A study of the spatial variability of soil water retention by mixed effects linear models with a spatial continuous autoregressive correlation structure

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OBJECTIVE

The accurate evaluation of soil hydraulic characteristics is necessary for the reliable application of spatial distribution models, for the simulation of the soil water content in environmental studies and land planning (Romano and Santini 1997). This has both economical and environmental important consequences, the former related to production costs and productivity enhancement, the latter to social costs and soil degradation. As hydraulic characteristics are generally quite difficult to be determined and require high labour costs, they are often predicted by the use of other data readily available in soil surveys (such as soil texture, organic matter content and bulk density). In the standard agronomical practice this kind of data is generally treated by general linear models with uncorrelated errors. However soil hydraulic characteristics are known to be related to the landscape position at the catchment scale. So the assumption of independence seems unrealistic. The aim of this work is to use a linear mixed effects model in order to explicitly consider the spatial correlation structure within the dependence model. Results are then compared to those of a general linear model.

MATERIALS AND METHODS

The study area is located on a hill slope of the Sauro river catchment in Southern Italy. The soils develop mainly in xeric moisture and mesic temperature regimes, and parent materials consist mostly of clayey components. From the geomorphological point of view the area is quite heterogeneous with slope gradients ranging from -0.13 to 0.44 and elevation from 458 m to 1,073 m. Soil samples were collected from topsoil along a transect at 100 locations 50 m apart. Standard laboratory measurements were used to determine the following soil properties: texture (%), bulk density (g cm-3), particle density (g cm-3), porosity, organic carbon content (%). The measured topographic variables were elevation (m) and slope. The volumetric water content at –0.1 m pressure head was measured with a suction table. Exploratory data analysis showed that water retention data had a linear trend with respect to the position on the transect side (Figure 1) and a marginal bell shaped distribution (Figure 2). Both considerations lead to analyse the possible relation between water retention data and the topographic (elevation and slope), physical (bulk density, particle density, porosity, clay, silt and sand contents) and chemical (organic carbon) variables by mixed effects linear models with an autoregressive correlation structure (Pinheiro and Bates 2000) to express the dependence among the observed values collected along the transect. Then the model assumptions were assessed by the comparison of the residuals and the estimated random effects with the quantiles of a standard normal (figure 3 and 4).

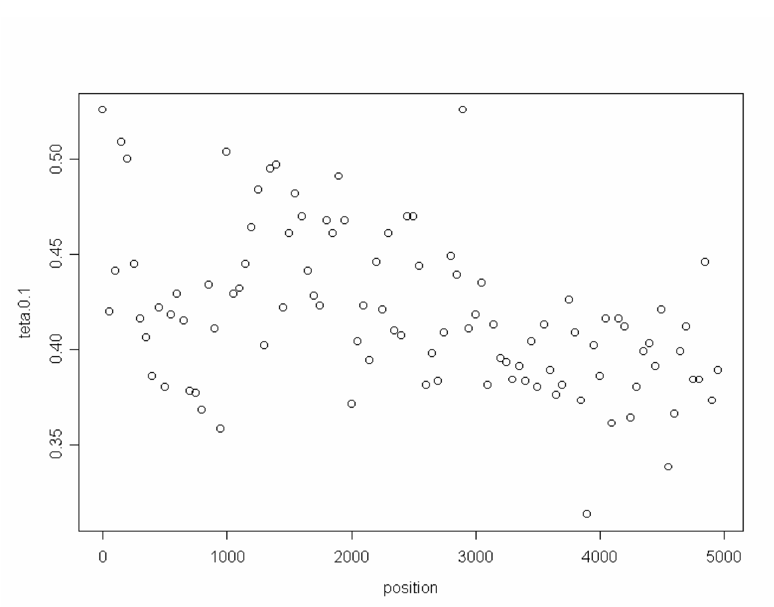

Fig. 1. Spatial distribution of the soil water retention respect to the 100 sites

