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Multi-scale assessment of the risk of soil salinization in an area of south-eastern Sardinia (Italy)

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Abstract The assessment and mapping of the risk of soil salinization can contribute to sustainable land planning aimed at mitigating soil degradation and increasing crop production. A probabilistic approach, based on multivariate geostatistics was used to model the spatial variation of soil salinization risk at the landscape scale and to delineate the areas at high risk. The study site is a citrus growing area in south-eastern Sardinia (Italy). Electrical conductivity (EC_e), exchangeable sodium percentage (ESP), pH and 'total clay + fine silt content' (FIN), were measured in the topsoil (0–40 cm). The method requires indicator coding, which transforms measured data values into a binary variable according to critical thresholds. These latter were set to: 4 dS m^{-1} for EC_e, 10% for ESP, 8 for pH, and 40% for 'total clay + fine silt content'. To determine the probability of exceeding these critical values, multi-collocated indicator cokriging was used. Factorial kriging was also applied to identify one regionalized factor that summarizes the effects of the selected variables on soil salinization. Maps of each soil indicator and regionalized factor were produced to show the areas at risk of salinization. The results are valuable for planning the management of salinity.

Keywords Soil salinity · Salinization risk · Indicator cokriging · MultiGaussian approach

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Introduction

Precision agriculture aims to vary the inputs of agro-chemicals to individual fields to avoid under- and over-application, which can lead to under-production, decreased profitability and adverse environmental effects. To achieve this goal, accurate maps of the soil properties likely to influence crop yield within fields are needed. Producing such maps is usually a private sector initiative and the prerogative of individual farmers. Conventional maps of soil classes produced by public sector agencies such as the U.S. Department of Agriculture (USDA) or an Environmental Protection Agency (EPA) are often used to identify potential management zones, especially when the intensive soil sampling required to produce accurate contour maps of soil properties is unaffordable. As a rule, such agencies identify environmental problems on a broad scale and alert farmers about these sensitive zones. The EPA (CRAS) for the island of Sardinia (Italy) wished to determine which areas over the whole island were at risk from salinization, and what soil and environmental factors contributed to producing, or increasing, such risk. The main aim was to assist farmers to make appropriate decisions about crop production and management, and to determine the areas where further mapping of soil salinity on a field-by-field basis would be sensible. In recent decades, many citrus groves of the costal plain of Muravera-Villaputzu (12.50 km^2, south-eastern Sardinia) have undergone progressive and severe salinization of the groundwater and then of the irrigated soil (Barbieri et al. 1983). In Sardinia citrus fruits are important crops and varying salinity levels of the soil result in a failure to maximize yields (Castrignanò and Puddu 2005). Precise management of soil salinity has been shown to increase growers' net returns (Sevier and Lee 2005). Knowledge of soil salinity and its variability is essential in order to evaluate the extent of salt build-up and to recommend appropriate management practices to increase crop yield. The soil salinization processes may operate at a local or regional scale. Various factors can be of influence at an individual site, at the farm level, within a catchment or even outside the catchment. It would be particularly useful for both land planners and farmers to have a method that enables them to identify areas of poor soil quality and focus on those areas where the progress and effectiveness of the site-specific solutions adopted can be monitored. Such a method would also be suited to identifying the areas in which private and public-sector cooperation could be developed. A public environmental protection agency, such as CRAS, should survey the soil for land management planning and to promote some soil remediation. The implementation of precise management and site-specific irrigation should be the farmers' task; they would also need to sample and monitor the soil. Such a framework could support precision agriculture and define the roles of public and private sector agencies in allocating financial resources.

To characterize soil salinization and determine its causes adequately, it is necessary to use more advanced geostatistical analysis than is often used in precision agriculture. This is because the key variables for soil salinization (electrical conductivity, exchangeable sodium percentage, pH, and total clay + fine silt content) are often strongly skewed and are also related to other potential causal variables that require investigation. In addition, there are at least two processes that cause salinization: one process can occur naturally where high levels of soluble salts are stored in the soil and ground water. In such cases, the accumulations of salts have originated from landscape processes or sea water intrusion into fractured rock of the aquifer. Increasing salinity can also result from human activities, such as the excessive use of groundwater in agriculture or by local populations that increases sea water intrusion to aquifers. In addition, poor management of irrigation, particularly where the soil is heavy clay and water is allowed to accumulate over the soil surface and evaporates leaving salts behind. Given the different potential causes for salinization, it is important to use a technique that can separate out these different processes which are generally scale-dependent. Moreover, because the sample data characterizing the site are inevitably limited, knowledge of the real situation is always incomplete and so estimates at unsampled locations are needed that account for uncertainty. Therefore, a probabilistic approach is preferable to a classical estimator because it treats uncertainty explicitly.

The main objective of this paper is the application of an approach based on multivariate geostatistics to delineate areas at risk of salinization in the study area and to determine the scale-dependent factors that cause soil salinization.

