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Original Research Article

GIS-based soil maps as tools to evaluate land capability and suitability in a coastal reclaimed area (Ravenna, northern Italy)

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A B S T R A C T

Land capability and suitability maps are useful tools for soil resource conservation. This study aimed to build land capability and suitability maps using a multi-thematic approach by GIS in a salt-affected coastal area of Italy. Topographic, morphological, geological, pedological delineations and land cover maps, remote sensing image and climate data were acquired and the main physical and chemical properties, including electrical conductivity (EC) and available water capacity, were analysed on the soil samples collected in the study area. The acquired information were elaborated through QGIS software to obtain the land capability and suitability maps. The suitability map showed that most of the area (80%) is suitable for cultivation and, therefore, can be addressed for agricultural purposes without risk of degradation. In fact, the land capability map showed that 42% of the investigated area belongs to class I and II indicating that they can be used for a wide range of cultivations. While 44% of the investigated area clustered in class III and IV. In these latter the cultivation should be allowed to a limited range of crops due to the high sand content, which does not allow a good water retention, and due to a strong intrusion of sea water with consequent increase of the soil EC. In our study area, where agricultural productivity and environmental impact are in conflict, to classify the lands on base the land capability and suitability could help to define the best agricultural practices to apply in order to preserve soil functions.

1. Introduction

Coastal areas are often affected by salinization due to the seawater intrusion in aquifers and to the improper use of poor (high salt content) water quality (Canfora et al., 2017; Tedeschi & Menenti, 2002; Vittori Antisari et al., 2020). Salinity and sodicity in the soils of these areas pose serious limitations to agricultural production (Shrivastava & Kumar, 2015) and use (Tóth et al., 2008, pp. 61–74). The impact to agricultural production ranges from slight yield loss to complete crop failure, depending on both the crop type and the physicochemical soil features, including their salt content (Gupta et al., 2008; Munns, 1999). Salt affected soils can be also found in inland areas where salts are naturally present in the soil and in those areas characterized by low rainfall and high evapotranspiration rates (Raimondi et al., 2010; Walter et al., 2018). Soil salinity is thus a fundamental issue in agriculture, affecting a substantial amount of land throughout the world in diverse countries and geographical zones, in both irrigated and dryland soil. However, the localization and extent of the areas affected by soil salinization is still controversial. The FAO/UNESCO soil map of the world (1970–1980) suggested that in Europe saline soils made up 6.7 Mha, or 0.3% of the total area, and sodic soils are 72.7 Mha, 3.6%. According to Stanners (1995), salinization affects around 3.8 Mha, while more recent investigations reported that saline and sodic soils cover about 30.7 Mha of Europe (Rengasamy, 2006).

Measurement of soil salinity is essential for effective management and planning of agricultural activity in salinity-affected soils and, for individual crops, localised measurement is required to optimise crop management. At a larger scale, mapping of salinity is required to delineate crop management zones and for regional land management. In this context, both land capability and land

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Fig. 1. Topographic map (left side) and remote sensing image (right side) of the coastal area located in the North-eastern Italy. The topographic map was elaborated using the Regional Technical Paper of Emilia-Romagna Region (RER, 1998). The remote sensing image was elaborated using the Google Earth™ imagery.

suitability can be useful tools to ensure delineation of management zones aimed to suitable land use. In fact, land capability is referred to the ability of soil to grow the cultivated crops and pasture plants without deterioration over a long period of time (Klingebiel & Montgomery, 1961). Closely associated land capability, land suitability is defined as the soil ability to sustain the cultivated plants and their yields in a sustainable way (FAO, 2007; Field & Odgers, 2016). Therefore, land capability allows the assessment based on inherited permanent physical properties of the lands and climate, while land suitability includes economic, social and/or political factors (Grose, 1999). The concept of land suitability acquires meaning if the characteristics and qualities of soil are compared with the requirements of each use (Burian et al., 2018; FAO, 1981). Consequently, soil properties and land use are equally fundamental to land suitability evaluation (Verheye et al., 2003).

The classification of soils on the base of their capability and suitability is necessary to ensure both food production and the protection of the natural resources (Deshmukh, 2016; Hudson, 1992). Furthermore, the knowledge of land capability and suitability allow to plan land uses and to develop those land management able to improve productivity. However, in order to obtain accurate classes of land capability and suitability, there is the need to pay attention to the high soil spatial variability (Elkateb et al., 2003; Stoyan et al., 2000). In this context, the Soil Science Division Staff (2017) suggests the use of the Geographic Information System (GIS) as an important tool to map soils and interpret the variations of their physicochemical properties in space and in time (Vacca et al., 2014). In fact, GIS is used to predict the soil type distribution in the space undergoing periodic geomorphological and hydrogeological changes due to both natural causes (Ciavola et al., 2006, pp. 18–25) and anthropic interventions (Romano & Zullo, 2014; Sekovski et al., 2015). Additionally, GIS is helpful for processing large amounts of spatial data and providing accurate and accessible information for land (Dan et al., 2018; Smiraglia et al., 2013). Hence, since its high potential on soil variability assessment, recent studies used this tool to identify the land capability and suitability (AbdelRahman et al., 2016; Montgomery et al., 2016). Zurqani et al. (2019) stated that GIS is very useful tool for monitoring both temporal and spatial changes of soil salinity.

In this framework, the aim of the present study was to build detailed land capability and suitability maps using a multi-thematic approach by GIS in a salt-affected coastal area of Italy.

Specifically, the procedure is based on four steps: land unit maps building, realization of a detailed soil map, development of the salinity and the available water capacity maps, and development of the land capability and suitability maps (Fig. S1 of the Supplementary materials).

2. Materials and methods

2.1. Study area

The studied coastal area is located in the North-eastern Italy, and is bounded to the North and South, respectively, by the last stretch of the Reno River and the Lamone River, to the East by the Adriatic Sea and to the West by the eastern edge of the Comacchio Valleys (Fig. 1).

The area has a total surface of 3488 ha, it is in plain and it is characterized by alluvial deposits that totally or partially buried the pre-existing brackish marshes and dune cords of Adriatic Sea (Antonellini et al., 2019; Ciavola et al., 2007). Most of the area is subjected to subsidence and it underwent reclamation between the end of the 19th and the beginning of the 20th century (Carbognin & Tosi, 2005; Zerbini et al., 2005). Furthermore, soil salinization, due to saline wedge, is one of the main soil threats currently affecting the agricultural land exploitation (Antonellini et al., 2008; Giambastiani et al., 2007).

The ten-year (2010–2019) climatic data, provided by the meteorological observatories of Marina di Ravenna (33T 4933700.44 mN; 268184.47 mE, −1 m a.s.l.) and Mezzano (33T 4930070.66 mN; 284087.15 mE, −3 m a.s.l.), indicate that the climate of the area can be classified as mesothermal subcontinental temperate according to Peel and Bloeschl (2011) with about 650 mm of annual rainfall, mainly concentrated in the periods October–November and May–June (150 and 115 mm per month, respectively), while mean temperatures range from 23.5 °C in July to 1.5 °C in January. The soil moisture and temperature regimes according to the SSS (2014) are Ustic and Mesic, respectively. Rainfalls, temperature oscillations, and evapotranspiration phenomena deeply affect the groundwater depth and the magnitude of saltwater intrusion in the deep aquifer (Ferronato et al., 2016; Laghi et al., 2010, pp. 1124–1135).