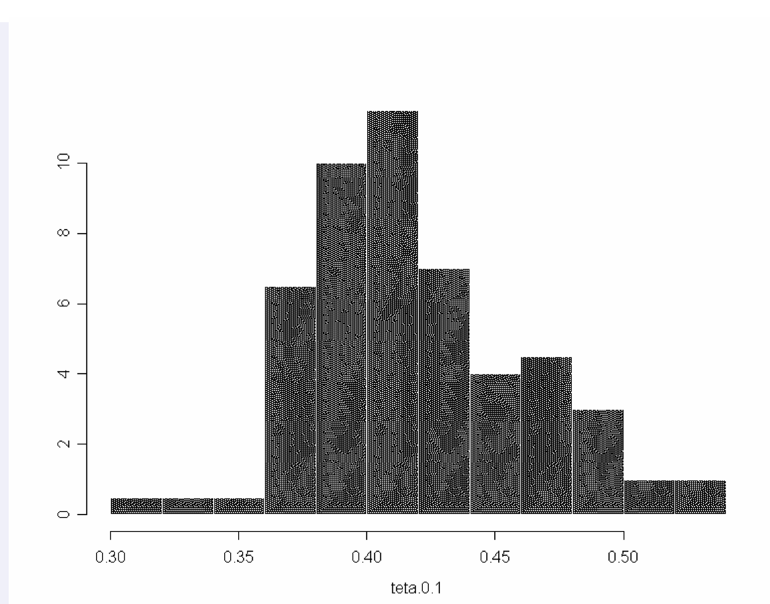

Fig. 2. Marginal distribution of soil water retention

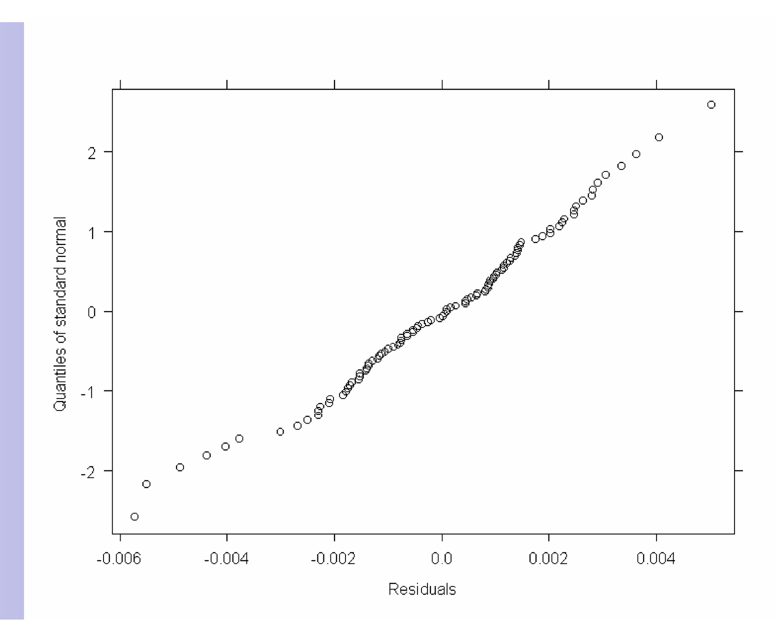

Fig. 3. Normal plot of residuals for the fitted linear mixed model

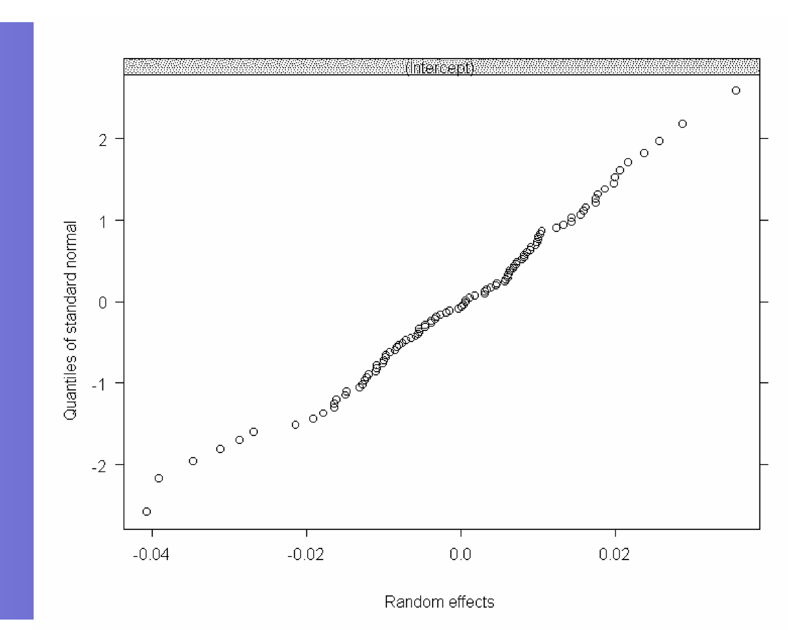

Fig. 4. Normal plot of random effects for the fitted linear mixed model

RESULTS

Simultaneous estimates of fixed effects (table 1) and correlation structure parameters (table 2) were obtained by the proposed parametric modelling approach. The inspection of table 1 shows that bulk density and porosity are negatively linked to water retention. On the contrary, the clay and silt content and particle density are positively linked, which means that textural classes may significantly affect the soil's hydraulic properties. The dependence of the -0.1 m water retention on topographic variables resulted significantly only for altitude. This dependence probably exists because the –0.1 m water retention exhibits a dependence on soil textural components and because substantial differences in the soil structure were encountered along the transect at the different elevations (Romano and Palladino 2002). Then the estimated model was compared with a general linear model with uncorrelated errors, such as those generally used for this kind of