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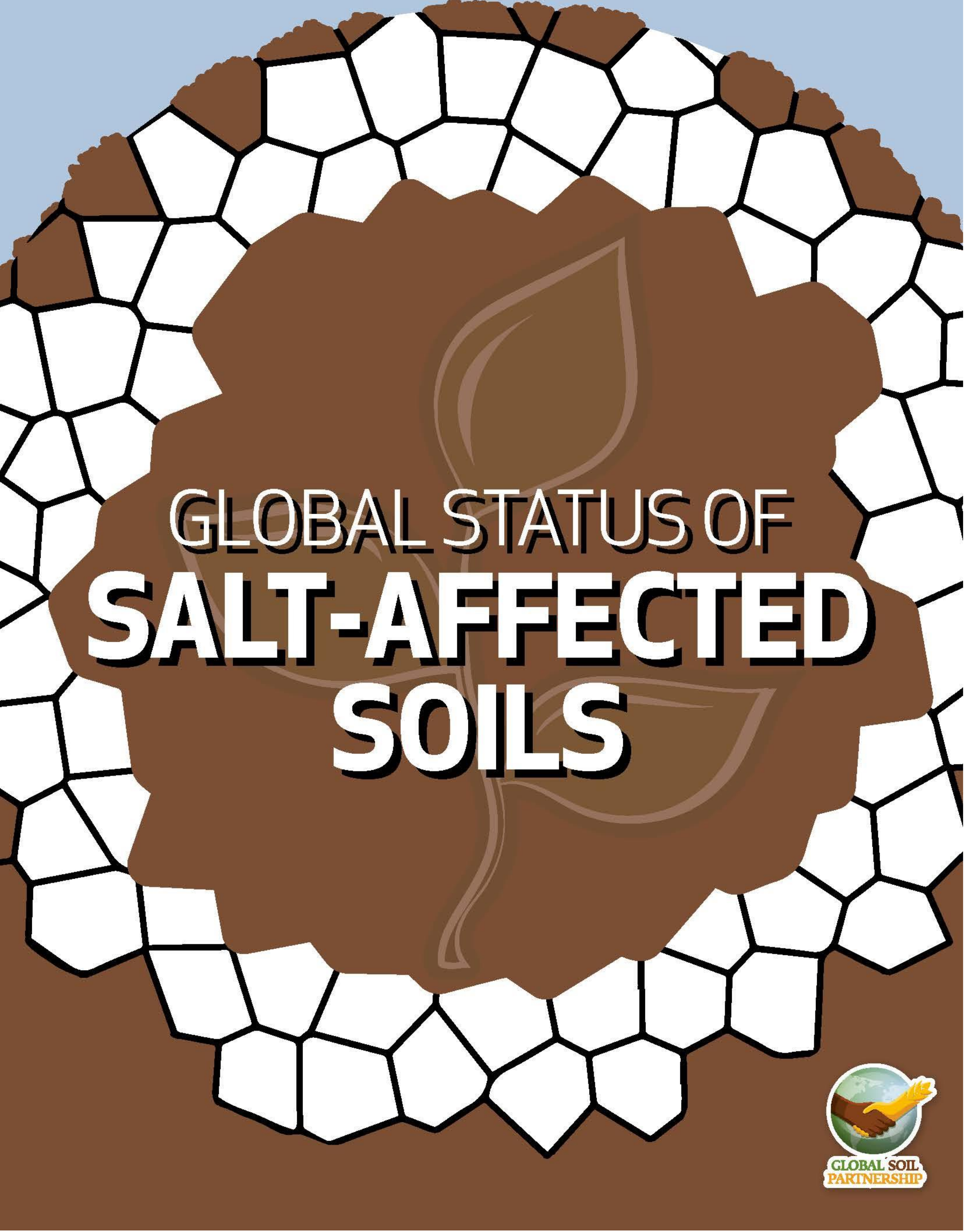

GLOBAL STATUS OF
SALT-AFFECTED SOILS

GLOBAL SOIL
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Salt-affected soils in Italy

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1 Introduction

Soil salinization/sodification risk is considered one of the main threats in agricultural soils of Italy (Dazzi, 2008). It is mainly due to irrigation with saline or brackish waters in particular in the plains and along the coastal areas (Dazzi & Lo Papa, 2013). Even if a general map showing the distribution of saline soils is not available for Italy, an exploratory survey identified some risk areas (Dazzi, 2008): 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 (SAS) by considering 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 socio-economic indicators.

