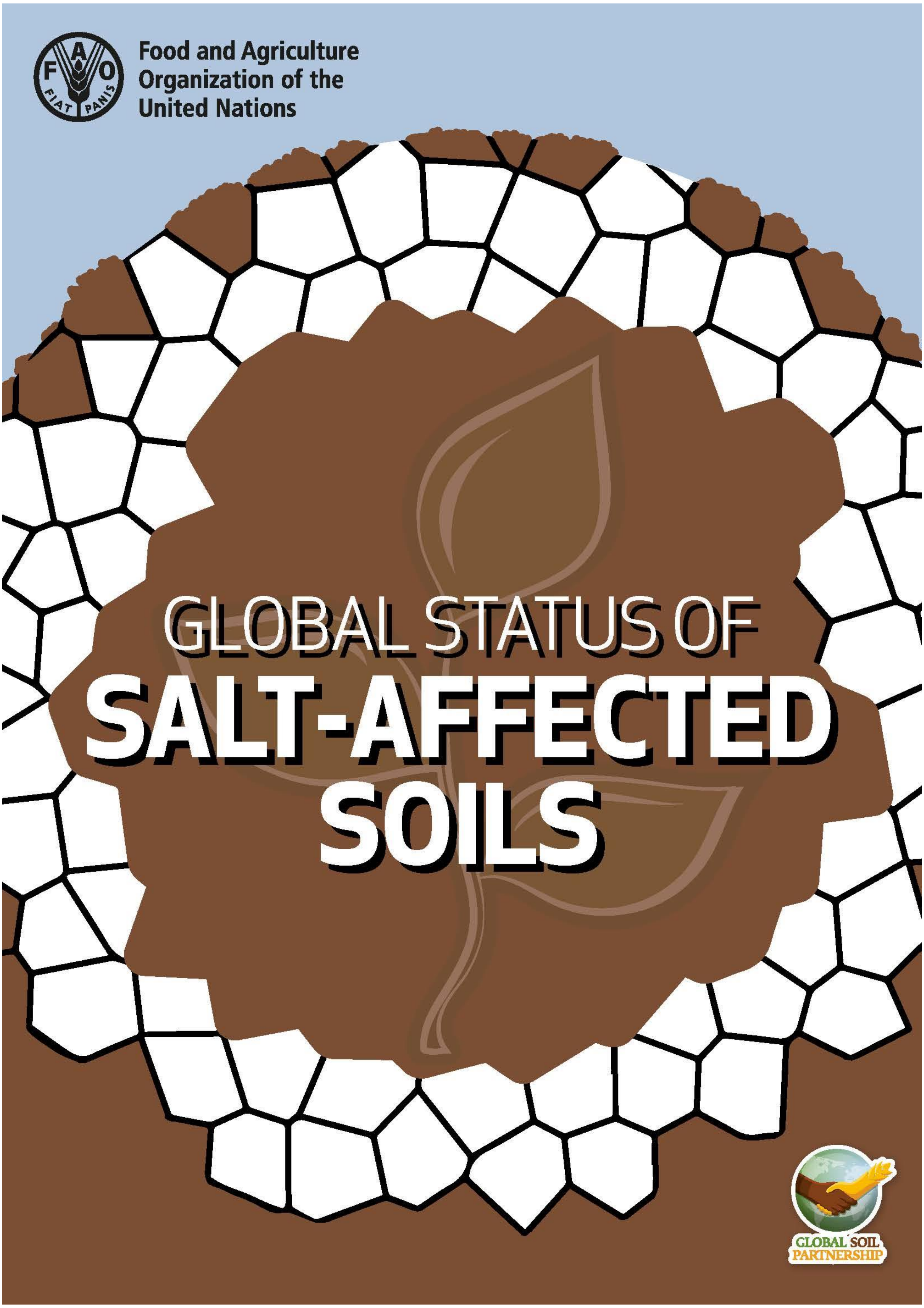
Food and Agriculture
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GLOBAL STATUS OF
SALT-AFFECTED
SOILS
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National mapping and reporting of salt-affected soils of Italy

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1 Introduction

The risk of soil salinization and sodification is considered one of the main threats in agricultural soils of Italy (Dazzi, 2008). In Italy, this occurs mainly due to irrigating with saline or brackish water, in particular on the plains and along the coastal areas (Dazzi and Lo Papa, 2013). Even though a general map showing the distribution of saline soils was not available for Italy, an exploratory survey identified some risk areas (Dazzi, 2008) including the lowlands of the Po Valley, the coastal areas of central and southern Italy – including the major islands – and, in scattered areas, the internal hilly areas of central-southern Italy. Given the lack of harmonized data required to represent the situation at a national scale, Costantini *et al*. (2009) proposed a modelling approach for defining potentially salt-affected soils areas by considering the distance from the coast, relative elevation, soil parent material, and soil typologies. Based on these estimates, Salvati (2014) studied the links between soil salinization and socioeconomic indicators.