In about 60% of the study area, the Digital Terrain Model, deriving from light detection and ranging (LiDAR) scan and with 1 m ground resolution, shows a morphology with altitudes below

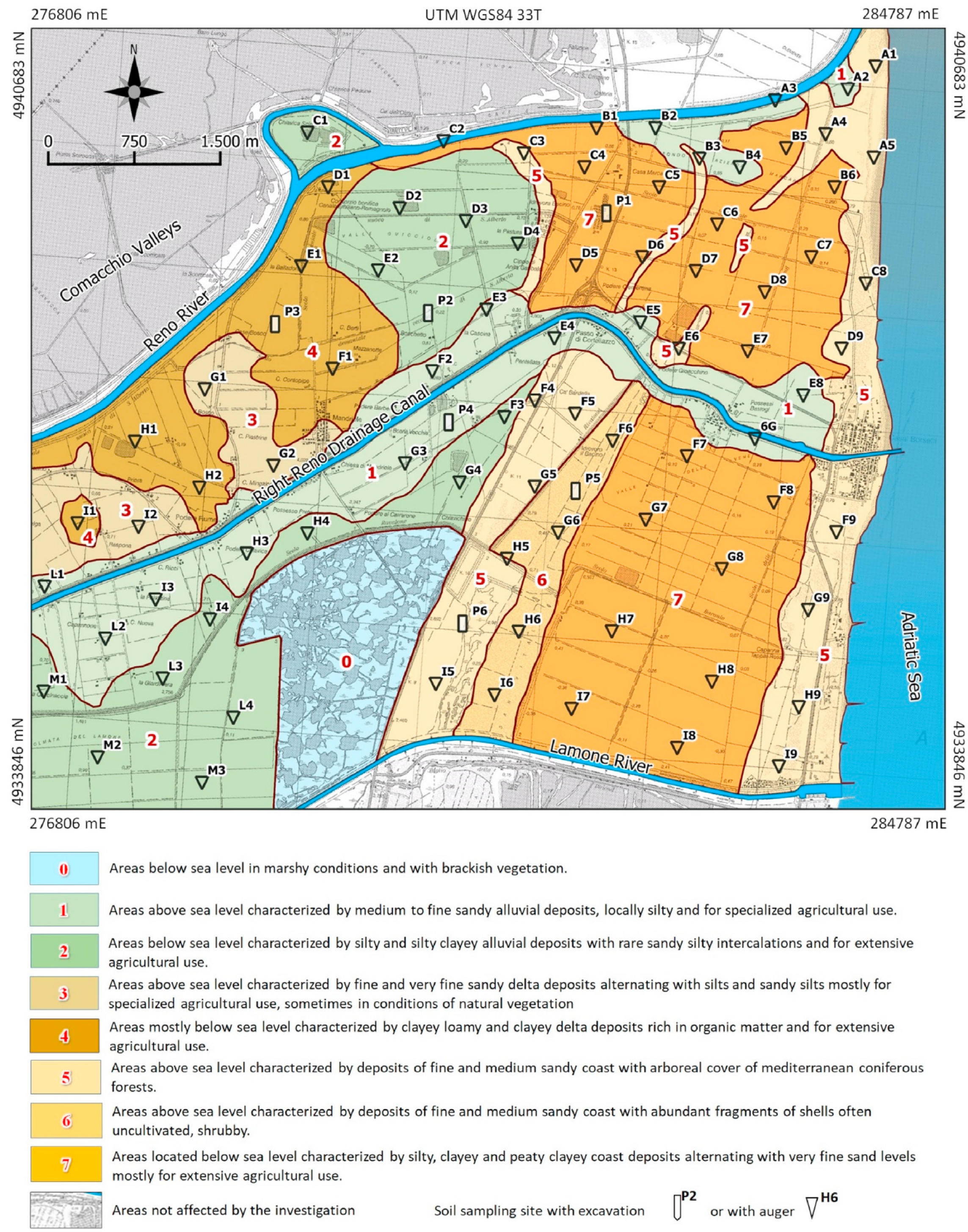

Fig. 2. Land units map and soil sampling sites location of the coastal area located in the North-eastern Italy.

sea level which sometimes reach −2 m a.s.l. Elevations above 1 m extend laterally to the Right Reno Drainage Canal which in the past held the ancient course of the Lamone river frequently affected by floods. The territory bands above 2 m correspond to the ancient dune structures (Fig. S2a of the Supplementary materials).

The area is characterized by silty-clayey alluvial deposits that, in the western part, have buried the brackish marsh and cordon deposits of the previous coastal alignments, while, in the central part, the cords and dunes are still visible in elongated areas oriented according to the current and past coastal alignments. Immediately behind the coast line there is a band of cords and dunes with a mainly sandy texture (Fig. S2b of the Supplementary materials). According to the Soil Service of the Emilia-Romagna Region (RER, 2018a), the area is characterized by soils with moderate pedogenesis (Cambisols - IUSS, 2015; Inceptisols – SSS, 2014) often affected by hydromorphy (stagnic, gleyic); close to the coast, on the ancient and recent dune systems, there are soils with a high sand content (Arenosols - IUSS, 2015; Psamments – SSS, 2014) (Fig. S2c of the

Table 1
List of maps and images used for building the land units map.

Map	Description	Source
Topographic map (Fig. 2)	It was obtained by assembling the Regional Technical Paper at scale 1:5000 in Tiff format	RER, (1998)
Remote sensing image (Fig. 2)	High resolution Google satellite orthoimage, download performed via SAS Planet GIS. Reference year 2018.	Google Earth™
Morphological map (Fig. S1a)	It was acquired by Ministry of the Environment and the Protection of the Territory and the Sea through light detection and ranging (LiDAR) scan.	RER, (2010)
Geological map (Fig. S1b)	It is a vector layer in shapefile format digitized starting from the Tiff raster data of Geological Map of Italy - Map Sheet 223 Ravenna (scale 1:50,000) of the Geological Service of Italy (1999) and of the Geological Map 1:10,000 of the Emilia-Romagna Region Seismic-Geological Survey	RER, (2006)
Pedological delineations map (Fig. S1c)	It was acquired as a vector layer in shapefile format digitized from the Soil Map 1:50,000 of the Emilia Romagna Region Soil Service	RER, (2018a)
Land cover map (Fig. S1d)	It was acquired as a vector layer in shapefile format created by the Emilia-Romagna Region.	RER; (2018b)

Supplementary materials).

Land cover (Fig. S2d of the Supplementary materials), classified according to the 3-level hierarchical of the Corine Land Cover System (EEA, 2007), shows the prevalence of agricultural areas, characterized by irrigated lands and pastures, followed by forests and seminatural areas (coniferous and mixed forests, and sclerophyllous vegetation). Wetlands are represented by inland marshes and water bodies. The artificial surfaces include residential units, business entities, port areas, sport and leisure facilities (RER, 2018b).

2.2. Land units map

The map of land units (Fig. 2), defined as zones with a significant degree of environmental homogeneity (Omernik & Bailey, 1997), was built through the reasoned vector overlay of remote sensing image, and topographic, morphological, geological, pedological delineations and land cover maps. Maps overlapping was performed through Intersection procedures on the vector data with reference to the Datum UTM-WGS84 33T. The land unit map was created by the open source QGIS 3.12 software, overlaying maps and generating a new level of data as a product of existing layers (DiBiase, 2014; DiBiase et al., 1994). Source of each existing layers is reported in Table 1.

2.3. Soil map

2.3.1. Soil sampling

The soil survey was carried out on the basis of the delineations identified by the land units map. The number of sampling points was based on the size of each delineation (Deckers et al., 2006). Specifically, 79 sites were identified, corresponding to about one sampling point every 50 ha, and a soil profile was opened in each site by auger. The position of each sampling point was georeferenced (Garmin GPS) and the coordinates were expressed as WGS84 UTM 33T Datum. In each profile, soil samples were collected from four different fixed depths (0–10, 10–30, 30–60, 60–100 cm). The choice to sample by fixed depths was based on the fact that this sampling method is considered correct for the evaluation of the main chemical properties (i.e. nutrients and organic carbon contents) in arable lands due to similar bulk density along depth caused by plowing (Wendt & Hauser, 2013). Moreover, the soil sampling by fixed depth is a common procedure when the GIS technology is used for the assessment of lands (Denton et al., 2017; Emadi et al., 2010). Further, from each fixed depth, additional soil samples (undisturbed soil samples) were collected using an Eijkelkamp sampler ring kit model C, ⌀53 mm (Eijkelkamp, Soil & Water, Giesbeek, The Netherlands). The soil sampling was carried out in winter (December) and in the following summer (July) season in order to evaluate the seasonal variation of soil salinity and water content.

