Ecological Indicators 129 (2021) 107906

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Monitoring the coastal wetlands dynamics in Northeast Italy from 1984 to 2016

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ARTICLE INFO

Keywords:
Coastal wetland
Remote sensing
Landuse
Natural reserve
Sea-level rise

ABSTRACT

The Adriatic coast of Northeast Italy is one of the representative areas holding high ecological value in the Mediterranean. In this research, we have monitored the environmental change of coastal wetland in ten studied sites that covered all the Ramsar sites and most of the natural reserves in Northeast Italy from 1984 to 2016. The results show that the coastal wetland environment has been changing associated with a multitude of influential factors, including economic development, reserve initiatives, and sea-level rise, which have been quantitively analyzed for each of the studied wetland sites. The results of the analysis confirm that (1) with robust reservation policy, the landuse of the coastal wetland sites remained generally stable despite the continuous anthropogenic disturbance; (2) wetlands located in the insular area with low elevation are subject to more severe impact from sea-level rise inundation; (3) the continental coastal wetlands in reserve area show the polarization phenomenon which is strengthened by strict reservation policy and contiguous aggressive anthropogenic activities. To protect the insular coastal wetlands and reduce the polarization effects on continental coastal wetlands, more efficient measures should be taken to strengthen and implement the existing reservation directives and regulations actively.

1. Introduction

A wetland is a land area that is saturated with water, either permanently or seasonally, such that it takes on the characteristics of a distinct ecosystem (Mitsch and Gosselink, 2000b). Although they cover less than 1.5% of the earth's terrestrial surface, wetlands provide more than 35% of ecosystem services. Hence they are among the most essential and valuable ecosystems on the earth (Costanza et al., 2014; Fickas et al., 2016). In the coastal area, wetlands are crucial not only for sediment retention, offshore productivity, improving the quality of polluted water and recharging groundwater system, flood control, and drought prevention but also for serving as wildlife corridors and waterfowl habitats (Mitsch and Gosselink, 2000a). Furthermore, coastal wetlands provide essential direct livelihood services, including fishing harvest, fuel, construction materials, and other products, to most people living in or near them (Walters et al., 2008).

Remote sensing has been proved useful to monitor land ecosystems as it can provide consistent measurements at a multi-temporal scale (Held et al., 2003; Houborg et al., 2015; Lhermitte et al., 2011; Song et al., 2020). However, its application to monitoring coastal wetlands is still limited, though increasing (Chen et al., 2014). Green et al. (1998) identified mangrove classes and calculated leaf area index (LAI) in the Turks and Caicos Islands using airborne multispectral images. Silvestri et al. (2003) estimated salt marsh vegetation in the Venetian Lagoon, Italy, by unmixing hyperspectral remote sensing. Wang et al. (2007) mapped mixed vegetation with a neural network classifier. Aslan et al. (2016) estimated mangrove areas in Mimika district, Indonesia, by applying image segmentation on the composite PALSAR image. Nevertheless, one major problem with the application of hyperspectral, high spatial resolution, or Radar datasets results from the deficient data source availability and the limited coverage for the widely distributed coastal wetland area (Wen and Hughes, 2020). On the contrary, satellite-based multispectral sensors, such as the Landsat series, can provide continuous datasets that are suitable for monitoring and mapping the multitemporal changes of the coastal wetland at regional to national scales.

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https://doi.org/10.1016/j.ecolind.2021.107906
Received 11 March 2021; Received in revised form 4 June 2021; Accepted 15 June 2021

