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How to Preserve Coastal Wetlands, Threatened by Climate Change-Driven Rises in Sea Level

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Abstract A habitat transition model, based on the correlation between individual habitats and micro-elevation intervals, showed substantial changes in the future spatial distributions of coastal habitats. The research was performed within two protected areas in Slovenia: Sečovlje Salina Nature Park and Škocjan Inlet Nature Reserve. Shifts between habitats will occur, but a general decline of 42 % for all Natura 2000 habitats is projected by 2060, according to local or global (IPCC AR4) sea level rise predictions. Three different countermeasures for the long-term conservation of targeted habitat types were proposed. The most "natural" is displacement of coastal habitats using buffer zones (1) were available. Another solution is construction of artificial islets, made of locally dredged material (2); a feasible solution in both protected areas. Twenty-two islets and a dried salt pan zone at the desired elevations suitable for those habitats that have been projected to decease in area would offer an additional 10 ha in the Sečovlje Salina. Twenty-one islets and two peninsulas at two different micro-altitudes would ensure the survival of 13 ha of three different habitats. In the area of Sečovlje Salina, abandoned salt pans could be terrestrialized by using permanent, artificial sea barriers, in a manner close to poldering (3). By using this countermeasure, another 32 ha of targeted habitat could be preserved. It can be concluded that, for each coastal area, where wetland habitats will shrink, strategic plans involving any of the three solutions should be prepared well in advance. The specific examples provided might facilitate adaptive management of coastal wetlands in general.

Keywords Sea level rise · Coastal wetlands · North Adriatic seacoast · Habitat transition model · Coastal management · Conservation countermeasures

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Introduction

Sea level change is a high-profile aspect of climate change, and many studies have confirmed that there are potentially significant impacts for our modern coastal society (Church et al. 2011; Nicholls 2011). During the 21st century, global average sea level is expected to rise considerably faster than in the 20th, even if a common conclusion from all the coupled atmospheric-ocean general circulation models is that sea level change will be far from uniform (Gregory et al. 2001; IPCC 2007; Carbognin et al. 2010; Church et al. 2011). Relative sea level rise (RSLR; sea level rise adjusted for the sedimentation rate and subsidence) has already been recognized as a serious threat to coastal wetlands, particularly along low-lying sedimentary seacoasts worldwide, where inundation or displacement of coastal wetlands is predicted. Approximately 50 % of saltmarsh area worldwide has already been lost or degraded (Adam 2002). Nicholls et al. (1999) predicted that the impact of RSLR will be particularly severe in certain regions such as the Mediterranean and the Baltic, where coastal wetlands could almost completely disappear by the 2080s. This phenomenon presents considerable challenges for developing cost-effective plans to preserve biodiversity (Runting et al. 2013), specifically to re-establish or create saltmarsh covering the full range of habitats that will have been lost (Mossman et al. 2012).

RSLR will not only affect the target habitats and their halophyte flora, but may also lead to the loss of breeding grounds for diverse avian and marine fauna, along with increased coastal flooding, erosion and saltwater intrusion into estuaries, deltas and aquifers (McLean et al. 2001; Lombard et al. 2003; Fuentes et al. 2010).

However, coastal habitats, especially on the densely populated European coasts, are already severely endangered by rapid, anthropogenically driven, landscape changes in recent decades. People have often favored coastal locations for settlement because, among other benefits, these areas tend to contain the greatest biological productivity. Over half of the world's population lives within 60 km of the shoreline, and coastal populations in many countries are growing at double the national rate (Turner et al. 1996). Historic human intervention within the coastal zone and upstream in catchment areas has often led to non-sustainable levels of resource exploitation (Lundin and Linden 1993; Turner et al. 1996). Nowadays urbanization, agriculture, and tourism (together with RSLR) are considered major threats to coastal wetlands and have already caused substantial destruction of most endangered habitats such as coastal dunes (Van der Meulen and Salman 1996). Moves toward integrated coastal zone management are urgently required to guide the coevolution of natural and human systems (Turner et al. 1996).

Coastal wetlands have adapted their shape and size to changing sea levels throughout history (Nicholls and Cazenave 2010; Chu-Agor et al. 2011; Runting et al. 2013). Moreover, an absolute increase in the elevation of the marsh platform in response to rising sea level should cause a landward migration of the marsh (Gardner et al. 1992; Gardner and Porter 2001; Chu-Agor et al. 2011; Runting et al. 2013), and this may change total wetland area and consequently total production, depending on local geomorphology and anthropogenic barriers to migration (Morris et al. 2002; French and Burningham 2003). However, it is reported that changes in the marsh surface are not as dynamic as changes in sea level. Therefore, the threshold for RSLR should be lower in coastal wetlands that are deprived of sediment and/or are facing rapid surface subsidence (Day and Templet 1989; Britsch and Dunbar 1993; Morris et al. 2002). Owing to these threats and pressures, the current area of valuable sedimentary coast, which harbors priority habitats and threatened biota, is limited to the current protected areas and mainly bordered by roads, dykes, channels, intensive agriculture (characteristic of lowlands), or urban areas. Thus, this landward migration of habitats on European coasts is not easy to accommodate simply by setting aside areas that are free of physical barriers for the retreat of these ecosystems (Chu-Agor et al. 2011). Some authors have named this problem the "coastal squeeze" (Bayliss et al. 1997).

RSLR is a complex process, including many other factors that can cause changes in coastal morphology: sediment supply, tidal currents, wave action, extreme weather events (Cooper et al. 2011), and in some areas land subsidence (Lambeck et al. 2004; Church et al. 2008). Neither should biotic processes such as plant competition or accretions be neglected. It is reported (Morris et al. 2002; French and Burningham 2003; Baustian et al. 2012) that under certain situations, such as high sedimentation by both organic and inorganic materials, coastal wetlands may be able to keep pace with rising sea levels. However, human-induced accelerated RSLR has already become a global problem. Nevertheless, the projections of RSLR differ significantly across the globe (Church et al. 2008), and in the Mediterranean Sea (Cazenave et al. 2002; Fenoglio-Marc 2002) in particular. Cazanave et al. (2001) and Tsimplis and Rixen (2002) observed that, for the coastal sea level in the Mediterranean, water thermal expansion due to heating cannot be the only factor responsible for the measured oscillations. Other effects, such as a salinity increase triggered by higher evaporation rates (Tsimplis and Baker 2000), an increase in atmospheric pressure due to the high state of the North Atlantic oscillation (Tsimplis and Josey 2001), or changes in the hydraulic conditions at the Strait of Gibraltar (Ross et al. 2000), may be linked with the observed sea level changes yielding predictions that are even more fuzzy (Carbognin et al. 2010).

Thus, the only relevant bases for reliable predictions in these areas are local measurements on the actual sites being studied. For the Northern Adriatic Sea, data are available from the sea level height measuring stations in Trieste and Koper. Although it is believed that the current and anticipated sea level rise is mainly caused by thermal expansion of the ocean and melting of land-based ice sheets (Akumu et al. 2011), we should also consider other important factors when predicting RSLR, especially on the local scale, as mentioned before. Lambeck et al. (2004) pointed out that several morpho- and litho-stratigraphic markers indicate dynamic tectonic movements in Italy and elsewhere in the Mediterranean and can influence RSLR predictions. The coastal zone of the Northern Adriatic Sea appears to be mostly a region of subsidence, with an average rate of approximately 0.15 mm year^{-1} (Lambeck et al. 2004). This process is actually accelerating the encroachment of the sea on the coast, but is then in one way compensated by the sediment supply from the rivers. The sedimentation rate in the Gulf of Trieste, especially in the inner part of the Koper and Piran bays, is quite high according to the measurement of ^{210}Pb activity in the surficial sediments, which revealed a trend of 5.3 mm year^{-1} (Ogorelec et al. 1991). Similar results were presented by Ogorelec et al. (1984), using pollen analysis: i.e., about 5 mm year^{-1}. In addition to predictions made on the basis of local measurements, the predictions available within the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) updated global average sea level change data (Church et al. 2011) were also added.

In this paper, we upgraded the previous study (Ivajnšič et al. 2012) where a habitat transition model was preliminarily tested. It was confirmed that every single coastal habitat type from the two investigated coastal wetlands (Škocjan Inlet Nature Reserve and Sečovlje Salina Nature Park) is linked to a certain micro-altitudinal interval. Similar patterns for marsh vegetation elevational zonation in the Venice lagoon (Italy) and Morecambe Bay (United Kingdom) are reported by Marani et al. (2013). The occurrence of a specific halophyte habitat type area is correlated with the micro-altitude with statistical significance (Tables 2, 3). Presuming that RSLR will cause a change in vegetation composition, creating the possibility of re-establishing the species at a higher level (Vestergaard 1997), enables us to model the habitat transitions according to RSLR, but also to take into consideration sedimentation and subsidence rates, something which has not previously been done. The main aim of this study is to make a prediction of coastal wetland habitat shift for the years 2020, 2040, 2060, 2080, and 2100. With such a prediction, we can calculate the habitat loss (or gain) for each habitat type within the predicted milestone year. With this knowledge, we could suggest new management regimes by proposing concrete countermeasures for specific protected areas.

