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Four Decades of Progress in Monitoring and Modeling of Processes in the Soil-Plant-Atmosphere System: Applications and Challenges

Towards improved understanding of land use effect on soil moisture variability: analysis and modeling at the plot scale

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Abstract

Understanding and characterizing the soil moisture spatial variability and its relevant physical controls is a main challenge in hydrological sciences. In this work we examine the spatial variability characteristics of soil moisture data at 0-30 cm depth collected over three years (2006-2008) on a plot (about 200 m^2) in Grugliasco (Po Plain, Northern Italy) by means of 21 Time Domain Reflectometry probes. The plot is divided into two subplots: one covered by grapevine plants, the other covered homogeneously by grass. The site is almost flat and the soil is sandy. The characteristics of the site allow to isolate the contribution of soil hydraulic properties and land use to soil moisture variability. Examination of the data shows higher soil moisture values in the vineyard than in the meadow, implying the influence of vegetation cover during the growing season; correspondingly, the spatial soil moisture variability is systematically lower in the vineyard than in the meadow. Evaluation of the main physical controls on the spatial mean and the variability of soil moisture is carried out by using a simple bucket model, forced by using local rainfall and evapotranspiration data. The model is calibrated by using mean soil moisture daily time series over one year for the two sites. The model accuracy is verified for the other two years, showing a relatively good prediction capability. The model is also shown to be able to capture the main differences between the two sites in terms of spatial variability.

Keywords: soil moisture, dynamic model, spatial variability, land use

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1. Introduction

Soil moisture is a key variable controlling hydrological and energy fluxes at different spatio-temporal scales [1,2]. Soil moisture plays an important role in climate dynamics from the regional to the global scale by controlling the exchange and partitioning of water and energy fluxes at the land surface. Agricultural and irrigation management practices largely depend on a timely and accurate characterization of temporal and spatial soil moisture dynamics in the root zone. In addition, soil moisture also plays a major role in the organization of natural ecosystems and biodiversity.

Numerous studies have examined the spatial variability of surface soil water content as a function of the mean soil moisture status and of controlling variables related to soil properties, vegetation and topography, with varying conclusions. One main generalisation is that as the mean soil moisture approaches limiting states, at the dry or wet ends, the absolute spatial variability of soil moisture becomes smaller. Between these bounds, however, the trajectories of the spatial variability can be non-unique and dependent on climate, soil, vegetation, topography, and antecedent states [3]. Relatively few studies have focused on the impact of land use characteristics on the main statistics of soil moisture fields, owing to the difficulties in isolating and examining the vegetation contribution with respect to that of the soil properties and topography.

The aim of this work is to analyse the spatial variability characteristics of soil moisture data at the plot scale characterized by two different land uses, i.e., grapevine plants and grass.

A simple dynamic model is used to simulate the two main spatial statistics. The capability of the model to simulate the two spatial statistics time series over the two sites is evaluated and discussed.

2. Study area and observed data

Soil moisture observations were collected over three years (2006-2008) on a plot (about 200 m^2) in Grugliasco (Po Plain, Northern Italy) at 290 m a.s.l. (Fig. 1) by means of 21 Time Domain Reflectometry probes. A broader description of the study site is reported in Baudena et al. [4]. The probes are vertically inserted generating minimal disturbance, owing to the sandy texture and the lack of stones, in the 0-30 cm depth. The plot is divided into two subplots: one covered by grapevine plants (monitored with 12 probes), the other covered homogeneously by grass (with 9 probes). The terrain slope is about 1%, the soil is sandy and around the measurement field there is a buffer grass area about 20 m wide. Precipitation and temperature are recorded continuously on site. The characteristics of the site allow to isolate the contribution of soil hydraulic properties and land use to soil moisture variability.

Rainfall climatology in this area is characterized by two maxima, respectively in spring (April–May) and fall (October–November), with relatively dry winter and summer [5]. During the three observation years the annual precipitation ranged between 755 mm (2007) to 1183 mm (2008), whereas potential evapotranspiration (estimated by means of the Hargreaves method) ranged between 935 mm (2008) and 1001 mm (2007).