Recent research further analyzed the effects of anthropogenic activities, including agriculture, urbanization, tourism, and management/restoration initiatives, on wetland change. Primarily, direct human modification is the primary cause of historical and contemporary coastal wetland loss (Kirwan and Megonigal, 2013; Pijl et al., 2018; Viero et al., 2019). Zorrilla-Miras et al. (2014) assessed changes in ecosystem services in the Doñana wetland, Spain, during 1918–2006 and concluded that 70.5% of the natural or semi-natural land covers had been converted to intensive agriculture or other mono-functional uses. Unlike in the historical period, urbanization rather than agriculture now accounts for the majority of wetland loss (Faulkner, 2004; NRCS, 2000). In rapidly expanding metropolitan areas, wetlands can be extensively invaded, fragmented, and destroyed by non-native species (Pauchard et al., 2006). Apart from causing direct habitat loss, the urban expansion also impacts the wetlands by suspended solids additions, hydrologic changes, and altered water quality (Azous and Horner, 2000). By quantifying the annual rate of urban land-use change in Lianyungang, China, Li et al. (2010) have demonstrated close relationships between large-scale wetlands degradation and urban development policy implementation. Rojas et al. (2019) quantified recent wetland loss by urbanization in the Concepción Metropolitan Area (Chile), indicating that the coastal wetlands are threatened by urbanization. Notably, it has been concluded that wetland loss due to development was three times greater in coastal areas than inland (Brady and Flather, 1994).

Accelerating sea-level rise is another major threat to coastal wetlands at regional to global scales (Spencer et al., 2016). Although vegetation species in the coastal wetland are adaptable to saline water, they can only survive a limited frequency and duration of inundation (He et al., 2007; Möller, 2019). Morris et al. (2002) and Marani et al. (2007) suggest that salt marsh plant communities cannot sustain a relative sea-