2.3.2. Physical and chemical soil characterization

The undisturbed soil samples were placed in a water bath for 24 h until water saturation. Afterwards, the samples were left to percolate by gravity for 24 h at 25 °C and were then weighed (mwet). Finally, the soil samples were placed in an oven at 105 °C for 24 h, and the weight of the dried samples was then recorded (mdry). Gravimetric water content (θg; Bilskie, 2001; Copper, 2016) was calculated according to the following equation [1]:

$$\theta g\ (g) = mwet\ (g) - mdry\ (g) \quad [1]$$

Because of 1 g θg is equal to 1000 mm^3 of water, the available water capacity (AWC) of each soil depth was calculated dividing the θg by the area of Eijkelkamp sampler ring used for the collection of undisturbed soil samples and taking in account the thickness of each soil layer.

The disturbed soil samples of each layer were air-dried at room temperature, then ground and sieved at 2 mm. On the sieved samples, pH was determined potentiometrically in a 1:2.5 (w/v) soil:distilled water suspension with a Crison pH-meter. The electrical conductivity in the water extract obtained from 1:2.5 (w/v) soil:water ratio was measured by conductimeter (Orion; $EC_{1:2.5}$). For soil salinity mapping, the $EC_{1:2.5}$ was reported as EC on the saturation extract (EC_e) according to Sonmez et al. (2008) as follows:

$$ECe\ [dS\ m^{-1}] = 4.34 \cdot EC_{1:2.5} + 0.17 \text{ for sandy soils} \quad [2]$$

$$ECe\ [dS\ m^{-1}] = 3.84 \cdot EC_{1:2.5} + 0.35 \text{ for loamy soils} \quad [3]$$

$$ECe\ [dS\ m^{-1}] = 3.68 \cdot EC_{1:2.5} + 0.22 \text{ for clay soils} \quad [4]$$

The carbonate content was measured by volumetric analysis of the carbon dioxide released when putting the soil samples in contact with a 6 M HCl solution (Loeppert & Suarez, 1996), using a Dietrich-Fruehling apparatus. The soil organic matter (SOM) content was measured by loss of ignition at 450 °C according to Schulte and Hopkins (1996) and Cambardella et al. (2001) and the total organic carbon (TOC) was calculated using 1.72 correlation factor (Abella & Zimmer, 2007; De Vos et al., 2005; Howard & Howard, 1990). The particle size distribution was determined by the pipette method after dispersion of the sample with a sodium hexametaphosphate solution (Gee & Bauder, 1986).

The soil at each sampling point was then classified according to

Table 2
Mean ± standard error of pH, electrical conductivity in winter and summer periods (ECew and ECes, respectively), content of carbonates ($CaCO_3$), sand, silt, clay and total organic carbon (TOC), and available water capacity (AWC) of the soils of the coastal area located in the North-eastern Italy.

