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# The fate of coastal habitats in the Venice Lagoon from the sea level rise perspective

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## ABSTRACT

Coastal wetlands worldwide are retreating owing to several anthropogenic pressures and accelerated sea level rise (SLR). The importance of preserving salt marshes and the services they provide is being increasingly recognized and wetlands have become the target of several international initiatives and conservation regulations. Thus, geospatial models with applicable high spatial resolution results estimating the potential development of wetland habitats under climate change are urgently needed in order to prepare proper conservation measures and management strategies in an opportune moment. This study aimed at predicting the potential impact of SLR on salt marsh habitats in the Venice Lagoon. Habitat turnover over time was modelled based on a fine-scale vegetation map, relative elevation measurements, and most relevant environmental data (subsidence and accretion) connected with SLR. Three model-based SLR scenarios (GFDL P50, RCP4.5, RCP8.5) and the local linear trend were considered. Clear differences between the northern and southern parts of the lagoon emerged. By 2075, 37 to 48% (model-based scenarios) or even 51% (linear scenario) of the Venice lagoon coastal habitats could lie under water. Although nearly all habitats evidenced a decrease in their extent by 2050 and beyond, our results also suggest that different types of marshes will respond differently to SLR. Exactly this information (what, where and when) is of crucial importance for decision makers to initiate enhance planning and management policies. Moreover, the forecasted changes in tidal marsh area and the presented cost effective methodological approach is transferable to other temperate areas faced with comparable SLR rates.

## 1. Introduction

Estuarine and coastal ecosystems (ECEs) such as seagrass, mangroves and tidal marshes are considered as 'economically important' ecosystems on Earth. This fact is a result of their ecosystem functions and services they provide. Most of them are heavily exploited and threatened (Craft et al., 2009; Kirwan & Megonigal, 2013). Their recently accelerated rate of loss is much higher than any other ecosystem on the planet (Nellemann et al., 2009; Pendleton et al., 2012). Although varying globally, causes of habitat decline in ECEs could be linked to agriculture, urban development, industrial use, dredging, and mariculture in relation to accelerated sea-level rise (SLR) (Duke et al., 2007; Waycott et al., 2009). Thus, SLR would therefore exacerbate the already intensive anthropogenic impact on coastal wetland communities. From that perspective half of the European coastal wetlands could disappear, particularly those in the Mediterranean and Baltic Seas (Airoldi & Beck, 2007).

The global decrease in ECEs will affect several key ecosystem services. Thus, a decline in filtering and detoxification services (63%) could be expected following by a decline in water quality, resulting in lower number of viable fisheries (33%) and higher possibility for biological invasions (Barbier et al., 2011). Among coastal ecosystems, salt marshes are a major, widespread habitat in temperate zones (Reed, 1990; Van Dijkeman, Bossinade, Bouwema, & Glopper, 1990) and typically occupy the upper intertidal zone on low-energy shorelines, exposed to low hydrodynamic conditions and tidal flooding. They occur along soft coasts characterized by limited wave action and mud accumulation (Adam, 2002; Allen & Pye, 1992). Within the Mediterranean region, salt marshes reach their greatest extent along the low-energy Northern Adriatic coastal area, which includes the Venice Lagoon and the Po River Delta, where the presence of lagoons, marshes and reclaimed land, in some cases lying below the mean sea level, are dominant. The outflow of big rivers as Po or Isonzo substantially contribute to the availability and transport of sediment, which in turn play

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an important role in the occurrence and dynamics of North Adriatic salt marshes. The complex, relatively flat landscape of the Veneto region, covered by low, dense and heterogeneous halophytic vegetation is frequently inundated by the tide (in the Venice Lagoon, twice a day on average) (Marani, Lanzoni, Silvestri, & Rinaldo, 2004). The tolerance for inundation by sea-water determines the lover limit of halophyte vegetation whereas biological interactions (interspecific competition) crucially influence the upper border of the marsh system (Hughes, 2004).

Although not particularly variable, the micro-topography, i.e. the small elevation gradients, induces a nonrandom, spatially correlated distribution of halophytic vegetation (zonation) (Chapman, 1976, p. 292; Marani et al., 2004) by affecting other environmental parameters, e.g. flooding periods, soil salinity and root oxygen availability. In turn, vegetation plays a pivotal role in determining the stability of tidal marshes, e.g., by stabilizing marsh surface sediments, reducing water sediment transport capacity or lowering wave height. Thus, the presence and distribution of vegetation become key elements, both as morphological indicators and for their intrinsic ecological importance (Baustian, Mendelssohn, & Hester, 2012; Marani et al., 2004).

The importance of preserving salt marshes and the services they provide is being increasingly recognized in Europe (Airoldi & Beck, 2007), where wetlands have become the target of several international initiatives and conservation regulations. Salt marshes are specifically listed as habitats of Community interest or priority habitats in Annex I of the Habitats Directive (European Commission, 1992). Being positioned at the interface between land and sea, salt marshes are likely to be particularly vulnerable to SLR. According to the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5; Church et al., 2013), SLR is predicted to increase by 30–100 cm by 2100 and will thus reshape coastal wetlands globally. This is of particular concern in all those areas (e.g., the Mississippi Delta or the Venice Lagoon) where sediment accretion rates are too low as to compensate for relative SLR (Bakker et al., 2016). Here, the extensive die-back of marsh vegetation (Kearney, Rogers, Townshend, Rizzo, & Stutzer, 2002) or habitat loss (Mander, Cutts, Allen, & Mazik, 2007; Pye & Blott, 2006) will affect other population of dependent organisms (Fujii & Raffaelli, 2008; Galbraith, Jones, Park, Clough, & Herrod-Julius, 2002; Hughes, 2004). In particular, accelerated SLR is likely to affect the salt marsh halophyte vertical distribution: depending on the level of change, some communities may adapt to sea level rise while others may either disappear or migrate inland-provided that there is suitable area inland (Bakker et al., 2016).

