soil types described in the Estaña catchment (NE Spain).

Soil type	Area		Depth	BD	Stoniness	Clay	OM	θ_{FC}	K_{fs}	ϕ
	ha	%	cm	g cm^{-3}	%	%	%	% vol	cm s^{-1}	cm^2 s^{-1}
Calcisol	73	32	28	1.22	33	21	3.9	31.8	0.00044	0.0146
Gleysol	10	4	35	1.07	18	20	3.6	33.7	0.00003	0.0009
Gypsisol	16	7	35	1.15	12	22	2.2	36.4	0.00001	0.0002
Leptosol	73	32	21	1.20	31	22	4.6	34.7	0.00095	0.0016
Regosol	49	22	29	1.29	26	22	3.2	36.2	0.00030	0.0033
Vertisol	7	3	40	1.23	16	22	2.0	31.5	0.00017	0.0006

Table 2. Seasonal rainfall and solar radiation (*SR*, for a 15-days period) and basic statistics of field measured (θ_0) and relative estimated (θ_R) topsoil moisture during the four seasons in 236 control points in the Estaña catchment (NE Spain).

s.d., Standard deviation.

Season	Rainfall (mm)	SR (kWh m^{-2})	θ_0 (%Vol)				θ_R (%)			
		Mean	Mean	Min.	Max.	s.d.	Mean	Min.	Max.	s.d.
Spring (May)	168	106.9	15.6	8.4	27.4	3.7	45.2	10.2	110.4	17.0
Summer (Aug.)	147	98.3	10.7	4.9	19.5	2.2	32.1	9.3	66.5	7.8
Autumn (Dec.)	175	30.1	17.7	8.9	35.3	3.5	53.2	22.8	121.1	12.7
Winter (Feb.)	95	34.6	13.1	4.1	36.3	4.3	39.3	11.7	119.3	14.1

Table 3. Estimated solar radiation (*SR*) in steep northern, gentle northern, gentle southern and steep southern slopes for the four seasons in the Estaña catchment.

Physiographic units	SR (kWh m^{-2})			
	Spring (May)	Summer (Aug.)	Autumn (Dec.)	Winter (Feb.)
Steep northern	98.5	87.6	14.2	18.1
Gentle northern	106.7	95.4	21.3	25.6
Gentle southern	109.0	100.3	30.9	35.7
Steep southern	107.0	101.2	40.2	45.3

Table 4. Means of relative topsoil moisture (θ_R, %) for the main soil types and during the four seasons in the Estaña catchment.

Within columns, values followed by the same letter are not significantly different at *P*=0.05 (using Fisher's least significant difference procedure).

Soil type	*n*	Spring (May)		Summer (Aug.)		Autumn (Dec.)		Winter (Feb.)	
Calcisol	79	48.2	b	32.0	a	56.4	a	44.8	b
Leptosol	82	38.3	a	30.4	a	51.4	a	39.6	ab
Regosol	51	42.7	ab	32.9	a	50.6	a	34.5	a

Table 5. Basic statistics of relative topsoil moisture (θ_R) and maximum annual variation ($\theta_{MaxAnnVar}$) calculated for the main soil types in the Estaña catchment during the four seasons and for the different physiographic conditions.