Along the coasts, the main driver of soil salinization is seawater intrusion, further exacerbated by groundwater overexploitation for agriculture and civil uses. The effects can spread for kilometers inland along fluvial plains, as in the case of southern Sardinia (Castrignanò, Buttafuoco and Puddo, 2008).

In the twentieth century, vast areas were reclaimed for agricultural purposes around the Po delta and north to the areas surrounding the Venice Lagoon. The water level is strictly regulated by channels and pumping stations (Antisari *et al*., 2020; Buscaroli and Zannoni, 2010; Teatini *et al*., 2007), and seawater intrusion along rivers, canals and in the groundwater aquifer is exacerbated by subsidence (Teatini *et al*., 2005). The freshwater deterioration represents a further risk for soil salinization in irrigated areas (Vittori Antisari *et al*., 2020). In southern Italy, a salt content increase at the end of the cropping season has been demonstrated (Cucci *et al*., 2009), which is then counterbalanced by the winter rainwater.

Salinity is a well-known issue in Sicily (Dazzi and Fierotti, 1994), with a widespread risk along the coastal areas and in the central part of Sicily. Here, salinity is due to geology for the presence of a gypsum sulphurous formation, a salt-rich lithology that affects the soils directly and indirectly by enriching irrigation waters with salt (Dazzi and Lo Papa, 2013; Selvaggi *et al*., 2010).

Other geological formations leading to salt-affected soils are the marine deposits dating back to the Pliocene-Pleistocene boundary, which are widespread in Sicily and in continental Italy. In the case of eroded soils, the salt-rich parent material can be exposed and create problems for vegetation and crops. In some areas, the bad physical conditions of these soils can lead to the formation of badlands (Piccarreta *et al*., 2006; Cocco *et al*., 2015).

In recent years, some Italian regional administrations produced soil salinity (risk) maps for Veneto (Vinci, 2020) Emilia-Romagna (Emilia-Romagna Region, 2020) Tuscany (GEOscopio WMS, 2020) Sardinia (Sardinia Agriculture, 2020), Sicily (Canfora et al., 2017). These maps differ each other in mapping approach (geostatistical in some cases, and using soil mapping units in others), but all are based on systematic soil surveys. Most of these data were used for the salt-affected soils map of Italy.

2 Methodology

2.1 Input data

The number of data points for electrical conductivity (ECe), pH, and exchangeable sodium percentage (ESP) differs, reflecting the different data sources.

The data for ECe have a clustered and biased distribution, given that in most of the country – except for Tuscany and Sicily – soil salinity was only investigated in risk areas. The spatial distribution of pH and ESP values is less clustered, although some regions were better surveyed than others.

As for ECe, 12 324 sites are available with ECe data at least in one horizon, for a total of 25 287 measurements. Samples were collected between 1969 and 2019. EC is measured on different soil:water ratios (1:2, 1:2.5, and 1:5) and a saturated extract. The EC 1:2.5 and 1:5 data were converted to the saturated paste using conversion functions calibrated for the Emilia Romagna region (Staffilani *et al*., eds, 2015) and used in other Italian regions. The EC 1:2 data were converted to the saturated paste using the function of Datta *et al*. (2017), which performed the best with the data. The average values for the reference depth intervals (0–30 cm and 30–100 cm) were calculated fitting to data with a mass-preserving spline (Malone *et al*., 2009) using the Spline Tool Version 2.0 (ASRIS, 2011). For the

0–30 cm interval, the dataset was further integrated with 1 461 point data retrieved from the LUCAS 2015 TOPSOIL dataset (JRC ESDAC, 2015). The LUCAS points were also used for integrating the EC dataset in the 30–100 cm interval, using the minimum ECe value recorded for the same soil types.

The final dataset sums up to 13 784 data points for the 0–30 cm interval, and 10 024 for the 30–100 cm interval. In Figure 1, the classed post plot for EC is reported for topsoil and subsoil.

