Mapping soil erosion risk using multivariate geostatistics

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Abstract
The assessment of erosion risk at regional scale requires modelling spatial variability of soil erodibility. The traditional soil cartographic approach, in many cases has been considered unsatisfactory for this purpose. This paper presents an approach in which two global risk indices are estimated and mapped using multivariate geostatistics and GIS. The proposed method takes into account some indicators, for which critical threshold values must be defined. This paper presents an application to a study area in Sardinia (Italy), representative of the Mediterranean zones at high erosion risk.

Key words: soil erosion, risk, GIS, multivariate geostatistics, indicator kriging

Introduction
European Mediterranean areas are very vulnerable to water erosion due to geomorphologic, climatic and human factors (Rubio and Calvo, 1996); European Community studies showed that 19% of these areas are at high erosion risk (CORINE, 1992). In Sardinia intense soil erosion processes have often been started or intensified by unsustainable agricultural practices mainly related to pastures management (d'Angelo et al., 1998 and 1999). The assessment and mapping of erosion risk is a useful tool to support sustainable land planning and mitigate soil degradation risk (Zucca et al., 1999). That can be done by individuating specific indicators, by defining a methodology for appropriately weighting and combining them and by using adequate mapping techniques (Goovaerts and Journel, 1995). This paper presents an assessment method based on multivariate geostatistics and GIS, in which six variables affecting soil erosion have been selected and their spatial variability has been modelled by using the indicator kriging approach.

Materials and methods
The study area

The study area (50,000 ha in size) is located in central-eastern Sardinia (Italy) and is characterised by shallow soils, often degraded by over-cultivation and overgrazing. Erosion processes are widespread and locally intense, in relation to vegetation cover and soil erodibility.

The indicator Kriging approach

Indicator Kriging is a non-parametric type of ordinary kriging (Journel, 1983). The method is based on a simple binary transformation whereby each datum is transformed into a binary indicator, before variography and kriging. By convention, data are coded as 0s or 1s, if they lie above or below given critical threshold values or conversely, in conformity with a definition of erosion risk. These criteria have to be calibrated locally. Each soil indicator is then mapped as the probability that the corresponding variable is beyond (or below) the defined threshold (Journel, 1988), so that the area may be subjected to the risk of erosion in relation to that parameter. A synthesis evaluation can then be done by weighting and summing the different variables using Principal Component Analysis.

The data set and the selected variables

In this study, 152 multi-layer samples were used, mostly collected during a previous soil survey within the MEDALUS III Project (Contract ENV4-CT95-0115). Each record was composed by the site description (slope, elevation, stoniness) and by chemical and physical standard measurements. In order to define the soil erosion risk, six properties were selected: soil depth (cm), slope (%), sand (%), silt (%), clay (%) and organic matter (%). The critical threshold values for the six variables are reported on Table 1.

Table 1. Critical threshold values and number of samples above the threshold

Variable	Threshold	N° of samples
Soil depth	< 30 cm	92
Slope	> 20 %	75
Sand	< 15 or > 75 %	72
Silt	< 10 or > 60 %	40
Clay	> 40 %	0
Organic matter	< 1.7 %	25

After the binary transformation a new data set was obtained, composed of 'indicator variables' whose values are 0s or 1s. Experimental direct and cross-variograms were computed for these indicators and a linear model of coregionalization was fitted to the variogram matrix (Castrignanò et al., 2000). The fitted variogram models were used to estimate values at the nodes of a dense grid using indicator cokriging, thus obtaining the individual probabilistic maps. A principal component analysis was finally carried out on the estimated indicator variable to produce a synthetic representation of the results. All geostatistical analyses were performed using the software Isatis® version 6 (http://www.geovariances.com).

Results and discussion

The binary transformation highlighted that for some variables the number of samples above the threshold was limited (table 1). In particular it was 0 for clay, which was then eliminated from the following elaboration. The fitted coregionalization model included three different structures: a nugget effect, a spherical structure with a short range (2500 m) and a spherical structure with a long range (10000 m). The two ranges represent a double spatial variability structure, at short and long scale. This is probably due to two different causes of variability: one more related to local morphology and land use and the other one more correlated to the main factor of soil forming.

The values represented by the maps (Fig. 1) show the probability of exceeding the critical threshold value for each individual property.