Projecting future changes is thus a crucial step towards planning for and mitigating the impact of climate change on biodiversity. The Venice Lagoon is particularly well suited to such a study, since given its wide area (about 55,000 ha) and its hydro-morphology, the system is characterized by considerable natural spatial heterogeneity, leading to a mosaic of habitats and multiple environmental gradients. Moreover, the entire zone has experienced notable geomorphological and ecological changes due to the combined effect of land subsidence, mostly anthropogenic, with sea level rise and severe weather events, strongly linked to regional/global climate change (Carbognin & Tosi, 2002). Furthermore, a certain periodicity in sea level heights (five and eight year's cycles) has already been documented and correlated with large-scale atmospheric variability over the Euro-Atlantic sector (Zanchettin, Rubino, Traverso, & Tomasino, 2009). A significant fraction of the inter-annual sea level variability along the Adriatic coasts during the cold season is also related to the forcing of the North Atlantic Oscillation (NAO) – more specifically - the sensibility to the NAO is estimated for sea levels in the Venice lagoon: when the NAO moves from a strong positive anomaly to a strong negative anomaly, an increase in sea levels of 20 cm or more could be expected (Zanchettin, Traverso, & Tomasino, 2006). In addition to that, also to global climate shifts and hazardous events, such as El Ninõ or explosive volcanic eruptions should not be neglected (Zanchettin, Traverso, & Tomasino, 2007).

However, the urban ecosystem of Venice and its lagoon is among the most intensively studied urban and environmental systems in the world (Tagliapietra et al., 2011). Being a densely populated and infrastructure-rich coastal city, and because of its charismatic cultural heritage, the city of Venice has a hot topic in the climate change impact studies. Many previous studies aimed at modeling halophyte vegetation in connection to climate change and SLR (Day et al., 1999; Marani et al., 2004; Silvestri, Defina, & Marani, 2005; D'Alpaos, Lanzoni, Marani, & Rinaldo, 2007; Bellafiore, Ghezzo, Tagliapietra, & Umgiesse, 2014). However, there are still gaps in our knowledge about how the salt marsh communities in the region will react to SLR, since previous studies either were restricted to very small areas or relied on simplified data where the vegetation map was based on remotely sensed signals rather than on detailed field surveys. Here we employ the best available data on recorded occurrences of all habitats (1:5000 vegetation map) to generate a statistical model describing turnover in habitats as a function of relevant environmental gradients and SLR, taking advantage of the previously available environmental data, on e.g., sedimentation, subsidence and accretion.

In light of this, the aim of the study is to estimate the potential impact of climate change on salt marsh habitats in the Venice Lagoon and analyze the lagoon's halophyte vegetation vulnerability to different SLR scenarios. In particular, we aim to understand how salt marsh habitats will face the accelerated SLR: what halophyte habitat types are likely to be created or lost, and by what extent? Where are such habitats most likely to occur under spatially precise scenarios of future climate change?

### 1.1. Study area

The Venice Lagoon is a large, shallow microtidal basin located in the Northwest Adriatic Sea (about 45°N, 12°E) (Fig. 1), the northern and coldest part of the Mediterranean Sea (Buffa, Fantinato, & Pizzo, 2012). The lagoon originated nearly 6000 years ago, after the last glacial maximum during the Holocene transgression (Carbognin, Teatini, Tomasin, & Tosi, 2010) and has co-evolved in past centuries with human presence, which modified the natural processes in the system to maintain the lagoon's morphological structure (e.g. river diversion out of the lagoon, sea inlet maintenance, etc.). The lagoon covers now an area of approximately 500 km$^2$ (mean depth 1.1 m, tidal range 0.6–1 m), with the major axis oriented NE to SW, and water is exchanged through three large inlets, fixed by long jetties. A complex network of channels and intertidal flats forms a unique landscape (Ferrarin, Vucco, Umgiesse, Ballafiore, & Amos, 2010). Extensive intertidal salt marshes are located mostly in the SW and NE parts of the lagoon (Day, Rismondo, Scarton, Are, & Cecconi, 1998).

Salt marsh species like *Limonium narbonense*, *Salicornia procumbens* ssp. *procumbens*, *Arthrocnemum macrostachyum*, *Sarcocornia fruticosa*, *Atriplex portulacoides*, *Puccinellia festuciformis* and *Spartina maritima* occupy the numerous intertidal flats. The discussed habitats have a high conservation priority status in Europe owing to their areal extent, high productivity, and value for vegetation (e.g. Ravera, 2000) and breeding birds (Scarton, Valle, & Borella, 1994). However, scientists already evidenced (Carniello, Defina, & D'Alpaos, 2009; Day et al., 1998) that these valuable and protected habitats follow a decreasing trend (from ca. 12,000 ha at the beginning of the century, to present ca. 4000 h) as a consequence of amelioration, erosion and natural or human-induced processes causing large-scale morphological changes in the lagoon (Sarretta et al., 2010) thus, without even considering climate change and SLR.

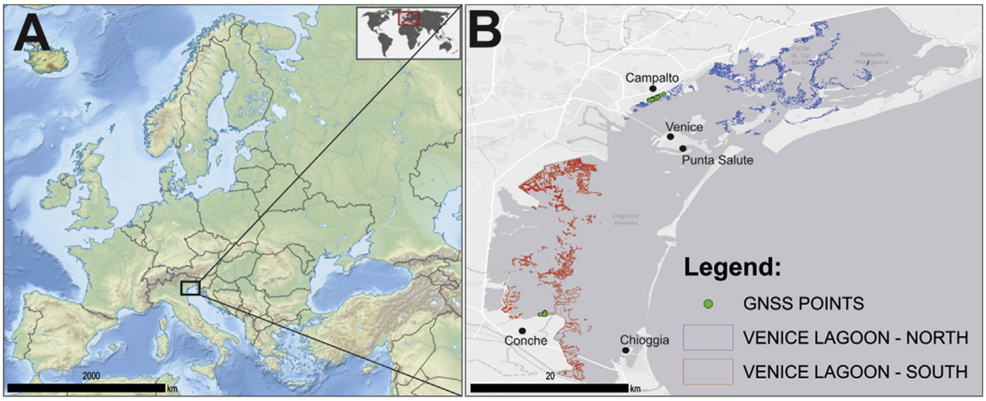

**Fig. 1.** Location of the study area (a), divided into the northern and southern subsections (b) with indication to GNSS sampling localities.