Soil (Number of profiles)	Soil depth	pH	ECew	ECes	$CaCO_3$	Sand	Silt	Clay	TOC	AWC
	cm		dS m^{-1}	dS m^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	mm H_2O
fv AR (2)	0–10	7.7 ± 0.4	1.04 ± 0.08	1.34 ± 0.06	139 ± 4	709 ± 21	205 ± 18	86 ± 4	4.10 ± 0.09	14.6 ± 0.7
	10–30	7.6 ± 0.1	1.21 ± 0.10	1.39 ± 0.07	145 ± 3	698 ± 15	205 ± 22	98 ± 5	5.80 ± 0.07	29.6 ± 0.8
	30–60	7.4 ± 0.2	1.99 ± 0.12	1.60 ± 0.11	149 ± 8	752 ± 12	164 ± 17	84 ± 4	5.20 ± 0.11	35.1 ± 1.2
	60–100	7.9 ± 0.3	0.99 ± 0.04	1.78 ± 0.09	149 ± 3	871 ± 19	122 ± 9	7 ± 1	1.00 ± 0.03	46.0 ± 0.9
fv CM (10)	0–10	7.44 ± 0.08	1.62 ± 0.50	1.43 ± 0.40	195 ± 37	304 ± 63	478 ± 49	218 ± 45	12.6 ± 1.3	20.5 ± 1.1
	10–30	7.69 ± 0.28	1.39 ± 0.63	1.54 ± 0.35	177 ± 62	312 ± 65	470 ± 61	218 ± 46	12.0 ± 1.2	40.8 ± 1.0
	30–60	7.69 ± 0.31	1.58 ± 0.55	1.66 ± 0.50	195 ± 50	354 ± 83	423 ± 51	223 ± 55	9.96 ± 1.64	62.4 ± 1.3
	60–100	8.00 ± 0,50	1.57 ± 0.47	1.92 ± 0.45	198 ± 42	314 ± 81	482 ± 71	204 ± 56	6.80 ± 1.31	81.2 ± 1.7
fv/s CM (2)	0–10	7.46 ± 0.01	2.15 ± 0.05	2.31 ± 0.25	190 ± 25	340 ± 21	510 ± 19	150 ± 2	13.0 ± 4.5	18.5 ± 0.8
	10–30	7.43 ± 0.01	2.54 ± 0.40	2.77 ± 0.45	192 ± 38	281 ± 15	566 ± 14	153 ± 11	11.9 ± 2.6	38.8 ± 1.0
	30–60	7.65 ± 0.03	5.27 ± 1.51	7.15 ± 0.89	197 ± 26	244 ± 13	637 ± 20	120 ± 7	6.65 ± 2.76	59.4 ± 1.1
	60–100	7.70 ± 0.19	8.45 ± 1.24	10.4 ± 1.54	209 ± 26	275 ± 56	583 ± 46	142 ± 10	5.70 ± 0.28	73.6 ± 0.8
st FL (9)	0–10	7.79 ± 0.49	0.89 ± 0.25	0.93 ± 0.10	184 ± 49	304 ± 96	470 ± 78	226 ± 51	13.1 ± 3.2	18.6 ± 0.8
	10–30	7.75 ± 0.43	0.81 ± 0.10	1.04 ± 0.35	171 ± 40	348 ± 88	441 ± 65	212 ± 54	13.5 ± 1.0	35.4 ± 0.4
	30–60	7.59 ± 0.02	0.85 ± 0.05	2.15 ± 0.50	161 ± 31	171 ± 26	587 ± 42	242 ± 69	9.21 ± 0.11	61.2 ± 1.6
	60–100	7.74 ± 0.09	1.04 ± 0.40	2.39 ± 0.45	196 ± 49	339 ± 97	408 ± 98	253 ± 44	10.9 ± 0.1	71.6 ± 1.4
st CM (3)	0–10	7.50 ± 0.09	1.40 ± 0.35	1.43 ± 0.20	210 ± 24	118 ± 16	559 ± 91	323 ± 75	13.6 ± 1.8	20.4 ± 0.7
	10–30	7.38 ± 0.10	1.62 ± 0.10	1.69 ± 0.25	215 ± 17	116 ± 28	489 ± 36	395 ± 64	11.2 ± 2.1	41.4 ± 0.9
	30–60	7.66 ± 0.37	1.95 ± 0.56	2.24 ± 0.79	221 ± 13	126 ± 16	524 ± 75	350 ± 58	9.90 ± 0.14	61.2 ± 1.3
	60–100	8.04 ± 0.03	1.88 ± 0.81	3.05 ± 0.97	230 ± 26	71 ± 33	558 ± 11	371 ± 21	21.8 ± 2.9	84.8 ± 1.5
st/vr CM (2)	0–10	7.76 ± 0.05	1.18 ± 0.10	1.36 ± 0.10	196 ± 44	96 ± 26	484 ± 75	420 ± 54	10.3 ± 0.1	22.0 ± 0.8
	10–30	7.43 ± 0.04	1.69 ± 0.05	2.17 ± 0.68	200 ± 35	112 ± 18	429 ± 10	459 ± 21	11.5 ± 0.3	44.1 ± 0.9
	30–60	7.63 ± 0.13	2.80 ± 0.20	2.98 ± 0.58	184 ± 4	102 ± 37	452 ± 42	447 ± 38	8.70 ± 1.59	66.3 ± 1.2
	60–100	7.93 ± 0.14	5.41 ± 0.15	6.62 ± 0.94	205 ± 11	44 ± 32	391 ± 67	566 ± 48	7.99 ± 1.08	93.2 ± 1.9
gl CM (3)	0–10	7.73 ± 0.28	1.31 ± 0.40	1.27 ± 0.35	200 ± 19	247 ± 81	533 ± 50	219 ± 37	11.7 ± 3.5	21.2 ± 0.6
	10–30	7.56 ± 0.13	1.35 ± 0.35	1.43 ± 0.50	189 ± 2	240 ± 85	505 ± 42	255 ± 44	8.30 ± 2.20	43.0 ± 0.9
	30–60	7.69 ± 0.36	1.43 ± 0.34	1.77 ± 0.55	193 ± 58	230 ± 87	534 ± 53	236 ± 68	7.20 ± 1.15	65.1 ± 1.3
	60–100	8.26 ± 0.36	1.81 ± 0.77	2.62 ± 0.45	185 ± 18	292 ± 82	607 ± 94	101 ± 26	5.93 ± 1.85	90.0 ± 1.7
vr CM (7)	0–10	7.56 ± 0.22	1.32 ± 0.25	1.21 ± 0.20	185 ± 9	161 ± 77	549 ± 61	291 ± 47	10.8 ± 3.7	20.7 ± 0.4
	10_30	7.49 ± 0.15	1.25 ± 0.10	1.29 ± 0.25	184 ± 13	175 ± 70	509 ± 55	316 ± 57	10.5 ± 1.6	41.2 ± 0.6
	30–60	7.79 ± 0.25	1.18 ± 0.25	1.43 ± 0.35	179 ± 26	163 ± 28	528 ± 72	309 ± 46	9.23 ± 2.48	62.4 ± 1.1
	60–100	7.99 ± 0.16	1.32 ± 0.45	1.54 ± 0.50	194 ± 9	123 ± 75	494 ± 54	383 ± 63	9.15 ± 2.77	86.4 ± 1.8
gl AR (9)	0–10	7.64 ± 0.16	0.69 ± 0.35	1.30 ± 0.25	92 ± 11	845 ± 100	110 ± 42	45 ± 24	12.1 ± 3.5	17.3 ± 0.7
	10–30	7.63 ± 0.04	0.56 ± 0.05	2.38 ± 0,35	111 ± 3	809 ± 74	108 ± 77	82 ± 14	4.85 ± 1.06	36.8 ± 0.9
	30–60	7.67 ± 0.31	0.91 ± 0.56	2.34 ± 0.55	100 ± 4	829 ± 56	98 ± 12	72 ± 41	4.75 ± 1.61	41.4 ± 1.3
	60–100	8.36 ± 0.07	3.29 ± 0.40	4.42 ± 0.75	155 ± 31	828 ± 58	98 ± 13	74 ± 39	4.35 ± 0.07	55.2 ± 1.9
eu AR (7)	0–10	7.49 ± 0.20	0.78 ± 0.45	0.73 ± 0.35	118 ± 53	860 ± 92	94 ± 27	46 ± 21	20.9 ± 6.3	17.0 ± 0.8
	10–30	7,57 ± 0.27	0.78 ± 0.25	0.99 ± 0.15	107 ± 23	847 ± 98	97 ± 34	56 ± 17	17.7 ± 2.4	34.7 ± 1,2
	30–60	7.56 ± 0.34	0.86 ± 0.35	2.21 ± 0.40	115 ± 21	894 ± 78	62 ± 17	45 ± 22	3.75 ± 2.31	31.2 ± 1.6
	60–100	7.83 ± 0.51	1.69 ± 0.55	2.73 ± 0.45	122 ± 31	878 ± 72	72 ± 15	49 ± 23	2.57 ± 1.56	46.4 ± 1.9
eu RG (4)	0–10	7.58 ± 0.03	2.99 ± 0.40	2.82 ± 0.35	77 ± 10	822 ± 78	118 ± 40	60 ± 4	8.15 ± 2.82	8.01 ± 0.3
	10–30	7.62 ± 0,09	2.82 ± 0.55	2.73 ± 0.45	69 ± 1	846 ± 67	98 ± 5	55 ± 6	5.52 ± 0.51	18.7 ± 0.9
	30–60	7.40 ± 0,01	3.43 ± 0.60	3.47 ± 0.55	99 ± 16	841 ± 98	96 ± 23	63 ± 9	4.24 ± 2.13	28.7 ± 0.7
	60–100	7.44 ± 0,07	3.44 ± 1.04	3.99 ± 0.89	89 ± 16	929 ± 66	52 ± 5	20 ± 2	4.20 ± 1.63	20.9 ± 0.9
vr/gl CM (5)	0–10	7.45 ± 0.19	1.66 ± 0.55	2.39 ± 0.53	161 ± 24	146 ± 43	511 ± 21	343 ± 23	15.6 ± 5.3	21.1 ± 0.4
	10–30	7.65 ± 0.13	1.43 ± 0.50	2.76 ± 0.45	152 ± 32	150 ± 64	491 ± 43	359 ± 24	12.6 ± 2.5	42.4 ± 0.9
	30–60	7.70 ± 0.10	1.62 ± 0.88	3.20 ± 0.55	149 ± 47	115 ± 37	438 ± 83	447 ± 111	8.47 ± 2.33	65.7 ± 1.1
	60–100	7.69 ± 0.17	2.46 ± 1.09	4.64 ± 1.17	166 ± 37	169 ± 26	579 ± 63	253 ± 55	5.73 ± 1.72	81.7 ± 1.9
gl/s CM (8)	0–10	7.51 ± 0.19	3.54 ± 0.89	3.81 ± 0.55	191 ± 32	162 ± 53	567 ± 78	271 ± 26	13.7 ± 1.9	17.6 ± 0.6
	10–30	7.49 ± 0.05	4.61 ± 1.11	5.03 ± 0.45	195 ± 33	159 ± 31	531 ± 67	310 ± 49	13.8 ± 2.2	35.7 ± 0.4
	30–60	7.57 ± 0.15	6.95 ± 1.18	8.07 ± 0.72	205 ± 28	116 ± 19	554 ± 85	330 ± 76	10.7 ± 2.2	49.2 ± 0.8
	60–100	7.80 ± 0.29	10.2 ± 1.53	12.1 ± 1.09	186 ± 21	320 ± 97	443 ± 55	237 ± 69	4.95 ± 2.3	67.3 ± 3.6
gl(s) CM (7)	0–10	7.47 ± 0.32	2.80 ± 0.88	3.05 ± 0.56	194 ± 30	235 ± 55	429 ± 67	336 ± 63	13.8 ± 3.8	17.5 ± 0.6
	10–30	7.46 ± 0.16	3.24 ± 1.35	3.68 ± 1.01	180 ± 35	250 ± 64	416 ± 81	334 ± 67	11.7 ± 3.0	35.6 ± 0.8
	30–60	7.77 ± 0.31	3.83 ± 1.43	4.12 ± 1.35	192 ± 31	176 ± 76	441 ± 70	383 ± 73	9.31 ± 2.53	53.8 ± 1.6
	60–100	7.84 ± 0.35	4.27 ± 1.51	7.51 ± 1.11	200 ± 38	171 ± 38	506 ± 94	323 ± 84	7.25 ± 1.98	65.1 ± 3.8

fv AR: fluvic Arenosol (stagnic); fv CM: fluvic Cambisol (loamic); fv/s CM: fluvic salic Cambisol (loamic); st FL: stagnic Fluvisol (siltic); st CM: stagnic Cambisol (siltic); st/vr CM: stagnic vertic Cambisol (clayey); gl CM: gleyic Cambisol (siltic); vr CM: vertic Cambisol (oxiaquic); gl AR: gleyic Arenosol (stagnic); eu AR: eutric Arenosol (humic); eu RG: eutric Regosol (arenic); vr/gl CM: vertic endogleyic Cambisol (siltic); gl/s CM: endogleyic salic Cambisol (siltic); gl(s): endogleyic (salic) Cambisol (siltic). World Reference Base for Soil Resources taxonomic system (IUSS, 2015).