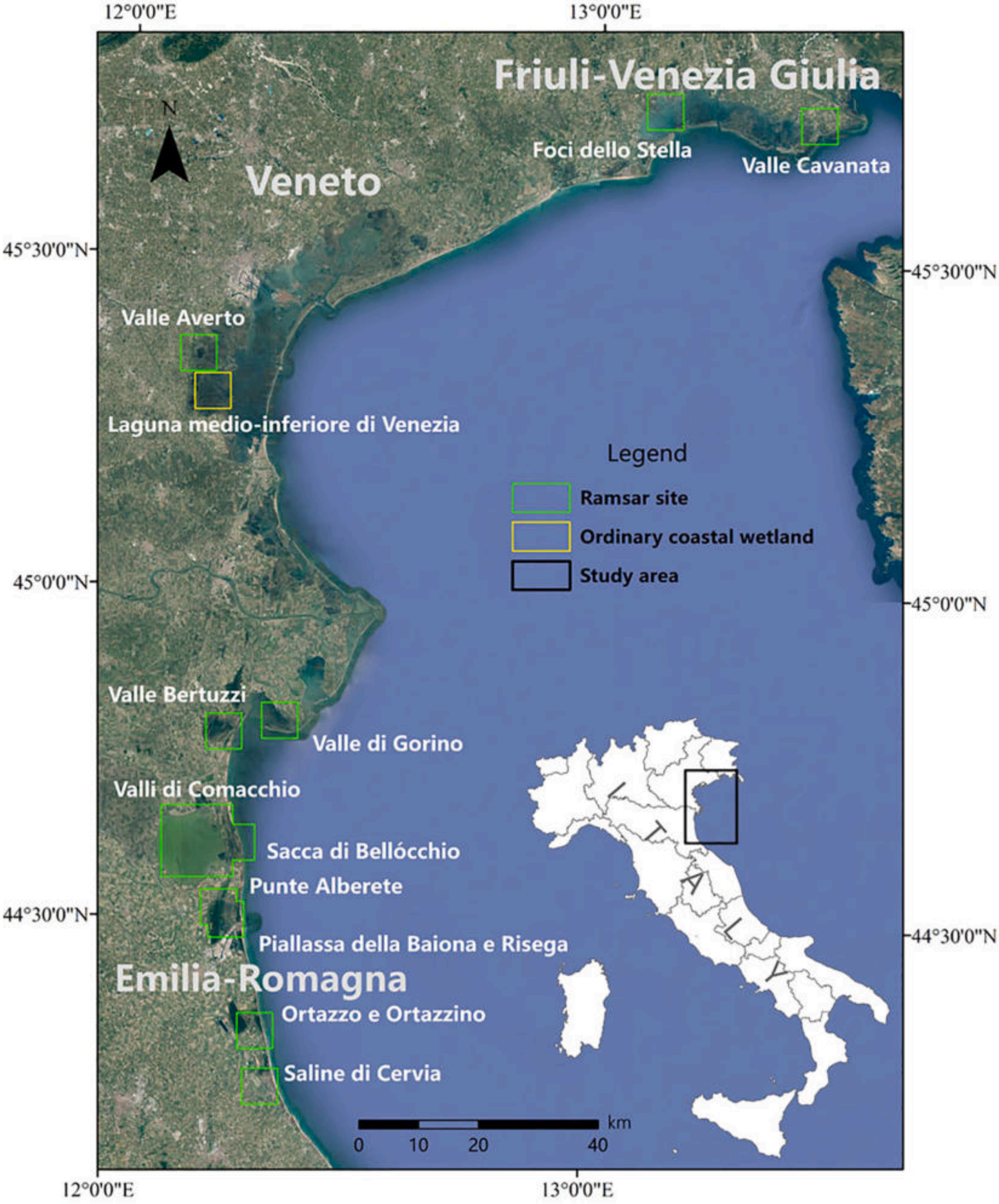

Fig. 1. Study area location in NE Italy.

level rise (RSLR) increasing faster than an optimal rate. By considering flow attenuation effects, Rodríguez et al. (2017) has indicated that the coastal wetland is increasingly vulnerable to sea-level rise by addressing the hydrodynamic attenuation effects. Of the Adriatic Sea, The observed sea level showed conspicuous rising ranging from 2.9 to 5.7 cm (1993–2005), which is much higher than the Mediterranean mean or global mean (Umgiesser et al., 2011). In this area, as much as 44% of the wetland sites bear high vulnerability to the sea-level rise (Torresan et al., 2012). Moreover, many places along the Adriatic Sea coast with the elevation below the mean sea level, particularly in the Venetian Lagoon and the Po River Delta, suffer from natural or man-induced subsidence. As a result, sea-level rise can profoundly impact the coastal wetland in these areas (Carbognin et al., 2010; Torresan et al., 2012).

Since the 1970 s, considerable efforts were taken to manage and restore coastal wetland systems, and much progress has been achieved (Erwin, 2009). Serving as the backbone of modern wetland management, the Ramsar Convention fosters a critical international comprehensive framework both theoretically and practically (Hettiarachchi et al., 2015; Junk et al., 2013). To date, 169 countries have signed the Ramsar Convention and declared 2289 internationally important sites, covering more than 2.2 million km^2 (Secretariat, 2017). Even in rapidly developing regions, large areas of wetlands could be adequately protected and restored with the implementation of strict regulations and the establishment of reserve areas (Cui et al., 2009; Haapalehto et al., 2011; Zheng et al., 2012; Zorrilla-Miras et al., 2014).

Italy has a long history of nature and landscape conservation dating back to 1905 when the politician Luigi Rava promoted the Law 411 in 1905, the first law for landscape protection in Italy. It is worth mentioning that the law was issued for protecting the “Pineta di Ravenna”, which is located in one of the studied sites (Site 9: *Ortazzo e Ortazzino*) in this research (Fig. 1). Since 1959, fully protected natural reserves gradually established nationwide with a series of state ministerial decree issued (Bianchi et al., 2011). Afterward, state protected areas, including State Natural Reserves and National Parks, were legally defined and established with the announcement of the Law 394, “Framework Law on Protected Areas” in 1991. Consequently, the urbanization rate in these protected areas decreased to only 4.5% (MATTM, 2013). Now covering 1300 km^2 throughout the country, each state-protected area is strictly protected and administered by an authority supervised by the Minister of the Environment.

As one of the representative areas in the Mediterranean, the Adriatic coast of NE Italy holds high ecological value and subjects to constant natural and anthropogenic pressure (Simeoni and Corbau, 2009; Torresan et al., 2012). Although exiting research has analyzed the effects of specific physical or anthropogenic processes on the coastal wetlands, very few of them provided a comprehensive perspective on multiple key factors and their interactions. Moreover, the wetland evolution of only very few significant sites was investigated (Torresan et al., 2012).