Along the coasts, the main driver of soil salinization is seawater intrusion, further exacerbated by groundwater over-exploitation for agriculture and civil uses. The effects can spread for kilometers in the inland along fluvial plains, as in the case of southern Sardinia (Castrignanò et al., 2008). Around the Po delta and norther, until the areas surrounding the Venice Lagoon, vast areas were reclaimed for agricultural purposes in the past century. The water level is strictly regulated by channels and pumping stations (Vittori Antisari et al., 2020; Buscaroli et al., 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), 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 the Gypsum-Sulfurous 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 Pliocene-Pleistocene, which are widespread in Sicily and in continental Italy. In 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: Veneto (http://geomap.arpa.veneto.it/layers/geonode%3Acarta50_250_salinita_UTS1), Emilia-Romagna (https://ambiente.regione.emilia-romagna.it/it/geologia/suoli/proprieta-e-qualita-dei-suoli/salinita), Tuscany (http://www502.regione.toscana.it/geoscopio/pedologia.html), Sardinia (http://www.sardegnaagricoltura.it/index.php?xsl=443&s=76894&v=2&c=3533), Sicily (unpublished data). These maps differ each other for mapping approach (geostatistical in some cases, soil mapping units based in others), but are all based on systematic soil surveys. Most of these data were used for the SAS map of Italy.

2 Methodology

2.1 Input data

The number of data points for ECe, pH, and ESP is not the same, 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 investigated only 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, 1:5, saturated) extracts. 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., 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 was the best performing one for our 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 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 (https://esdac.jrc.ec.europa.eu/content/lucas2015-topsoil-data). The LUCAS points were also used for integrating the EC dataset in the interval 30-100 cm, 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 Fig.1, the classed post plot for EC is reported for topsoils (left) and subsoils (right).

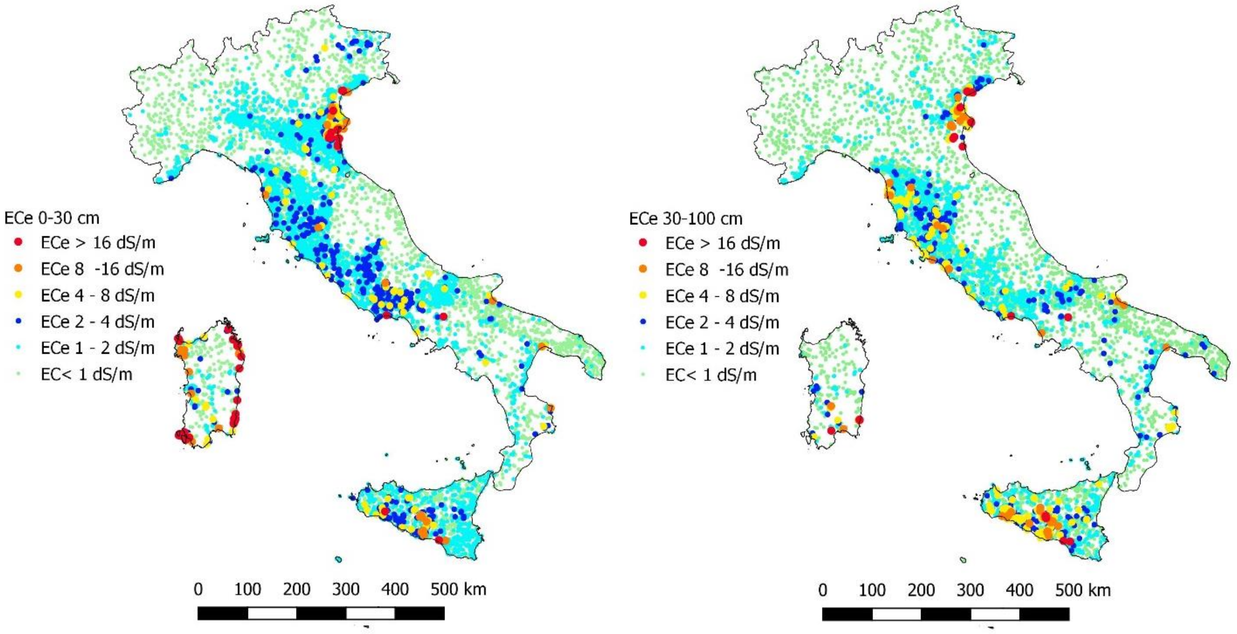

Figure 1. ECe dS/m classed post plot: 0-30 cm (left) , 30-100 cm (right).

