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Soil moisture spatio-temporal behavior of *Pinus pinaster* stands on sandy flatlands of central Spain

V. Gomez-Sanz[1]* and J. I. Garcia-Viñas[2]

[1] *Departamento de Silvopascicultura. EUIT Forestal. Universidad Politécnica de Madrid. Ciudad Universitaria, s/n. 28040 Madrid. Spain*

[2] *Departamento de Producción Vegetal: Botánica y Protección Vegetal. EUIT Forestal. Universidad Politécnica de Madrid. Ciudad Universitaria, s/n. 28040 Madrid. Spain*

Abstract

Pinus pinaster stands in the center of the Iberian Peninsula frequently grow in a unique hydrological system characterized by a variable groundwater table near the soil surface and highly permeable soils (arenosols). Over the last few decades, this superficial aquifer has been overused as a water resource, especially for irrigated crops. Overuse has reached a critical level and has caused various environmental impacts and a water sustainability crisis wherein rainfall variability does not allow for a sufficient level of aquifer recharge by natural means. Within this changing scenario, soil water significantly affects the spatio-temporal ecological response, necessitating more extensive characterization of the complex soil-tree water relationship. The primary goal of the present work was to evaluate the influence of root zone soil moisture on the observed spatial response of *Pinus pinaster* stands. Volumetric soil moisture content was measured at eleven forest sites, using time-domain reflectometry (TDR), over a two-year observation period. The results demonstrate that the combined effect of groundwater table proximity and dune morphology associated with this area are the main factors driving very different water availability conditions among the monitored hydrological response units, which modulate maritime pine installation and development. Topographically lower areas are more heterogeneous in terms of soil moisture behavior. In these areas, the conifer forests that are connected to the water table may be the most sensitive to land use changes within current environmental change scenarios. Consequently, in these pine ecosystems, the combined influences of geomorphology and water table proximity on variations in root zone soil moisture are essential and must be considered to develop adequate adaptive management models.

Key words: water availability; hydrological response unit; hydrological landscape; *Mediterranean maritime pine*.

Resumen

Comportamiento espacio-temporal de la humedad edáfica en masas de *Pinus pinaster* de las llanuras arenosas del centro de España

Las masas de *Pinus pinaster* del centro de la Península Ibérica se desarrollan con frecuencia sobre un sistema hidrológico singular, caracterizado por la presencia de una capa freática próxima a la superficie y de suelos altamente permeables (arenosoles). A lo largo de las últimas décadas, este especial acuífero superficial ha sido sobreexplotado como recurso hídrico, sobre todo para satisfacer las demandas de la agricultura intensiva. Este proceso ha alcanzado niveles críticos y ha provocado diferentes impactos ambientales y problemas de disponibilidad hídrica en aquellas zonas donde la entrada de agua por precipitación no permite la recarga natural de los niveles freáticos. En este escenario de cambio, el agua del suelo determina significativamente la respuesta ecológica a distintas escalas espacio-temporales, lo que hace necesaria una caracterización más precisa de las complejas relaciones hídricas que se establecen entre los árboles y el suelo. El principal objetivo del este trabajo ha sido evaluar la influencia de la humedad edáfica en la zona de enraizamiento sobre la respuesta espacial de las masas de *Pinus pinaster*. El contenido volumétrico del agua en el suelo ha sido medido en once localizaciones forestales, empleando equipos TDR (time-domain reflectrometry), a lo largo de un periodo de observación de dos años. Los resultados demuestran que la proximidad de los niveles freáticos junto a la morfología dunar característica del área de estudio son los principales factores que determinan la variabilidad en las condiciones de disponibilidad hídrica entre las unidades de respuesta hidrológica identificadas, modulando tanto la instalación como el desarrollo de *Pinus pinaster* en este territorio. Las zonas topográficamente más bajas son las más heterogéneas en términos de comportamiento de la humedad edáfica. En estas áreas, los roda-

* Corresponding author: valentin.gomez@upm.es
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les de pino que están conectados a los niveles freáticos pueden ser los más sensibles al cambio en el uso del suelo dentro de los actuales escenarios de cambio ambiental. Consecuentemente, en estos pinares, la influencia combinada de la geomorfología y la proximidad de los niveles freáticos sobre la humedad edáfica en la zona radical del suelo resulta esencial y debe ser considerada en el desarrollo de adecuados modelos de manejo adaptativo para estas masas.

Palabras clave: disponibilidad hídrica; unidad de respuesta hidrológica; paisaje hidrológico; pino rodeno.