s.d., Standard deviation

Physiographic units	*n*	θ_R (%)																$\theta_{MaxAnnVar}$ (%)
		Spring (May)				Summer (August)				Autumn (December)				Winter (February)				
		Mean	Min.	Max.	s.d.	Mean	Min.	Max.	s.d.	Mean	Min.	Max.	s.d.	Mean	Min.	Max.	s.d.	Mean
Calcisol																		
Steep northern	10	60.3	33.9	95.5	17.4	37.5	17.4	50.7	10.6	49.0	30.1	77.0	16.7	50.4	15.7	99.9	31.9	134.8
Gentle	58	47.4	18.1	110.5	20.0	31.0	9.3	61.4	9.7	56.6	29.5	103.0	16.8	45.2	15.6	119.8	22.2	138.2
Steep southern	11	41.3	10.4	78.5	23.8	31.0	21.5	43.9	9.9	65.8	36.5	134.6	37.3	33.4	23.9	42.6	7.3	168.9
Leptosol																		
Steep northern	6	54.4	25.9	75.3	22.3	30.1	25.5	37.7	6.6	45.5	28.8	61.7	16.5	61.4	32.8	98.0	33.4	172.9
Gentle	38	42.0	15.8	71.8	15.8	30.9	18.7	50.1	9.2	50.9	28.7	78.3	13.9	44.3	17.9	107.0	18.9	144.0
Steep southern	38	33.0	16.0	78.1	15.5	30.0	15.7	66.5	9.9	52.2	33.1	111.5	16.7	33.3	11.9	65.6	11.1	118.5
Regosol																		
Steep northern	3	47.4	33.0	58.9	13.2	25.0	19.7	33.3	7.3	50.4	33.4	69.5	18.1	60.3	27.0	80.1	29.0	214.6
Gentle	32	46.4	16.7	91.0	16.5	35.3	18.4	58.6	10.9	51.2	27.3	95.4	15.6	33.6	12.7	62.0	12.0	111.8
Steep southern	16	34.7	10.7	70.4	14.9	29.6	16.8	44.4	8.7	49.2	23.6	73.3	16.8	31.1	18.9	62.6	13.4	99.6

Table 6. Correlation coefficients (r-Pearson) calculated between values of relative topsoil moisture (θ_R, %) and solar radiation (*SR*, kWh m^{-2}; for a 15-days period) for the four seasons and for the different soil types in the Estaña catchment.

Soil type	*n*	Spring (May)	Summer (Aug.)	Autumn (Dec.)	Winter (Feb.)
Calcisol	79	0.23	0.36	0.11	0.38
Gleysol	7	**0.52**	0.41	0.02	**0.65**
Gypsisol	9	0.37	**0.76**	0.22	**0.59**
Leptosol	82	0.41	0.23	0.15	**0.64**
Regosol	51	0.16	0.01	0.08	0.43
Vertisol	8	0.13	0.38	0.43	**0.85**

Fig. 1. Geographic situation of the Estaña catchment in NE Spain and monthly values of precipitation and temperature registered during the period 1993-2006. Map of soil types of the study area and location of the measurement points of topsoil moisture. Photos of some soil types and of a frozen soil.