## 2. Materials and methods

### 2.1. Vertical vegetation zonation and digital elevation model (DEM) development

The development of the DEM was based on the most recent vegetation type map (1:5.000; minimum patch dimensions equal to 25 $m^2$) (Cazzin, Ghirelli, Mion, & Scarton, 2008; Ghirelli, Scarton, Mion, Cavalli, & Cazzin, 2007). Based on this data, salt marshes in the Venice Lagoon extend over slightly more than 4000 ha. Natural land cover types were mapped in seventeen different plant communities, including 4 EC habitat types sensu EC Directive 92/43.

Based on the extant vegetation map, we selected two areas (the Campalto salt marsh very close to Venice and the Conche salt marsh, located in the southern sector of the lagoon) of about 100 ha each, characterized by such a degree of landscape heterogeneity to allow us to measure the elevation of the 17 different natural plant communities. High horizontal and vertical resolution GNSS (Global Navigation Satellite System) elevation points were randomly selected and measured ($N = 246$, plus 20 additional control point measurements for better horizontal accuracy) with a Leica GX 1230 GNSS device by applying the Italgeo geoid model (Italian Military Geographic Institute).

To simplify the micro-morphological articulation, the 17 different habitat types were then aggregated according to their mean elevation level, using Ward cluster analysis (distance squared Euclidean) in R statistical software (R Development core, 2008), following the methodological procedure published by Ivajnšič and Kaligarič (2014) (Fig. 2). The frequency distribution of the measured elevation values in the resulting Modified Ward Habitat Aggregates (MWHA) served as control samples in the initial digital elevation model (DEM) development. In each MWHA, we then created random points (173.594 in total) using the Create Random Points tool in ArcGIS 9.3 (ESRI, 2010). The number of random points within each MWHA was weighted by the surface cover of each category (Fig. 2). Afterwards, a frequency distribution of 30 values, within the identified elevation extent (min-max), for each random point corresponding to MWHA was created and then tested for homogeneity of variances and differences in mean elevation value against the above mentioned control samples, using the two-sample F- and T-tests in R statistical software (R Development core, 2008). In each MWHA, only those random points which did not significantly differ in mean elevation when compared to the control sample were selected (Fig. 2). The resulting 167.514 random points were then interpolated using the Radial basis functions in the ArcGIS Geostatistical wizard (ESRI, 2010), resulting in the initial DEM of the Venice Lagoon salt marsh with a horizontal resolution of 2 m (Fig. 2).

In order to validate the resulting initial DEM, the mean elevation values and their standard deviation per MWHA, derived with the Zonal statistics tool (ESRI, 2010), were compared against the control GNSS samples. No differences were found ($p > \alpha$; $\alpha = 0.05$).

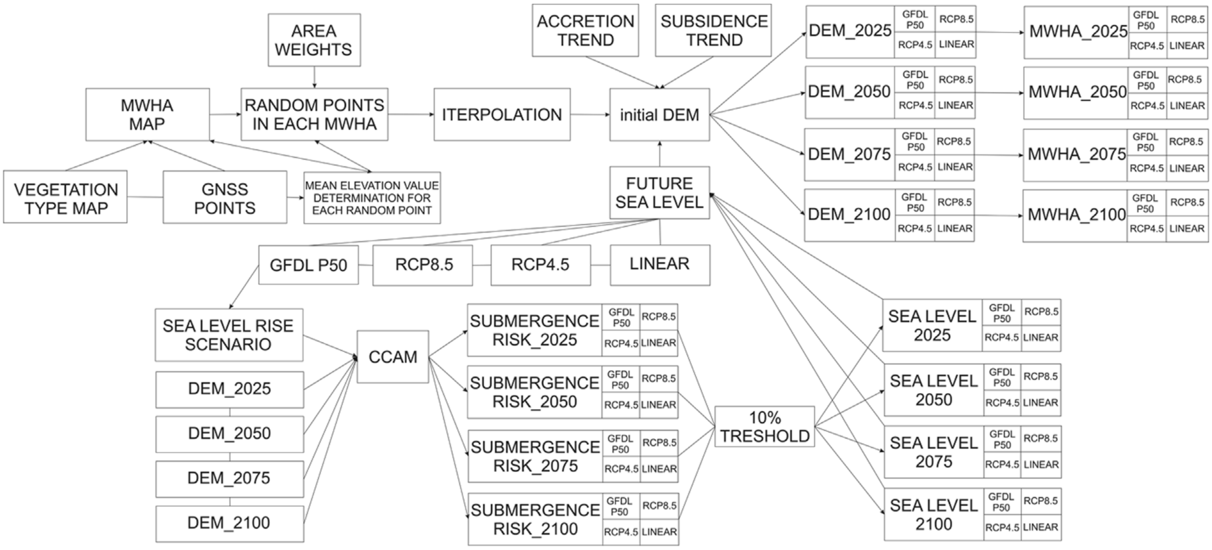

**Fig. 2.** Schematic view of the methodological procedure.

**Table 1**
Summary of selected sea level rise scenarios.

| SLR scenario | Name | Type | RSLR rang (in respect to 2014) |
|---|---|---|---|
| Scenario 1 | GFDL P50[a] | model based | 2 cm (2025) - 48 cm (2100) |
| Scenario 2 | RCP4.5 | model based | 5 cm (2025) - 48 cm (2100) |
| Scenario 3 | RCP8.5 | model based | 3 cm (2025) - 68 cm (2100) |
| Scenario 4 | linear | data based | 5 cm (2025) - 42 cm (2100) |

[a] Additional inputs: (1) mid-range carbon cycle uncertainties (1.1 GtC per year), including the effect of carbon cycle feedbacks; (2) variable thermohaline circulation, representing a case where thermohaline circulation slows as the earth's temperature increases; (3) low aerosol forcing ($-1.3\text{Wm}^{-2}$); (4) vertical diffusion default value of 2.3 $\text{cm}^2/\text{s}$; (5) a high ice melt setting; (6) MAGICC default value for climate sensitivity (3 °C) which accounts for the earth's temperature response to a doubling of the $CO_2$ concentration.