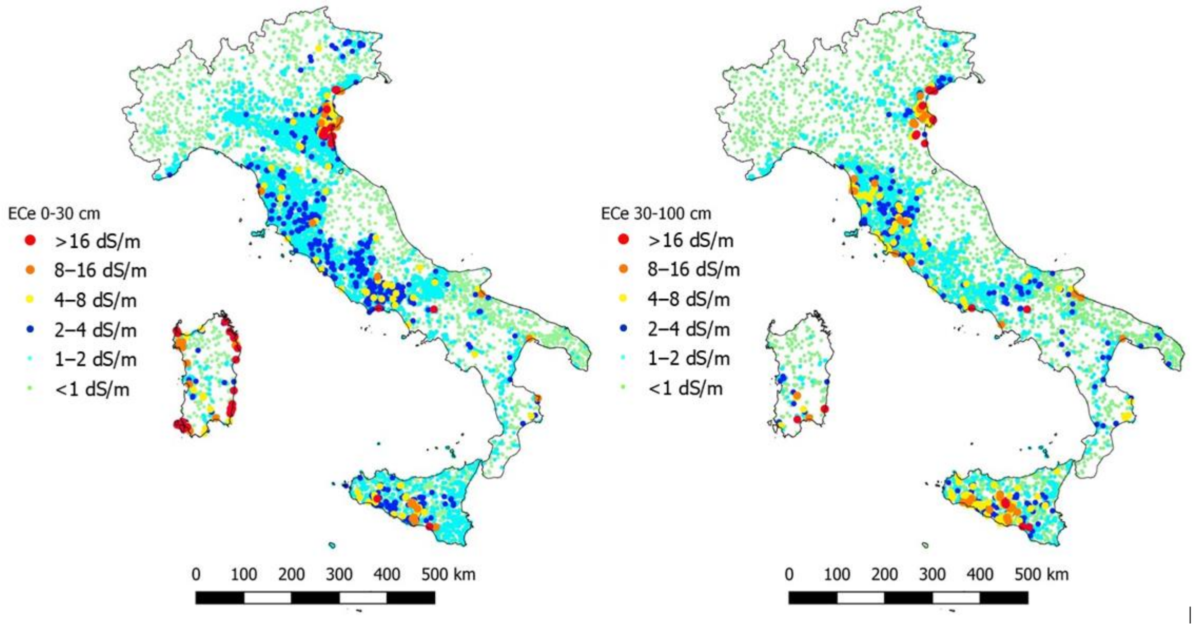

Figure 1. ECe (dS/m) classed post plot: 0–30 cm (left) and 30–100 cm (right)

The same procedure was used for calculating the average values for the two reference depth intervals for pH and ESP. The final dataset for pH counts 31 239 and 22 533 points for topsoil and subsoil, respectively, while for ESP, the final dataset counts 12 563 and 10 403 points for topsoil and subsoil, respectively.

2.2 Covariates selection procedure

A preliminary statistical analysis was used for the selection of the relevant covariates to be used in modelling, checking redundancy, significance, and congruency. The covariates used for creating spatial predictions of the map of salt-affected soils are listed in the Annex. Table 1 reports the selected covariates, both continuous and categorical, for ECe, pH, and ESP (topsoil at 0–30 cm, and subsoil at 30–100 cm).

Code	Description	ECe top	ECe sub	pH top	pH sub	ESP top	ESP sub
Categorical variables							
lito	Lithology (13 classes)	X	X	X	X		
salt	Salt-affected soils (2 classes)	X	X			X	X
SR	Soil regions (10 classes)	X	X	X	X	X	X
sub_reg	Soil subregions (49 classes)	X	X	X	X	X	X
Continuous variables							
coastd	Distance from coast					X	X
dem	Digital Elevation Model			X	X		
evi	EVI (enhanced vegetation index)	X		X	X		
fc50	Water content at field capacity					X	X
gfctcov	Global forest tree canopy cover	X					
ihug	Huglin index					X	X
ihumid	Humidity index						
lst	Modis (Land Surface Temperature)		X	X	X		
mrvbf	Multi Resolution Index of Valley Bottom Flatness	X	X				
ndvi5	Modis NDVI Sum of June-September (5 layers)					X	X
ndvi16	Modis NDVI Max. diff. March–November (16 layers)						
nir	Landsat Band 4 (near infrared reflectance)		X				
nort	Northness (orientation in combination with the slope)	X	X				
raina	Mean annual rainfall		X			X	X
red	Landsat Band 3 (Red)	X				X	X
sai	Soil aridity index	X		X			
sgpH	pH SoilGrids			X	X	X	X
sgsand	Sand SoilGrids			X	X		
sgsilt	Silt SoilGrids					X	X
sic500	Soil inorganic carbon stock (50–100 cm depth)		X	X	X		
swir1	Landsat Band 5 (Shortwave infrared)	X	X	X	X		
twi	Topographic Wetness Index	X					
vdepth	Valley depth		X				