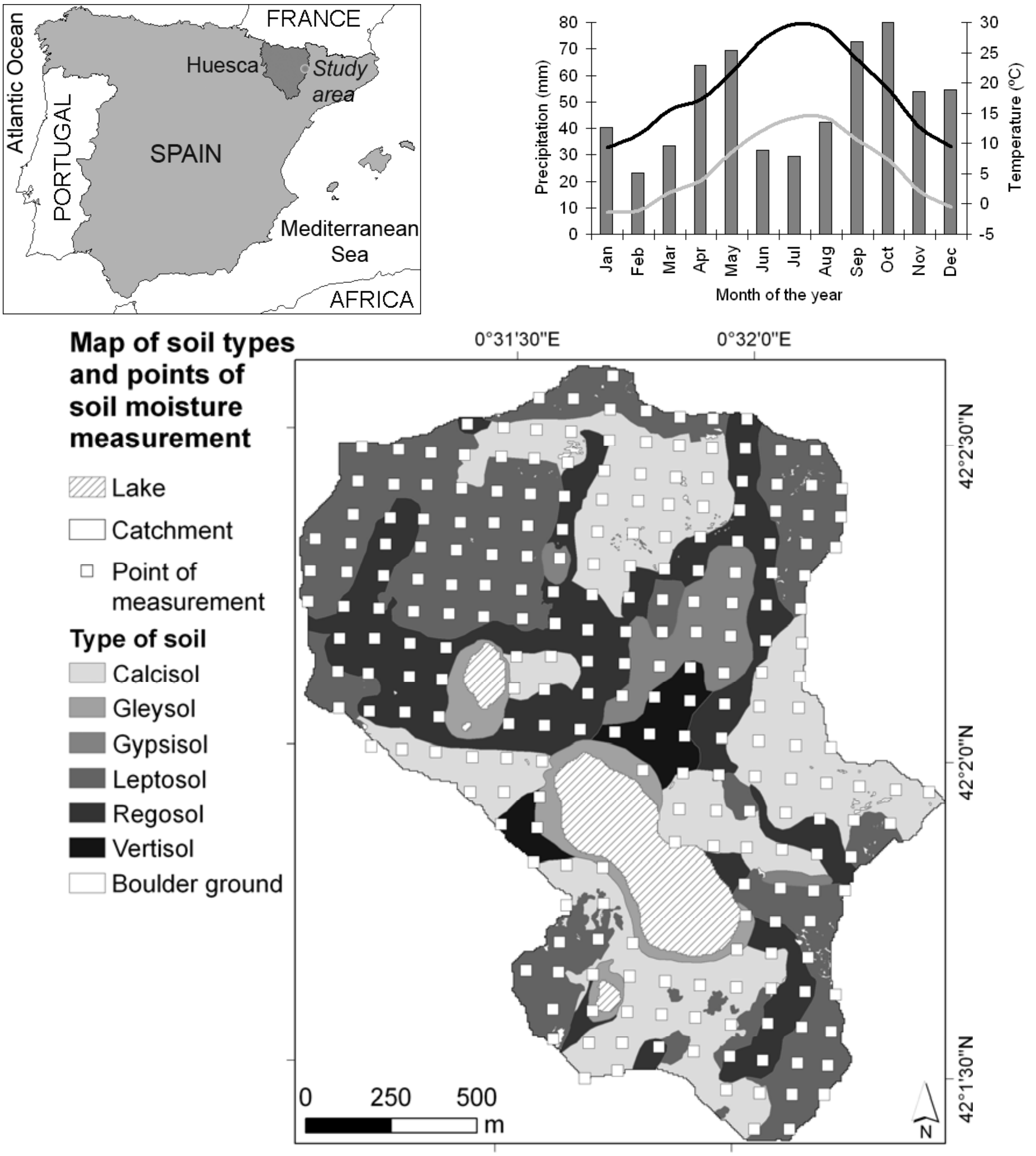

Fig. 2. Relative topsoil moisture content (θ_R, %) in spring, summer, autumn and winter, and maximum annual variation of relative soil moisture in the Estaña catchment (NE Spain).