IUSS Working Group (2015) and SSS (2014).

2.3.3. Soil cartographic units

The field survey and laboratory data allowed to evaluate the correspondence between the limits of land units with those of the pedological delineations. In the case of soil features differences within same land unit, field observations were applied with the application of the transect method (Webster & Cuanalo de la Cerda, 1975; Wang, 1982). The pedological delineations are then grouped in cartographic units according to the soil classification.

2.4. Available water capacity and salinity maps

In order to obtain the AWC of the entire soil depth down to 1 m, the sum of the AWC of each layer at fixed depth was calculated (Hollis et al., 2015). Then, in order to build the AWC map, the soils were clustered according to their AWC (Gagkas et al., 2018; Lilly et al., 2012).

The winter and summer salinity maps were built averaging the soil ECe values across all soil layers of the 79 profiles sampled in the winter and replicated in the following summer season and taking in account the soil layer thicknesses. The salinity maps represent the mosaic of vector tiles layer, with cells 50 m × 50 m wide, where each cell contains salinity class according to USDA Soil Survey Manual (Richards, 1954).

2.5. Land capability and suitability maps

The land capability map was created according to land capability classification (LCC) proposed by USDA (Klingebiel & Montgomery, 1961). The LCC reference system, on the base of the type and quantity of internal and/or external limiting factors (particle size distribution, AWC in 0–100 cm soil depth, TOC content in 0–30 cm soil depth, EC values in 0–30 and 30–100 cm soil depths, drainage potential, flooding risk), classify the soils into eight land capability classes under two broad groups as: from class I to class IV include lands suitable for agriculture, while from class V to class VIII include lands not suitable for agriculture but suited for forestry, grass land and protected areas.

The drainage potential was evaluated on the base of particle size distribution analysis (higher drainage with higher sand content, while lower drainage potential with higher clay content) and on the development of gleyed subsoil horizons which is an indicator of an inhibited drainage (O'Geen, 2013; Phillips et al., 2001). The flooding risk information were acquired from the romagna land reclamation authority (CBR, 2018).

Each limiting condition has been assigned as an increasing numerical value as a function of the limitations intensity (higher numerical value corresponded to higher limitation severity); the total score, given by the sum of each numerical value related to the six limiting factors, has allowed to identify the soil capability within one of the eight USDA land capability classes (Tables S1 and S2 of the Supplementary material). Further class assignments were conditioned by legislative rules such as coastline respect and constraints due to the presence of protected landscapes (Delta del Po Emilia-Romagna Regional Park) and urban areas. The lands subjected to these rules and constrictions are not cultivable and, therefore, they belong to class VIII of the land capability.

The land suitability map was developed according to land suitability classification (FAO, 1981) and following the basic principles for land evaluation (FAO, 2007). Specifically, land suitability is assessed and classified with respect to specified kinds of use; suitability for each use is assessed by comparing the required input, such as labour, fertilizers or irrigation, with the goods produced or other benefits obtained; the suitability evaluation should be performed through a multidisciplinary approach that include, for example, soil scientists, ecologists, geomorphologists, agronomists economists and sociologists; evaluation is made in terms relevant to the physical economic and social context of the area concerned; the suitability assessment requires to take in account the environmental degradation; the suitability evaluation involves comparison of more than a single kind of use, for example, between agriculture and forestry, between two or more different farming systems, or between individual crops. On the base the principles of land evaluation, the lands are classified using two hierarchical levels: orders and classes. The orders indicated with S and N letters delimit areas suitable or unsuitable, respectively, for sustainable use; the classes define the degree of aptitude for a sustainable use. Therefore, the lands are divided into highly (S1), moderately (S2), marginally (S3) suitable and currently (N1), permanently (N2) not suitable.

2.6. QGIS software

The QGIS 3.12 software was used for data input and processing, and map elaboration. QGIS allows users to analyze and edit spatial information, in addition to composing and exporting georeferenced maps. QGIS supports both raster and vector layers; vector data are stored as point, line, or polygon features. Multiple formats of raster images are supported. The software also supports georeferencing of images using the Georeferencer Core Plugin, a tool for generating world files for rasters. The spatial processing framework of QGIS 3.12 is based on the Python plugin SEXTANTE, which integrates a large number of analysis algorithms from different open source projects.

3. Results and discussion

3.1. Land units map

The "Land Units Map" highlighted eight homogeneous areas which were mainly identified by the land morphology associated to sea level, the depositional system and the sediment texture (Fig. 2). Land use and tree cover were driven by the land morphology, where remnants of woods (Mediterranean coniferous forest) were located in cords of raised sand dunes parallel to the coast line. Parallel to the dunes, there are raised areas characterized by shell fragments, not cultivated or with shrubby vegetation. Among these raised areas, lower lands were present, dedicated to extensive agriculture. Generally, the extensive agriculture was in the lands below sea level. The soil profiles of the Land Units below the sea level were characterized by gleyic features in 50–60 cm soil depth layer (Table S1), while Eutric Arenosol and Fluvic Cambisol (calcaric) developed in higher morphological land.

3.2. Soil map

3.2.1. Soil physico-chemical data

The field observations together with the data obtained from the soil chemical-physical analysis allowed to confirm the geographical limits defined by the land unit maps, and in few cases a subdivision within the same land unit were necessary. Thus, land units in the investigated area well grouped pedogenic factors, allowing to a quite overlapping between land and soil units.

In the whole investigated area, soils had a slightly alkaline pH without differences along the soil depth (Table 2), and calcium carbonate was always present (ranging from 69 to 230 g kg^{-1}). As expected instead a great variability in particle size distribution was found in accordance to the land units (Table 2 and Fig. 2): soils of areas above sea level were characterized by deposits of fine and medium sandy coast, by silty and silty loam alluvial deposits, and by silty clayey loam delta deposits, and soils located below the sea level were characterized by silty clay coast deposits.

The ECe values measured during winter season (ECew; Table 2) were generally lower than those measured in summer season (ECes), ranging from 0.56 to 10.20 dS m^{-1} and from 0.73 to 12.10 dS m^{-1}, respectively. The temporal variation of soil salinity is closely related to seasonal temperature and rainfall patterns (Silvestri et al., 2005; Tho et al., 2008). However, on average, no differences occurred among the soil types.. Along soil depth the ECe values increased, suggesting that soil salinity was affected by saline groundwater. In this case, as shown in Table 2, some soil types (i.e. Fluvic Salic Cambisol, Stagnic Vertic Cambisol and Endogleyic Cambisol) had ECe values > 4 dS cm^{-1} in the deepest parts of soil profiles, which is considered as a critical soil salinity threshold for plant growth (Munns, 2009).