Introduction

Soil moisture plays a significant role in many of the biogeochemical processes involved in landscape pattern dynamics (Kimmins, 1997; Barnes *et al.*, 1998; Beldring *et al.*, 1999; Winter, 2001; Paul *et al.*, 2003; Bürgi *et al.*, 2004). This relationship is emphasized in hydrological systems with special features such as a variable groundwater table near the soil surface or highly permeable soils, which are controlled by a special geological substratum like wind sands (Ronen *et al.*, 2000; Nielsen and Perrochet, 2000; Chen and Hu, 2004). Both of these critical conditions are present in vast areas in the center of the Iberian Peninsula. They strongly affect human land use and consequently influence the structure and function of the resulting landscape.

Over the last few decades, this superficial aquifer has been overused as a water resource, especially for irrigated crops. Overuse has reached a critical level and has caused various environmental impacts and a water sustainability crisis wherein rainfall variability does not allow for a sufficient level of aquifer recharge by natural means (MIMAM, 1998). In areas where fewer good dam sites are available for construction, groundwater is the primary component of the water supply, and its use can be expected to increase as growing populations demand more water.

In natural systems, soil moisture in the unsaturated zone changes as a result of precipitation recharge and water exchange with both atmosphere and groundwater. Between precipitation events, the soil moisture content has a maximum value at a state of hydrostatic equilibrium; this value is determined by the physical characteristics of the soil and the depth to the groundwater table (Beldring *et al.*, 1999; Rodríguez-Iturbe and Porporato, 2004).

This implies that variability in soil moisture conditions at the patch scale depends, in a first approximation, on heterogeneous soil characteristics. Nevertheless, above a certain threshold scale, variations in soil characteristics are smoothed out and the spatial variability of soil moisture content becomes primarily controlled by depth to the groundwater table and topographic variability. Topography has a significant effect on subsurface flow and moisture conditions in a catchment and can therefore be used to distinguish among hydrological response units (Thompson and Moore, 1996; Beldring *et al.*, 1999; Chen and Hu, 2004).

Likewise, the definition of the equilibrium state assumes that the soil moisture tension at any given depth depends on the distance to the groundwater table. In areas with shallow groundwater (a high groundwater table), soil moisture variations are very different from those in areas with a deep groundwater table. A significant hydraulic gradient between the saturated zone and the root zone leads to a continuous supply of groundwater to the root zone. The effect of groundwater on variations in root zone soil moisture is essential (Or and Wraith, 2000; Chen and Hu, 2004), and this process creates an additional spatial heterogeneity, similar to that created by variations in topography, vegetation cover, and soil properties. Consequently, the volumetric moisture in the upper soil centimeters shows as main characteristic a considerably high variability over short distances due to combine effects of this set of driving factors.

The temporal and spatial variations in soil moisture are essential components of the processes that affect ecosystem dynamics and biogeochemical cycles in the land-atmosphere system (Evett, 2000). Soil water availability is directly associated with the spatial variability in soil moisture generated by the factors discussed above, and it is without question a dominant factor in shaping the distribution of forest vegetation communities. For this reason, the spatial characterization of soil water is critical for understanding current distributions of vegetation and for predicting future adjustments to the spatial response of forest stands under climate change scenarios (Pastor and Post, 1988; Lookingbill and Urban, 2004).

Soil moisture behavior is important not only for explain the vegetation spatial response o for improving the capacity of atmospheric models for accurately describing the hydrological processes occurring in land-atmosphere systems but also for improving our understanding of the processes of land use change that are related to and influenced by soil moisture variations (Bürgi *et al.*, 2004; Chen and Hu, 2004).

In recent years, in response to the lack of available long-term measurements, a series of international efforts have been undertaken to estimate global soil moisture with temporal resolutions ranging from daily to annual. Several land and soil hydrological models have been developed that include soil moisture effects, although their reliability is largely dependent upon model formulation, assumptions related to model parameterization, input data quality and characterization of land surface heterogeneity (Mahmood and Hubbard, 2003; Paul *et al.*, 2003; Chen *et al.*, 2002). Nevertheless, several journals articles have suggested that there is a dearth of knowledge regarding the factors that control soil moisture content (Ceballos *et al.*, 2002; Chen and Hu, 2004; Lookingbill and Urban, 2004).

This study therefore hypothesizes that the spatial response of forest vegetation at a landscape scale is controlled by the spatio-temporal variability of available soil water. From this starting point, the main aim of this paper was to evaluate the spatio-temporal behavior of soil water availability using observational data of root zone soil moisture as well as to relate different aspects of hydrological land behavior (the «hydrologic landscape») to the observed spatial response of *Pinus pinaster* stands. These results can improve comprehension of the mechanisms underlying the ecological response of mediterranean pine species to scenarios of changing water availability and of the interactions among different components of future environmental changes.