Study Sites

The flysch bedrock derived sedimentary coast of Slovenia was in some parts converted to salt pans or dried out in the past. However, some parts were abandoned and even artificially enlarged with soil deposits (Kaligarič and Škornik 2006). Thus, there are three such coastal wetlands (protected areas) in Slovenia, of which the two most important were chosen for our study areas: the Sečovlje Salina (Sečoveljske soline) and the Škocjan Inlet (Škocjanski zatok). Both locations are on the tiny Slovenian seacoast, lying in the North Adriatic, the northernmost part of the Mediterranean Sea in Europe. The first is located along the Slovene-Croatian boundary in the extreme south-western part of Slovenia, 45°29′N and 13°37′E, and the second one lies on the outskirts of the town of Koper 45°32′N and 13°37′E (Fig. 1). Owing to the geographic position to the south and southwest of the Alpine-Dinaric barrier, whose relief opens toward the Adriatic Sea, these areas have a Sub-Mediterranean climate. This area has the most days with sun (up to 2,350 h per year), the average temperatures of the coldest month are above the freezing point, and those of the warmest months are above 20 °C (Ogrin 2004). Owing to the moderating action of the sea, temperatures in October are higher than those in April. The precipitation regime is also Sub-Mediterranean, with high precipitation in the fall and at the end of spring or the beginning of summer, and low precipitation in the winter and summer (Ogrin 2004). The Sečovlje salina area is a Nature Park, established in 2002, which covers about 650 ha. Although the salina was made by man in the early Middle Ages, today it is a mosaic of natural habitats, containing not less than 5 Natura 2000 habitat types: 1. Mudflats and sand flats not covered by seawater at low tide (code 1140) 2. Tall rush saltmarshes (code 1410)—communities of *Juncetalia maritime* (association *Juncetum maritimi-acuti*) 3. *Spartina* swards (code 1320)—*Spartinion maritimae* (association *Limonio-Spertinetum maritimae).* 4. *Salicornia* and other annuals colonizing mud (code 1310) (*Thero-Salicornietea: Suaedo maritime-Salicornietum patulae* and *Salicornietum emerici*) 5. Mediterranean and thermo-Atlantic halophilous scrubs (code 1420)—*Sarcocornetea fruticosi* (*Puccinellio-Sarcocornetum, Puccinellio-Halimionetum fruticosae and Limonio angustifoliae-Artemisietum caerulescentis*). Škocjan Inlet Nature Reserve is a Mediterranean wetland, established in 1998 and covers an area of 122 ha. The reserve is commonly known as "the green heart of the town of Koper''. After restoration in 2007, Škocjan Inlet has regained its past biodiversity or has even been improved in terms of the surface area of coastal Natura 2000 habitats (Ivajnšič et al. 2012).

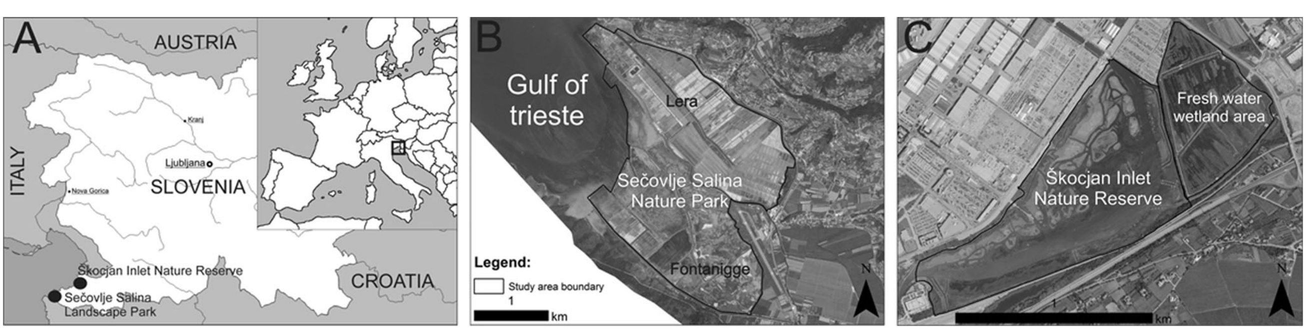

Fig. 1 Geographic position of study sites (**a**); Sečovlje Salina Nature Park (**b**) and Škocjan Inlet Nature Reserve (**c**)

Methods

Sea Level Rise Prediction

In response to several reports about the non-uniform SLR predictions in the Mediterranean Sea (including the Northern Adriatic), we used primarily local measurements. The sea level height measuring station of Koper (ARSO 2011), a town located 1.5 km from the Škocjan Inlet Nature Reserve study area and 10 km from the Sečovlje Salina Nature Park study area, was used. In the RSLR prediction, we also considered the average sedimentation rate in the Gulf of Trieste after Ogorelec et al. (1991) and the average subsidence rate in the Gulf of Trieste after Lambeck et al. (2004) (Fig. 3). With this adopted SLR trend (RSLR), upgraded with sedimentation and subsidence rates, we predicted the average sea level for the milestone years 2020, 2040, 2060, 2080, and 2100 in both study areas (with respect to 2010).

In addition to this, we also compared our data with the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) updated global average sea level change data (Church et al. 2011), which includes changes in ocean heat content and thus ocean thermal expansion, changes in glacier mass, surface mass balance changes for the ice sheets and changes in ice sheet flow; these are based on global climate model simulations completed as part of an internationally organized set of climate simulations called CMIP-3, available at http://www.cmar.csiro.au/sealevel/sl_proj_21st.html (20.10.2013). For the twentieth century, the models used observed changes in greenhouse gas concentrations and other climatic forcing, while for the twenty-first century they used greenhouse gas emissions from the IPCC Special Report on Emission Scenarios (SRES). The greenhouse gas scenarios A1B, A1T, A1FI, A2, B1, and B2 to year 2100 (with respect to 2010) were included in the model (Table 1).

Table 1 The main characteristics of the included IPCC greenhouse gas emissions scenarios based on the special report on emission scenarios (SRES)

IPCC SRES Scenario	Description	Major themes	Scenario subtype	Technological emphasis
A1	Rapid economic growth	Convergence among regions	A1FI	Fossil intensive
	Global population peaking in mid-century and declining thereafter	Capacity building	A1T	Non-fossil energy sources
	Rapid introduction of new and more efficient technologies	Increased cultural and social interaction	A1B	Balance across all sources
		Substantial reduction in regional differences in per capita income		
A2	Very heterogeneous world in economic, demographic and technological aspects	Self-reliance	–	
		Preservation of local identities		
	Continuously increasing global population	regionally oriented economic development		
		More fragmented and slower technological change		
B1	Global population peaking in mid-century and declining thereafter	Global solutions to economic, social, and environmental sustainability	–	
	Rapid changes in economic structures toward a service and information economy	Improved equity without additional climate initiatives		
	Reductions in material intensity, and the introduction of clean and resource-efficient technologies			
B2	Local solutions to economic, social, and environmental sustainability	Environmental protection and social equity	–	
	Continuously increasing global population at a rate lower than A2	Focusing on local and regional levels		
	Intermediate levels of economic development			
	Less rapid and more diverse technological change than in B1 and A1			

IPCC (2013)

Habitat Mapping

The PHYSIS typology (Anonymus 2007), based on Palearctic classification (Devilliers and Devilliers-Terschuren 1996), was chosen as one of the most accurate for habitat mapping. The base for Palearctic classification is syntaxonomy, the hierarchically ordered Braun-Blanquet system of plant associations. Where the names of associations or higher taxa (alliances and orders) are not applicable, the physiognomical aspect of vegetation is applied. The name PHYSIS derives from this. The hierarchically based PHYSIS enables us to refine the habitat type with additional information about the vegetation level. This classification was adopted and modified for Slovenian conditions (Jogan et al. 2004). Because halophyte habitats in both study areas can change in really short distances, the "hybrids" (transitional forms, mixtures or mosaics) between two habitat types were also used. Both study areas were mapped in the field with a resolution of 1 m. Habitat types were drawn on printed orthophoto imagery (0.5 m pixel size) (GURS 2010) as polygons and later digitalized using ArcGIS 9.3 (ESRI 2010) (Fig. 2—Step 1).