For the purpose of the analysis, soil moisture observations are aggregated at the daily time step, retaining the day when at least four instantaneous observations are available. Due to the varying temporal sampling over the three years, there is a different availability of daily soil moisture data over the three years. Table 1 summarizes the main characteristics of the observed data, including the averages of the spatial means and standard deviations. Inspection of the data shows that mean soil moisture is higher for vineyard than for the meadow; correspondingly, the average of the spatial variability of soil moisture (expressed by the standard deviation) is higher for the meadow than for the vineyard. This is consistent with earlier observations [6,7] and indicates that the variability of soil moisture distributions decreases when the mean soil moisture value increases.

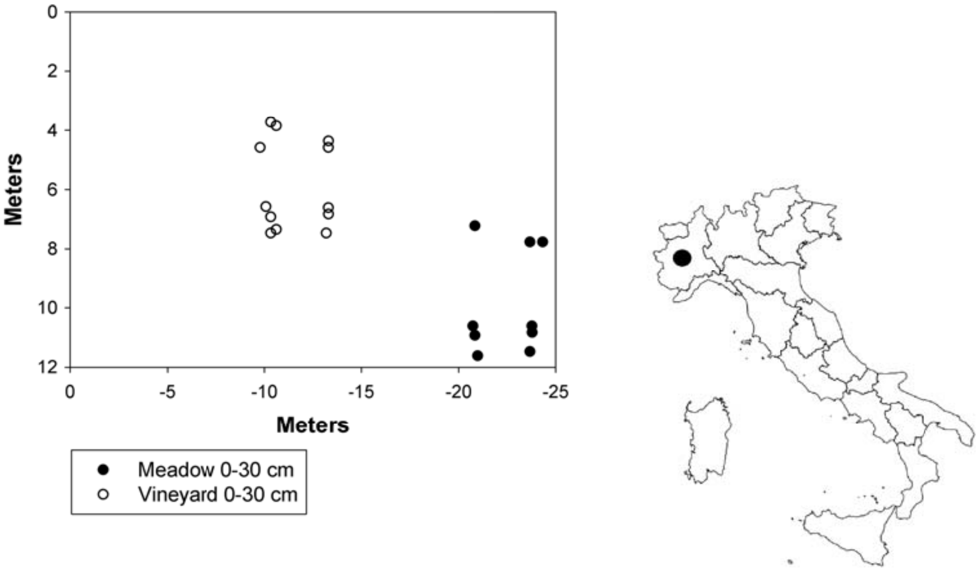

Fig. 1. Map of the experimental site in Grugliasco.

Table 1. Summary of soil moisture statistics over the two land uses for 2006-2008 (only common sampling times are considered).

Summary statistics		Meadow	Vineyard
No. of sampling points		9	12
	2006	151	150
No. of sampling times (days)	2007	206	229
	2008	293	321
Mean (%)		12.9	16.1
Mean of standard deviation (%)		1.2	1.0

Figure 2 shows the distributions of soil moisture spatial statistics: spatial mean and spatial standard deviation for the three years. The statistics are reported for the growing (from April to September) and for the dormant season (from October to March). Consistently with the observations reported above, the mean spatial soil moisture is significantly (Mann-Whitney test $p < 0.001$) higher in the vineyard than in the meadow for both seasons. Not surprisingly, the spatial variability of soil moisture is significantly (Mann-Whitney test $p < 0.001$) higher for the meadow than for the vineyard for both seasons. Particularly, the standard deviation in the vineyard is much higher for the growing period than for the dormant period, implying the effect of the increasing Leaf Area Index (LAI) during the growing season.