### 2.2. Land subsidence and accretion rates in the Venice lagoon salt marsh area

Another dominant process involved in wetland conversion added to the models was land subsidence. Vertical tectonic motion of the Italian Adriatic coast was studied by Lambeck, Antonioli, Purcell, and Silenzi (2004), who calculated a subsidence rate of 0.7 $\text{mm yr}^{-1}$ near Venice. Conversely, Bellucci et al. (2007), based on sediment core sampling and a constant flux model applied to excess $^{210}$Pb distributions, calculated an average accretion rate > 0.2 $\text{cm yr}^{-1}$ over the past 100 years (vertical growth of the marsh which occurs when organic and/or inorganic sediments are deposited onto the marsh during inundation [allochthonous growth], as well as when salt marsh plants grow and decompose [autochthonous growth] (Dijkema, 1987; Kolker, Goodbred, Hameed, & Cochran, 2009)). Moreover, they found significant differences in accretion speed between the northern and the southern parts of the Venice Lagoon salt marsh. Accordingly, the study area was divided into two parts (N and S) where different accretion rates ($N = 0.21\ \text{cm yr}^{-1}$ and $S = 0.46\ \text{cm yr}^{-1}$) were considered (Fig. 1). Accretion rates were calculated as averages from four (4) representative sediment core samples from Bellucci et al. (2007). Both processes were added to the produced DEMs for each selected future time window (2025, 2050, 2075 and 2100) and climate change (CC) sea level rise scenario (Fig. 2).

### 2.3. The submergence risk parameter of the Venice Lagoon salt marsh area under selected climate change scenarios

The Climate Change Adaptation Modeler (CCAM) toolbox and the Sea Level Rise Impact model within TerrSet software (Eastman, 2015) were applied to estimate the extent and the specific land areas likely to be affected by SLR under selected CC scenarios. The PCLASS algorithm provides a better tool for modeling projected sea level rise as it can take into account uncertainty in both future projections (CC RMSE) and DEMs (DEM RMSE).

The output of the Sea Level Rise Impact model is a float raster probability map representing the likelihood of an area being submerged or inundated (Eastman, 2015). The model works by calculating the area under a normal bell curve, defined by the threshold value, with the RMSE standing in for standard deviations. From that perspective, the submergence risk maps were produced by considering four (4) CC scenarios of SLR and four (4) time windows (2025, 2050, 2075 and 2100) (Table 1; Fig. 2). Scenario 1 was produced using the MAGICC/SCENGEN module within TerrSet software. Among the different emission scenarios, we chose the P50 option (average of all SRES scenarios [Nakicenovic and Swart, 2000];), with some additional inputs (Joos et al., 2001; Kheshgi & Jain, 2003; Sutterlay et al., 2014) (see Table 1, note).

Scenarios 2 and 3 were based on modelled IPCC AR5 sea level rise estimates. We chose Representative Concentration Pathways climate

**Table 2**
Habitat types aggregated to MWHA with corresponding elevation intervals and area cover.

| MWHA | Description | Mean Elevation (m) | SD (m) | Cover ($\text{km}^2$) | Main plant community | N2K habitat |
|---|---|---|---|---|---|---|
| 0 | sandbanks, mudflats and sandflats, and pioneer stands of perennial cord grasses (*Spartina maritima* community) | 0.3 | 0.05 | 9.4 | *Limonium narbonense* and *Spartina maritima* comm. | 1320 |
| 1 | perennial saline rush marsh vegetations subjected to prolonged flooding regime | 0.26 | 0.09 | 9.0 | *Puccinellia festuciformis* and *Juncus maritimus* comm. / *Limonium narbonense* and *Juncus gerardii* comm. | 1410 |
| 2 | pioneer, irregularly flooded stands of annual succulent halophytes (*Salicornia* spp.), and perennial grasslands and herb-rich vegetation periodically inundated by saline or brackish water | 0.31 | 0.07 | 13.5 | *Salicornia procumbens* ssp. *procumbens* comm. / *Limonium narbonense* and *Puccinellia festuciformis* comm. | 1310/1410 |
| 3 | perennial salt-marsh vegetations dominated by succulent dwarf chenopod scrub | 0.37 | 0.08 | 6.9 | *Puccinellia festuciformis* and *Sarcocornia fruticosa* comm. | 1420 |
| 4 | halophilous, sub-nitrophilous, supratidal, annual vegetation on accumulations of drift material rich in nitrogenous organic matter | 0.42 | 0.08 | 0.2 | *Atriplex portulacoides* and *Suaeda maritima* comm. | – |
| 5 | meso-eutrophic brackish swamp reeds | 0.49 | 0.08 | 0.5 | *Elytrigia atherica* comm. / *Puccinellia festuciformis* and *Phragmites australis* comm. | – |