Determination of Micro-Elevations

Geodetic measurements were carried out in both study areas by professional geodesists using a high resolution GNSS (Global Navigation Satellite System) instrument (Zmax Thales Navigation, geodetic accuracy of 1 cm), measuring points above average sea level in each habitat type according to the Slovenian Geoid Model (GURS 2010) for 2010. In addition to this data, we scanned the Škocjan Inlet Nature Reserve area and the surroundings with airborne light detection and ranging (LIDAR) technology, following the methodologies of various studies which investigated the SLR effect on coastal wetlands around the world (Gesch 2009; Clough et al. 2010; Akumu et al. 2011; Runting et al. 2013). The data were taken from a height of 650 m with a recording frequency of 142 kHz and a flight speed of 85 kn. Thus, we obtained an average point density of 4 points per square meter and a horizontal accuracy of 10 cm. Because the halophyte vegetation cover is not too dense, we measured 550,000 clear bare-earth shots out of 6.3 million total recorded points. The LIDAR point cloud was calibrated using 110 high resolution GNSS points (randomly dispersed over the Škocjan Inlet land) that were measured according to average sea level in 2010 with respect to the Slovenian Geoid Model (GURS 2010). Elevation data must be corrected, which means that the mean tide level is set to zero (Clough et al. 2010). A detailed digital elevation model (DEM) was developed using the radial base function of the geostatistical wizard in the ArcGIS 9.3 spatial analyst tool (ESRI 2010). As in the sea level affecting marshes model (SLAMM) (Clough et al. 2010), high vertical-resolution elevation data are in our case the most important data requirement. Owing to the

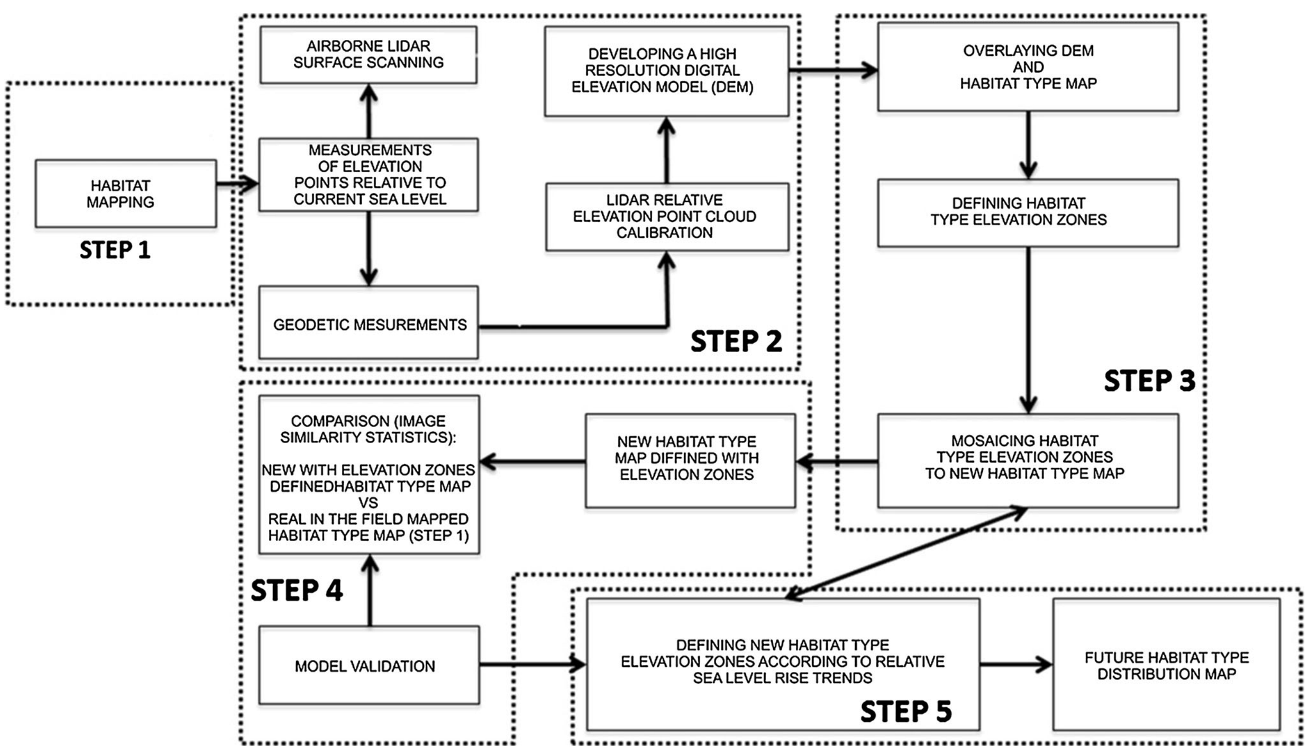

Fig. 2 Schematic view of the "Habitat transition model" according to sea level rise scenarios

high costs of the airborne LIDAR scanning method, we were forced to simplify the method for DEM creation in the second study area in Sečovlje Salina Nature Park. There the geodesists measured 221 elevation points dispersed over the whole investigation area as repeating transects of 3 points per habitat type. Thus, we obtained 73 transects in 28 different habitat types. Because the halophyte vegetation is developed in layers that are linked to the elevation gradient, the first transect point was measured near the first contact zone between two habitats, the second in the middle of the habitat, and the third near the second contact zone. Then, we used the zonal statistics tool in ArcGIS 9.3 (ESRI 2010) to calculate the mean elevation with respect to 2010 for each habitat. Finally, we attributed the mean elevation values to 307998 randomly dispersed points (100 per polygon) all over the Sečovlje Salina Nature Park and created a DEM (Fig. 2—Step 2).

Attribution of Micro-Elevation Intervals to Mapped Habitat Types

In order to simplify the modeling procedure, we aggregated the field-based (mapped) habitat types in each study area into eight groups, using the Ward classification method (distance = square Euclidean) within the R statistical software (R Development Core Team 2008) according to average habitat elevation with respect to 2010. The aggregation method is therefore site-specific, and groups (aggregates) can be formed with different habitat types in different study areas. Most of the groups follow the average habitat type elevation, but not all: accordingly, we aggregated four groups which appear at higher altitude, independent of tidal regime and salinity-moisture gradient, into one aggregate. Consequently, five groups [modified ward habitat aggregates (MWHA)] remained (Tables 2, 3), which are all arranged across a micro-altitudinal gradient.

The ArcGIS 9.3 Spatial analyst tool enabled us to combine the micro-elevation data with the habitat type map and to define the micro-elevation intervals for each MWHA (Fig. 2—Step 3). We decided to choose the mean ± 1SD interval, since the frequency distributions of heights/elevations per MWHA were not normally distributed (owing to the shallow sedimentary coast).

The Habitat Transition Model

Following the concept of the "coastal squeeze" process (Bayliss et al. 1997), we built a GIS-based habitat transition model to predict the spatial distribution of protected habitats in relation to the average SLR trend (Fig. 2) with respect to 2010.

When micro-elevation intervals for each MWHA were determined, then each of the five aggregates was attributed to a single elevation zone for 2010 on the DEM, using ArcGIS 9.3 spatial analyst (ESRI 2010). It should be emphasized that the modeled future scenarios are therefore very dependent on the morphology of the study area relief. A newly defined MWHA map for 2010 (based on elevation zones) emerged (Fig. 2—Step 3). We validated this map by comparing it with the actual (field based mapped and to MWHA aggregated) habitat type map for year 2010, using image similarity statistics (Chi square test, Kappa index of agreement; Idrisi Selva software—Eastman 2012) (Fig. 2—Step 4). We decided to continue the modeling procedure only if the overall Kappa index of agreement between these two maps reached at least approximately 70 %. In that case, the accuracy of future MWHA distributions according to RSLR with respect to 2010 was at a satisfactory level. Finally, we defined new relative elevation zones for each MWHA, considering local and global (IPCC AR4) RSLR predictions and developed future MWHA maps (Fig. 2—Step 5).

Results

Losses and Gains in Habitat Areas Driven by Sea Level Rise

On the basis of the trends calculated from the locally gathered data, and also considering the sedimentation rate and coastal land subsidence, we obtained a speed of sea level rise of about 0.28 cm $year^{-1}$ (Fig. 3) in the last 30 years. With this modified linear trend, we predicted that the sea level would rise (with respect to average sea level height in 2011—the last whole measured year) by 5 cm by 2020, 11 cm by 2040, 16 cm by 2060, 22 cm by 2080, and finally by 28 cm in 2100. Additionally, a comparison between the local modified sea level trend and the global, with scaled-up ice sheet discharge updated, IPCC AR4 sea level predictions to 2100, according to SRES scenarios (A1B, A1T, A1FI, A2, B1 and B2), showed that sea levels could rise by 2100, in the worst-case scenario (A1FI; 95-percentile range), by up to 75 cm compared with levels in 2010.