Material and methods

The study area is located in Segovia (Spain) and extends over 1,000 ha (UTM coordinates: ED50 391500-396500 and 4569750-4572750) (Fig. 1). The physical environment is quite homogeneous, presenting a typical geomorphology known as «*Tierra de Pinares*», which is characterized by Quaternary incoherent detritic materials (wind sands) in a fairly flat land area with soft slopes and some depressions that may hold small pools at the end of winter or spring. The average elevation is around 800 m, and the altitudinal range is lower than 100 m. Soils are sandy, quite permeable and aerated, and they have limited organic matter, low fertility and near-neutral pH.

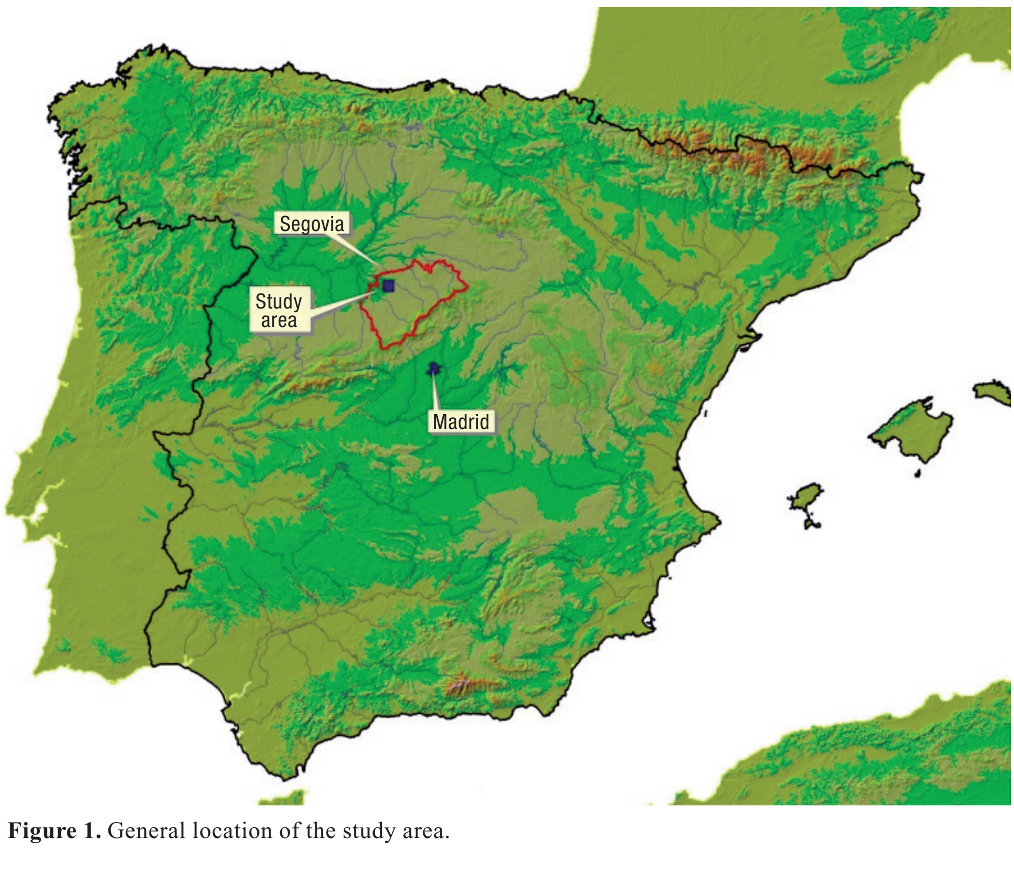

Figure 1. General location of the study area.

The area's climatic conditions are Mediterranean with continental influences. The average annual precipitation is around 480 mm. Maximum precipitation occurs in November (over 50 mm) and minimum precipitation occurs in August (often less than 15 mm). The average annual temperature is close to 12°C, with a maximum monthly average of 22.5°C in July and a minimum of 3.5°C in January.

This particular physical environment serves as a biotope for various plant groups. The most extensive is a woodland formation that is dominated by Mediterranean *Pinus pinaster* in different stand states that coexist with intensive agricultural land use.

The role of soil moisture in plant response has been explored through the analysis of spatio-temporal patterns of Soil Water Availability (SWA), defined as:

$$SWA = \frac{\theta - \theta_{WP}}{\theta_0 - \theta_{WP}} \cdot 100$$

where θ = volumetric soil moisture content (%), θ_{WP} = volumetric soil moisture content (%) for pF = 4.2 (wilting point), and θ_0 = volumetric soil moisture content (%) for pF = 0.0 (at saturation).