This research aimed to monitor the coastal wetland change and assess the associated factors by investigating the wetland sites that covered all the Ramsar sites and most of the natural reserves in the Adriatic coast of NE Italy. The specific objectives of this research were to (1) provide a quantitative analysis of landuse and vegetation change in coastal wetland areas in the period 1984–2016; (2) present a methodology for assessment and visualization of the influential factors associated with the change of coastal wetland environment. Based on the demonstrated approaches, this research attempts to provide scientific evidence for the future implementation of the coastal wetland reservation policy.

2. Material

2.1. Study area

Ranging from 12°04′ E to 13°33′ E and 44°11′ N to 45°48′ N (Fig. 1), this research was carried out in three administrative Region of NE Italy, namely Friuli-Venezia Giulia (FVG), Veneto, and Emilia-Romagna. The study areas, located in the coastal area of Padana Plain, are characterized by several west-east oriented rivers that flow into the Adriatic Sea, forming large areas of coastal wetland. Among them, the Po River Delta is the largest wetland area in Europe (Torresan et al., 2012). Covering only 2.72% of the terrestrial region of Italy, the study area contains 20% of all the Ramsar sites throughout the country.

In this research, ten labeled wetland sites composed of Ramsar sites, state/regional reserves, and other wetland-distributed areas were closely studied (Table 1). Between the Tagliamento and Isonzo River deltas, Site 1: *Valle Cavanata* and Site 2: *Foci dello Stella* are both located in Laguna di Marano, FVG, a well-protected shallow system with Limonium, Zostera, and Ruppia Maritima. The two sites respectively lie near Grado and Lignano Sabbiadoro, small towns where populations less than 10,000. The whole area hosts tourism and other industrial services. Fishing, clam harvesting, and fish farming comprise the most important resources for local inhabitants (Bettoso et al., 2013).

Site 3: *Valle Averto and Site* and 4: *Laguna medio-inferiore di Venezia* are both significant parts of the famous Venetian Lagoon, the largest lagoon in the Mediterranean basin and the most important in Italy (Coccon and Baldaccini, 2017; Franco et al., 2006). Supporting brackish and freshwater wetland with wood and reed species, including alders, poplars, elms, cattails, rushes, sedges, and water lilies, Valle Averto has been protected by Ramsar Convention since 1989. Similar to Valle Averto, Laguna medio-inferiore di Venezia is covered by large areas of salt marshes (Sfriso and Marcomini, 1996). To date, it has been recognized as a site of community importance and protected by the Veneto Region. However, severe adverse environmental impacts of many activities occur in this area (Suman et al., 2005). In this research, Laguna medio-inferiore di Venezia was investigated to provide a comparative study with the Ramsar sites in NE Italy.

To the south, the other eight studied Ramsar sites are located along the coast of Emilia-Romagna region. Generally, they are covered by salt-tolerant vegetation and emergent reedbeds. Three Ramsar sites in this area (Punte Alberete, Piallassa della Baiona, and Ortazzo e Ortazzino) are less than 6 km away from Ravenna, a popular touristic destination with unique historical importance. Apart from tourism, intensive human activities, including fish-farming, agriculture, salt production, and even military training, significantly impact the wetland environment in this area.

2.2. Data source

For covering all the wetland sites in the study area from 1984 to 2016, eleven cloud-free multispectral images were collected as the main data source for this research (Table 2). The multispectral images were all acquired between June and July for detecting deciduous vegetation and avoiding seasonal tide effects. The data set includes eight Landsat-5 TM and three Sentinel-2A images, all registered to the Transverse Mercator Projection System. The geometric and radiometric corrections were performed using the files released by USGS EROS Data Center and ESA Payload Data Ground Segment with high accuracy. FLAASH module was used for the atmospheric correction.