In the Škocjan Inlet Nature Reserve study area, the first MWHA—which is a mosaic of intertidal "mudflats and sandflats" (Natura 2000 code 1140) and "Mediterranean glasswort swards" (code 1310) and develops closest to the sea—will rapidly decrease its area cover by 2020 and then stay constant till 2040, covering approximately 12 % in our RSLR prediction scenario (Fig. 4). By 2080 or 2100 this MWHA could decrease in area to cover just 3 %. The global SLR scenarios predict a similar evolution of area cover for this MWHA. It should be emphasized that all six IPCC AR4 SRES scenarios predict more rapid decrease by

Table 2 Palearctic classification code of the mapped habitat types, frequency of elevation points per habitat type, average elevation of habitat types with respect to 2010, Ward aggregate and MWHA, average elevation and standard deviation of WMHA, land cover (m^2) and Pearson's correlation coefficient with significance values (*P* value) between elevation and area cover per WMHA in the Škocjan Inlet Nature Reserve study area

Palearctic code of habitat types	Lidar elevation point frequency	Average habitat elevation (m)	Ward aggregate	Modified ward habitat aggregate (MWHA)	Average elevation + SD (m)	Area (m^2)	Corr. coef.	*P* value
14	7,945	0.19	1	1	0.24 ± 0.10	10,5807	−0.75	0.0000
14 × 15.11	25,279	0.22	1					
Aster tripolium stands (AT)	1,077	0.24	1					
15.113	175,161	0.24	1					
15.11 × 15.61	76,081	0.26	1					
14 × 15.61	500	0.28	2	2	0.33 ± 0.15	23,182	−0.82	0.0000
15.61 × AT	4,454	0.30	2					
15.113 × AT	1,221	0.32	2					
15.61	58,800	0.34	2					
15.61 × 53.1112	10,786	0.42	3	3	0.42 ± 0.16	4,133	−0.66	0.0012
53.1112 × AT	979	0.43	3					
15.61 × 87.2	8,493	0.62	4	4	0.62 ± 0.22	2,820	-0.3	0.1897
15.61 × 31.8122	147	0.62	4					
31.8122 × 86.6	351	0.73	5	5	1.12 ± 0.72	69,261	0.23	0.3259
31.8122 × 53.1112	8,639	0.78	5					
53.1112	63,141	0.80	5					
31.8122 × 87.2	5112	0.86	5					
84.2 × 87.2	3,247	1.07	6					
53.1112 × 87.2	16,977	1.13	6					
31.8122 × 84.2	12,207	1.47	7					
84.2	388	1.61	8					
31.8122	3,284	1.63	8					
87.2	26,788	1.76	8					

Key: 14 (Mud flats and sand flats = Natura 2000 code 1140), 15.11 (Glasswort swards = Natura 2000 code 1310), 15.113 (Mediterranean glasswort swards = Natura 2000 code 1310), 15.61 (Mediterranean saltmarsh scrubs Natura 2000 code 1420), 31.8122 (Sub-Mediterranean blackthorn-privet scrub), 53.1112 (Saline water *Phragmites* beds), 84.2 (Hedgerows), 87.2 (Ruderal communities)

2020 (to just 10 % of area cover). After 2050, all of them predict lower area cover compared with our RSLR prediction and until then do not markedly differ (Fig. 4). The most optimistic SRES scenario for the MWHA 1 is the B1 (economic, social, and environmental sustainability), while the worst-case scenario belongs to A1FI (fossil intensive technology), predicting less than 2 % of remaining area in 2100. The "Mediterranean saltmarsh scrubs" (Natura 2000 code 1420) are mainly grouped in the second WMHA, which follows the first aggregate on the elevation gradient. It is predicted that in the Škocjan Inlet Nature Reserve, this habitat will lose 17 % in area, half of that by 2040 (Fig. 4). Compared with the six global RSLR scenarios, our prediction assumes more rapid area loss till 2050. Afterwards, only B1 coincides with our prediction for this WMHA; all other scenarios predict more rapid losses. Again, A1FI on average predicts that this habitat aggregate could almost completely disappear by 2100 (Fig. 4). The predicted spatial distribution of the "*Phragmites* stands" (MWHA no. 3) in the Škocjan Inlet Nature Reserve will steadily decrease in area from 22 % today to only 5 % in 2100, according the local modified RSLR trend (with respect to 2010). Global RSLR scenarios indicate more regular area cover changes till 2040. In the second half of the 21st century, the global scenarios differ from our prediction, but all of them estimate very similar spatial distribution and area cover for this MWHA 3.

MWHA no. 4 is composed of various combinations of ruderal stands. Predictions for the future land cover of this habitat are more or less linear. Our prediction again assumes more rapid changes in the next few years than in the global IPCC AR4-SRES scenarios. The turning point comes in 2040, when B1 predicts similar results, but all other scenarios predict more dramatic changes in this

Table 3 Palearctic classification code of the mapped habitat types, frequency of elevation points per habitat type, average elevation of habitat types with respect to 2010, Ward aggregate and MWHA, average elevation and standard deviation of WMHA, land cover (m^2) and Pearson's correlation coefficient with significance values (*P* value) between elevation and area cover per WMHA in the Sečovlje Salina Nature Park study area

Palearctic code of habitat types	Elevation point frequency (random dispersed points)	Average habitat elevation (m)	Ward aggregate	Modified ward habitat aggregate (MWHA)	Average elevation + SD (m)	Area (m^2)	Corr. coef.	*P* value
15.51 × 15.61	446	0.24	1	1	0.29 ± 0.04	1218,209	0.35	0.0517
15.51	811	0.25	1					
14	136,397	0.28	1					
14 × 15.11	7,712	0.29	1					
15	230	0.32	1					
15.113	68,663	0.32	1					
15.11 × 15.61	8,635	0.34	1					
15.11 × 87.2	188	0.38	2	2	0.41 ± 0.09	145,431	0.79	0.0060
14 × 15.61	7,469	0.40	2					
15.61	18,979	0.42	2					
15.51 × 53.1112	2,135	0.48	3	3	0.51 ± 0.11	49,274	−0.01	0.9750
15.61 × 53.1112	1,121	0.51	3					
53.1112	5,720	0.53	3					
14 × 87.2	1,175	0.64	4	4	0.70 ± 0.14	345,337	0.89	0.0430
15.61 × 87.2	22,163	0.68	4					
15.51 × 87.2	39	0.69	4					
87.2	28,732	0.71	4					
53.1112 × 87.2	10,873	0.72	4					
31.8122 × 86.6	42	0.77	5	5	0.81 ± 0.43	144,223	-0.16	0.1240
OTHER	7,816	0.78	5					
31.8122 × 53.1112	2,110	0.78	5					
31.8122 × 87.2	2,706	0.78	5					
31.8122	3,936	0.79	5					
31.8122 × 83.324	284	0.81	5					
86.6	633	1.14	6					
PATH	7,147	1.33	7					
83.324	11	1.35	7					
86.2	917	1.40	7					

Key: 14 (Mud flats and sand flats = Natura 2000 code 1140), 15 (saltmarshes, salt steppes, salt scrubs), 15.11 (Glasswort swards = Natura 2000 code 1310), 15.113 (Mediterranean glasswort swards = Natura 2000 code 1310), 15.51 (Mediterranean tall rush saltmarshes = Natura 2000 code 1410), 15.61 (Mediterranean saltm arsh scrubs = Natura 2000 code 1420), 31.8122 (Sub-Mediterranean blackthorn-privet scrub), 53.1112 (Saline water *Phragmites* beds), 83.324 (Locust tree plantation), 84.2 (Hedgerows), 86.2 (houses or settlements), 86.6 (Archaeological sites), 87.2 (Ruderal communities)

MWHA. The last (5th) MWHA is an aggregate of 10 habitat types, not dependent on micro-elevation, mainly transitions to or mosaics with Sub-Mediterranean scrub. It will lose its surface substantially, mainly due to the impossibility of landward migration. This MWHA is squeezed between the landward movement of other habitat types and the surrounding infrastructure. However, changes in this MWHA will be small. To conclude, our predicted rise in water level by 2050 is comparable to scenarios A1B (mean value) and A1T (mean value). Afterwards, our predictions are more comparable to the B1 (mean value) scenario. In general, all predictions of water level rise serve to raise awareness and call for mitigation measures, especially within the protected areas.