2.3 Model definition

For the identification and application of suitable digital soil mapping (DSM) models, we used the R script provided by FAO (Omuto *et al.*, 2020). The selected covariates were used to create a stack for predictors, and all target variables were normalized via a Box-Cox transform. The DSM models were calibrated and validated on transformed data. For all variables at all depths, the model with the lowest root mean square error (RMSE) and highest R^2 was the cubist. For example, in the case of ECe (0–30 cm), the cubist model returned a RMSE of 1.16 dS/m and a R^2 of 0.41, while for ECe (30–100 cm) the corresponding figures were 0.77 dS/m and 0.71 for RMSE and R^2, respectively.

2.4 Validation

Once the DSM model to be used has been identified, the R script divides the dataset into two subsets, one for calibration (75 percent of the data) and one for validation (25 percent of the data). The procedure, called *stratified random splitting,* is repeated five times, and finally selects the model with the lowest RMSE value. Table 2 reports the validation statistics for the six target variables (Box-Cox transforms).

Table 2. Validation statistics

Variable	ME	RMSE	R^2	NSE
ECe 0–30 cm	−1.186	1.720	0.449	−0.688
ECe 30–100 cm	−1.155	1.208	0.742	0.154
pH 0–30 cm	3 307.3	3 512.7	0.958	0.0001
pH 30–100 cm	3 367.1	3 545.1	0.961	0.0001
ESP 0–30 cm	−1.468	2.280	0.545	−0.723
ESP 30–100 cm	−1.453	1.632	0.872	0.030

Note: ME = mean error (Obs-Est); RMSE = root mean square error; and NSE = Nash-Sutcliffe coefficient of efficiency.

Source: **Omuto, C.T., Vargas, R., Viatkin, K. & Yigini, Y**. 2020d. *Mapping of salt-affected soils: Lesson 4 – Spatial modelling of salt-affected soils*. Rome, FAO. https://www.fao.org/3/ca9209en/ca9209en.pdf

2.5 Mapping

The selected model is eventually used to estimate the normalized target variables in each cell of the 1km raster using the inputs contained in the raster stack of the selected predictors. An inverse transformation is then applied to the estimated values to produce the final maps. To this, a standard deviation map and an uncertainty (i.e. prediction width) map (obtained resorting to a bootstrap approach) were added. The final maps for ECe, pH, and ESP at the two reference depths are shown in Figure 2, Figure 3, and Figure 4.