The experimental approach was spatially organized based on eleven identified monitoring sites, corresponding to different hydrological response units. This process was the result of a combination of two main factors that control soil moisture content: runoff balance and water table position. Figure 2 shows a diagram of the spatial distribution of all sites chosen for monitoring.

Soil moisture was measured using the principle of time-domain reflectometry (TDR) —TRASE SYSTEM1, 6050X1—. The TDR measurements were performed using 45-cm-long electrodes that were inserted perpendicular to the soil surface, into the current root zone, for two years (from December 2003 to November 2005). Measurements were made monthly, around the 15th of each month, on days without rainfall to observe soil in the draining phase. Monthly soil moisture data were used to examine seasonal trends.

Additionally, three piezometers from the Spanish Department of Agriculture network were selected, and the site elevations as well as the relative positions of the piezometers were determined to the nearest centimeter. The approximate position of the groundwater table at each site was established by combining the piezometer reading and the elevation difference.

A full soil survey was also conducted at all monitoring sites. The soil profile was sampled to a depth of 1.25 m, and texture, organic matter content and the soil-moisture characteristic curve [pF 0 (at saturation); pF 2.5 y pF 4.2 (wilting point)] was determined. All analytical procedures were performed at the soil laboratory of «Centro de Ciencias Medioambientale-CSIC» in Madrid (Spain), following standardized and validated methods.

Finally, the water input to the system was assumed to be the daily rainfall recorded at the automated weather station Gomezserracín —SG01— (INFORIEGO System, Junta de Castilla y León, Department of Agriculture).

Table 1 presents an overview of the monitoring sites, including the type of vegetation cover, highest position (closer to the surface) of groundwater table, and soil conditions. Notably, the sites have homogeneous soil conditions, very high amounts of sand, and low organic matter contents. The high variability of ages and development stages that show the selected pine stands hasn't made feasible the use of site index equations (Bravo-Oviedo *et al.*, 2004, 2007) to evaluate its quality.

Numerical analyses were performed using the SPSS 15.0 statistical package. The significance of the differences among soil water availability results for the considered factors was evaluated following a Repeated Measures ANOVA within a multivariate general linear model developed for this purpose. Means were separated using Bonferroni adjustment. All statistical tests were considered significant when $p < 0.05$.

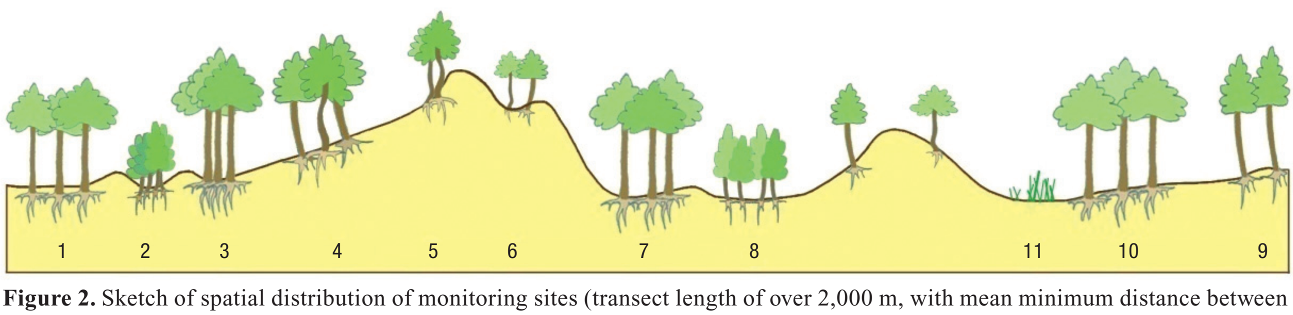

Figure 2. Sketch of spatial distribution of monitoring sites (transect length of over 2,000 m, with mean minimum distance between sites of 150 m).