Theory

Soil salinity

Salinization is the accumulation of excess soluble salts in the root zone of arid and semi-arid irrigated soil. It is a widespread problem that affects crop productivity throughout the world (Lesch et al. 1992; Corwin et al. 2007). The predominant mechanism causing the accumulation of salt in irrigated agricultural soil is evapotranspiration, which concentrates salts in the remaining soil water and at the soil surface. The effects of salinity are evident in the loss of productive agricultural land, reduced rates of plant growth and yields, and in severe cases total crop failure (Rhoades and Loveday 1990; Corwin et al. 2007). Salinity limits plant water uptake by reducing the osmotic potential and thus the total soil water potential. When sodium is an important component of the salts, there can be a significant amount of adsorbed sodium making the soil sodic. Under sodic conditions the adsorbed sodium may disperse soil colloids and develop undesirable physical properties, such as the collapse of soil structure (Foth 1990). Moreover, soil sodicity can have indirect effects on plant growth through deleterious modification of soil properties because it predisposes it to compaction and surface sealing, excessive runoff and erosion if soil management is inappropriate (Hillel 1998). In general, the physical properties of fine textured soil are affected more adversely at a given exchangeable sodium percentage than coarse textured soil because the former have higher cation exchange capacities than the latter (Richards 1954).

Quantitative criteria for diagnosing soil salinity were originally formulated by the U.S. Salinity Laboratory in its Handbook 60 (Richards 1954). Although there have been newer publications (Hillel 2000), some of the definitions and concepts of Handbook 60 are still widely used (Hillel 2003). Total salinity is usually defined and assessed in terms of measurements of the electrical conductivity of the extract of a saturated soil-paste sample (EC_e, dS m^{-1}) (Rhoades et al. 1999; Corwin and Lesch 2003). Soil salinity can also be determined indirectly from the measurement of the electrical conductivity of the bulk soil (EC_a, dS m^{-1}) (Rhoades et al. 1999; Corwin and Lesch 2003). This can be measured either in the field with electrodes placed in contact with the soil or remotely by electromagnetic induction devices, such as the Geonics EM38 (Rhoades et al. 1999). In the application of the apparent soil electrical conductivity (EC_a) measurements obtained with electromagnetic induction devices to precision agriculture, the fact that the EC_a is a function of several soil properties, such as soil salinity, texture, and water content, is often overlooked (Corwin and Lesch 2003). The relations between EC_a and soil properties can be inconsistent because of the combination of factors that influence EC_a over the units of land management and confound interpretation (Corwin and Lesch 2003).

From the agricultural standpoint, the distinguishing characteristic of saline soil is that it contains sufficient neutral soluble salts to affect the growth of most crop plants adversely (Rhoades et al. 1999). Soil salinity limits citrus production in many areas worldwide including Mediterranean coastal areas (Levy and Syvertsen 2004). Although data on the response of fruit crops to salinity are limited, they indicate that oranges are among the most sensitive agricultural crops (Maas 1993; Al-Yassin 2004; Prior et al. 2007). Fruit yields show an almost 13% decrease for each 1.0 dS m^{-1} increase in electrical conductivity of the saturated-soil extract (EC_e) once soil salinity exceeds a threshold EC_e of 1.4 dS m^{-1} (Maas 1993). Accumulation of Cl^- and Na^+ can cause specific ion toxicities, but this problem can be minimized by selecting rootstocks that restrict the uptake of these ions.

Excess salinity of the soil solution can be corrected by leaching with water that has a small salt content, whereas the removal of excess exchangeable sodium requires the soil to be remediated by applications of finely ground gypsum ($Ca\ SO_4 \cdot 2H_2O$). The development and maintenance of soil remediation requires accurate and updated information about the spatial distribution of electrical conductivity and exchangeable sodium (Pozdnyakova and Zhang 1999). More advanced techniques of data processing are required to support decision-making for managing salinity. There is a variety of options that can be adopted to manage salinity depending on the objectives and on the local biophysical environment and climate. A combination of these options is required to solve salinity problems at both farm and regional levels. At the farm level, land managers can adopt better management practices, such as conservative tillage, new and improved plant varieties and new farming systems. Improved and ongoing evaluation and monitoring of the soil and water resources to check the effectiveness of salinity management responses are also required.

Geostatistical methods

The soil properties used in salinity risk assessment are likely to have a few very large or small values—i.e. an underlying asymmetric distribution or the presence of outliers that increase the skewness of the data. The variogram is sensitive to strong departures from normality, because a few exceptionally large or small values may contribute to several squared differences and inflate the average variance (Webster and Oliver 2001). We used multiGaussian cokriging to deal with this problem (Verly 1983; Goovaerts 1997; Wackernagel 2003) because regardless of the shape of the sample histogram, the data are transformed to a Gaussian distribution with zero mean and unit variance by an expansion into Hermite polynomials (Chilès and Delfiner 1999; Webster and Oliver 2001; Wackernagel 2003). The transformed data are estimated at all unsampled locations by ordinary cokriging (Wackernagel 2003).