data in the standard agronomical practice. The comparison of the two models showed that the residuals of the fitted mixed model were clearly smaller than those obtained by a general linear model (figure 5) and that the former residuals had a white noise appearance at a significance level of 0.05 (figure 6). As consequence of these considerations, the fitted values of the linear mixed model with the autoregressive correlation structure were clearly much more close to the observed values then those fitted by the linear model (figure 7).

Table 1. Significance of tests on fixed effects

Fixed Effects	Value	Std. Error	p-value
Intercept	1,505711	0,573861	0,0102
Elevation	0,000052	0,000018	0,0041
Bulk density	-1,565164	0,506142	0,0026
Particle density	0,974541	0,281290	0,0008
Porosity	-3,251124	1,278185	0,0127
Clay	0,000708	0,000214	0,0014
Silt	0,000862	0,000279	0,0027

Table 2. CAR correlation parameters and 95% approximate confidence bounds

Parameter	lower	estimate	upper
σ_S	0.00233	0.01153	0.05700
ϕ	0.32901	0.39293	0.46073
σ_ε	0.02740	0.02989	0.03261

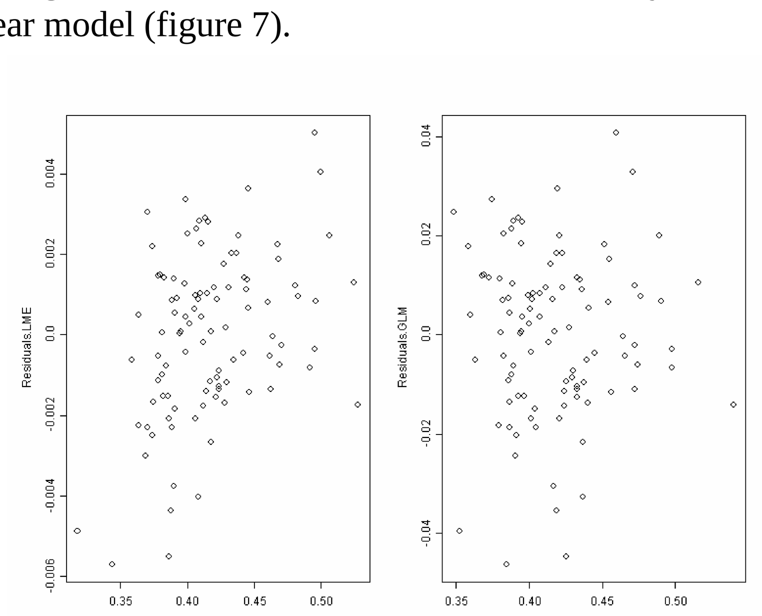

Fig. 5. Left: The scatter plot of the fitted mixed model residuals versus fitted values. Right: The scatter plot of the fitted general linear model residuals versus fitted values.