The model predicts more drastic changes in future habitat type distributions in the Sečovlje Salina Nature Park than in the Škocjan Inlet Nature Reserve. The explanation lies in the relief of this man-made area. The abandoned salt pans are intertwined with dikes and channels; habitats change in shorter distances, following the sharper elevation gradient. The first MWHA, in addition to the same type in the Škocjan Inlet, here also contains the

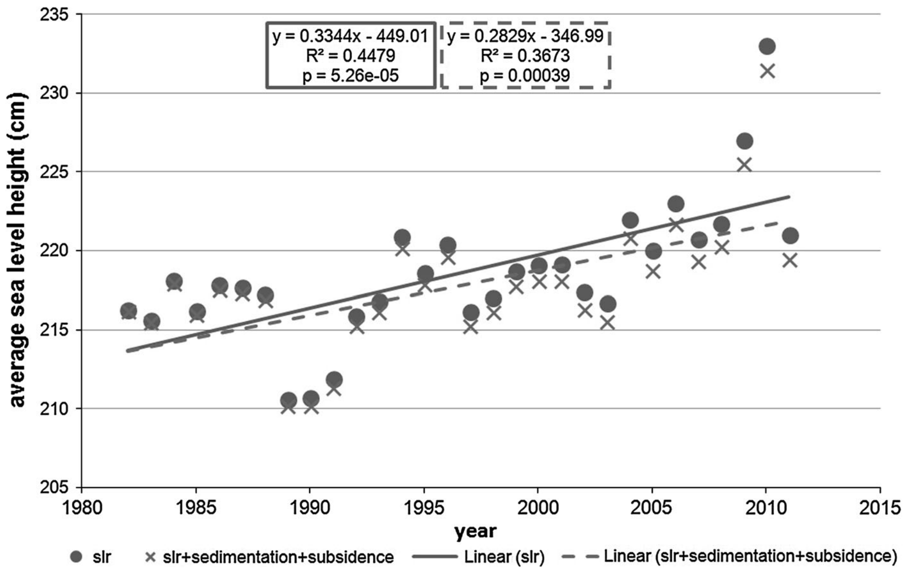

Fig. 3 Average 30 year sea level trend (0.33 cm year^{-1}) and the same trend adapted to average sedimentation rate (0.053 cm year^{-1}) and average coastal subsidence rate (0.0015 cm year^{-1}), for the sea level height measuring station in Koper (0.28 cm year^{-1}) with some statistical parameters (1982–2011; ARSO 2011)

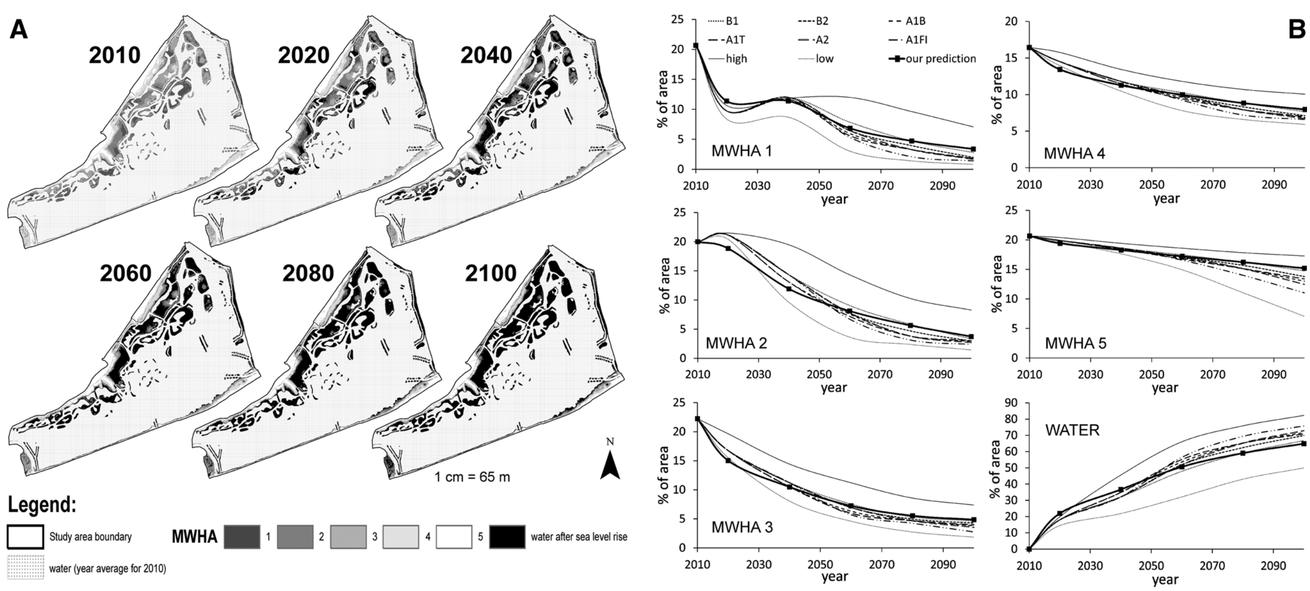

Fig. 4 Predicted spatial distribution of MWHA for the years 2010 (field mapping), 2020, 2040, 2060, 2080, and 2100 in Škocjan Inlet Nature Reserve, based on local RSLR measurement (**a**) and comparison of predicted percentage of area cover per MWHA according to local modified RSLR prediction with respect to 2010 (*bold black line* with markers) and the global IPCC AR4, with scaled-up ice sheet discharge updated, RSLR predictions to 2100 with respect to 2010. "Low" and "high" indicate the 5- to 95-percentile range, and the full lines are the average of these, showing percentages of area cover

N2000 habitat type "Mediterranean salt meadows" (code 1410) and some ruderal transitional habitats. The prediction of future land cover is similar to that in Škocjan Inlet, but even more drastic. In all RSLR predictions (local and global), the WMHA will dramatically decrease in area from a predicted 62 % today to only approximately 2 % in 2100. Following the local SLR trend, a more drastic decrease in area by 2060 is predicted and comparable with the low 5 percentile rate of all global scenarios. Only the A2 scenario predicts some increase in potential future area for this WMHA between 2080 and 2100. As in the Škocjan Inlet, in Sečovlje Salina, the second WMHA is mainly composed of "Mediterranean saltmarsh scrubs" (Natura 2000 code 1420). We predict that the area cover could increase by 3 % by 2020 and then slowly decrease to cover just 2 % of the whole study area of Sečovlje Salina. Surprisingly, the global SLR scenarios predict different evolutions of spatial distribution of this second WMHA. Before 2060, minor changes are predicted in 5 out of 6 scenarios. Only A1FI predicts a major decrease in area by

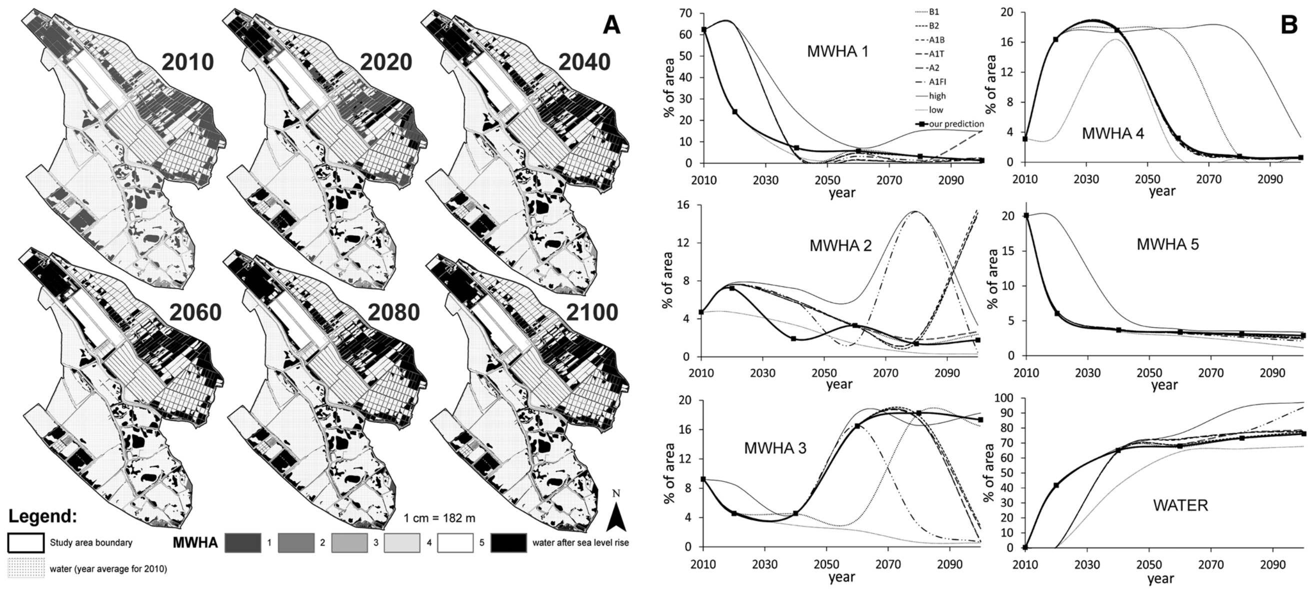

Fig. 5 Predicted spatial distribution of MWHA for the years 2010 (field mapping), 2020, 2040, 2060, 2080, and 2100 in Sečovlje Salina Nature Park, based on local RSLR measurement (**a**) and comparison of predicted percentage of area cover per MWHA according to local modified RSLR prediction with respect to 2010 (*bold black line* with markers) and the global IPCC AR4, with scaled-up ice sheet discharge updated, RSLR predictions to 2100 with respect to 2010. "Low" and "high" indicate the 5- to 95-percentile range, and the full lines are the average of these, showing percentages of area cover