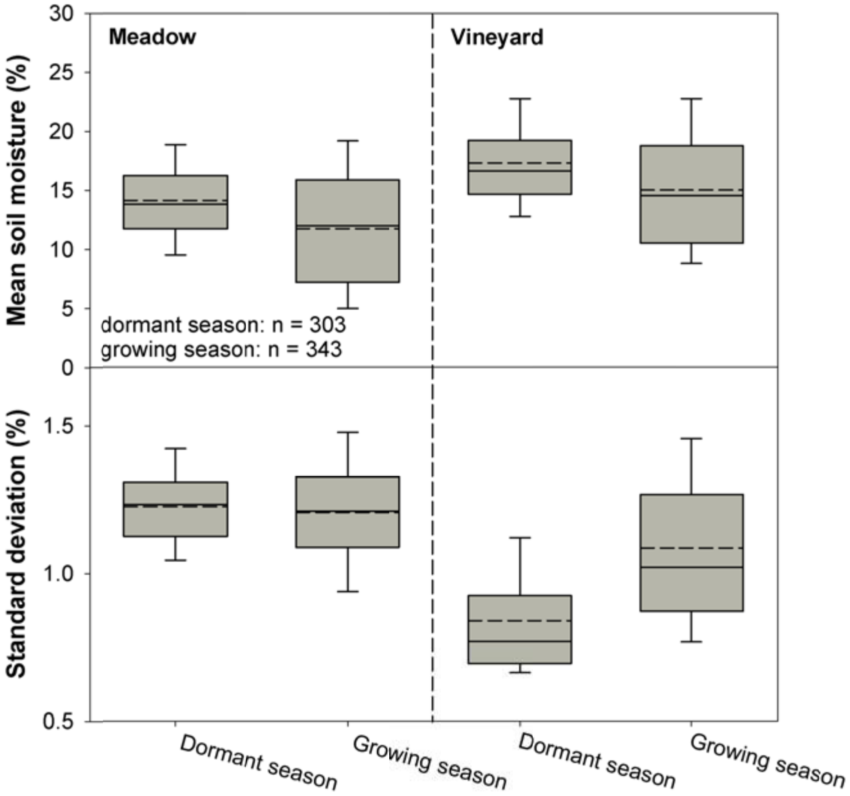

Fig. 2. Boxplots of the mean soil moisture and standard deviation for 2006-2008. The statistics are reported for the meadow and the vineyard and for the growing season (April to September) and the dormant season (October to March). The boxes indicate the 25th and 75th percentile, the whiskers indicate the 10th and 90th percentile, the horizontal line within the box marks the median and the dash line marks the mean.

3. Model description and application

To assess the influence of the land use characteristics on the soil moisture variability, we applied a soil moisture dynamics model developed by Teuling and Troch [8]. The advantage of this model approach is that the number of parameters is small, while the parameters still reflect observable properties [9]. Models of similar complexity have been shown to correctly simulate the root zone soil moisture dynamics under different climatic conditions. The equations of the model are given as follows [8].

The point-scale soil moisture dynamics is spatially unconnected. Vertical redistribution of soil moisture is assumed to occur instantaneously (at the daily time step). The daily water balance for a number of independent soil columns is solved following:

$$\frac{d\theta}{dt} = \frac{1}{Z}(T - S - E - R - q) \tag{1}$$

where θ is the volumetric soil moisture, Z is the depth of the root zone, T the throughfall (i.e., the rainfall that is not intercepted by the vegetation), S the root water uptake, E the evaporation from the soil surface, R the saturation excess runoff (i.e., the part of T that causes oversaturation of the soil) and q the deep drainage. Lateral flow is assumed to be negligible in the root zone. Deep drainage is computed using the following parameterization [10]:

$$q = k_s \left(\frac{\theta}{\phi}\right)^{2b+3} \tag{2}$$

where k_s is the saturated hydraulic conductivity, b is the pore size distribution parameter, Φ is the porosity. The vertically integrated root water uptake is thought to be proportional to a maximum transpiration rate E_p, a soil moisture stress function $\delta(\theta)$ and a function accounting for spatially variable response of unstressed transpiration to atmospheric boundary layer conditions [11]. The root water uptake is computed as follows:

$$S = f_r \delta(\theta)\left[1 - \exp\left(-c\ \xi\right)\right] E_p \tag{3}$$

where f_r is the root fraction in the layer of depth Z, δ is a soil moisture stress function, c is a light use efficiency parameter, ξ is the LAI. The factor [1-exp(-cξ)] allows to account for LAI (ξ). Soil moisture stress is modelled as:

$$\delta = \max\left[0; \min\left(1; \frac{\theta - \theta_w}{\theta_c - \theta_w}\right)\right] \tag{4}$$

where θ_c is the critical soil water content and θ_w is the wilting point, which defines the transition between unstressed and stressed transpiration.