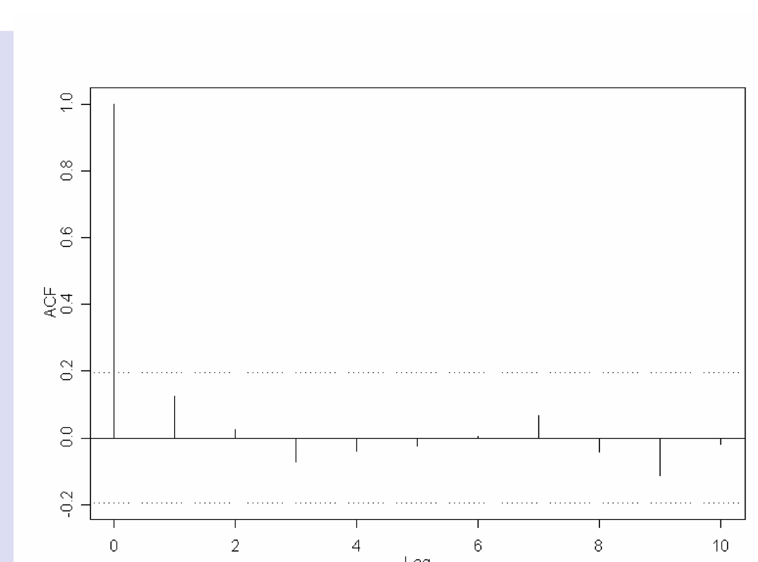

Fig. 6. Empirical autocorrelation function of the normalized residuals for the linear mixed model with the significance level for critical bounds (alpha=0.05).

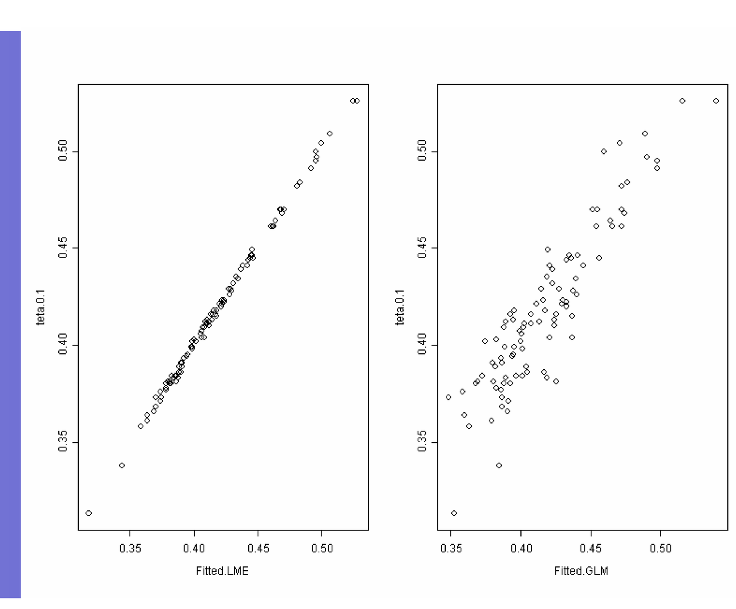

Fig. 7. Left: The plot of the observed values vs mixed model fitted values. Right: The plot of the observed values vs general linear model fitted values.

CONCLUSIONS

The proposed approach results to be a quick and effective method to predict soil hydraulic characteristics by other more easily available variables. The paper shows an application of the linear mixed model approach to the estimation of the volumetric water content at –0.1 m pressure head. Different types of statistical tests have proved the necessity to take into account error correlation structure and terrain parameters in fitting regression model. Therefore, a wider use of linear mixed models is recommended in hydrology for characterising the relationship of water content to matric soil water pressure.

REFERENCES

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