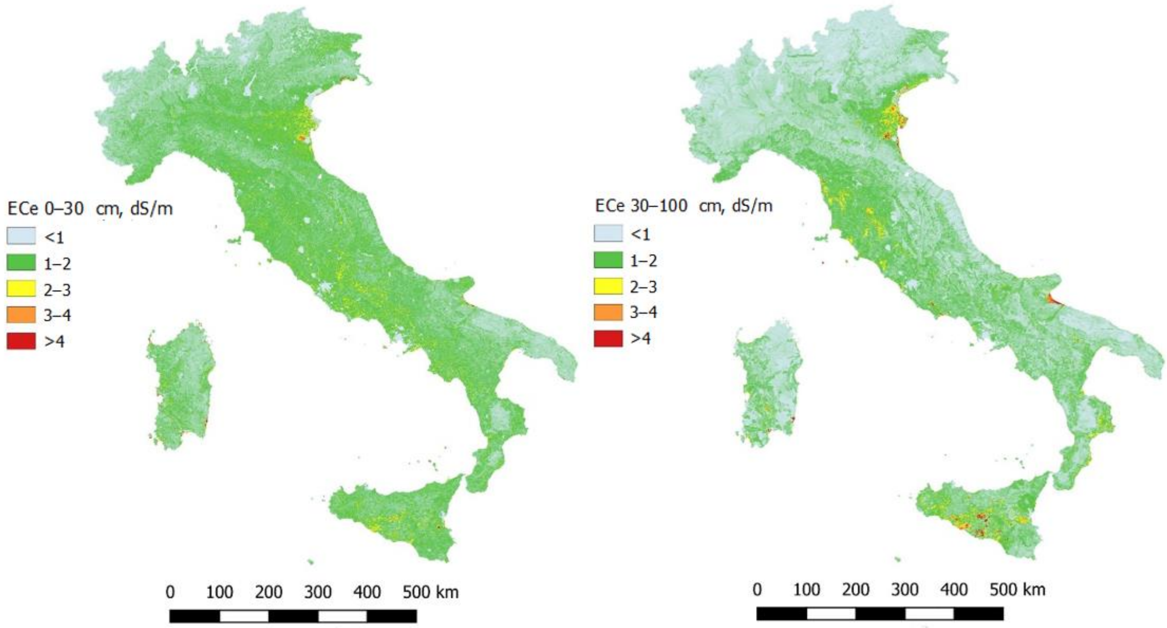

Figure 2. ECe map (dS/m): 0–30 cm (left) and 30–100 cm (right).

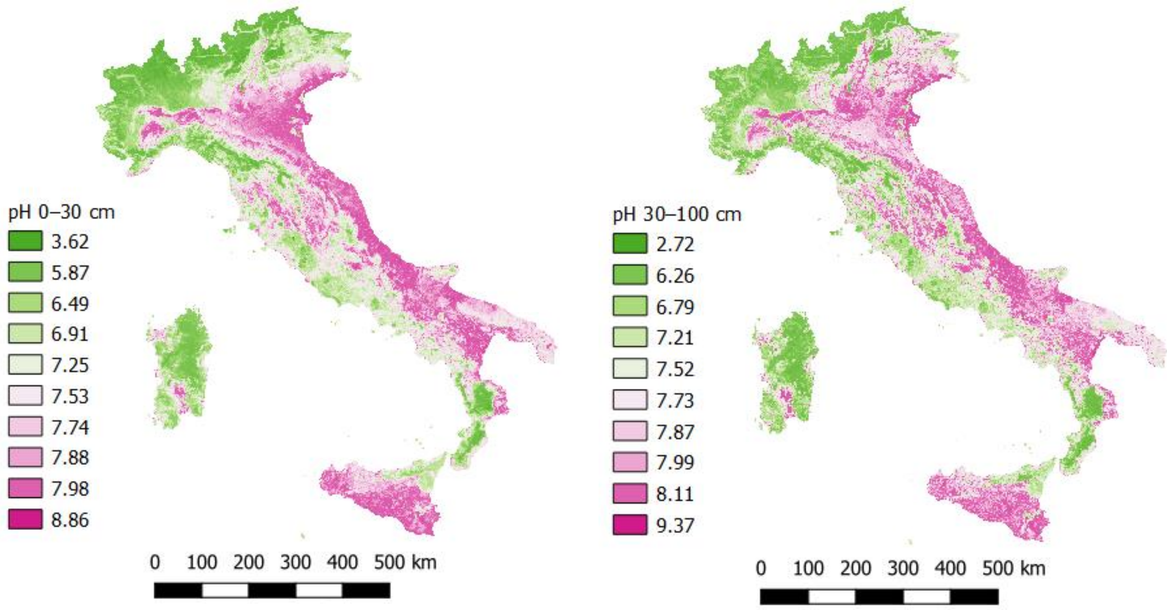

Figure 3. pH map: 0–30 cm (left) and 30–100 cm (right). Classes based on the deciles of the distributions.