Table 1. Characteristics of the monitoring sites

Site	Forest Stand			H.L.G.[1] (m)	Soil conditions						
	Dominant height (m)	Density (stems/ha)	Basal area (m^2/ha)		Sand (%)	Clay (%)	O.M.[2] (%)	θ(pF 0.0) (%)	θ(pF 2.5) (%)	θ(pF 4.2) (%)	B.D.[3] (g/cm^3)
1	16.0	547	50.44	1.29	98.0	1.0	0.24	28.58	2.21	1.37	1.67
2	< 1.0	> 10,000	0.00	1.48	97.1	1.9	0.48	28.73	3.77	2.00	1.65
3	19.0	945	76.19	1.85	95.3	3.7	0.43	30.81	4.64	2.41	1.65
4	13.0	448	65.37	3.78	97.1	1.9	0.33	30.10	2.71	1.61	1.66
5	13.0	547	47.83	11.03	98.2	0.8	0.49	26.80	3.22	1.38	1.66
6	7.5	199	11.69	9.35	99.0	0.5	0.16	30.29	1.85	0.79	1.68
7	20.5	498	50.39	1.11	96.0	3.1	0.36	30.35	3.66	1.53	1.66
8	< 1.0	> 10,000	0.00	0.91	93.3	5.7	0.49	34.87	6.16	2.52	1.64
9	12.3	249	19.62	2.90	97.7	2.3	0.23	32.03	1.86	0.87	1.67
10	20.0	348	39.34	2.13	97.1	2.9	0.47	29.58	3.16	1.50	1.65
11	0.0	0	0.00	1.12	91.1	7.2	0.89	38.41	9.96	4.16	1.60

[1] Highest level of groundwater table (lowest depth respect to soil surface). [2] Organic matter. [3] Bulk density [Pedotransfer function of Santos (1979), validated with analytical date of Ceballos *et al.* (2002)]. Analytical methods: texture, Bouyoucos densimeter; O.M., Walkley and Black; humidity curve, Richard's membrane.

Results

The main descriptive statistics for SWA in each site are shown in Table 2. Overall, three sites appear to have a different behavior from the rest. The greatest water availability is present in Site 3, which has the maximum SWA mean and range. At the other extreme is Site 4, where data have a more centered behavior and appears the lowest water availability. Between both of them, the site 11 shows the greatest variability, with the highest value of SWA standard deviation. Comparing the two years of study, no differences in behavior are identified transcendent, while the second is somewhat drier and less variable than the first (during the second year of observation, the winter-spring period was slightly drier while the summer-autumn period was wetter than the previous year).

Table 2. Descriptive statistics for Soil Water Availability (SWA) by monitoring site

SWA (%)	Site										
	1	2	3	4	5	6	7	8	9	10	11
Year 1 (n = 12)											
Mean	16.04	19.30	34.47	9.70	19.58	15.91	13.72	23.84	14.94	16.59	14.60
S.D.	11.43	11.38	14.36	5.93	10.80	7.70	7.92	13.94	7.50	12.44	16.33
Max.	33.55	39.28	63.35	19.27	34.30	27.15	22.45	42.91	24.81	37.04	37.49
Min.	0.11	4.49	15.11	2.42	4.01	3.76	0.94	3.96	3.63	1.78	–4.55
Year 2 (n = 12)											
Mean	11.81	20.36	26.55	10.79	19.45	15.85	14.73	22.17	15.66	15.67	12.21
S.D.	8.74	9.09	10.20	6.65	10.84	8.20	11.14	13.95	6.42	11.88	12.08
Max.	28.78	38.53	49.61	22.08	35.48	27.49	29.39	42.29	25.13	37.39	32.23
Min.	1.58	8.23	14.40	2.07	3.23	2.41	0.24	1.48	3.95	2.49	–0.18
Total (n = 24)											
Mean	13.92	19.83	30.51	10.25	19.52	15.88	14.22	23.01	15.30	16.13	13.40
S.D.	10.18	10.09	12.84	6.19	10.58	7.78	9.47	13.67	6.84	11.90	14.10
Max.	33.55	39.28	63.35	22.08	35.48	27.49	29.39	42.91	25.13	37.39	37.49
Min.	0.11	4.49	14.40	2.07	3.23	2.41	0.24	1.48	3.63	1.78	–4.55

S.D.: standard deviation. Max.: maximum. Min.: minimum.

Table 3. Multivariate contrasts of the MLG repeated measures procedure for SWA by month of the year

Effect	Test	Value	F	Hypothesis D.F.	Error D.F.	Significance level
Year	Pillai's trace	0.175	2.121	1.000	10.000	0.175
	Wilks' lambda	0.825	2.121	1.000	10.000	0.825
	Hotelling's trace	0.212	2.121	1.000	10.000	0.212
	Roy's largest root	0.212	2.121	1.000	10.000	0.212
Month	Pillai's trace	1.000	1,422.155	10.000	1.000	0.021
	Wilks' lambda	0.000	1,422.155	10.000	1.000	0.021
	Hotelling's trace	14,221.546	1,422.155	10.000	1.000	0.021
	Roy's largest root	14,221.546	1,422.155	10.000	1.000	0.021

In order to deepen the understanding of the intra-annual variability of SWA, the general linear model developed following the repeated measures procedure allows to identify a clear seasonal variation throughout the two years of observation, and two well-defined periods can be recognized. Table 3 includes the results of multivariate test used to compare the effects of factors year and month on the dependent variable SWA. The contrast is significant for the effect of the month factor, while not for the year factor.