The AWC showed a declining trend with soil depth in Arenosol,

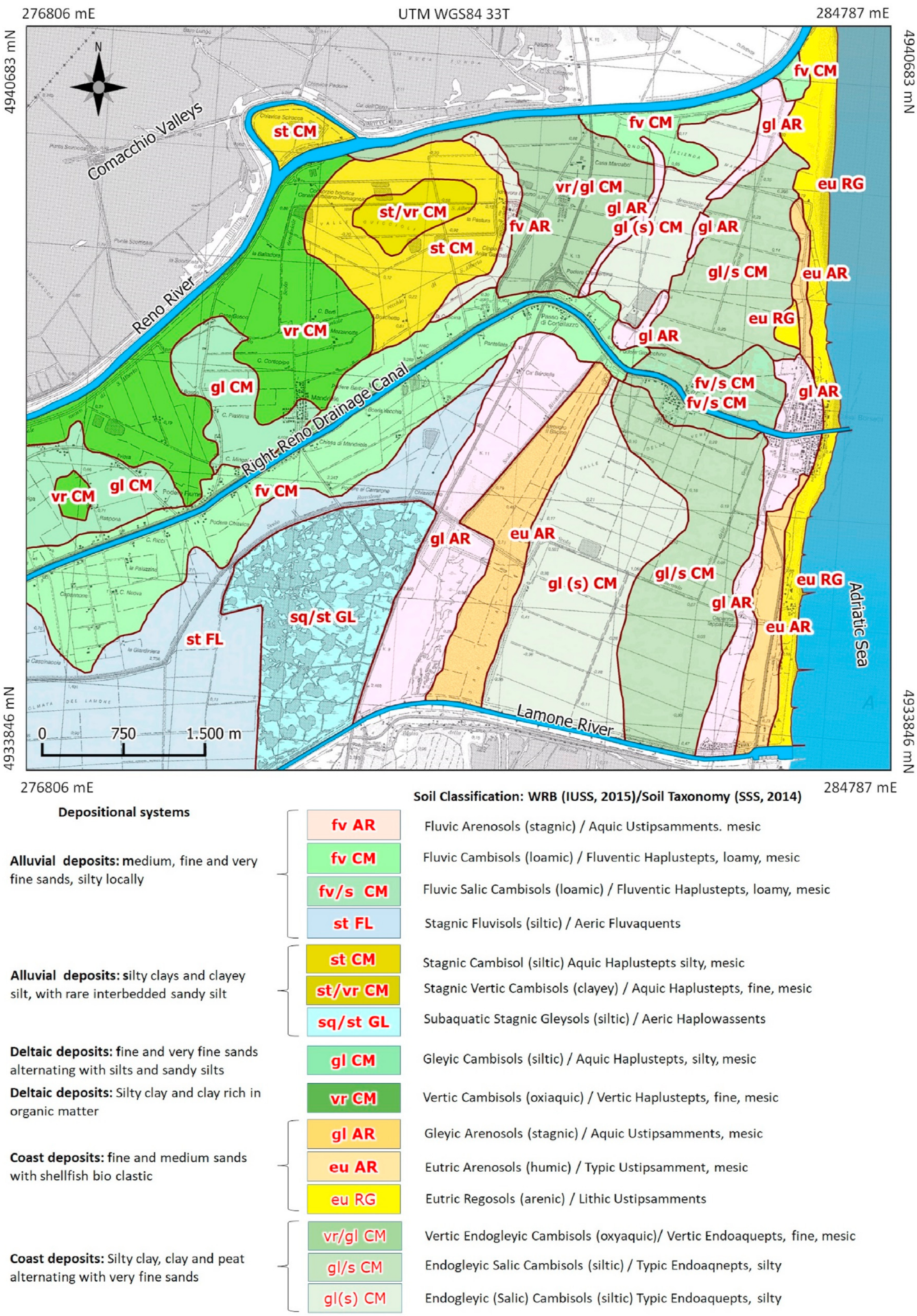

Fig. 3. Soil map of the coastal area located in the North-eastern Italy.

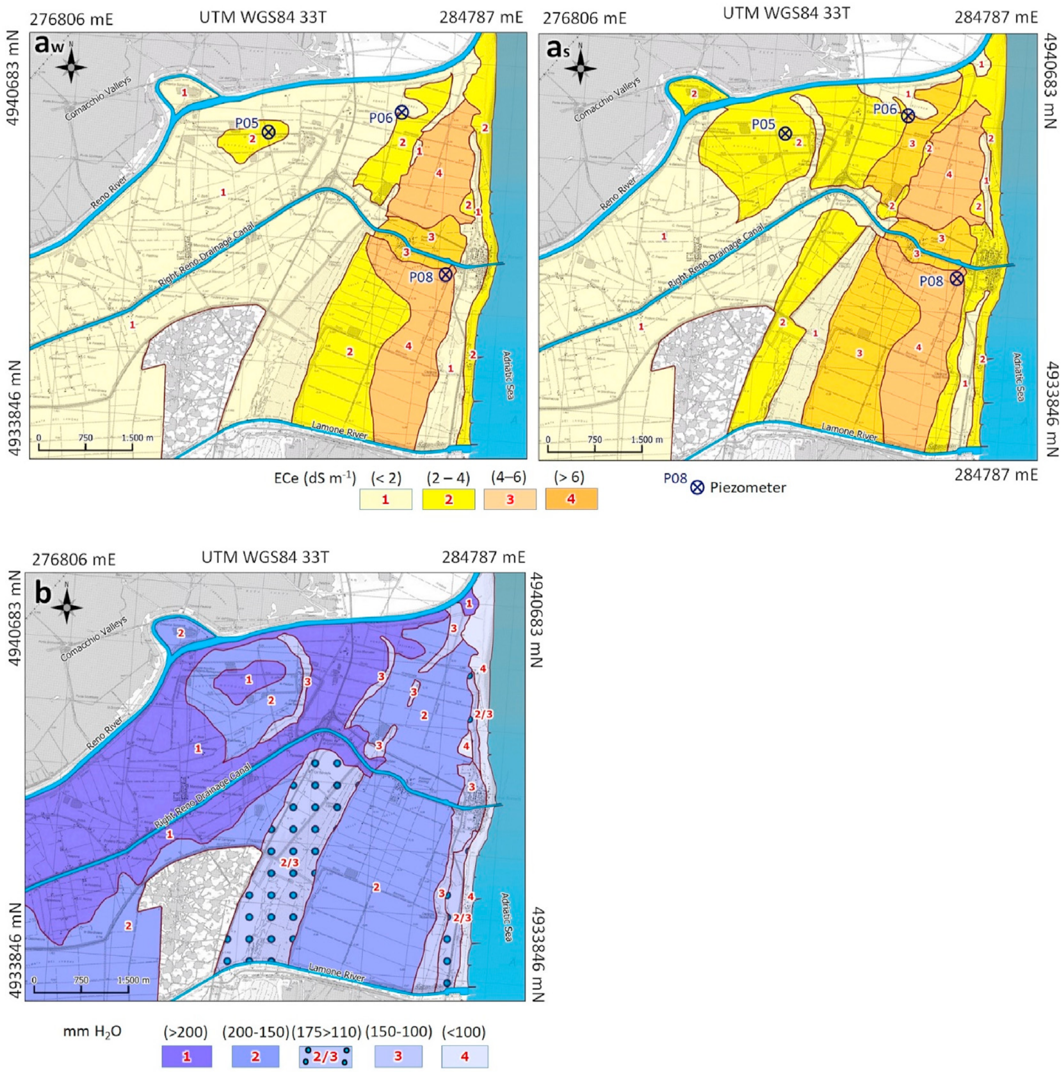

Fig. 4. Soil salinity map in winter (a_w) and summer (a_s) seasons, and soil available water capacity map (b) of the coastal area located in the North-eastern Italy.

while in Cambisols, Fluvisol and Regosol the AWC is similar among the soil layers. Furthermore, on average, while Arenosol, Cambisol and Fluvisol showed similar AWC values, Regosol had the lowest ones.

Higher TOC contents were found in soils with finer texture compared to those with coarser texture, further, in all soils the TOC content reduced with depth (Table 2).