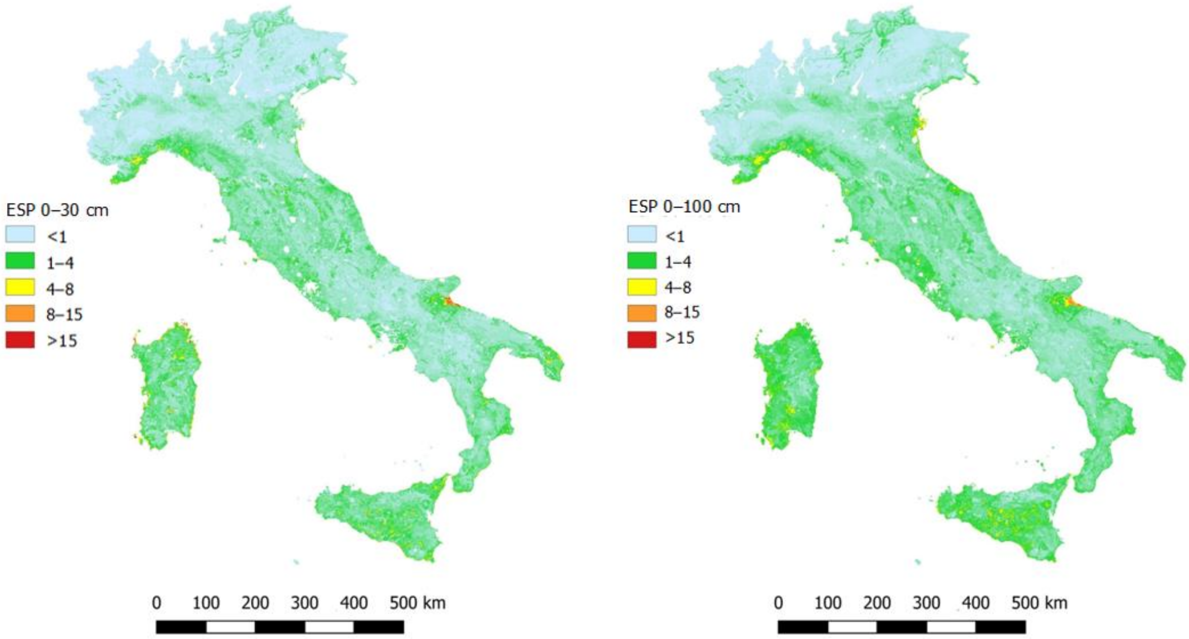

Figure 4. ESP map (percentage): 0–30 cm (left) and 30–100 cm (right).

3 Status of salt-affected soils in Italy

The status of salt-affected soils in Italy – according to the maps showed in Figure 2, Figure 3 and Figure 4 – was assessed using the classification scheme in Table 3.

Table 3. Classification scheme for salt-affected soils (FAO, 2006; Abrol et al., 1988; Richard, 1954)

Class	ECe	ESP	pH
None	<0.75	<15	-
	<0.75	>15	<8.2
Slightly saline	0.75–2.0	<15	-
Moderately saline	2.0–4.0	<15	-
Strongly saline	4.0–8.0	<15	-
Very strongly saline	8.0–15.0	<15	-
Extremely saline	>15.0	<15	-
Slightly sodic	<4.0	15–30	>8.2
Saline sodic	>4.0	15–70	-
Slightly saline sodic	0.75–2.0	>15	<8.2
Moderately saline sodic	2.0–4.0	>15	<8.2

The relevance of each class at the two reference depth intervals is summarized in Table 4. Salt-free soils represent 55 percent and 77.8 percent of topsoils and subsoils, respectively, slight salinity (ECe 0.75–2 dS/m) affects 44.5 and 20.5 percent of topsoils and subsoils, respectively, while moderate salinity (ECe 2.0–4.0 dS/m) affects 0.35 and 0.79 percent of topsoils and subsoils, respectively. In the case of topsoil, 60 percent of the ECe values classified as slightly saline are below 1 dS/m, while for the subsoil 64 percent of estimated values classified as slight saline are below 1 dS/m. The two additional saline sodic classes, slightly and moderate, have been used to account for specific conditions at a local level. Figure 5 illustrates the distribution of salt-affected soils for the two reference depth intervals.

Table 4. Status of salt-affected soils in Italy

Class	Depth 0–30 cm	km^2	Depth 30–100 cm	km^2
None	54.96	164 224	77.82	232 989
Slightly saline	44.55	133 116	21.06	63 049
Moderately saline	0.349	1 042	0.92	2 763
Strongly saline	0.046	138	0.140	420
Very strongly saline	0.005	14	0.012	35
Extremely saline	0.001	3	0.000	0
Slightly sodic	0.005	14	0.001	3
Slightly saline sodic	0.066	198	0.005	14
Moderately saline sodic	0.016	48	0.027	81
Saline sodic	0.010	31	0.007	21