LAI (ξ) is modelled with a spatial and temporal component [6,8]:

$$\xi = \xi_{\max}\left[c_1 - (1 - c_1)\sin\left(2\pi \frac{DOY - c_2}{c_3} + \frac{\pi}{2}\right)\right] \tag{5}$$

where ξ_{max} is the local maximum of ξ, and the parameters c_1 and c_2 indicate the seasonal variation of ξ.

Bare soil evaporation is assumed to be small in comparison to the root water uptake over the entire soil profile. The root zone depth is assumed equal to 30 cm. During the implementation, the model was initialised by using observed soil moisture values. The model was applied at the daily time step, using local rainfall and potential evapotranspiration. The model was calibrated based on the time series of mean soil moisture for 2008 and verified over 2006 and 2007. The index of efficiency and the Root Mean Square were used to quantify the model adequacy. Values for the calibration and the verification periods are reported in Table 2, for both sites. The values show a good predictive capability of the model, particularly when considering that 2008 was much wetter than the other two years. The parameters identified by means of the calibration process are reported in Table 3, showing a good correspondence with similar parameters obtained in the model application exercise described in previous works [4]. The comparison between the time series of simulated and observed daily values is reported for the year 2008, showing both good simulation performances (particularly during the spring and fall months) and less good modelling capability in the late summer season for the meadow site (Fig. 3).

Table 2. Indexes of performance between observed and simulated mean soil moisture data. NS: Nash-Sutcliffe efficiency index; RMSE: Root Mean Square Error.

	Meadow			Vineyard		
	2006	2007	2008	2006	2007	2008
NS	0.80	0.52	0.74	0.82	0.65	0.72
RMSE	2.05	2.77	2.60	1.78	2.37	2.77

Table 3. Parameter values used in the simulation.

Simulation parameters	Meadow	Vineyard
μ_k, σ_k	8.6, 0.32	7.8, 0.40
θ_w	0.19ϕ	0.25ϕ
θ_c	0.22ϕ	0.31ϕ
μ_ξ, σ_ξ	1.6, 0.1	3.5, 0.6
c	0.55	0.55
f_r	0.8	0.8
c_1, c_2, c_3	1, 260, 366	60, 260, 290

μ_k, σ_k = mean and standard deviation for spatial distribution of $\ln(k_s)$
ϕ = porosity
θ_w = wilting point
θ_c = critical moisture content
μ_ξ, σ_ξ = mean and standard deviation for spatial distribution of LAI at its maximum (ξ_{max})
c = light use efficiency parameter
f_r = root fraction in the layer of depth Z (Z = 0.3 m)
c_1, c_2, c_3 = parameters that specify the seasonal development of LAI