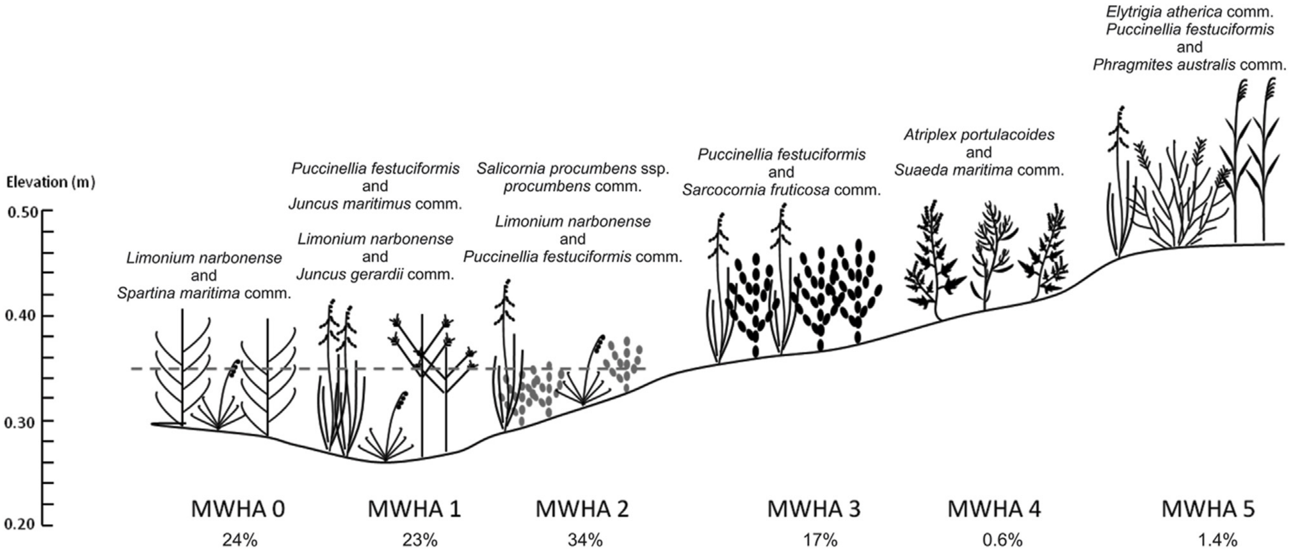

**Fig. 3.** Salt marsh transect. MWHAs are sorted according to their elevation. Grey line represents the mean excursion of neap tide (35 cm); extraordinary tide (spring tide) has a mean excursion of 1 m (Molinaroli, Guerzoni, Saretta, Cucco, & Umgiesser, 2007). For MWHAs description see Table 2.

scenarios RCP4.5 and RCP8.5, which differed in the intensity and trend of greenhouse gas emissions. The IPCC AR5 (Church et al., 2013) sea level rise estimates for the Northern Adriatic Sea (44.5 N, 13.5 E) were downloaded from the University of Hamburg's Integrated Climate Data Centre web site (Live Access Server) (http://icdc.cen.uni-hamburg.de/las/getUI.do). Scenario 4 (local linear SLR) was based on the sea level rise trend as derived by measurements recorded in the study area between 1984 and 2014 (two sea level height measuring stations; Punta Salute - Northern part; Chioggia - Southern part).

### 2.4. Future potential distribution of Venice Lagoon salt marsh habitats

The continuous probability maps indicating submergence risk under selected CC sea level rise scenarios enabled a more objective determination of future sea levels in the Venice lagoon salt marsh area by converting these probability maps according to the level of decision risk one is willing to assume. From that perspective, a 10% ($\alpha = 0.10$; $p < 0.1$) chance of being wrong was selected as the threshold value, resulting in several maps indicating new sea levels in the Venice Lagoon salt marsh under selected CC scenarios (Fig. 2). Accordingly, the initial DEM was calibrated for each future time window and CC sea level rise scenario reflecting new relative elevation considering subsidence and accretion rates as well. The future spatial distribution and potential area for each MWHA in the Venice Lagoon was then determined by reclassifying the relative DEMs, representing weather model-based or local linear CC sea level rise scenarios, with known (GNSS measurements) MWHA elevation intervals (mean ± 2SD) with respect to the reference year 2014.

## 3. Results

### 3.1. Salt marsh vertical vegetation zonation and the initial DEM

MWHAs identified through Ward cluster analysis are described in Table 2 and Fig. 3. Their spatial distribution is shown in Fig. 4A. The 6 MWHA in the Venice lagoon saltmarsh area differed in mean elevation and in the main vegetation types they hosted. MWHA 0, which occupied 24% of the total surface, mostly consisted of unvegetated land