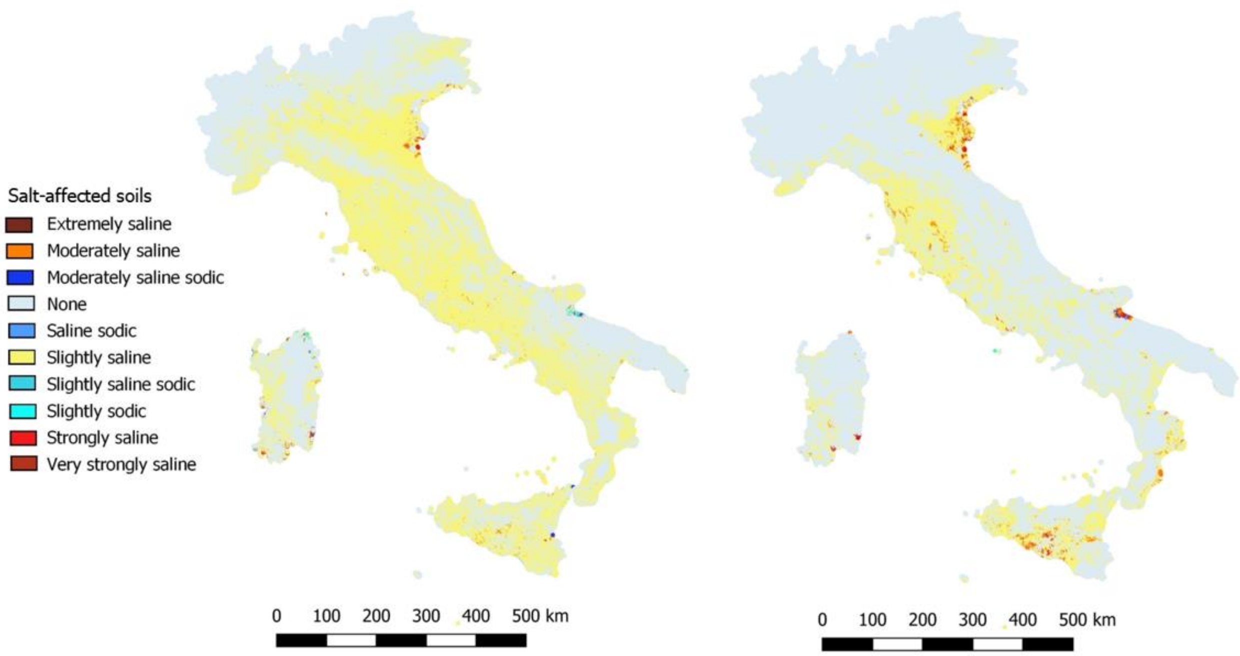

Figure 5. Maps of salt-affected soils: 0–30 cm (left) and 30–100 cm (right)

As already hypothesized by Dazzi and Lo Papa (2013), Dazzi (2008), and Costantini (2009), the main drivers of salinization (and sodification) are the seawater intrusion in both groundwater and channels near the coasts, and the related low-quality water used for irrigation. In the topsoils of the inland plains, the slight increase of ECe (mostly below 1 dS/m), is most probably due to the use of fertilizers, while in the inland hilly areas, the main driver is the salt content in the soil parent materials, as pointed out for Sicily by Dazzi and Fierotti (1996) and Dazzi and Lo Papa (2013). The soil developed on marine Pliocene-Pleistocene sediments show a relatively high ECe, particularly in subsoil and in eroded soils, where the parent material is exposed. This phenomenon is particularly diffused in Sicily and Tuscany. The same applies for the gypsum-sulphurous formation in Sicily.

In Sardinia, the areas at risk of salinization are mainly found along the coasts, but some inland agricultural plains are also affected, which is relevant in a mostly hilly and mountainous region (Puddu *et al*., eds, 2008).

As shown by the validation statistics (Table 2), ECe is slightly overestimated on average, but local underestimation is observed in particular in the coastal plains of Tuscany, Latium and Apulia. Therefore, even if the overall ECe spatial pattern is correct, in these cases, the modelled areas of salt-affected soils are not fully responding to the local experience. This is due to a number of reasons: first, the use of a unique set of PTFs for harmonising the original measures, which smooths the overall trend; second, the use of covariates with a spatial resolution which may be unsuited for catching the incidence of the main salinization drivers locally acting at more detailed scales; and third, the uneven distribution of the measured points (Figure 1).

As for ESP, which shows a difference from the model validation results, a slight underestimation is observed at national and (with a few exceptions) regional level, but in most cases, differences are below 1 percent. Therefore, this does not affect the overall risk classification for sodification.

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