In this study, multi-collocated cokriging (Rivoirard 2001) was used to integrate secondary information, known at all nodes of the interpolation grid, into modelling of the primary variable. The approach is quite similar to ordinary cokriging; the only difference is in the neighbourhood search. If all secondary exhaustive information within the neighbourhood is used, it can lead to matrix instability because of too much information. Therefore, the secondary variable is used only at the estimation node and at all the locations where the primary variable is defined within the neighbourhood. The modified version is less precise than full cokriging because it does not use all of the auxiliary information within the neighbourhood. However, because the collocated secondary datum tends to screen the influence of secondary data further away, there is little loss of information.

The indicator cokriging approach

Indicator cokriging was used to assess the risk of salinization probabilistically so that uncertainty of the estimates can be taken into account. The approach is based on a simple binary transformation, whereby each datum is transformed into an indicator, i.e. a binary value according to a critical threshold for each variable. Cokriging of binary indicators calculates the probability that the corresponding soil property value is beyond the defined critical threshold, i.e. the probability that the area might be at risk of soil salinization.

Factorial cokriging analysis

To separate the different causes of soil salinization and to define scale-dependent indices, which integrate information from several individual salinization indices, the multivariate indicator data were analysed by factorial cokriging analysis (FCKA), a geostatistical method developed by Matheron (1982). The theory underlying FCKA has been described in several publications (Wackernagel 1994; Goovaerts and Webster 1994; Castrignanò et al. 2000); here we describe only the most salient points.

The steps in FCKA are as follows:

(1) Modelling the coregionalization of a set of variables with the linear model of coregionalization (LMC), where each auto- and cross-variogram is estimated as a linear combination of basic spatial structures. Each of these structures describes variation at a given spatial scale.
(2) Analyzing the correlation structure between the variables by principal component analysis (PCA) so that a set of orthogonal components, the regionalized factors, can be extracted. The components (regionalized factors) reflect the main features of the multivariate information for each spatial scale.
(3) Cokriging and mapping the component mentioned in (2) at characteristic scales.

The best fitting function to the experimental variogram for the procedures described above was chosen by cross-validation. It takes each data point in turn, removes it temporarily from the data and uses its neighbouring values to predict the value of the variable at that point. The prediction is then compared with the measured value. Two measurements of goodness of fit are the mean experimental error and the variance of standardized error, which should be close to 0 and 1, respectively, if suitable models have been fitted.

Materials and methods

Study area and sampling

The area used for this investigation was a 12.5 km^2 area of irrigated farmland, within the plain of the River Flumendosa in south-eastern Sardinia (Italy) (Castrignanò and Puddu 2005; Puddu et al. 2005). The site (Fig. 1) was selected because irrigated agriculture predominates in the area, it is renowned for citrus production and is considered representative of many Mediterranean zones at risk of soil salinization. The soil has developed on a sandy-silty alluvial substrate and is characterized by the considerable homogeneity in its physical structural properties. According to Soil Taxonomy (Soil Survey Staff 1999) at

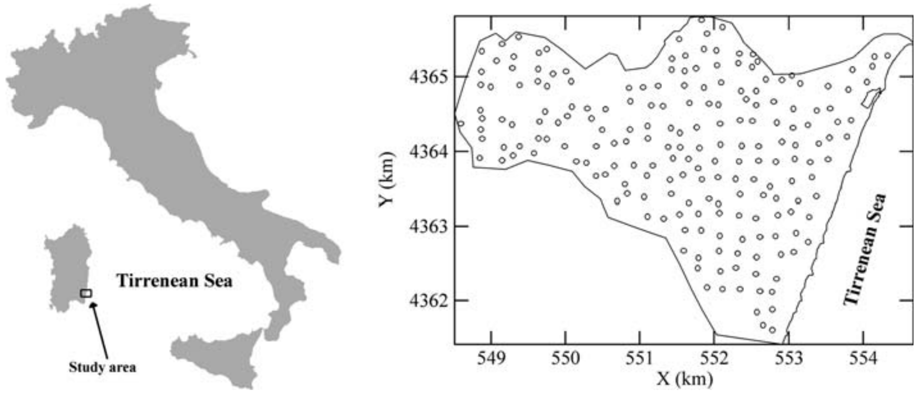

Fig. 1 Location of the study area and sampling points

the subgroup level, the soils are Typic Xerofluvents and Fluventic Xerochrepts. Textures range from loam and silty loam, to sandy loam and loamy sand.

The study area (12.5 km^2) was covered by a 1000 × 1000 m grid and each grid square was further subdivided into 16 cells of 250 × 250 m side. Within each 250 × 250 m cell, one soil sample was taken at random from a depth of 0–40 cm by hand augering (Endelman soil sampler). This resulted in 198 soil samples (Fig. 1).