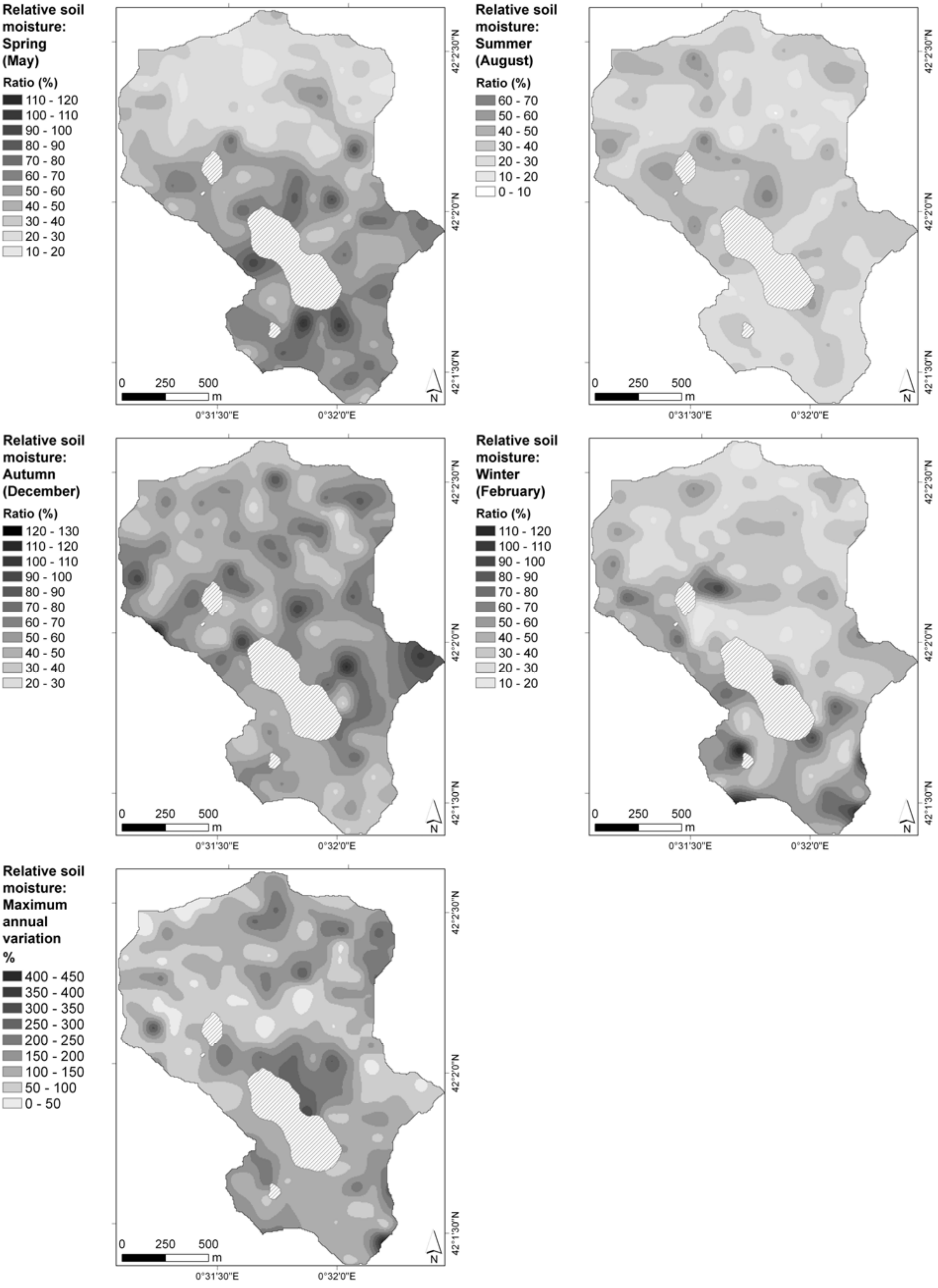

Fig. 3. Maps of physiographic units, annual solar radiation and topographic wetness index in the Estaña catchment (NE Spain).