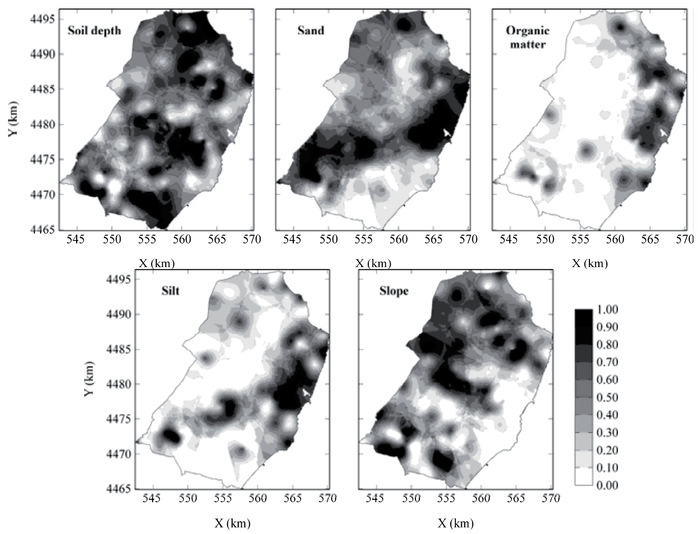

Figure 1. Kriged maps of the five soil indicators.

The maps show that the main factors affecting soil erosion are the high content of sand in correspondence of calcareous rocks in the whole median zone and the shallowness of most soils. Table 2 shows, for each property, the percentage of the total area that has a probability higher than 50 %, 75 % and 90 % of exceeding the threshold. The table also suggests that soil depth is the more risky parameter in the study area, followed by the sandy textures.

Table 2. Percentage of the total area with a given probability (P) of exceeding the critical threshold

Soil property	Percentage of the total area for		
	P > 50	P > 75	P > 90
Organic matter	13.1	2.4	0.1
Sand	49.0	19.1	6.8
Soil depth	61.8	24.6	8.6
Slope	44.9	15.8	5.5
Silt	19.3	7.3	2.8

The table also suggests that soil depth is the more risky property in the study area, followed by the sandy textures.

The results of the principal component analysis (Table 3) were used to have a synthesis picture of the results. Table 3 shows that factor 1 and 2 account for more than 70 % of the total variability and that factor 1 is particularly related to silt, organic matter and sand, while factor 2 is significantly related to soil depth and slope. Figure 2 shows the maps of the two principal components.

Table 3. Results of the Principal Components Analysis.

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
Ind-Sand	0.4424	0.4055	0.5614	0.3792	0.4253
Ind-Silt	0.5250	0.3443	- 0.1427	0.0837	- 0.7605
Ind-Organic matter	0.5185	0.0837	- 0.2539	- 0.7263	0.3636
Ind-Slope	- 0.4151	0.4773	0.5137	- 0.5339	- 0.2256
Ind-Soil depth	- 0.2959	0.6944	- 0.5797	0.1916	0.2400
Eigenvalue	2.6216	1.0752	0.6665	0.4059	0.2308
Percentage	52.43	21.50	13.33	8.12	4.62
Cumulative percentage	52.43	73.94	87.27	95.38	100

The approach based on principal component analysis represents a simple and objective way to synthetically present results, without making use of subjective weighting procedures.

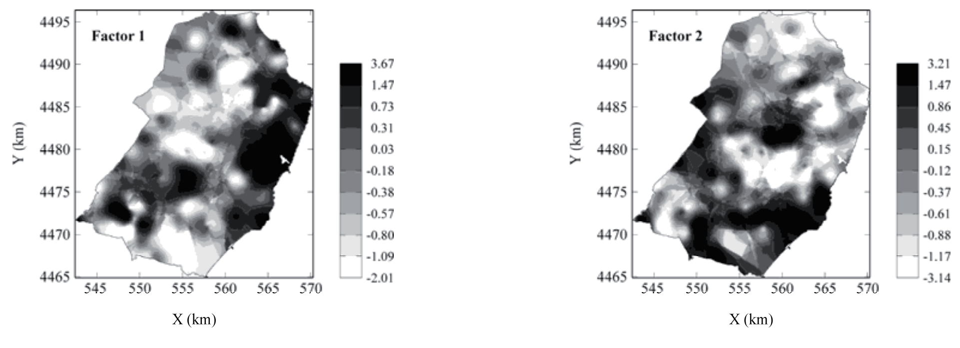

Figure 2. Kriged maps of the two principal components

The maps of the two factors can give a quick look of the areas at risk, but their values have neither physical nor probability meaning: their values must be interpreted in relative terms so that areas at high erosion risk can be delineated. A "structural" and a "morphological" meaning, could be assigned to Factor 1 and Factor 2, respectively, thus highlighting the two main components of soil vulnerability to erosion processes, one, related to soil structure (influenced by texture and organic matter), the other related to morphological aspects (depth and slope).

Conclusions

A probabilistic multivariate approach was proposed to assess erosion risk. Maps were produced for both individual soil indicators and synthetic indices. In this way the procedure allowed for the identification of both the areas at high erosion risk and the individual indicators that mainly affect the erosion in those zones.

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