Soil analysis methods

The 198 soil samples were air-dried, ground and passed through a 2 mm sieve. The soil was analysed for: electrical conductivity of a saturated paste extract (EC_e, dS m^{-1}), exchangeable sodium percentage (ESP, %), pH and 'total clay + fine silt content' (FIN, g kg^{-1}, particle size range: 0.0–0.02 mm). The four properties were determined according to standard methods of soil analysis (Pagliai 1997; Violante 2000). The Electrical conductivity of the saturated paste extract at 1:5 soil:solution ratio was determined with a conductivity meter (Violante 2000). The exchangeable sodium percentage (ESP, %) was calculated as [(Exch. Na^+/CEC) × 100]; cation exchange capacity (CEC) was determined after extraction with barium chloride (Violante 2000) and exchangeable sodium (Exch. Na^+) was analysed by flame photometry (Violante 2000). The soil pH was measured with a glass electrode in a 1:2.5 soil suspension (Violante 2000). Total clay and fine silt contents (g kg^{-1}) were determined by the pipette method (Pagliai 1997).

Threshold values for the indicator approach

To apply an indicator approach, the choice of critical thresholds of the four soil variables (EC_e, ESP, pH, and FIN) was made in relation to the agronomic and physiological responses of citrus trees to salinity in the specific environmental conditions under study. The choice was particularly difficult because of the differences in the response of citrus species to salt stress, the role of different rootstocks and the interactions of different environmental conditions or stresses (water and nutrient stresses) with salinity.

Sodic-saline soil can occur from the coast to a distance of 1 km inland where the water table depth varies between the soil surface and a depth of 1 m (Barbieri et al. 1983). Soluble salts are supplied continuously to the soil (particularly $MgCl_2$ and NaCl and Mg^{2+} and Na^+ cations), and so we set the critical threshold for EC_e to a large value (Ayers and Westcot 1985). The other thresholds were chosen on the basis of the average soil properties over the area. The critical values for the four properties were set to: 4 dS m^{-1} for EC_e, 10% for ESP, 8 for pH and 40% for 'total clay + fine silt content' (FIN).

Geostatistical analysis

In the geostatistical analysis, in addition to the four soil properties (EC_e, ESP, pH, and FIN), hereafter called primary variables, we used distance from the sea as an auxiliary variable. The latter enabled us to account for the sea water intrusion. The analytical measurements were interpolated at the nodes of a 10×10 m grid.

All statistical and geostatistical analyses outlined in the theory section were performed using ISATIS®, release 6.0.7 (Geovariances 2006).

Results and discussion

The summary statistics and histograms of the four soil variables (EC_e, ESP, pH, and FIN) and of the auxiliary variable (distance from the sea) are given in Fig. 2. All variables have a skewed distribution (Fig. 2). The four primary variables (soil properties: EC_e, ESP, pH, and FIN) and the auxiliary variable (distance from the sea) were then transformed to

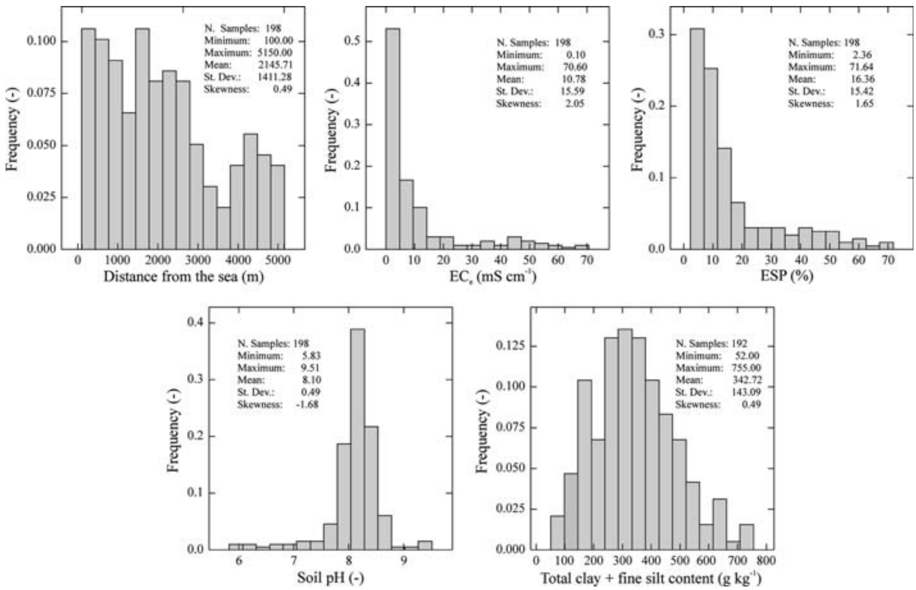

Fig. 2 Histograms of distance from the sea, electrical conductivity (EC_e), exchangeable sodium percentage (ESP), pH and 'total clay + fine silt content' (FIN)