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; in case of 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. Table 1 reports the selected covariates, both continuous and categorical, for ECe, pH, and ESP (top: 0-30 cm; sub: 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 (Short wave infrared)	X	X	X	X		
twi	Topographic Wetness Index	X					
vdepth	Valley depth		X				

Table 1. selected covariates for ECe, pH, and ESP modelling.

2.3 Model definition

For the identification and application of suitable 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. DSM model were calibrated and validated on transformed data. For all variables at all depths, the model with the lowest RMSE and highest R^2 was the cubist. For example, in the case of ECe 0-30cm, the cubist model returned a RMSE of 1.16 dS/m and a R^2 of 0.41, while for ECe 30-100 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% of the data) and one for validation (25% of the data). The procedure, called *stratified random splitting,* is repeated 5 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).

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	3307.3	3512.7	0.958	0.0001
pH 30-100 cm	3367.1	3545.1	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

Table 2. Validation statistics. ME, mean error (Obs-Est); RMSE, root mean-square error; NSE, Nash-Sutcliff coefficient of efficiency (Omuto et al., 2020).

2.5 Mapping

The selected model is eventually used to estimate the normalized target variables in each cell of the 1k 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 Figures. 2-4.

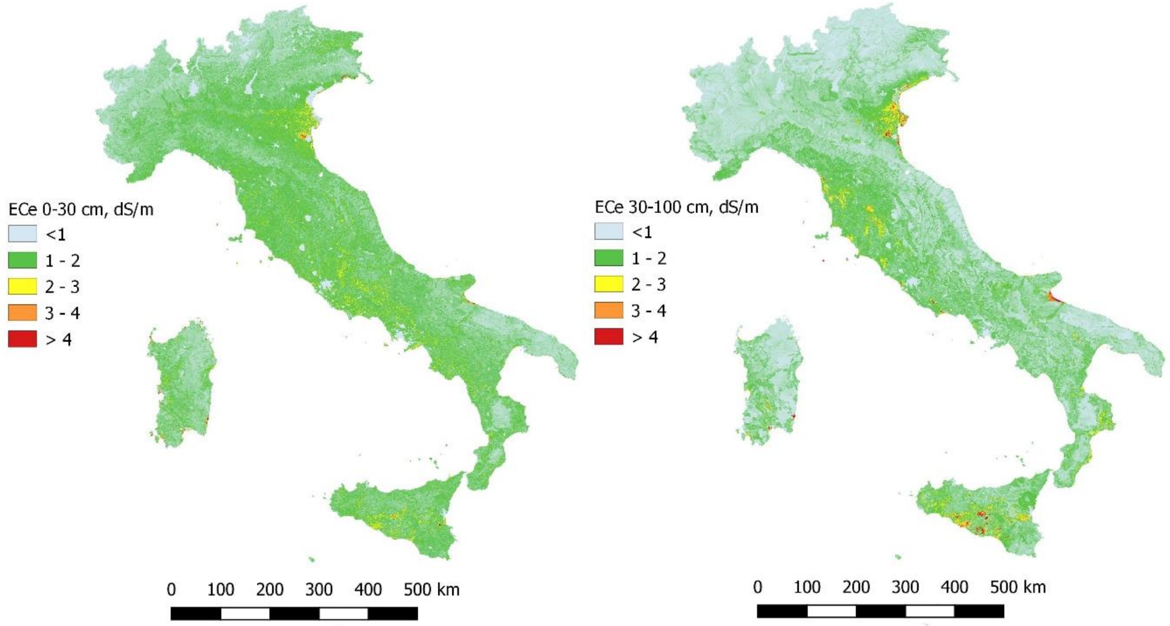

Figure 2. ECe map, dS/m: 0-30 cm (left), 30-100 cm (right).