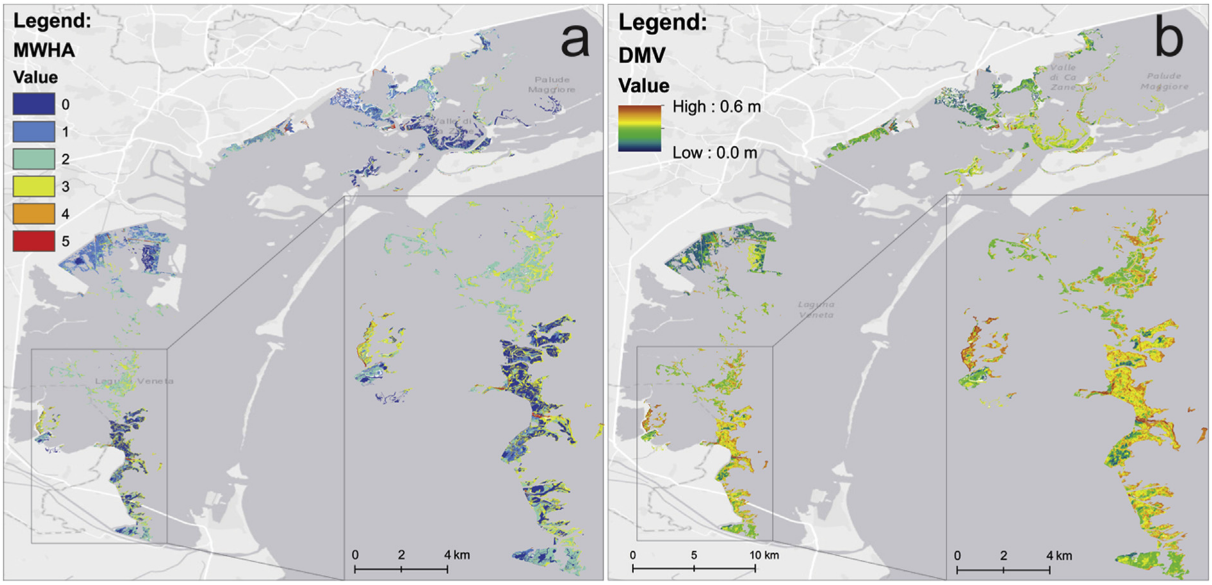

**Fig. 4.** Spatial distribution of MWHA (a) and the initial DEM of the Venice lagoon (b).

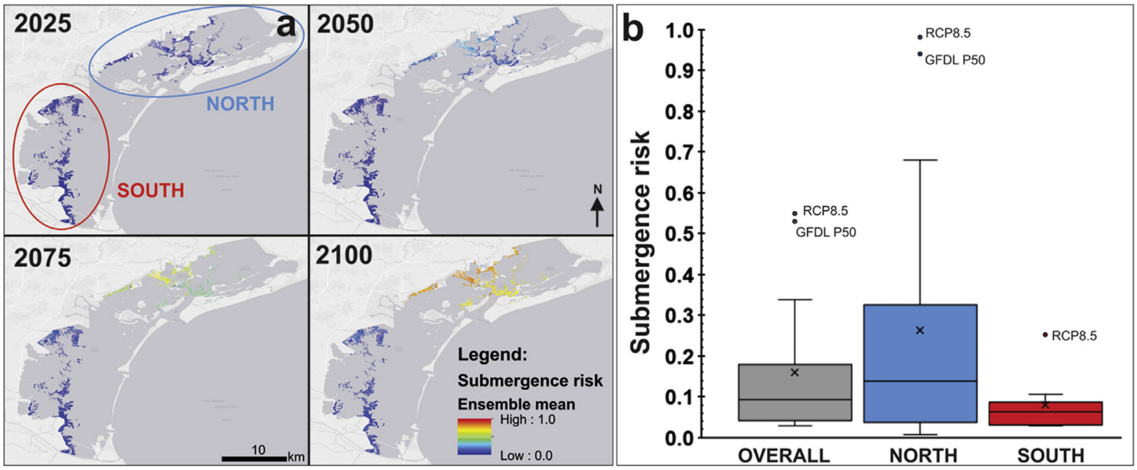

**Fig. 5.** Ensemble mean submergence risk maps of the Venice lagoon wetland for considered future time windows according to the GFDL P50, RCP4.5, RCP8.5 and local linear relative sea level rise (RSLR) scenarios (a), and box-plots showing the span of submergence risk between 2014 and 2100 by considering all models, CC scenarios and time windows (b).

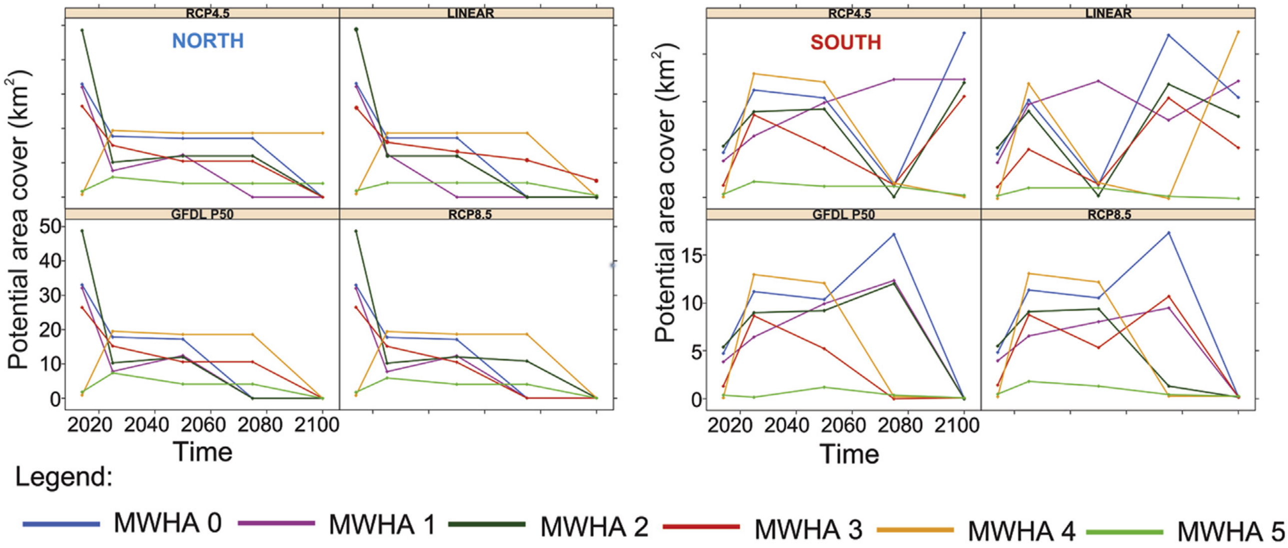

**Fig. 6.** Changes in potential cover of MWHAs in the Venice lagoon marsh according to CC-induced model-based relative sea level rise (RSLR) scenarios GFDL P50, RCP4.5, RCP8.5 and the local linear SLR trend.

areas usually located on the margins of the main channels, such as minor channels (locally called "ghebi"), permanently submerged sandbanks, mudflats and sandflats not covered by seawater at low tide, and pioneer stands of perennial cord grasses (*Spartina maritima* community). MWHA 1 mostly grouped perennial saline rush marsh vegetation subjected to prolonged flooding regimes. Dominant species were *Juncus maritimus*, *J. acutus*, *J. gerardii*, and *Bolboschoenus maritimus*. Both MWHA 0 and MWHA 1 occupied a similar share of area, 24% and 23%, respectively. MWHA 2 represented the most widespread category, covering 34% of the whole study area. It included pioneer, irregularly flooded stands of annual succulent halophytes (*Salicornia* spp.) on tidal mudflats and edges, and perennial grasslands and herb-rich vegetation periodically inundated by saline or brackish water, dominated by rosette-forming species (*Limonium* spp.) and grasses like *Puccinellia festuciformis*.