To identify periods with a significant difference between means, a pairwise comparison between monthly average values of SWA was performed using Bonferroni adjustment for the confidence interval and the significance. Results are shown in Figure 3. The higher average values of SWA were extracted over the period between November and April. This interval corresponds to the wet period and closely coincides with the late autumn and winter seasons. Low average values appear slowly, beginning in June and continuing until September. This interval corresponds to the summer season and represents the dry period of annual variation. May and October appear to be transition months.

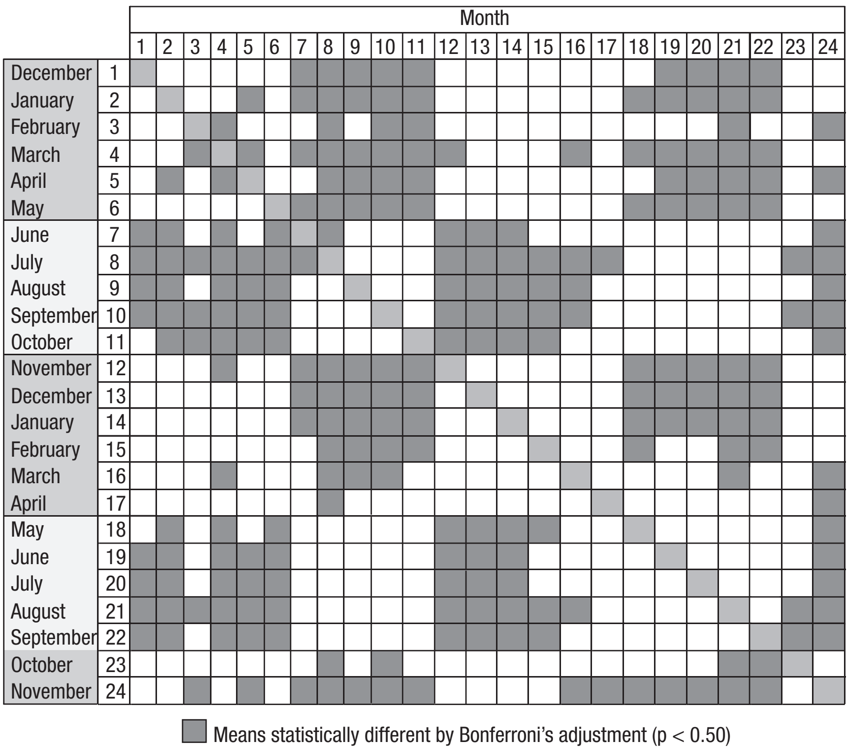

Figure 3. Univariate pairwise comparisions for the within-subjects factor: month.

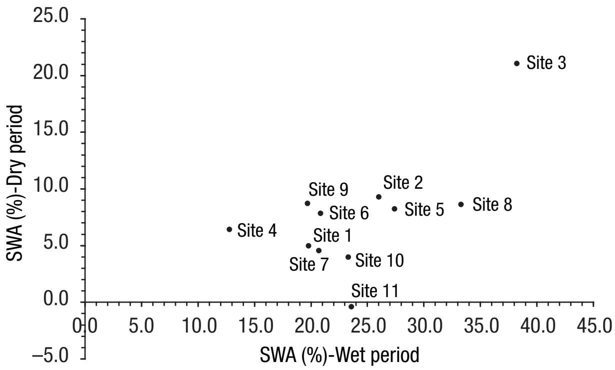

Figure 4. Average values of SWA by site in each annual period.

The average values for each site along the identified annual periods are depicted in Figure 4. The analysis of site spatial distribution indicates evident differences between them. The sites 3, 4, 8 y 11 delimit a polygon, with the rest of sites included within it, representing the most disparate SWA situations in the study area.

As expected, higher average values were found for sites located in slight depressions during both periods, where the gravitational water that enters into the system through rainfall accumulates and the groundwater table is enough close to soil surface. In these areas, the SWA behavior was more homogeneous, and lower average values were found in dune peak and hillside sites along the wet period.

More details of SWA behavior became visible during the dry period. The lower average values appeared in sites with endorheic features, which are associated with higher amounts of fine particles (clays) in the soils; although there is more soil water, it is also more strongly retained (Evett, 2000). A secondary minimum appeared in the flat sites, probably due to more plant material returning water to the atmosphere, largely through transpiration. The maximum average value was found in areas near the water table.