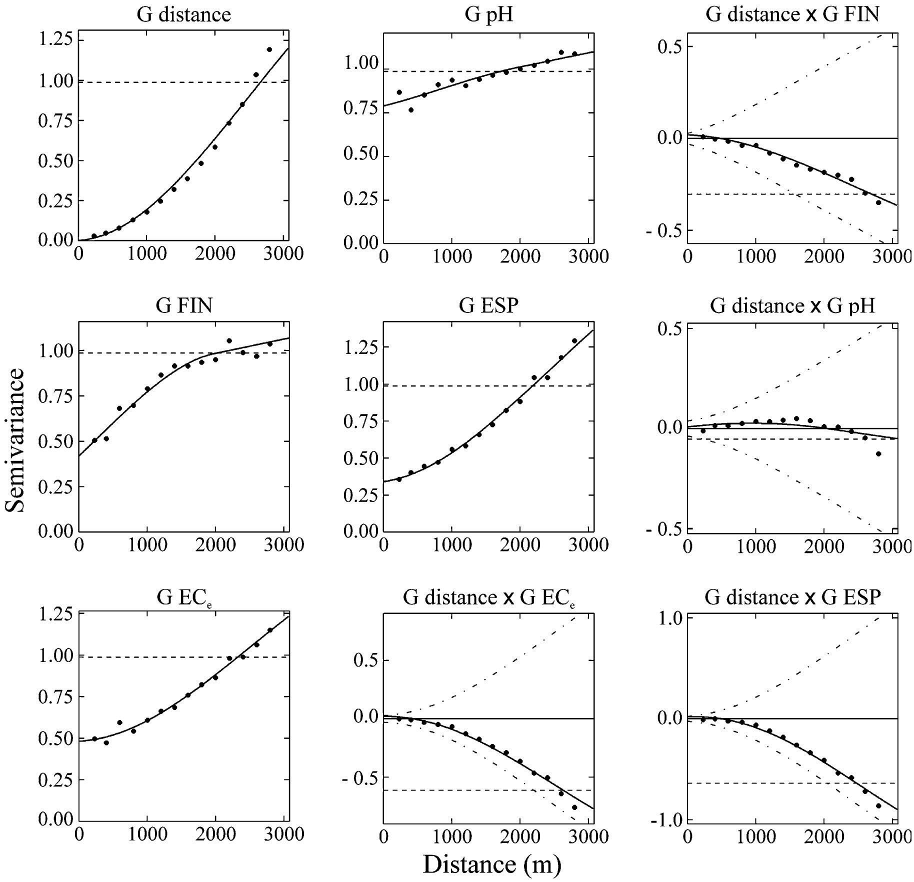

Fig. 3 Auto- and cross-variograms of the Gaussian variables of EC_e, ESP, pH, FIN, and distance from the sea. The experimental values are the plotted points and the solid lines are of the model of coregionalization. The dash-dotted lines are the hull of perfect correlation and the dashed lines are the experimental variances

normality by an expansion of Hermite polynomials restricted to the first 30 terms, which are sufficient to reproduce the value of the variance (Wackernagel et al. 2004).

No anisotropy was evident in the maps of the 2-D variograms (not shown) to a maximum lag distance of 1800–2000 m. A nested isotropic LMC (Fig. 3) was fitted to the experimental variograms. The LMC included three basic structures (Table 1): a nugget effect; a J-Bessel (Geovariances 2006; Chilès and Delfiner 1999) model with a range of 750 m and smoothing parameter of 4, and a spherical model (Webster and Oliver 2001) with a range of 2,000 m.

The appropriateness of the LMC used compared to alternative models was evaluated by cross-validation. The mean error and the variance of standardized errors for the selected model were close to 0 and 1, varying between −0.0265 and 0.0142, and 1.02 and 1.09, respectively.

Figure 4 shows the maps of the four soil properties. The values of EC_e and ESP (Fig. 4a, b) show an overall increase towards the coast, but there is still considerable

Table 1 Fitted linear model of coregionalization of the Gaussian variables (G)

	G distance	G FIN	G pH	G ESP	G EC_e
(*a*) *Nugget effect*					
G distance	0.4821				
G FIN	0.2625	0.3403			
G pH	0.0423	0.1745	0.7886		
G ESP	0.1656	0.0261	0.0679	0.4182	
G EC_e	0.0217	0.0183	0.0083	0.0192	0.0018
(*b*) *J-Bessel model* (*range 750 m; smoothing parameter = 4*)					
G distance	1.2099				
G FIN	1.2453	1.5726			
G pH	0.3781	0.3483	0.2964		
G ESP	0.5804	0.6105	0.2063	0.2875	
G EC_e	−1.3367	−1.6169	−0.1797	−0.6094	1.9467
(*c*) *Spherical model* (*range = 2000 m*)					
G distance	0.0289				
G FIN	0.0189	0.0879			
G pH	−0.0312	0.0266	0.1329		
G ESP	−0.0117	−0.0528	−0.0808	0.478	
G EC_e	0.0026	0.0472	0.0489	−0.0201	0.0378

evidence of local variation. The large negative cross-correlations (Fig. 3) between the two soil variables (EC_e and ESP) and the auxiliary variable (distance from the coast) support the overall increase in the former towards the coast.