MWHA 3 was entirely represented by perennial salt-marsh vegetation dominated by succulent dwarf chenopod scrub (mainly *Sarcocornia fruticosa*), covering ca. 17% of the total surface. MWHA 4 grouped annual halophilous, sub-nitrophilous, supratidal, non-inundated vegetation, occupying accumulations of drift material rich in nitrogenous organic matter. Finally, MWHA 5 was mostly composed of meso-eutrophic brackish swamp reeds, dominated by *Phragmites australis* and *Elytrigia atherica*. Both MWHA 4 and MWHA 5 were underrepresented if compared to previous categories, covering on the whole less than 2% of the area.

According to high-resolution initial DEM, the study area surface had a relative vertical span of 60 cm (Fig. 4B). Most of the Venice Lagoon salt marsh developed between 25 and 37 cm above average sea level. The southernmost part, near Chioggia, showed slightly greater elevations, but in general there were no substantial differences in the relative elevation of MWHA between the northern and southern parts of the salt marsh.

### 3.2. *The submergence risk of the Venice Lagoon salt marsh area*

When averaged across the four models (Fig. 5A), the resulting submergence probability distribution maps indicated that, globally, i.e. considering the whole lagoon, no drastic relative elevation changes were foreseen until 2050. However, clear differences did emerge among models, CC scenarios and between the northern and the southern parts (sectors) of the study area, as well. If all time windows, models and scenarios are considered, results indicate that the northern sector of the lagoon will be more exposed to CC induced sea level flooding than the southern part (Fig. 5B). By 2050, 1–3 km$^2$ of surface could be lost directly by submergence, but these would be mainly in the northern part of the lagoon. By applying Scenario 4, the assumed directly submerged area could reach almost 15 km$^2$ (37%) by then, mainly in the northern part, as well (Fig. 6). By 2075, 37–48% (model-based scenarios [1, 2 and 3]) or even 51% (Scenario 4) of the Venice Lagoon salt marsh could lie under water. The major difference in submergence risk between the considered SLR scenarios occurred in the period between 2075 and 2100. Scenarios 1 and 3 anticipated an almost complete retreat of the salt marsh (99.7–99.8%) by the end of the century, whereas Scenarios 2 and 4 predicted a submerged salt marsh area of about 16–22 km$^2$ (41–55%) in the same time window.

### 3.3. *The future of Venice Lagoon saltmarsh habitats*

Overall, all selected scenarios predicted a decrease in potential cover of salt marsh vegetation types, although with clear differences both among MWHAs and between the two sectors of the lagoon. The process of coastal shrinkage would begin and develop intensively in the northern part of the lagoon and would then expand to the southern part in the second half of the century. All considered SLR scenarios indicated a gradual decrease in the cover of pioneer stands of perennial cord grasses (MWHA0) (*Spartina maritima* community), particularly in the northern part of the lagoon, where a total retreat was foreseen in three out of four models (Fig. 6).

Especially in the first half of the century, MWHA0 spatial distribution could shift to the southern part of the lagoon, where a positive trend of suitable area was expected. The development of habitat types of MWHA1 (*Puccinellia festuciformis* and *Juncus maritimus* community and *Limonium narbonense* and *Juncus gerardii* community) and MWHA2 (*Salicornia procumbens* subsp. *procumbens* community and *Limonium narbonense* and *Puccinellia festuciformis* community) would seemingly follow a comparable pattern. In the northern part, MWHA0, MWHA1 and MWHA2 or MWHA3 habitats could completely disappear as early as 2075, whereas in the southern part some areas could remain occupied by these types of vegetation if optimistic CC SLR scenarios (2 and 4) become reality. In general, an almost linear trend described the potential decrease in the area of MWHA3 (*Puccinellia festuciformis* and *Sarcocornia fruticosa* communities). However, according to Scenario 2, perennial salt-marsh vegetation dominated by succulent dwarf scrub could increase its potential area in the southern part by 4 or even 8 times, compared to present conditions. The supratidal MWHA4 showed a more conservative temporal trend and, at least according to the least severe scenarios (2 and 4), sub-nitrophilous annual vegetation types could possibly be maintained even in the northern sector. Finally, MWHA5 (mostly represented by meso-eutrophic brackish swamp reeds) appeared as the most constant habitat type, facing minor fluctuations in its potential area. However, under climate conditions in Scenarios 1 or 3, these habitats could also disappear from the northern part of the Venice lagoon salt marsh.

## 4. Discussion and conclusions

Our study has shown that the upcoming climate conditions could significantly affect salt marsh habitat cover and spatial arrangement in the Venice Lagoon trough SLR. Although nearly all habitats evidenced a decrease in their extent by 2050 and beyond, our results also suggest that different types of marshes will respond differently to estimated rising sea levels. As ecosystem engineers, plants tend to modify and stabilize their habitat (Fagherazzi et al., 2012). Thus, halophytic vegetation is considered a key determinant for tidal saltmarsh stability and functioning, and its loss is likely to exacerbate any projected adverse effects of climate change. Moreover, the loss of salt marsh vegetation would be reflected in the whole biota (van der Maarel & van der Maarel-Versluijs, 1996). The disappearance or transition of coastal wetlands could thus trigger alterations in delivery of the ecosystem services provided by these sites, making the projection of future changes a crucial step towards planning and mitigating climate change impacts.

Our study was designed based on findings presented by Bellafiore et al. (2014), who applied a modeling tool to predict the evolution of Venice Lagoon's salt marshes in the future as well. They considered some physical parameters and their variability, such as changes in bathymetry, exposure time and water salinity, to influence the distribution of selected five halophyte species (*Limonium narbonense, Spartina maritima, Sarcocornia fruticosa, Inula crithmoides* and *Salicornia veneta*) in the lagoon. However, we upgraded this study in certain aspects, by considering other predictors and most importantly, the whole vegetation (not only single species) surveyed on the basis of field mapping.