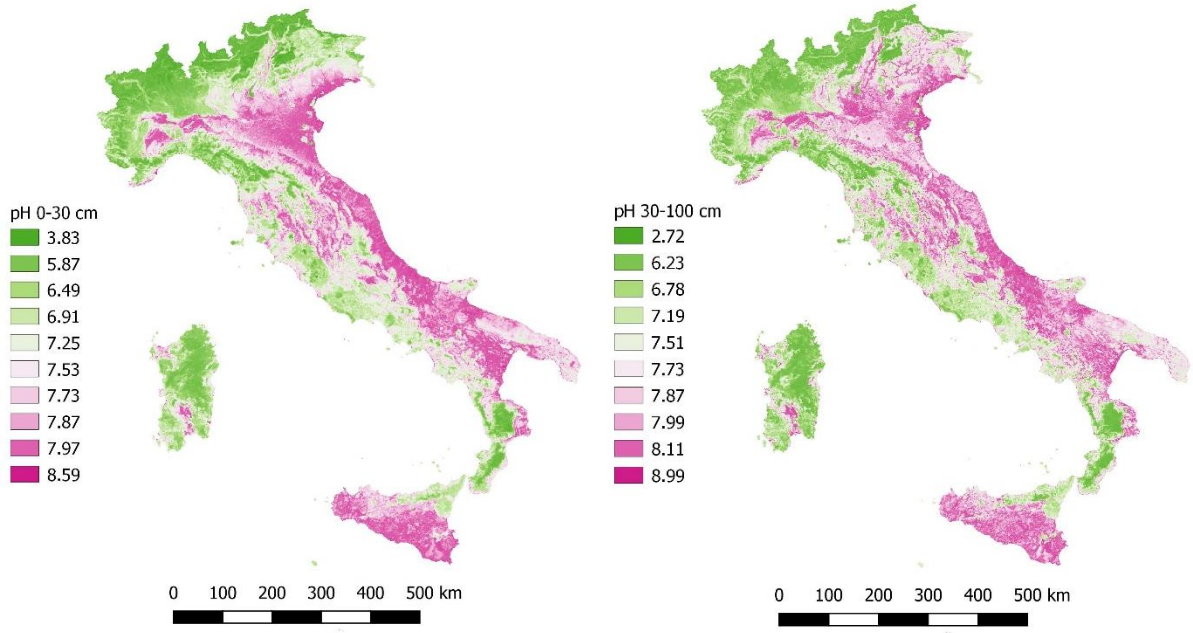

Figure 3. pH map: 0-30 cm (left), 30-100 cm (right). Classes based on the deciles of the distributions.

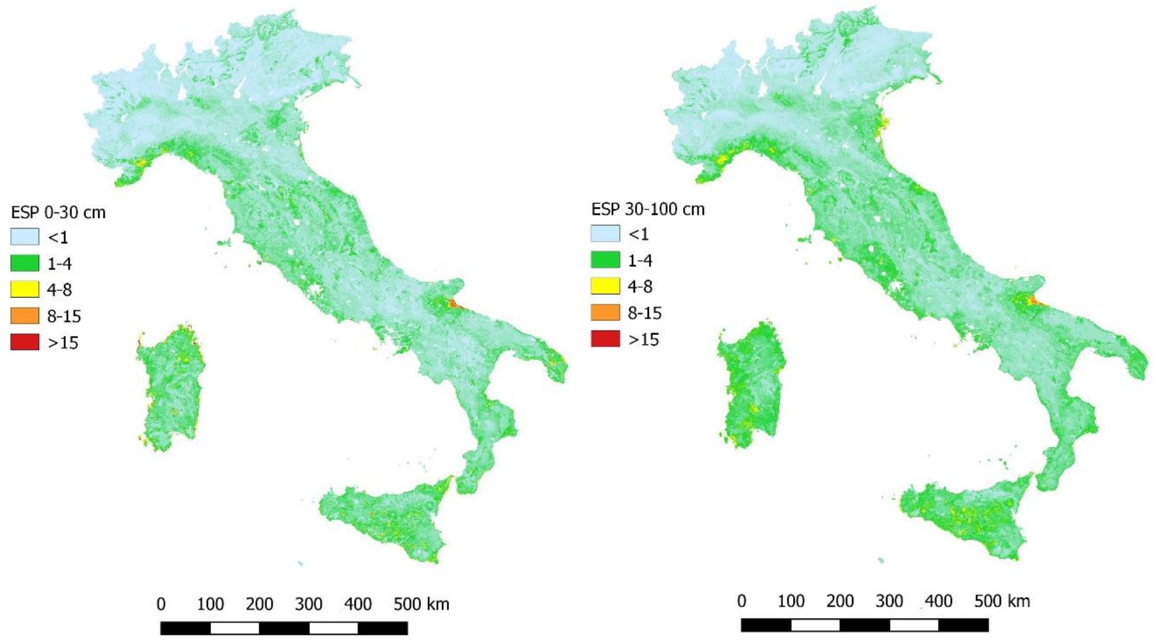

Figure 4. ESP map, %: 0-30 cm (left), 30-100 cm (right).

3 Status of salt-affected soils in Italy (463 parole)

The status of salt-affected soils in Italy, according to the maps showed in Figures 2-4, was assessed using the following classification scheme:

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

Table 3. Classification scheme for salt affected soils.