then. A2 and B1 predict similar results from 2060 onwards, similar to our local modified SLR trend. A1FI assumes a massive increase in total area cover between 2060 and 2080, from 1 to almost 15 %, but after that also a massive decrease to near an extinction level. A2, A1B, and A1T predict a slow WMHA decrease from 2020 to 2080 but then a rapid increase till 2100 to almost 15 %. We can divide the predicted spatial distribution of the "*Phragmites* stands" (MWHA no. 3) in the Sečovlje Salina Nature Park into two parts. All scenarios (local and global) predict a decrease in area from today's 9 to 4 % by 2040 and then a rapid increase to 18 % of area cover by 2080. Until then, only the A1FI and B1 scenarios differ from the others. A1FI predicts a decrease of this WMHA after 2060 and it is near disappearance by 2100. The B1 scenario diverges as early as 2040; it assumes constant area cover till 2060 and then a rapid increase to 17 % at the end of the century. Five scenarios, except for ours and B1, predict an almost complete loss of this WMHA by 2100. For WMHA 4, all scenarios indicate a sixfold increase in area cover from the recently modeled situation by 2040. Afterwards, all of them predict a massive decrease to just 1 % of area. The B1 scenario predicts this rapid decrease a bit later, in 2060. The 5th WMHA will face a rapid decrease in area cover, owing to the impossibility of landward migration. It is squeezed between the landward movement of other habitat types and the surrounding infrastructure, as in the Škocjan Inlet Nature reserve. Water level could rise to cover almost 77 % of the area in Sečovlje Salina, if we consider just the mean RSLR projections. In the worst-case scenario, seawater could inundate 97 % of this protected area (Fig. 5).

Adapted Management: 3 Mitigation Measures

According to these predictions, it is clear that RSLR forms a serious threat to Northern Adriatic coastal wetlands, which will require adapted management. Such management should include countermeasures, which could go in three directions, depending on the natural features of each area.

Buffer Zones

The most suitable countermeasure seems to be the simple use of allocated buffer zones at the edges of the coastal wetlands. However, these buffer zones are not available everywhere, although many protected areas had already been planned to include such areas. Such buffer zones could be further pre-prepared for colonization of new habitats by, e.g., removing the woody species or ruderal vegetation and preparing a suitable elevation by filling or leveling the existing ground to reach the target micro-elevations.

Artificial Islets

On shallow sedimentary coasts, the construction of small artificial islets or mudflats is the most simple and straightforward measure. The islets should be sited at the desired micro-altitude, depending on the target habitat type. The islets can be constructed so that they look as natural as possible, especially when fitted properly within the natural bays of lagoons. The newly constructed islets need to be leveled to a previously determined micro-elevation and consolidated at the edges with wooden kerbs.

Sea Level Height Regulation

The less common possibility is applicable only in cases where there is an option to regulate the sea level in areas where the targeted habitats occur, by using artificial sea barriers. This poldering-like approach has already proved to be useful in the Sečovlje Salina area: closed areas of abandoned salt pans, with levels below the average sea level, were artificially closed and later colonized spontaneously with perennial halophyte vegetation. The idea is to use dykes to disconnect areas that are currently inundated by the regular influx of seawater.

For the two actual protected areas, all three of these countermeasures are possible, but only in certain combinations adapted to site-specific conditions.

In Škocjan Inlet, it is possible to use a buffer zone approach, a set-aside freshwater wetland area, currently with no Natura 2000 habitats, in order to compensate for the projected loss of 29 % of coastal Natura 2000 habitat area by 2060. We suggest connecting the coastal wetland area with the freshwater wetland and submerging it, because it has developed in a small relief depression with most of the core area lying lower than the average sea level. New shoreline with optimal conditions for halophyte vegetation will develop. To secure sufficient area for target habitat types, we planned an additional 21 islets and 2 "peninsulas", with a total area of 6.5 hectares (Fig. 6). The total (new shoreline + islets) new available area for halophyte vegetation development would then be 13 hectares. If we want to preserve the habitat types that will decrease in the model scenarios by 2060, we have to build 18 out of 21 islets at the desired elevation interval of 33 ± 15 cm, which is suitable for MWHA 2 ("Mediterranean saltmarsh scrubs"—N2000 code 1420). This will result in 9 % overall area cover. The remaining 3 islets and 2 peninsulas should be at an elevation of 42 ± 16 cm above average sea level, which is suitable for MWHA 3 (*Phragmites* stands), for which the model also predicts a steady decrease of area in Škocjan Inlet Landscape Reserve. This could provide 2.4 new hectares of area in the 2060 scenario and overall the same percentage in area as today.

In the Sečovlje Salina Nature Park study area, we suggest countermeasures in the form of islets and terrestrialization of currently inundated abandoned salt pans within the abandoned southern part, called Fontanigge. As in the

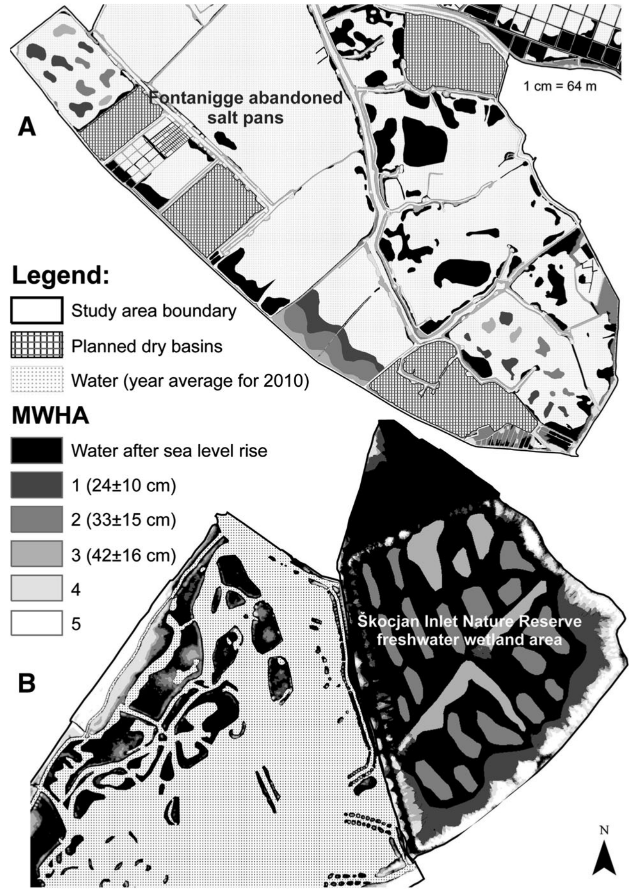

Fig. 6 Creation of artificial islets and dry basins as one potential mitigation measure to secure area for endangered Natura 2000 habitats in Sečovlje Salina Nature Park (**a**) and in Škocjan Inlet Nature Reserve (**b**), regarding the 2060 SLR scenario

Škocjan Inlet Nature Reserve, we planned here 22 islets at the desired micro-elevations suitable for MWHA 1 ["mudflats and sandflats not covered by seawater at low tide" (N2000 code 1140); "Mediterranean glasswort swards" (N2000 code 1310), and MWHA 2 ("Mediterranean saltmarsh scrubs" (N2000 code 1420)]. It has been outlined that those two habitat type aggregates, especially the first one, will decrease in area till 2060, according to the model results. Therefore, we planned 12 islets suited for MWHA 1 (29 ± 4 cm) with a total area of 2.1 hectare and also 2 hectares in one of the dried basins. This will enlarge the total area cover for habitat MWHA 1 from a predicted 2 % in 2060 to 4 %. Another 7 islets and a dried salt pan zone should be constructed at an elevation of 41 ± 9 cm. This will represent 4.1 hectares of "Mediterranean saltmarsh scrubs" in 2060. With this measure, the surface of this habitat type in 2060 will be placed on the same level as today (5 %). 1.7 hectares at an elevation of 51 ± 11 cm was planned for the "*Phragmites* stands" habitat type aggregate. In the milestone year 2060, this habitat type would cover 8 % more area than today.

Figure 6 shows the currently flooded abandoned salt pans (32 hectares), suggested to be terrestrialized and foreseen to be colonized with halophyte vegetation. However, it is not certain exactly which habitat type will develop on these salty soils when they dry out. This will become evident only after some years of observation.

