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Assessing and describing multi-scale spatial variability using factorial kriging.

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Soils are natural bodies which vary in space and time across landscapes. To understand and model how the different parts of a natural system interact requires a holistic approach. Soil-landscape modelling attempts to integrate pedology, geology, hydrology, topography and land use. These spatial models allow to describe the changes of soil attributes formed by a variety of factors. Geostatistical techniques have been applied in several studies to interpolate point observations and produce thematic maps of soil attributes. Any soil property measured at a certain location is the outcome of several physical, chemical or biological processes operating at different spatial scales from microscopic to global scales. In geostatistical terms, the combined effect of different sources of spatial variation produces variograms of the soil properties with nested structures related to different spatial scales. Factorial kriging analysis is a multivariate geostatistical technique which aims at estimating and mapping the different sources of spatial variability identified by the spatial scale at which they operate. It allows also at each spatial scale to describe the correlations between the variables and to summarise the sources of spatial variation captured by the sampling in a restricted number of regionalised factors which can be mapped. The main objective of this study was to identify, interpret and map the processes causing spatial variability in soil capability of water storage using factor kriging. Our analysis focuses on the pedological understanding of the results obtained by such a geostatistical approach.

The study was conducted for the whole Province of Siena in central Italy, an area of about 3,820 km^2. The climate of the Province of Siena is characterized by a high variability due to the differences in morphology and local elevations. The heights above sea level range in fact from about 300 m of the river valley floors to the 1,738 of

Mount Amiata, with the nearly 1,000 m a.s.l. of Chianti and Cetona mounts. The highest precipitations (above 1,000 mm on average, and up to 1,500 mm on Mount Amiata), and lowest mean annual temperatures (lower than 12 ˚C, and around 9 ˚C on Mount Amiata), localized along the two ridges at the higher altitudes, and with a relatively arid and warm zone in the Orcia river valley bottom (mean annual temperature of about 14 ˚C and average precipitations of less than 600 mm). Long term mean annual precipitation ranges from 630 to 1,275 mm. The geology of the province of Siena is rather variegated and complex. Marine clays and sands are the most diffused lithological types, followed by different kinds of limestone, marls and turbidites, and sandstone. Main soil typologies are Cambisols, Luvisols, Regosols and Andosols on metamorphic and volcanic rocks, and limestone; Cambisols, Regosols and Vertisols on Plio-Pleistocene marine sediments. Agricultural lands cover a 55% of the territory, woodlands are about a third of it.

Soil samples were taken at 742 locations according to a sampling carried out after a landscape analysis based on thematic maps and photointerpretation and, among others, the following soil properties were determined: depth, particle size, pH, total and active carbonates, organic matter, cation exchange capacity, exchangeable bases, electric conductivity, bulk density, amount of water at -33 and -1,500 kPa, available water capacity.

A multivariate geostatistical analysis was performed using four soil properties (depth, sand and clay contents and available water content). In order to study the impact of topography on soil-landscape characteristics the elevation from a digital elevation model (DEM) of 20 m x 20 m resolution was added as auxiliary variable. Since all variables showed non-normal distributions, they were transformed through a gaussian anamorphosis and standardised to zero mean and unit variance. Then, a linear model of coregionalization (LMC) was fitted to the matrix of all experimental auto- and cross-variograms and a principal component analysis of each coregionalization matrix was performed to yield sets of regionalised factors separately for each spatial scale. The individual gaussian variables and each factor were cokriged and mapped, after back-transformation to produce the maps of raw variables.

The LMC was modelled as the sum of three spatial structures, a nugget effect, a short-range spherical structure with a range of 7,000 m and a long-range gaussian structure with a range of 32,000 m. The greatest components of variation were represented by nugget and short-range structures, which denotes the complex pattern of spatial variation of the study site. From the analysis of the structures of the factors at each spatial scale it results that nugget variation is dominated by AWC variation (about 56%) and soil depth (about 31%); short-range variation by elevation (53%) and AWC (41%); long-range variation is mostly related to topography (about 80%) whereas only

16% of variation is affected by heterogeneity of AWC.

The cokriged maps of the first factor at nugget scale (high positive scores), of the second factor at short-range (high negative scores) and of the second factor at long-range (high negative scores) allow to delineate the areas characterised by potentially high capacity of soil water storage at the different spatial scales.

What is evident from such an analysis is the extremely erraticity of soil water storage properties of the site under study and the absence of main structures of soil dependence, probably due to the superimposition of several land properties and processes acting at different spatial scales. However factor kriging, separating the different spatial components of variation, helps us to understand soil-forming processes and to generate a conceptual model of soil distribution at a broad scale.