3.2.2. Soil classification and cartographic units

In the study area, 14 different soil types (Table 2 and Fig. 3) were identified. Most of the soils are moderately developed (Cambisols – IUSS, 2015; Inceptisols – SSS, 2014), confirming the RER (2018a) data, and are characterized either by reduction conditions (Gleyic, Stagnic) or by vertic properties (Vertic). In the area close to the coast lines, the soils are affected by salinity (Salic) caused by the marine water intrusion.

The central area is crossed from south-east to north-east by soils characterized by pedogenetic substrates originating from alluvial deposit alternations (Fluvisols and Fluvic Cambisols – IUSS, 2015; Aeric Fluvaquents and Fluventic Haplustepts – SSS, 2014). In the eastern portion of the paleo and recent beach-ridge systems there are soils with sand texture (Arenosols) partly influenced by Mediterranean coniferous forest cover which contributed to enriching the epipedons with organic substance (Humic), and partly uncultivated meadows and with shrubs (Eutric). Limited to beaches and small internal areas, soils do not have a significant profile development and therefore do not have diagnostic horizons (Regosols – IUSS, 2015; Entisols – SSS, 2014). While Subaquatic Stagnic Gleysols (IUSS, 2015) – Aeric Haplowassents (SSS; 2014) identify the marshy areas characterized by subaqueous soils (Ferronato et al., 2015, 2016, 2018).

3.3. Soil salinity and available water capacity

In the investigation area, the presence of soils affected by salinity was noted where marshy areas and brackish valleys persisted before reclamation (Fig. 4a_s, a_w). However, the proximity to the coast and the progressive increase in subsidence favor the marine water intrusion and in morphologically more depressed areas the soils are subjected to endopedon salinization phenomena. As shown in Fig. 4 a_s, the phenomenon is accentuated in the summer period due to the scarcity of rainfalls and capillary rise. The intrusion of seawater is confirmed by the piezometers installed by Lamberti et al. (2018, pp. 317–320) and Cipolla et al. (2019) which

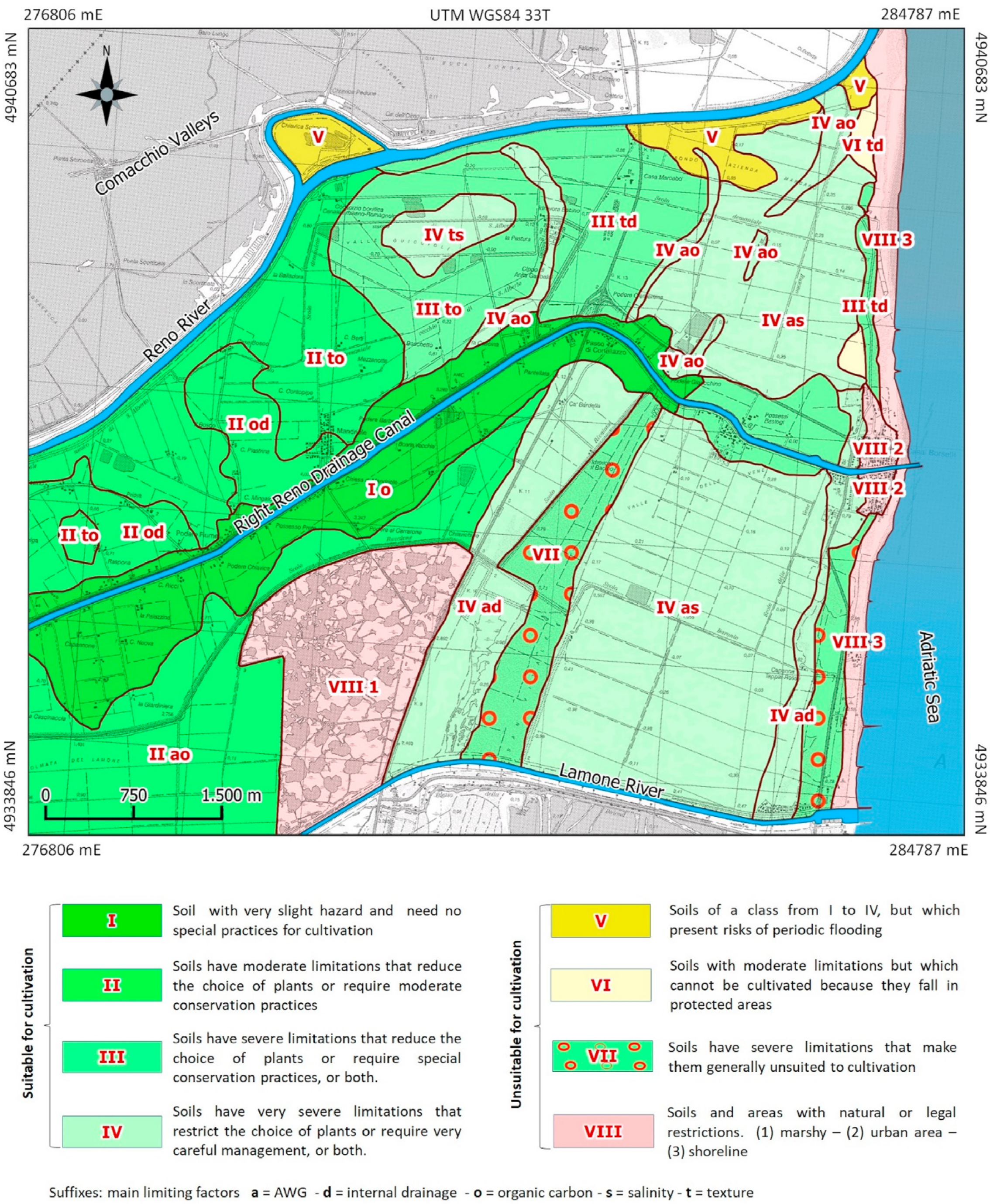

Fig. 5. Land capability map of the coastal area located in the North-eastern Italy.

allowed to record EC values > 30 dS cm-1 at 1 m depth in these more depressed areas. The salinization phenomenon is not contrasted by irrigation waters which in turn are of poor quality.

Most of the soils formed on alluvial and deltaic deposits (Fluvic, Gleyic, Stagnic, Vertic Cambisols) show satisfactory AWC (Fig. 4b) with values greater than 150 mm (Datta et al., 2017; Kirkham, 2014, pp. 153–170; O'Geen, 2013). Conversely, those formed on the coast deposits (Gleyic Arenosols and Eutric Regosols) show significant water availability deficiencies due to the sandy texture and the low TOC content. In fact, it is well known the low water holding capacity of sandy soils (Biswas, 2019), conversely, the ability of soil to store water is positively related to the soil organic matter content (Williams et al., 2016). An exception is the Eutric Arenosols (Humic) which, despite the sandy textures, are affected by a forest cover which promoted the formation of an epipedon enriched of organic matter and, as a consequence, the AWC values range from 175 mm in the surface soil layers to 110 mm in deepest ones.