Discussion

The restoration or creation of habitats lost, destroyed or substantially altered has become a potential method for many environmental agencies, parks, regions, states, or NGOs. Nowadays, it is possible to simulate many kinds of physical designs or hydrogeomorphology, but including the biological components usually takes a much longer time frame to respond, mostly beyond reasonable monitoring expectations. Furthermore, the complexity of natural or semi-natural plant communities, which are the targets of restoration or recreation aims, might lead to unpredictable vegetation development, driven by unforeseen factors or stochastic events. This is also true for coastal marsh plant communities, which are determined by biotic interactions such as plant competition (Pennings and Callaway 1992) and accretion—upward movements of marshes due to sequestration of sediments and biogenic production (Gardner et al. 1992; Gardner and Porter 2001; Chu-Agor et al. 2011; Runting et al. 2013) However, halophyte vegetation on shallow sedimentary seacoast represents a relatively simple biological system, based on the presence of only a few highly specialized species, where one species is usually dominant (*Salicornia emerici*, *Sarcoccornia fruticosa*, *Juncus maritimus* or *Phragmites australis*). On the basis of our own observations and those from Marani et al. (2013), the vegetation succession in such habitats is rather predictable, and species assemblages follow two main environmental gradients—salinity and moisture (inundation)—which are also correlated. However, determination of a spatial pattern for both of these direct factors influencing species assemblages in a satisfactory dense resolution is not a simple task. Thus, we selected a simply measured proxy for these two factors: micro-elevation. It has been established by several authors (e.g. Atwater et al. 1979; McKee and Mendelssohn 1989; Adams and Bata 1995; Baldwin and Mendelssohn 1998; Marani et al. 2013) that tidal marsh plant communities are distributed along salinity and inundation (moisture) gradients, which are largely determined by marsh elevation. This means that elevation changes of several centimetres may lead to a shift in the plant species and habitat structure of the marsh platform (McKee and Mendelssohn 1989; Zedler et al. 1999; Baldwin et al. 2001). However, the mutual relationship between plant growth and sediment availability and feedback between them is also an important factor, which should be proved experimentally "in situ" for each case. In that regard, there are two aspects: plants (and plant aggregations) are permanently moving upwards the surface of the marsh, which is therefore neither static nor dependent only on changes in water level. Another aspect is plant persistence in changed environmental conditions, especially the persistence of long-lived perennials, and this is species-specific. It simply means that to certain extend, the vegetation patterns and plant position within them could be a result of the legacy from previous sea levels. These aspects were not considered in this study because we considered them not negligible, but less important in comparison with the dramatic predictions of RSLR. The advantage of this study is, however, that we did consider the sedimentation rate and subsidence rate, which made the model more reliable.

Effective matching of micro-elevation intervals with spatial distribution (map) of aggregated habitat types was a pre-condition for all additional predictions in habitat shifts and for the designation of desired target habitat types. It was crucial to reveal the micro-elevation range of a single habitat aggregate occurrence. Of course, if RSLR did not alter coastal habitats, planning of new habitats would be much simpler; the leveling of newly created surfaces would not need to be so accurate. It has been reported (Baustian et al. 2012) that in certain situations, such as high sedimentation of both organic and inorganic materials, coastal wetlands may even be able to keep pace with the rising sea level. Such cases are rare; however, immediate many authors have concluded that it would be prudent to begin proactive planning for the potential impact of RSLR (Nicholls et al. 1999). A general decline of 42 % for all Natura 2000 habitats in both study sites, which is projected by 2060, should be cause for concern.

It was proposed by Yozzo et al. (2004) that sediment management may be a key feature of successful future restoration, since the use of dredged material may become increasingly important as a tool in creating marshes and upland wildlife refugia. However, there are certain potential limitations to using this approach: it is reported that newly developed marshes typically have low levels of soil organic matter (Craft et al. 2003; Woo et al. 2009). Thus, nutrient analysis for the dredged material would provide essential information for establishing good growing conditions, apart from the appropriately set micro-altitude. Of course, if the micro-altitudes are designed well in advance for the situation predicted for 2060, it can be expected that in the first years after construction, the vegetated islets will be colonized not by the target habitat types, but by various transitional forms, which may perhaps require some management, e.g., eradication of potential neophytes or even woody species. If the countermeasures are taken in the near future, the projected islets could also be designed on the intermediate micro-elevations.

Special attention should be paid to the proposed approach of terrestrialization of currently inundated abandoned salt pans in Sečovlje Salina Landscape Park. This poldering-like approach will prevent regular tides and the influx of fresh seawater rich with nutrients. That means that the nutrients in the soil might become depleted in a few years. In such a case, the nutrient status should be balanced by artificial fertilizing. However, this should be supported by further experiments.

As pointed out by Vestergaard (1997), other climate factors such as temperature and rainfall also are predicted to change and alter vegetation processes. Extreme events, such as summer thunderstorms, may be an additional factor in disturbing newly established artificial islets or other constructed habitats. This entire unpredictable event could have a cumulative effect on the immigration of new species and on changes in the balance of competition among species (Adam 1990).

Studies about accurate predictions of ecosystem responses to global change have been of limited use to decision makers without an indication of the cost-effectiveness of this information in terms of the outcome of such decisions (Possingham et al. 2007). The recent study by Runting et al. (2013) showed that conservation planning under SLR could be cost-effective: although less land area can be acquired with a fixed budget in this case, the acquired land provides greater overall benefits, which appear to be an important result for the design of plans to preserve biodiversity in coastal regions subject to SLR (Runting et al. 2013). One advantage of this study is precisely that: it offers concrete, site-specific and cost-effective mitigation measures, which allow enough space for the conservation of natural processes themselves, including biotic interactions such as adaptation and site-specific competition among species to physical features such as salinity, inundation, and sedimentation rate.

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References

Adam P (1990) Saltmarsh ecology. Cambridge University Press, Cambridge

Adam P (2002) Saltmarshes in a time of change. Environ Conserv 29:39–61

Adams JB, Bata GC (1995) Ecological implications of tolerance of salinity and inundation by Spartina maritima. Aquat Bot 52:183–191

Akumu CE, Pathirana S, Baban S, Bucher D (2011) Examining the potential impacts of sea level rise on coastal wetlands in north-eastern NSW, Australia. J Coast Conserv 15:15–22

Anonymus (2007) Interpretation manual of European Union habitats. European commission DG Environment, p 144. http://ec.europa.eu/environment/nature/legislation/habitatsdirective/docs/2007_07_im.pdf. Accessed 20 Dec 2011

ARSO (2011) Slovenian environmental agency. http://kazalci.arso.gov.si/?data=indicator&ind_id=146. Accessed 20 Dec 2011

Atwater BF, Conard SG, Dowden JN, Hedel CW, MacDonald RL, Savage W (1979) History, landforms and vegetation of the estuary's tidal marshes. In: Conomos TJ (ed) San Francisco bay: the urbanized estuary. Pacific Div/Amer. Assoc Adv Sci, San Francisco, pp 347–400

Baldwin AH, Mendelssohn IA (1998) Response of two oligohaline marsh communities to lethal and nonlethal disturbance. Oecologia 116:543–555

Baldwin AH, Egnotovich MS, Clarke E (2001) Hydrologic change and vegetation of tidal freshwater marshes: field, greenhouse, and seed-bank experiments. Wetlands 21:519–531

Baustian JJ, Mendelssohn IA, Hester MW (2012) Vegetation's importance in regulating surface elevation in a coastal salt marsh facing elevated rates of sea level rise. Glob Chang Biol 18:3377–3382

Bayliss B, Brenman K, Elliot I, Finlayson M, Hall R, House T, Pidgeon B, Walden D, Waterman P (1997) Vulnerability assessment of predicted climate change and sea level rise in the Alligator Rivers region, Northern Territory, Australia, Supervising Scientist Report 123. Supervising Scientist, Canberra

Britsch LD, Dunbar JB (1993) Land loss rates: Louisiana coastal plain. J Coast Res 9:324–338

Carbognin L, Tetini P, Tomasin A, Tosi L (2010) Global change and relative sea level rise at Venice: what impact in term of flooding. Clim Dyn 35:1039–1047

Cazanave A, Cabanes C, Dominh K, Mangiarotti S (2001) Recent sea level changes in the Mediterranean Sea revealed by TOPEX/poseidon satellite altimetry. Geophys Res Lett 28:1607–1610

Cazenave A, Bonnefond P, Mercier F, Dominh K, Toumazou V (2002) Sea level variations in the Mediterranean Sea and Black Sea from satellite altimetry and tide gauges. Glob Planet Chang 34:59–86

Chu-Agor ML, Muñoz-Carpena R, Kiker G, Emanuelsson A, Linkov I (2011) Exploring vulnerability of coastal habitats to sea level through global sensitivity and uncertainty analyses. Environ Modell Softw 26:593–604