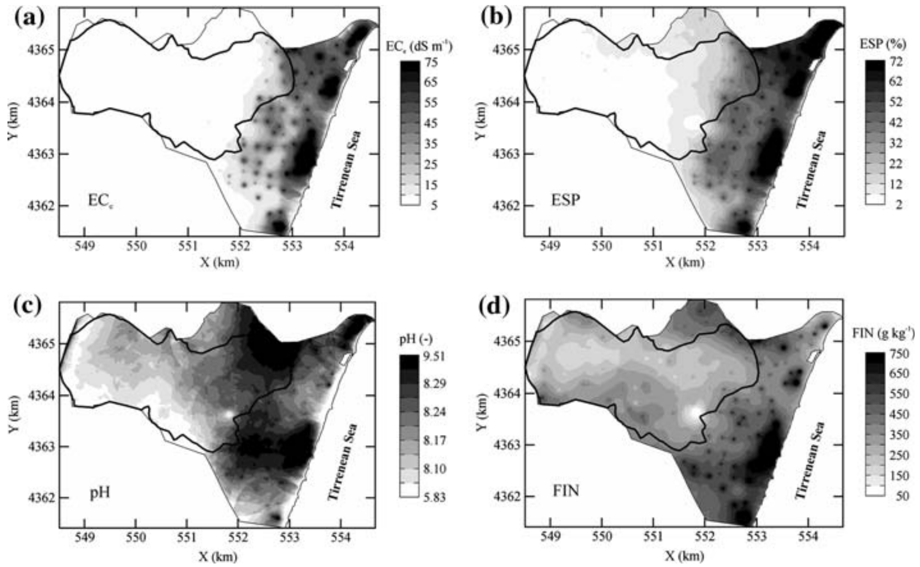

Fig. 4 Maps of the four variables produced using multi-collocated multiGaussian cokriging: (**a**) electrical conductivity (EC_e), (**b**) exchangeable sodium percentage (ESP), (**c**) pH, and (**d**) 'total clay + fine silt content' (FIN). The boundary of citrus fruit cultivation is also shown

Finer textured and sodic soil types are dominant in the wide coastal strip and to the north-east of the area. This more or less corresponds to the area under citrus production which extends for 2.5 km from the coast and is exposed to the risk of salinization.

This comprehensive assessment of soil salinity will assist both CRAS in developing targeted regional responses to the problem of salinity and the farming community in determining suitable management practices on the agricultural lands that are affected by, or are at risk from, salinity. The management of soil salinity is an important component of irrigation. High levels of salts in soil can result in stress in citrus trees because water is unavailable to them even when the soil has a relatively large water content. Moreover, the addition of fertilizer salts increases the osmotic stress to which tree roots are subjected. Therefore, frequent application of low salt index fertilizers at low rates can successfully minimize the effects of soil salinity.

The binary transformation has shown that the percentage of soil samples above the critical threshold was 51% for EC_e, 31% for ESP, 73% for pH and 30% for finer component of texture. These figures show that more than 50% of the surveyed area might be affected by a risk of salinity. The correlation coefficients between distance from the sea and the indicator variables of EC_e and ESP were −0.57 and −0.53, respectively, whereas the correlations were small for the finer component and pH. These results suggest that sea water intrusion into the aquifer might be one of the most likely causes of soil salinization in the study area. Therefore, we decided to analyze the four soil indicator variables (Ind EC_e, Ind ESP, Ind pH, and Ind FIN) together with distance from the sea (Norm. dist.) as the auxiliary variable estimated at each node of the interpolation grid by multi-collocated cokriging. For this analysis the data were standardized to zero mean and unit variance before fitting the LMC. The isotropic LMC (Fig. 5) included the same three basic structures used for the Gaussian variables: a nugget effect, a J-Bessel model with a range of 750 m and a smoothing parameter of 4, and a spherical model with a range of 2000 m. The goodness of fit of the selected models was evaluated by cross-validation. The mean error and the variance of the standardized error, varied between −0.0054 and 0.0043, 0.92 and 1.06, respectively.

The sum of the eigenvalues at each spatial scale gives an estimate of the variance at that scale (Table 2). The contribution of the longer range component of variation to the total variance is the least. Variation at this scale might be related to the intrusion of sea water and consequent contamination of fresh groundwater, as suggested by other researchers in the past (Ente Autonomo del Flumendosa 1999). It is evident from Table 2 that most variation occurs at the shorter scale, within a distance of 750 m. This latter can be regarded as variation at the farm scale and should be taken into account in strategic decision-making for the management of soil salinity. The increased withdrawal of water by farmers over the past few decades is probably related to the shorter range component of variation. The nugget component is also large; this comprises mainly variation at scales smaller than 200 m (the average sampling interval was 250 m) and to a lesser extent measurement error. To resolve some of the nugget component of the variation, further sampling on a finer spatial scale would be needed. However, data collection at this scale should be the responsibility of the private sector and not of a public environment protection agency.