The relevance of each class at the two reference depth intervals is summarized in Table 4. Salt free soils represent 55% and 77.8% of topsoils and subsoils, respectively; slight salinity (ECe 0.75-2 dS/m) affects 44.5 and 20.5 % of topsoils and subsoils, respectively, while moderate salinity (ECe 2.0 -4.0 dS/m) affects 0.35 and 0.79 % of topsoils and subsoils, respectively. In the case of topsoil, 60% of the

ECe values classified as slightly saline are below 1 dS/m, while for the subsoil 64% 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 local level. Figure 5 illustrates the distribution of salt-affected soils for the two reference depth intervals.

Class	GSS 0-30 cm	Km^2	GSS 30-100 cm	Km^2
None	54.96	164224	77.82	232989
Slightly saline	44.55	133116	21.06	63049
Moderately saline	0.349	1042	0.92	2763
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

Table 4. Status of salt-affected soils in Italy.

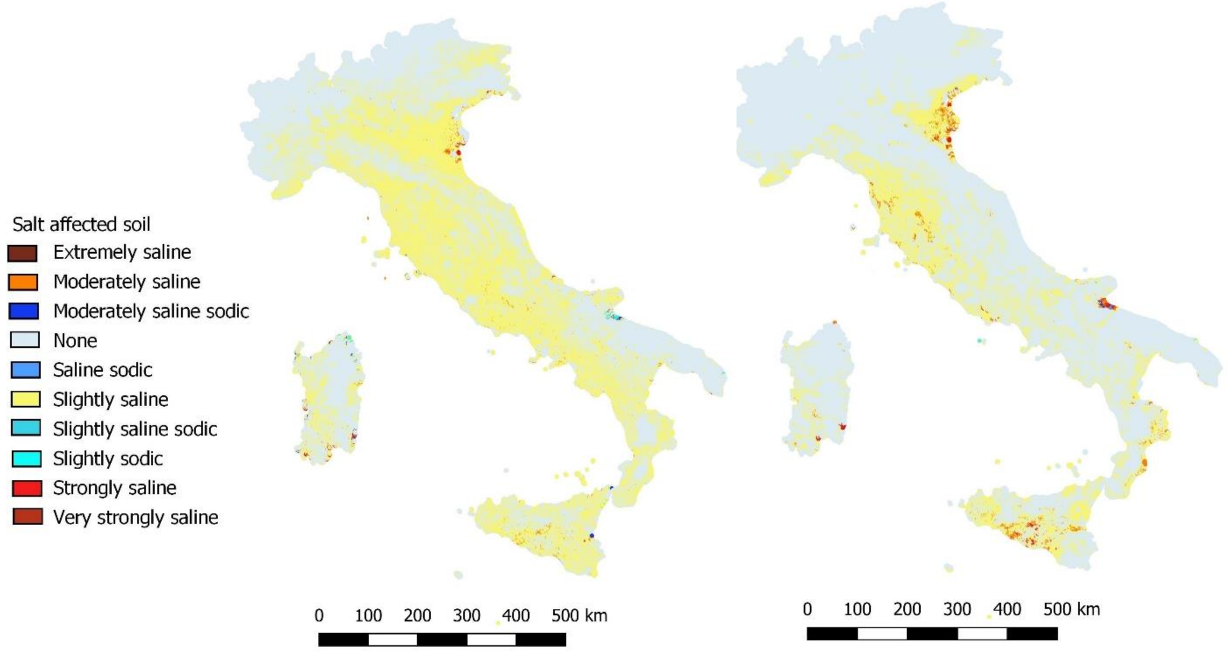

Figure 5. Maps of salt-affected soils: 0-30 cm (left), 30-100 cm (right).

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 groundwaters and channels near the coasts, and the related low quality waters used for irrigation. In the inland plains topsoils, the slight increase of ECe, mostly below 1 dS/m, is most probably due to fertilization, 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-Pleistocenic sediments show a relatively high ECe, in particular 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-Sulfurous Formation in Sicily.

In Sardinia, the salt risk areas 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., 2008).

As testified by the validation statistics (Table 2), ECe is on average slightly overestimated, 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, the modelled SAS areas are in these cases 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; third, the uneven distribution of the measured points (Fig. 1).

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

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6. Figures caption

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7. Table caption

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    e. Use the solidus (/) instead of a horizontal line in fractions
    f. Use of fractional powers instead of root sign
    g. Us *exp* for powers of e
    h. In chemical formulae, valence of ions should be given e.g., Ca^{2+}, not as Ca^{++}