3.4. Land capability and suitability maps

The study area shows a significant variability of capability use classes, ranging from the I to the VIII class, due to the different

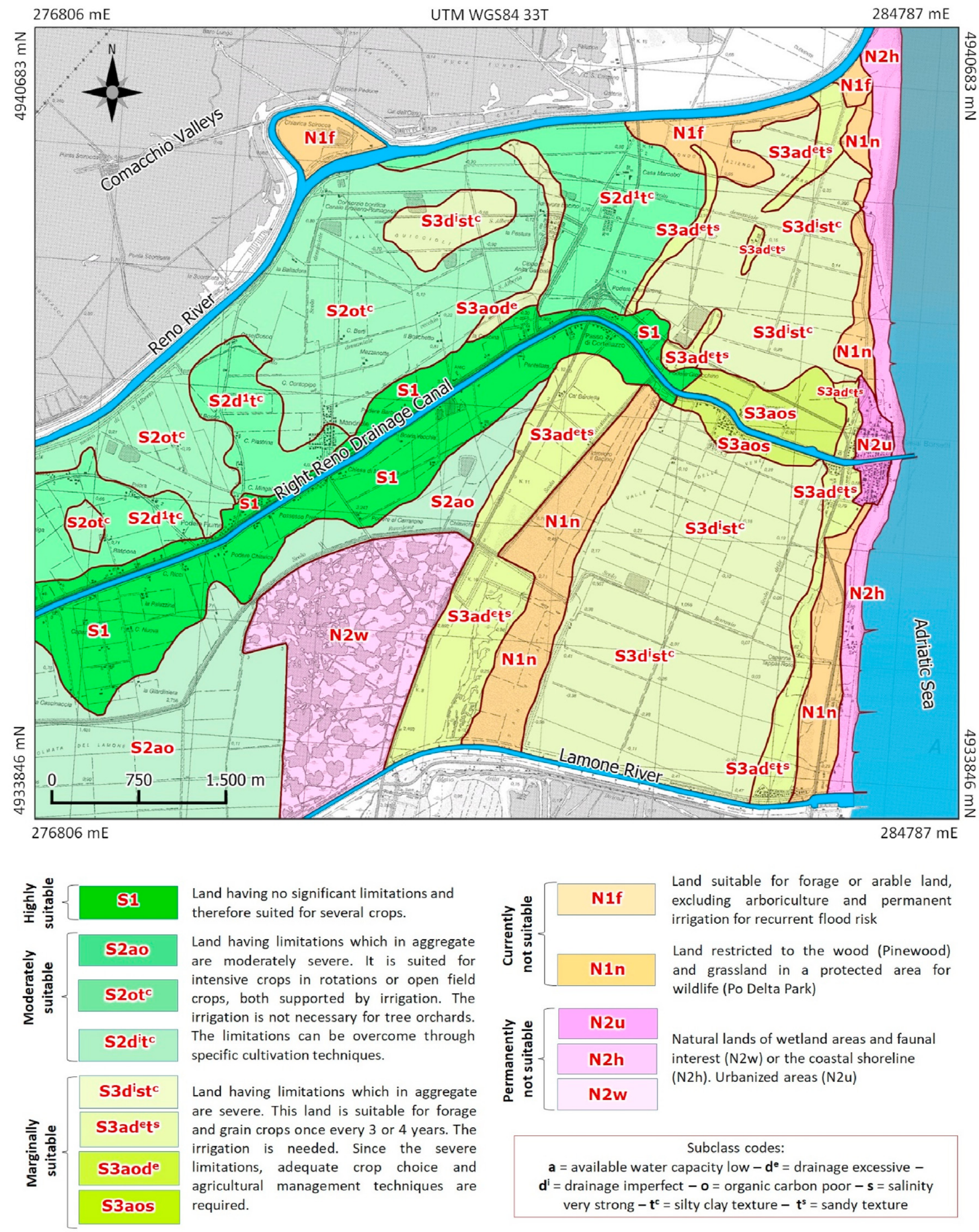

Fig. 6. Land suitability map of the coastal area located in the North-eastern Italy.

combination of soil limiting factors as the lack of water availability, the salinity accentuation, and the high content of sand or clay particles (Fig. 5; Table S2 of the Supplementary materials). Generalized is the organic carbon deficiency in the epipedons except in situations with forest cover or permanent lawn.

Specifically, 42% of the area under investigation is clustered in I and II classes of the land capability and, therefore, they are suited for a wide range of plants with none or few limitations (Klingebiel & Montgomery, 1961). The soils clustering in I and II classes showed a loam texture which allow both a good water retention performed by clay particles (Bouma & Bryla, 2000) and an optimal hydraulic conductivity due to the macropores governed by sandy particles (Mangalassery et al., 2013) promoting a regular or moderate drainage. Furthermore, these soils showed low EC values which allow the growth of glycophytes (Cheeseman, 2015).

About 44% of the investigated area belongs to class III and IV which indicates that they have severe limitations that reduce the choice of plants (Klingebiel & Montgomery, 1961). Compared to the soils of class I and II, these soils showed lower AWC and slight higher EC which limit plant growth and yields (Ould Ahmed et al., 2010).

A few portion of the area (4.5%) was classified as class V and VI of the land capability and, therefore, they are not cultivable and can be addressed only to pasture, woodland, or wildlife food and cover (Klingebiel & Montgomery, 1961). Specifically, in our case the areas belonging to class V and VI are characterized by flooding happening, on average, every 15 years (CBR, 2018) or by high sand content which do not allow the accumulation of soil organic carbon (Campos et al., 2020; Yost & Hartemink, 2019) and water (Biswas, 2019). Finally, 9.5% of the investigated area clustered in class VII and VIII because of the excessive drainage and land protection, respectively.

According to the land suitability, about 80% of the investigated area is characterized by suitability conditions (Fig. 6; Table S2 of the Supplementary materials) with prevalent classes of moderately (S2) and marginally (S3) suitable (33.9 and 35.7%, respectively). About 20% of non-suitable areas are characterized by current (N1) conditions corresponding to environments of naturalistic importance or subject to risk of flooding or in conditions of irreversibility (N2) (about 11% among urbanized areas, marshes and shorelines).

Because of the lower AWC and the higher EC values in S2 and S3 areas compared to S1 one, the cultivation is not suitable if some agricultural management techniques are not used. For example, the S2 areas can be cultivated also with intensive crops such as processing tomato, sunflower and melon, but the irrigation is needed. In fact, in these areas the irrigation has the dual purpose of keeping the soil moist and preventing saline waters from rising to the surface by evaporation (Vittori Antisari et al., 2020). For S3, instead, tree orchards should be excluded and should be addressed to open field salt tolerant crops such as barley or moderately tolerant ones such as wheat, soybeans and sorghum (FAO, 2006).

However, it is important to highlight that some agricultural practices could improve the soil properties and, therefore, could reduce the limitations. For example, the use of water with low EC values and of manures could reduce the soil salinity (Ould Ahmed et al., 2010) and increase the TOC content (Lal, 2006), respectively.

4. Conclusion

This work highlighted how the availability of good quality environmental databases supported by expert GIS systems allow to create in sequence a thematic map series of particular utility to evaluate the possible presence of external and/or internal soil limiting factors and possible interventions to correct or mitigate them. In particular, the information contained in the soil map and its derivatives (AWC and salinity maps) managed by QGIS allowed to identify areas belonging to different land capability and suitability classes. The coastal area investigated through the present work, although characterized by sea water intrusion, showed to be mostly (80%) suitable for cultivation and, therefore, can be addressed for agricultural purposes without the risk of degradation. In fact, taking in account the land capability, 42% of the investigated area belongs to class I and II indicating that they can be used for a wide range of cultivations. In order to avoid soil degradation, more attention should be paid for the lands clustering in class III and IV which represented 44% of the investigated area and where the cultivation should be allowed only to a limited range of crops. In fact, this area had a high sand content which does not allow a good water retention. Moreover, these sites are subjected to a strong intrusion of sea water with consequent increase of the soil electrical conductivity and where irrigation is necessary to contrast such sea water intrusion.

Because of inadequate land use could cause the loss of several hectares of agricultural area due to soil degradation, to classify the lands on base the land capability and suitability could help to define the best agricultural practices to apply in order to preserve soil functions. Therefore, the application of land capability and suitability models as tools should be considered as a mandatory action for the optimization of land use plans. Further, such tools could easily assist the authorities in decision-making regarding to accept or reject the alternative kinds of land managements.

The proposed model provides for the updating in progress of the database with the possibility of reporting in real time any changes on one or more of cartographic topics covered (AWC, salinity, SOM, drainage). Therefore, the model applied to the study area, where agricultural productivity and environmental impact are in conflict, implies that land capability and suitability maps should not be considered permanent documents, but rather modifiable in a positive or negative sense depending on anthropic interventions or natural impacts, climatic in particular.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.iswcr.2020.11.007.

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