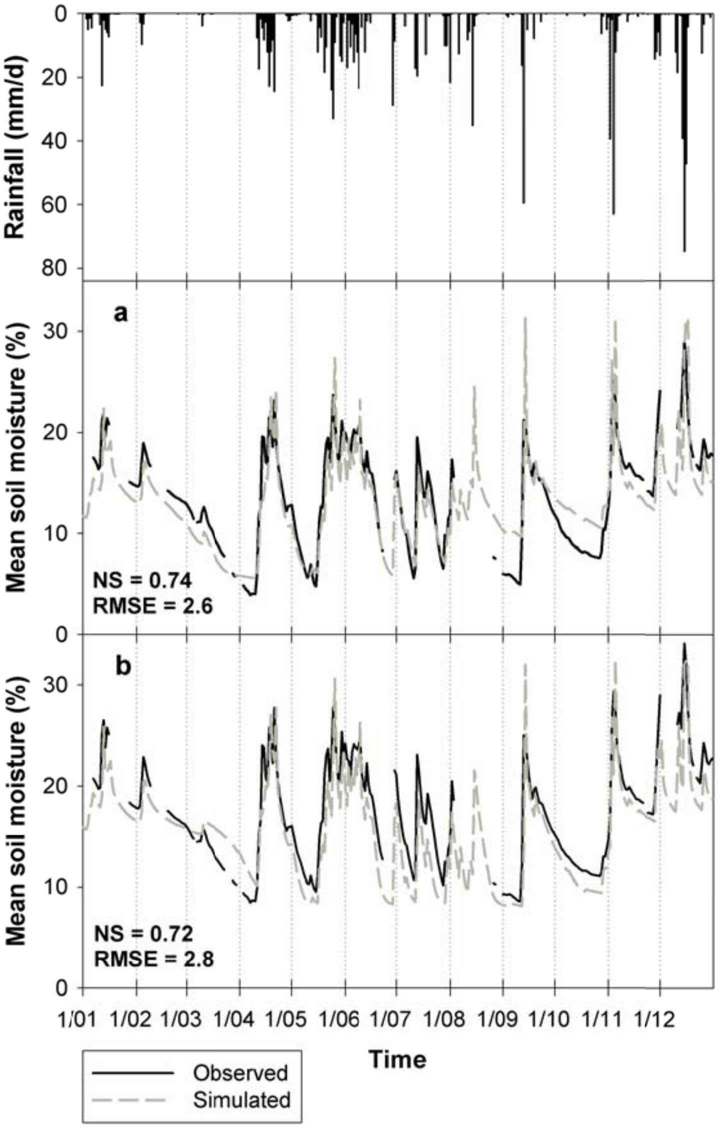

Fig. 3. Time series of spatial mean soil moisture and rainfall for the year 2008 for (a) meadow and (b) vineyard. NS: Nash-Sutcliffe efficiency index; RMSE: Root Mean Square Error.

4. Discussion and concluding remarks

Table 4 reports the comparison between simulated and observed average values of soil moisture spatial statistics, for both meadow and vineyard. Inspection of these statistics shows that the model reproduces well the spatial statistics in the two sites.

A more complete representation of the distribution of both the spatial mean values and the spatial standard deviation is reported in Fig. 4, corresponding to the period June-September 2008. The simulated mean soil moisture reproduces well the observations, for both the meadow and the vineyard. The simulation of the distribution of the spatial standard deviation captures the main differences between the two land uses, with a lower standard deviation for the vineyard than for the meadow. However, the ranges of the values are not well reproduced.

Table 4. Summary of soil moisture statistics over the two land uses for 2006-2008.

		Meadow			Vineyard		
		2006	2007	2008	2006	2007	2008
No. of sampling times		150	205	291	150	205	291
Mean (%)	Observed	11.6	12.9	13.5	14.4	15.8	17.2
	Simulated	12.0	13.1	13.1	15.0	15.2	15.7
Mean of standard deviation (%)	Observed	1.1	1.2	1.3	0.9	1.0	1.0
	Simulated	1.2	1.2	1.3	0.9	0.9	1.0

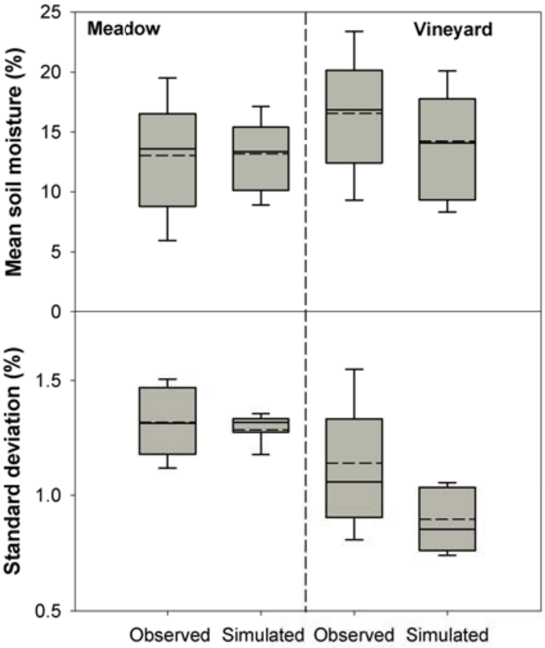

Fig. 4. Boxplots of the spatial mean soil moisture and standard deviation for the period June-September in 2008. The boxes indicate the 25th and 75th percentile, the whiskers indicate the 10th and 90th percentile, the horizontal line within the box marks the median and the dash line marks the mean.

While the results reported so far show that there are limitations in the model capability in reproducing the fine characteristics of the distribution of the spatial standard deviation, the model seems to be adequate to summarise the main differences between the two types of vegetation. On-going investigation aims to use the model to identify the role of vegetation, with respect to that of soil characteristics, to either create or destroy spatial variance along the year and in relation to the sequence of the precipitation events.

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