A vegetation map (Cazzin et al., 2008; Ghirelli et al., 2007), which describes the fine-scale spatial organization structure and in which each patch is characterized by a specific habitat type, strictly related to the micro-elevation, enabled the development of a statistical model describing habitat turnover over time as a function of plant's habitat preference and three most relevant environmental variables: subsidence (Lambeck et al., 2004), accretion (Bellucci et al., 2007) and SLR (Church et al., 2013, local measurements). Although the use of community-based models allowed us to simplify complex data, the resulting forecasted patterns showed an intricate situation. Studies in the Venice Lagoon have shown that patterns of soil accretionary dynamics reflect variability in sediment supply, hydrodynamic energy and sediment consolidation (Hensel, Day, & Pont, 1999). Various physical properties (e.g. the vicinity of river mouths, wave energy, which re-suspends sediment) of the northern and southern parts of the lagoon revealed a clear difference in the accretion rate. When this data were incorporated into the model, the submergence risk proved to be quite different for the two parts (sectors). In the northern lagoon, the salt marsh habitats will probably disappear by 2075, but in the southern part in some areas, habitat types could maintain a dynamic equilibrium between accretion and sedimentation vs. relative sea level rise (RSLR), even in the second half of the century. However, most of the habitats will decline. The general reason is that the available sedimentary coast of all micro-altitudes are strictly limited owing to anthropogenic barriers. Minor changes are foreseen only for supratidal habitat types, but there is no need for concern about their near future, being mostly represented by the least specific salt marsh plant communities. All SLR scenarios under consideration clearly indicate an increase in their potential area by mid-century, but under Scenario 3 (RCP8.5) conditions the fate of these sub-halophyte, sub-nitrophilous vegetation types in the next century is nevertheless uncertain. Bellafiore et al. (2014) outlined as well that the future sea level increase will cause important reduction of valuable salt marsh habitats which are unable to cope with these fast trends of SLR in the Venice Lagoon. More specifically, the halophytes that are more adapted to saltwater submersion (in our case MWHA0 to MWHA3) and therefore more tolerant to increased flooding and salinity have the highest probability to be present also in the near future.

However, we can agree with Clark et al. (2016), who summarized the misleading impression among the public that post-2100 changes are of secondary importance, or that these can be reversed with emission reductions at that time. In the 22nd century, humanity could face even higher SLR rates that could drastically reshape the face of our plant (Grinsted, Jevrejeva, Riva, & Dahl-Jensen, 2015; Jevrejeva, Moore, & Grinsted, 2012). Consequently, only the long-term projections need to be considered in mitigation and adaptation measures, especially in large shallow coastal areas such as the Venice Lagoon. The SLR in the Venice Lagoon will mean not only irreparable damage to the city of Venice itself and severe economic damage to the port of Venice, but an alarming threat to the largest coastal wetland area in the Northern Adriatic, which calls for special conservation countermeasures. Compared to marshes in low SLR and constant sedimentation, changes in the

Venice Lagoon's marsh system are rapid (Day et al., 1999), and quick action is required. Our results indicate that actions to conserve these valuable habitats with linked biota should start in the northern sector of the lagoon where predicted trends are clearly more pessimistic comparing to the southern part. The geospatial shifts or even disappearance of saltmarsh habitats can trigger a chain effect of events, which lead to negative processes in the saltmarsh environment, which can destabilize the entire ecosystem. In order to prevent such scenarios in salt marshes, several mitigation measures were already presented. Day et al. (1999) suggested to increase sedimentation by diverting river flow back into the lagoon or to reduce wave energy, particularly along the edges of the marsh, with permeable breakwaters or wave-stilling devices (partly realized in 2005 with the MOSE [Modulo Sperimentale Elettromeccanico—Electromechanical Experimental Module] project (Sharma, Balhara, & Bedi, 2016). Other directions of more environmentally friendly countermeaures were outlined by Ivajnšič and Kaligarič (2014) in the case of Sečovlje salina Nature Park (North Adriatic): buffer zones (where possible); sea level height regulation (where possible, e.g. closed lagoons) or artificial islets. The latter solution seems to be the most suitable to offer appropriate space for halophytic communities (nearly all Natura 2000 habitat types) in case of coastal squeeze due to the absence of buffer zones. However, we can agree with Bellafiore et al. (2014) who revealed the need of future measurements in order to select those physical or environmental variables that most accurately determine the suitability range of halophytes. It is still largely unknown to what extend is the vegetation, especially perennial, persistent on their substrates and resilient to the frequency and magnitude of extreme events; further studies to answer these questions are definitely needed. Indeed, biotic interactions are often an overlooked issue in the climate-change impact modeling approach as well. Community ecology has shown that biotic interactions can influence species' capability to adapt to environmental change (Beselga & Araujo, 2009) and should not be neglected. The loss or gain of plant species has the potential to generate drastic changes in salt marshes' vulnerability to climate change.

In the context of climate change impact analysis, the interaction between SLR and environmental and socioeconomic mechanisms, such as land-use change and urbanization, certainly goes beyond what we captured through the scenarios selected in this study. Nonetheless, the output from our models may be used to enhance planning and management policies by local authorities in the Venice Lagoon as we provide applicable results in the finest thematic and spatial resolution so far published. Moreover, the cost effective methodological approach is transferable to other temperate areas, where tidal marshes experience comparable rates of SLR. The main requirements are: (1) a habitat type map (vector or raster format), (2) a representative number of GNSS elevation measurements in each habitat type and (3) RSLR data (freely available). It should be pointed out that other predictors can be included into the model as well but the contribution and effects of these variables are beyond the scope of this study.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.apgeog.2018.07.005.

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