Discussion

These results show that the hydrological landscape (Winter, 2001) strongly affects the spatial variability of both soil moisture content and availability and, consequently, influences plant response. The combination of the groundwater table position and the dune landform in the study area caused higher spatial variability of SWA, which facilitated the identification of four hydrological response units (HRU) for soil moisture behavior (Fig. 5) with different impacts on plant response.

The first HRU corresponds to those zones with a deep water table (sites 4, 5, 6 and 9). In this scenario, soil moisture content is consistently low and remains within a narrow range of variation (to exception of site 5, where SWA shows unexpected high values in the wet period, probably consequence of the surrounding concave topography that tends to accumulate the superficial and subsuperficial water flows); however, it is always available for vegetation. In these zones, the pine stands often have low density, low growth, and tortuous stems.

Hydrologically, these zones act as primary recharge areas where downward groundwater movement leaves less water available to compensate for the deficit. The soil moisture deficit relative to the equilibrium value is highest in the upper parts of slopes; this result is supported by Thompson and Moore (1996).

The second HRU corresponds to zones with neutral runoff balance and a water table near the surface, ensuring a water intake (sites 1, 7 and 10). Soil moisture content is higher and consistently available. The vegetal response is good, and pine stands are strongly associated to high density, high growth, and stems more straight.

Those zones with light depression and water table near the soil surface make the third HRU (sites 2, 3 and 8). Currently, these areas show either dense and mature stands or pine seedlings with high density and growth rates, appearing after clear-cutting.

Both of these HRUs result from the effect of groundwater on maintaining the observed soil moisture, especially in deep layers and where the presence and size of the capillary fringe (located over the groundwater table in the unsaturated zone) is of special interest (Nielsen and Perrochet, 2000). It is well known that the position of the capillary fringe over the groundwater table has important seasonal fluctuations; Ronen *et al.* (2000) provide a studio where the average height of the capillary fringe in sandy soil is around 1.4 m. Capillary fringe values can change spatially as well. Surveys of sample sites within a 5 m area have shown that the capillary fringe position changes by 33% and 50% before and after the rainy season, respectively.

The extracted results for site 3 can be interpreted in terms of capillary fringe position. Soil capillary water is found in the top 45 cm during some periods of the year, which causes remarkably high and consistent soil moisture rates regardless of the amount of rainfall. The groundwater effect leads to an upward vertical gradient