The predictions of the individual soil indicators from multi-collocated cokriging on a 10 m × 10 m grid are shown in Fig. 6. These maps show that it is possible to delineate the areas that have a strong probability of failing to fulfil the selected criteria of good soil quality for citrus production. Figure 6a and b shows that soil at high risk of salinization and sodicity are within about 1500–1700 m from the coastline. The problems related to soil salinization become less severe further inland. The similarity between these two maps

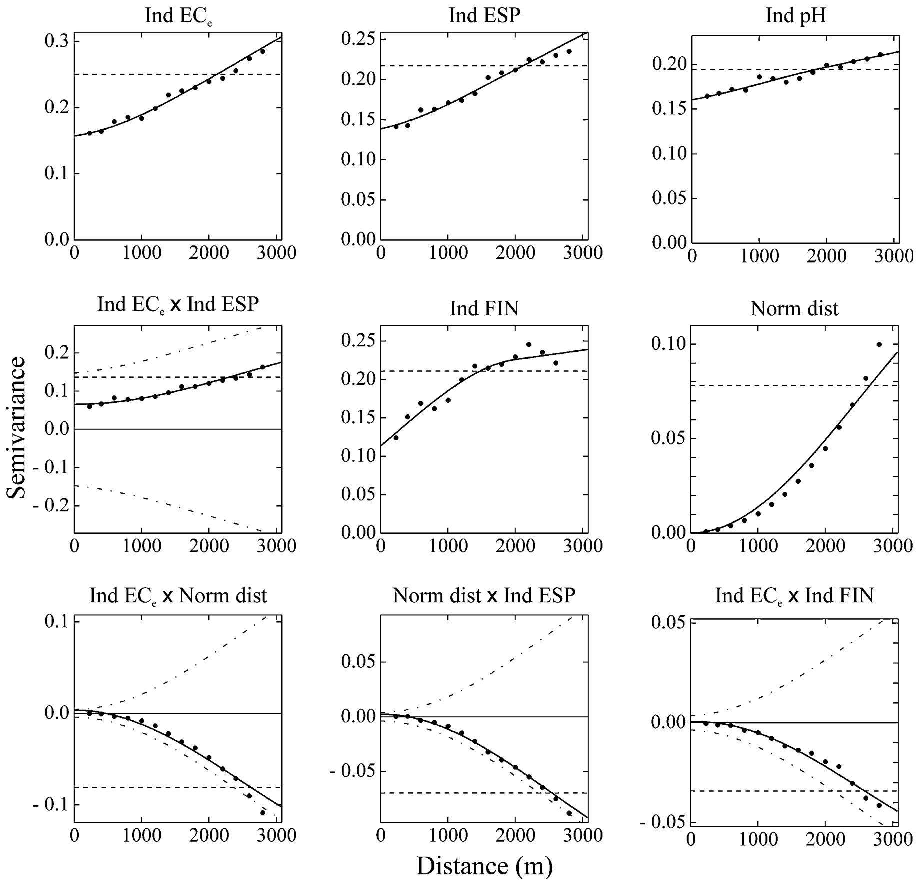

Fig. 5 Auto- and cross-variograms of the indicator variables of EC_e, ESP, pH, FIN, and normalized distance from the sea. The experimental values are the plotted points and the solid lines are of the model of coregionalization. The dash-dotted lines are the hull of perfect correlation and the dashed lines are the experimental variances

indicates that soil degradation is due mainly to the same process of sea water intrusion enhanced by the excessive pumping. Figure 6c and d reveals a different pattern of the areas at risk compared to the previous ones. The finer textured soil tends also to be more alkaline and occurs mainly along the coast and in an area to the north-east (Puddu et al. 2005).

Combining the effects of the different soil indicators shows that most of the coastal soil is at high risk of salinization and sodicity. To synthesize the results and identify the areas that are jointly affected by the factors promoting soil salinization, we did a factorial kriging analysis. We focused on principal component (factor) 1 at the shorter scale, which accounts for more than 89% of the total variation at this scale (Table 2) and omitted the nugget effect and longer range component because the former is mainly related to variation at distances less than the sampling interval and the latter explains only a small percentage of the total variance. Component 1 is positively related to distance from coast and negatively so to Ind EC_e and Ind ESP. To facilitate interpretation of the map of component 1 (Fig. 7), we divided the range of values into three classes to represent low, medium and high values in such a way that the three zones have an equal extent and the scores are proportional to

Table 2 Decomposition of the components (regionalized factors). The eigenvalues and the percentage variance accounted for at each spatial scale are also given

Component	Norm. dist.	Ind FIN	Ind pH	Ind ESP	Ind EC_e	Eigenvalue	Percentage
(*a*) *Nugget effect*							
1	−0.0192	−0.3228	−0.0615	−0.6244	−0.7083	0.2275	39.98
2	−0.0068	−0.1340	−0.9772	−0.0198	0.1635	0.1629	28.63
3	0.0111	−0.9368	0.1590	0.2293	0.2106	0.0988	17.36
4	−0.0101	0.0143	−0.1263	0.7464	−0.6532	0.0799	14.03
(*b*) *J-Bessel model* (*range 750 m; smoothing parameter* = *4*)							
1	0.5132	−0.2748	−0.0908	−0.5287	−0.6110	0.5758	89.48
2	−0.3594	−0.1384	−0.8987	0.0941	−0.1875	0.0677	10.52
(*c*) *Spherical model* (*range* = *2000 m*)							
1	0.0151	0.9680	−0.1461	0.0179	−0.2025	0.1053	65.56
2	0.0203	−0.0370	0.7162	−0.0387	−0.6956	0.0313	19.46
3	0.0089	0.0256	−0.0113	−0.9987	0.0428	0.0241	14.98

the impacts of Ind EC_e and Ind ESP on Component 1. The area with a high risk of salinization extends to 1.5 km from the coast; citrus cultivation should not be practiced here. The area of medium risk extends from about 1.5 km to 3.5 km inland; here salinity levels in the soil should be monitored and controlled carefully. Most citrus groves are in the zone of medium risk (Fig. 7), where continuous monitoring of the degree of salinization in the soil is advised. The zone of low risk, at the western extremity of the study area