Church JA, White NJ, Aarup T, Wilson WS (2008) Understanding global sea levels: past, present and future. Sustain Sci 3:9–22

Church JA, Gregory JM, White NJ, Platten SM, Mitrovica JX (2011) Understanding and projecting sea level change. Oceanography 24(2):130–143

Clough JS, Park RA, Fuller R (2010) SLAMM 6 beta Technical Documentation. http://waconservation.org/dl/dl_SLAMM6_Technical_Documentation.pdf

Cooper JAG, McKenna J, Jackson DWT, O'Connor M (2011) Mesoscale coastal behavior related to morphological self-adjustment. Geology 35:187–190

Craft CB, Megonigal JP, Broome SW, Cornell J, Freese R, Stevenson RJ, Zheng L, Sacco J (2003) The pace of ecosystem development of constructed Spartina alterniflora marshes. Ecol Appl 13:1417–1432

Day JW, Templet P (1989) Consequences of sea-level rise: implications from the Mississippi Delta. Coast Manag 17:241–257

Devilliers P, Devilliers-Terschuren J (1996) A classification of Palearctic habitats—Council of Europe, Strasbourg

Eastman JR (2012) IDRISI Selva. Clark University, Worcester
ESRI (2010) ArcGIS Desktop: Release 9.3. Environmental Systems Research Institute, Redlands
Fenoglio-Marc L (2002) Long-term sea level change in the Mediterranean Sea from multi-satellite altimetry and tide gauges. Phys Chem Earth 27:1419–1431
French JR, Burningham H (2003) Tidal marsh sedimentation versus sea-level rise: a Southeast England Estuarine Perspective. In: Proceedings Coastal Sediments '03, Sheraton Sand Key, Clearwater, Florida
Fuentes M, Limpus CJ, Hamman M, Dawson J (2010) Potential impacts of projected sea-level rise on sea turtle rookeries. Aquat Conserv 20:132–139
Gardner LR, Porter DE (2001) Stratigraphy and geologic history of a southeastern salt marsh basin, North Inlet, South Carolina, USA. Wetl Ecol Manag 9:371–382
Gardner LR, Smith BR, Michener WK (1992) Soil evolution along a forest-marsh transect under a regime of slowly rising sea level, North Inlet, South Carolina, USA. Geoderma 55:141–157
Gesch D (2009) Analysis of LIDAR elevation data for improved identification and delineation of lands vulnerable to sea-level rise. J Coast Res 53:49–58
Gregory JM, Church JA, Boer GJ, Dixon KW, Flato GM, Jakett DR, Lowe JA, O'Ferrell SP, Roeckner E, Russell GL, Stouffer RJ, Winton M (2001) Comparison of results from severeal AOGCMs for global and regional sea-level change 1900–2000. Clim Dyn 26:379–391
GURS (2010) Geodetska Uprava Republike Slovenije (The surveying and mapping authority of the Republic of Slovenia, Ministry of Infrastructure and Spatial Planning), Ljubljana
Intergovernmental Panel on Climate Change (IPCC) (2007) Climate change 2007. Synthesis Report. IPCC, Geneva, p 52
Intergovernmental Panel on Climate Change (IPCC) (2013). http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=3. Assessed 20 Oct 2013
Ivajnšič D, Kaligarič M, Gomboc S, Sovinc A (2012) Sea-level rising, derived by the climate change and its impact on Natura 2000 coastal habitats in two Northern Adriatic protected areas. IMPACT—International Conference on Managing Protected Areas under Climate Change. 24–26 September 2013, Dresden/Germany. Book of Abstracts p 27
Jogan N, Kaligarič M, Leskovar I, Seliškar A, Dobravec J (2004) Habitatni tipi Slovenije HTS 2004 (Habitat types of Slovenia HTS 2004) Ministrstvo za okolje, prostor in energijo, Ljubljana
Kaligarič M, Škornik S (2006) Halophile vegetation of the Slovenian seacoast: *Thero-Salicornietea and Spartinetea maritmae*. Hacquetia 5:25–36
Lambeck K, Antonioli F, Purcell A, Silenzi S (2004) Sea-level change along the Italian coast for the past 10,000 year. Quat Sci Rev 23:1567–1598
Lombard AT, Cowling RM, Pressey RL, Rebero AG (2003) Effectiveness of land classes as surrogates for species in conservation planning for the Cape Floristic region. Biol Conserv 112:45–62
Lundin CG, Linden O (1993) Coastal ecosystems: attempts to manage a threatened resource. Ambio 22:468–473
Marani M, Da Lio C, D'Alpaos A (2013) Vegetation engineers marsh morphology through multiple competing stable states. PNAS 110(9):3259–3263
McKee KL, Mendelssohn IA (1989) Response of a freshwater marsh plant community to increased salinity and increased water level. Aquat Bot 34:301–316
McLean RF, Tsyban A, Burkett V, Codignotto JO, Forbes DL, Mimura N, Beamish RJ and Ittekkot V (2001) Coastal zones and marine ecosystems. Climate change 2001: impacts, adaptation, and vulnerability Cambridge, UK and NY, USA
Morris JT, Sundareshwar PV, Nietch CT, Kjerfve B, Cahoon DR (2002) Response of coastal wetlands to rising sea level. Ecology 83(10):2869–2877
Mossman HL, Davy AJ, Grand A (2012) Does managed coastal realignment create saltmarshes with 'equivalent biological characteristics' to natural reference sites? J Appl Ecol 49:1446–1456
Nicholls RJ (2011) Planning for the impacts of sea level rise. Oceanography 24(2):144–157
Nicholls RJ, Cazenave A (2010) Sea-level rise and its impact on coastal zones. Science 328:1517–1520
Nicholls JR, Hoozemans FMJ, Marchand M (1999) Increasing flood risk and wetland losses due to global sea-level rise: regional and global analyses. Glob Environ Chang 9:69–87
Ogorelec B, Mišič M, Faganeli J (1991) Marine geology of the Gulf of Trieste (northern Adriatic): sedimentological aspects. Mar Geol 99:79–92
Ogorelec B, Mišič M, Faganeli J, Sercelj A, Cimerman F, Dolenec T, Pezdič J (1984) Quaternary sediment from borehole V-3 in the bay of Koper. Slov Morje Zaledje 6–7:165–186
Ogrin D (2004) Modern climate change in Slovenia. Slovenia: a geographical overview. Association of the Geographical Societies of Slovenia. Založba ZRC, Ljubljana
Pennings SC, Callaway RM (1992) Salt marsh plant zonation: the relative importance of competition and physical factors. Ecology 73(2):681–690
Possingham HP, Grantham H, Rondinini C (2007) How can you conserve species that haven't been found? J Biogeogr 34:758–759
R Development Core Team (2008). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, http://www.R-project.org
Ross T, Garrett C, Le Traon PY (2000) Western Mediterranean sea-level rise: changing exchange flow through the Strait of Gibraltar. Geophys Res Lett 27(18):2949–2952
Runting RK, Wilson KA, Rhode JR (2013) Does more mean less? The value of information for conservation planning under sea level rise. Glob Chang Biol 19:352–363
Tsimplis MN, Baker TF (2000) Sea level drop in the Mediterranean Sea: an indicator of deep water salinity and temperature changes? Geophys Res Lett 27:1731–1734
Tsimplis MN, Josey SA (2001) Forcing of Mediterranean Sea by atmospheric oscillations over the North Atlantic. Geophys Res Lett 28:803–806
Tsimplis MN, Rixen M (2002) Sea level in the Mediterranean Sea: the contribution of temperature and salinity changes. Geophys Res Lett 29:2136
Turner RK, Subak S, Adger WN (1996) Pressures, trends, and impacts in coastal zones: interaction between socioeconomic and natural systems. Environ Manag 20(2):159–173
Van der Meulen F, Salman AHPM (1996) Management of Mediterranean coastal dunes. Ocean Coast Manag 30(2–3):177–195
Vestergaard P (1997) Possible impact of sea-level rise on some habitat types at the Baltic coast of Denmark. J Coast Cons 3:103–112
Woo I, Dembosz LS, Gardiner R, Takekawa JY (2009) Early phase tidal marsh progression: the Guadalcanal tidal marsh restoration project. Data Summary Report, U.S. Geological Survey, Western Ecological Research Center, San Francisco Bay Estuary Field Station, Vallejo, CA
Yozzo DJ, Wilber P, Will RJ (2004) Beneficial use of dredge material for habitat creation, enhancement, and restoration in New York—New Jersey Harbor. J Environ Manag 73:39–52
Zedler JB, Callaway JC, Desmond J, Vivian-Smith G, Williams GD, Sullivan G, Brewster A, Bradshaw B (1999) California salt marsh vegetation: an improved model of spatial pattern. Ecosystems 2:19–35