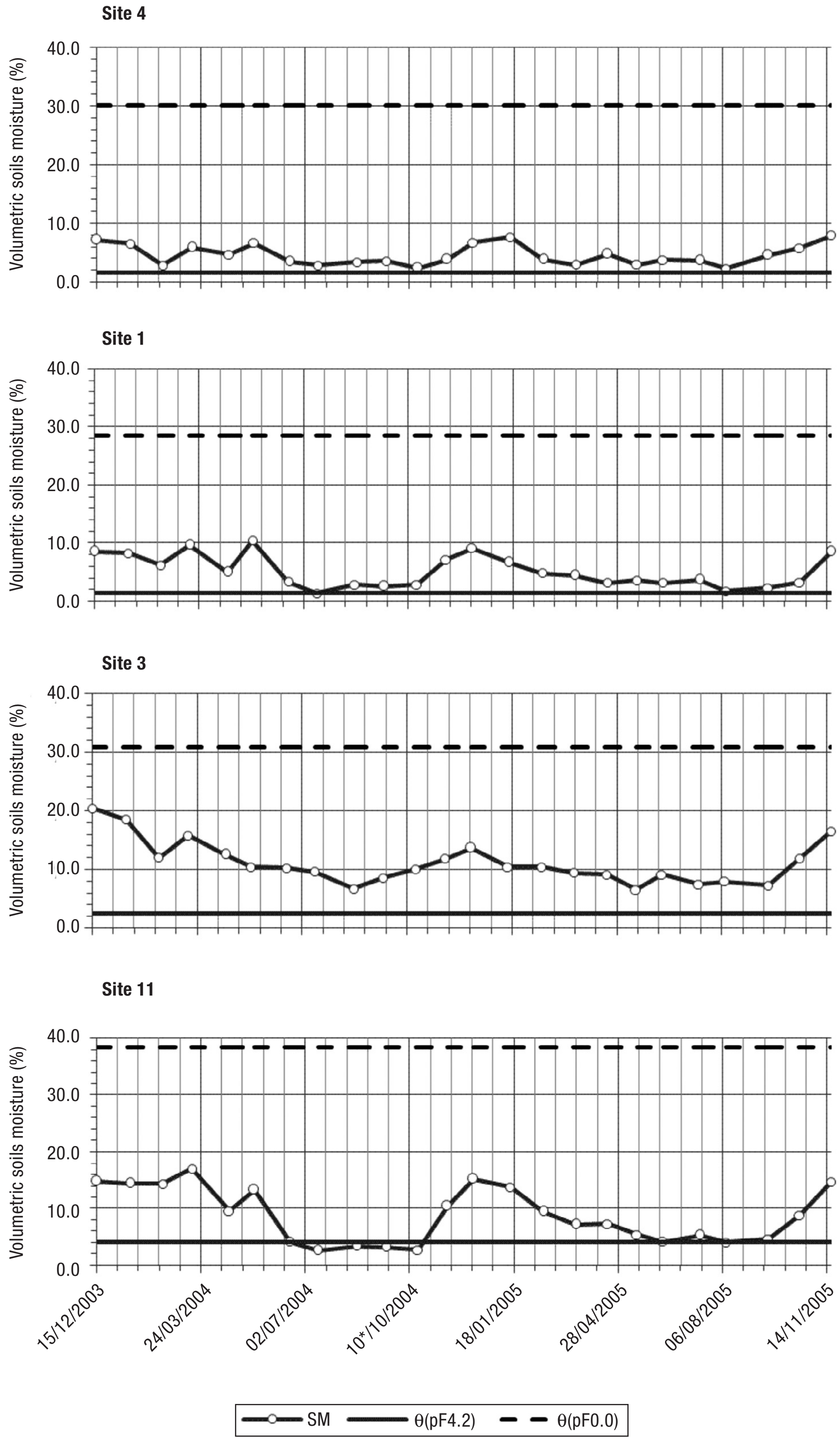

Figure 5. Temporal behavior of soil moisture in each identified HRU.

for the soil moisture and consequently a unique soil hydrological environment. According to Beldring *et al.* (1999), this is due to the capillary transport of water and means that the groundwater level determines the possible range of fluctuations in soil moisture content.

The second and third HRUs represents the zones that have been most changed by recent human uses, including intensive agriculture and conifer forest plantations of *Pinus pinaster*. Most of the root volume remains in the soil unsaturated zone, and only the pivoting root connects to the water table (wet season) or the capillary fringe (dry season). This water supply ensures much higher growth rates during dry periods. Changes in the use of the superficial aquifer could lead to changes in the ecological pattern of the landscape, especially in these lower zones where the effects of new land uses will be concentrated.

The last HRU corresponds to zones with endorheic features and a positive runoff balance (site 11). These areas are characterized by extreme seasonal behavior, somewhat larger than in the first scenario, with high soil moisture during the wet period and low moisture during the dry period. From an eco-physiological point of view, it is remarkable that there are times during the dry periods in which water is not usable (pF greater than 4.2). This condition can exclude many species, especially *Pinus pinaster,* and represents an ecologically important process driver.

These results demonstrate the important influence of SWA on the presence and the development of forest stands in the study area. The stands of *Pinus pinaster* in areas with a shallow water table are able to be partially connected to the groundwater and have soil moisture conditions that are especially conducive to growth. *Pinus pinaster* is one of the few tree species that preserves its pivoting root all the way into maturity. This root plays an important role in water and nutrient supply (Danjon *et al.*, 1999; Westerman *et al.*, 2000); a small quantity of deep, fine roots can be sufficient to provide combined breathing and water uptake processes during the dry period (Le Maitre *et al.*, 1999).

Consequently, special attention should be given to *Pinus pinaster* wood stands that are located in lower zones, where they are partially connected to the capillary fringe and the groundwater table. These stands could be highly sensitive to changes in underground water levels and could suffer negative impacts from new land uses if the trees are suddenly disconnected from the groundwater table or the area of influence of the capillary fringe.

Conclusion

The unique lithology and geomorphology (dune landform) of the sandy flatlands of central Spain strongly influence the spatial variability of soil moisture and, consequently, the availability of soil water for vegetation. This effect determines the current features of the ecological landscape and has far-reaching consequences for ecological system dynamics and human land use.

Within this apparently homogeneous region, areas where the proximity of the water table allows for high water availability during the dry period are more «fragile.» These zones have been most impacted by recent human uses such as intensive agriculture and conifer forest plantations of *Pinus pinaster*.

In this particular context, changes in the use of the superficial aquifer could lead to changes in the landscape ecological pattern by altering the relationship between soil moisture and vegetation. The pinus stands partially connected to the capillary fringe and the groundwater table could be highly sensitive to changes in the hydrological landscape, endangering their stability and persistence.

Consequently, readjustment of the ecological system is likely to influence vegetation composition. This ecological risk highlights the need for proper planning during the implementation of corrective actions like artificial aquifer recharge and for development of adequate adaptive management models for the *Pinus* forest stands.

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