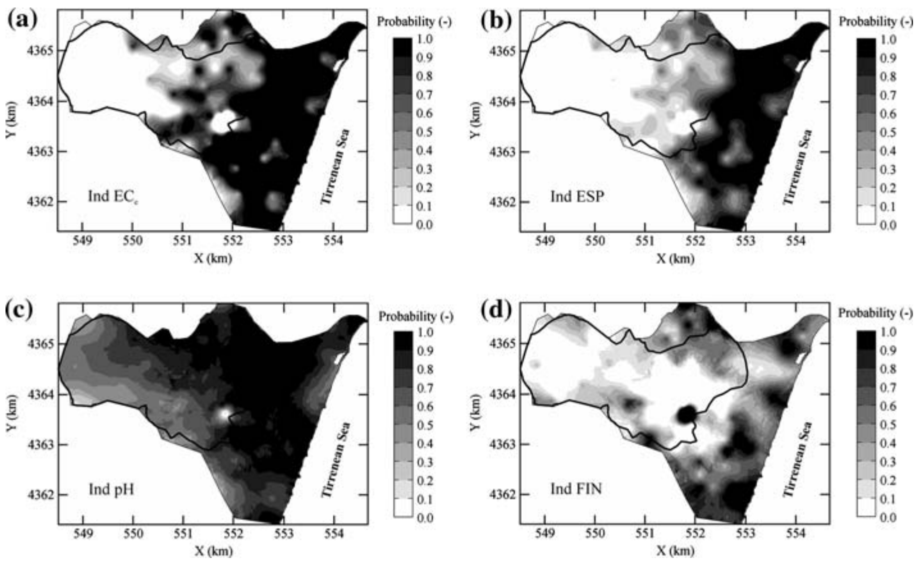

Fig. 6 Cokriged maps of the four indicator variables: electrical conductivity (EC_e), exchangeable sodium percentage (ESP), pH and 'total clay + fine silt content' (FIN). The boundary of citrus fruit cultivation is also shown

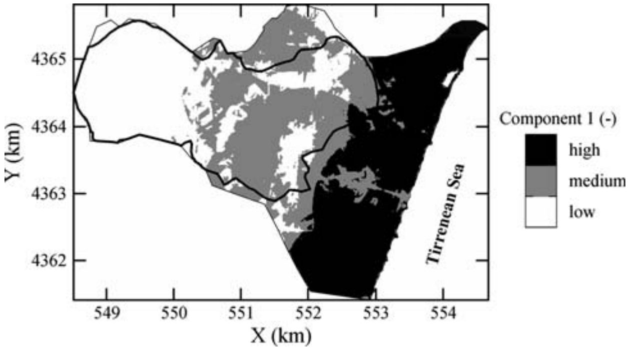

Fig. 7 Map of component 1 using an even class representation. The boundary of citrus fruit cultivation is also shown

is classified as safe and citrus cultivation should not suffer any marked effects from salinity.

Conclusions

The proposed probabilistic approach based on multivariate geostatistics has enabled us to partition an area in south-eastern Sardinia into zones at different risks of soil salinization. Such partitioning reduces the extent of areas that will need to undergo additional survey. This study has also helped to define the specific functions of a regional EPA, such as CRAS, that have a remit to encourage stewardship of the land and associated natural resources, and to protect it from the degradation caused by salinization and inappropriate management. At a smaller spatial scale the responsibility for maintaining the productivity of the land becomes a matter of local importance and of concern to the landowner or manager, rather than of regional government. The results from this study justify the application of precision agriculture at the farm level in this area. Both the soil properties and maps of risk can be used to alert farmers whose land is within an area at or potentially at risk of salinization. The EPA should then advise the farmer to apply the best agronomic practices to reduce or prevent soil degradation. The farmer might also decide to establish one or more sites to determine the hydrology of his farming system or to plan further sampling based on these results.

The methods described are flexible and could be used at any spatial scale to make comparisons of soil quality among different regions or within-field zones to ensure remediation focused on priority areas or those that are likely to bring greater gains in profitability. The approach also allowed us to identify those properties responsible for soil degradation within fields so that sustainable site-specific agriculture could be planned. This approach can be easily, and advantageously, interfaced with other recent technologies, such as remote sensing, proximal sensing, geo-radar, electrical conductivity sensors, etc., so that sparse primary data are effectively complemented with dense secondary data to improve the precision of estimates and reduce the costs of site-specific management.

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