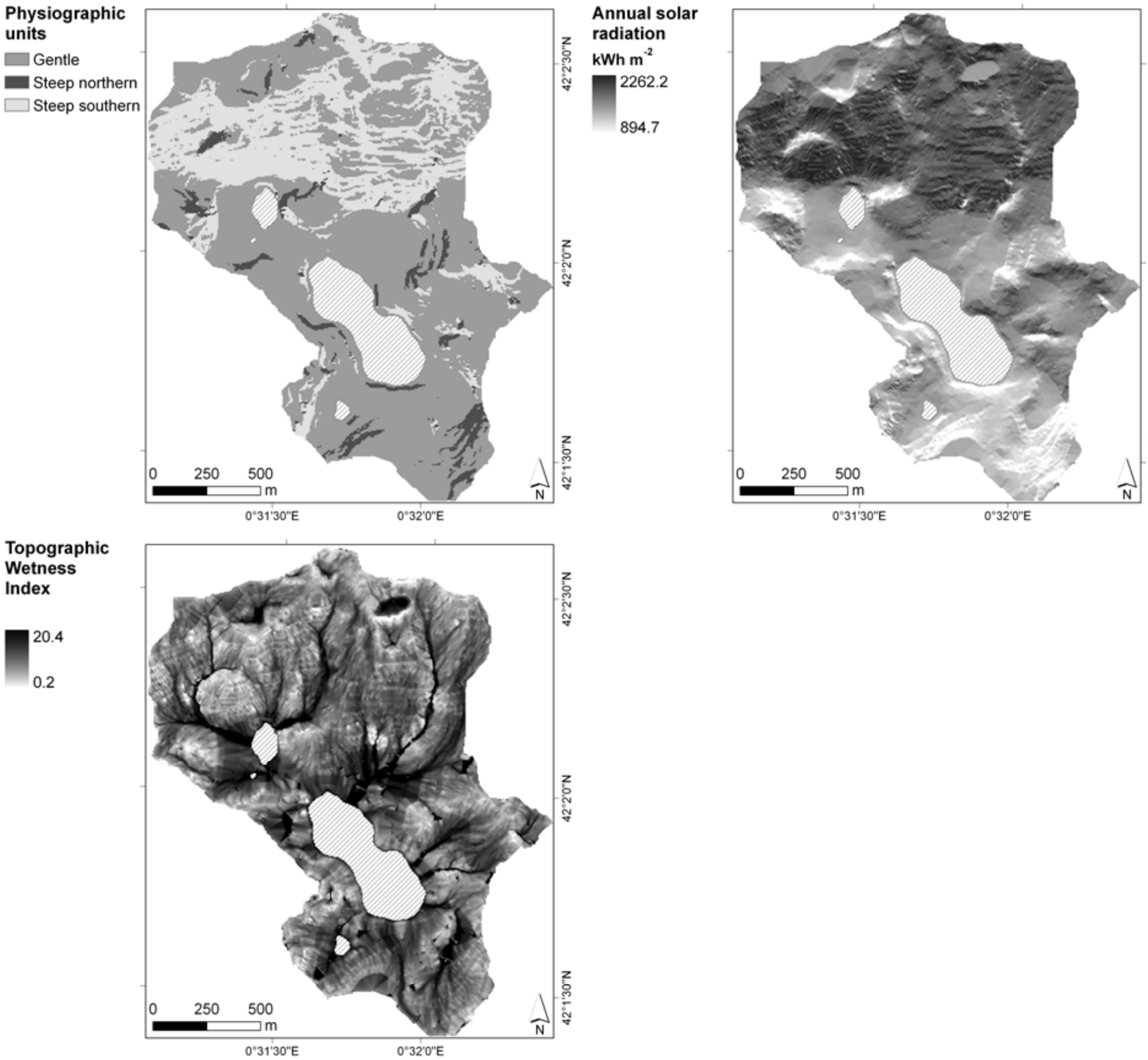

Fig. 4. Statistical values of the relative topsoil moisture content (θ_R, %) in steep northern, gentle northern, gentle southern and steep southern slopes measured in spring, summer, autumn, and winter in the Estaña catchment (NE Spain).

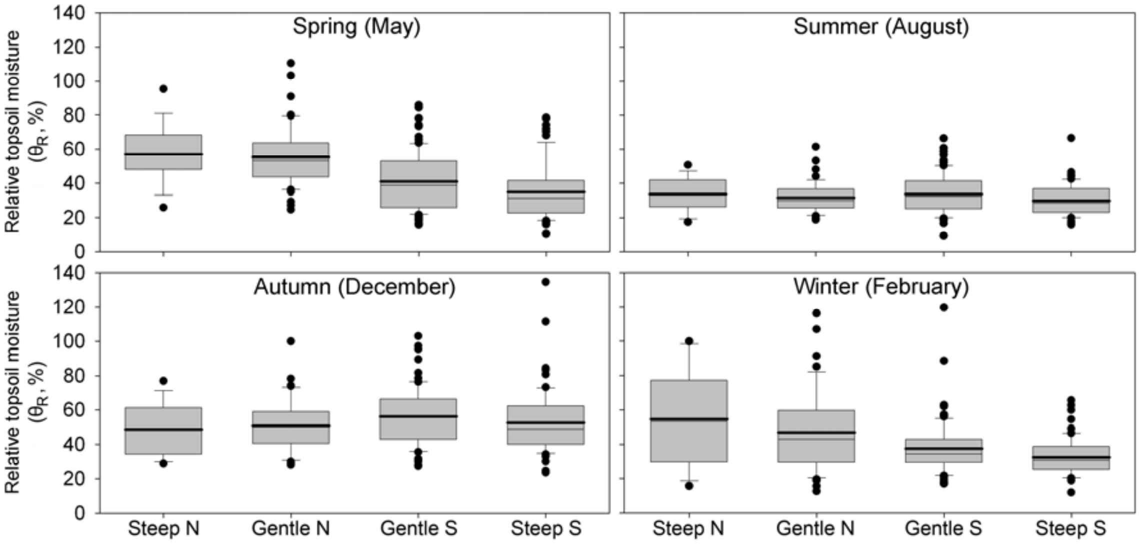

Fig. 5. Statistical values of the relative topsoil moisture content (θ_R, %) for the different soil types measured in spring, summer, autumn, and winter in the Estaña catchment (NE Spain).