The Sea Level Essential Climate Variables (ECV) product (DOI: https://doi.org//10.5270/esa-sea_level_cci-1993_2015-v_2.0-201612) provided by the ESA’s Climate Change Initiatives were collected for further exploring the relationships between sea-level rise and coastal wetland change. The calculation and correction of the sea level data were performed by ESA using satellite-based altimeter measurements, including Jason series, Topex, Envisat, and ERS series, etc., into monthly grids with a spatial resolution of 1/4 of degree. The period coverage of the sea-level records is 1993 to 2015 (Legeais et al., 2018; Quartly et al., 2017). Besides, the sea-level records from five tide gauge stations in the coast of the NE Italy coast documented by the Permanent Service for Mean Sea Level (PSMSL) were collected to verify the reliability of the satellite-based sea-level ECV data (Holgate et al., 2013; PSMSL, 2020).

Table 1
Coastal wetland areas in NE Italy.

Site number	Site name	Province, region	Reserve type (Year)	Vegetation type
Site 1	Valle Cavanata	Gorizia, FVG	Ramsar Sites (1978); Regional Reserve (1996)	Phragmites australis, salt-resistant vegetation, and submergent flora, including Zostera spp. beds.
Site 2	Foci dello Stella	Udine, FVG	Ramsar Sites (1979); Regional Reserve (1996)	Zostera spp. and Ruppia Maritima and submerged halophytic plants and are fringed by extensive phragmites australis.
Site 3	Valle Averto	Venezia, Veneto	Ramsar Sites (1989)	Cattails, rushes, sedges, the water lilies that populate the lacunar surfaces, and the banks and salicornia and salsola; alders, poplars blacks, elms, ash trees, and oaks.
Site 4	Laguna medio-inferiore di Venezia	Venezia, Veneto	/	The same as 3. Valle Averto
Site 5	Valle di Gorino	Rovigo & Ferrara, Emilia-Romagna	Ramsar Sites (1981);State Natural Reserve (1982); Regional Natural Park (1997)	Rich in thick marsh reeds and psammophilous vegetation. Zostera marina, Gracilaria confervoides, and Stuckenia pectinata can also be seen.
Site 6	Valle Bertuzzi	Ferrara, Emilia-Romagna	Ramsar Sites (1981);State Natural Reserve (1982)	Salt-resistant vegetation, and areas of reedbeds. Rare and endangered species such as Plantago cornuti and Bassia hirsuta have been reported.
Site 7	Valli residue del comprensorio di Comacchio	Ferrara & Ravenna, Emilia-Romagna	Ramsar Sites (1981); Regional Natural Park (1988)	There is Salicornia Veneta, a species of priority community interest. Rare and threatened species such as Bassia hirsuta, Plantago cornuti, Limonium bellidifolium, Triglochin maritimum, Halocnemum strobilaceum.
	Sacca di Belócchio	Ferrara & Ravenna, Emilia-Romagna	Ramsar Sites (1976);State Natural Reserve (1972)	
Site 8	Punte Alberete	Ravenna, Emilia-Romagna	Ramsar Sites (1976);State Natural Reserve (1977)	Pine forest is one of the most studied. Rare and threatened species: Helianthemum jonium, Centaurea Spinoso-ciliata subsp. Tommasini.
	Piallassa della Baiona e Risega	Ravenna, Emilia-Romagna	Ramsar Sites (1981)	Herbaceous vegetation with particular naturalistic value, such as Silene colorata and Vulpia membranacea. The waters of the Pialassa host Ulvacee. Pinus pinaster forest with a dense undergrowth of Juniperus and Quercus ilex, Prunus spinosa. Agropyron junceum, Phleum arenarium, Medicago marina, Echinophora Spinosa, Cyperus Kalli and Salsola tragus habitats on the remaining dune edges Close to the pine forest.
Site 9	Ortazzo e Ortazzino	Ravenna, Emilia-Romagna	Ramsar Sites (1981);State Natural Reserve (1979)	Venetian Salicornia, a priority species of Community interest. Rare and threatened species: Bassia hirsuta, Erianthus ravennae, Plantago cornuti, Spartina Maritima, Trachomitum venetum.
Site 10	Saline di Cervia	Ravenna, Emilia-Romagna	Ramsar Sites (1981);State Natural Reserve (1979)	Chenopodiaceae and amaranths dominate in this area. Salicornia Veneta gains priority community interest species. Rare and threatened species: Althena filiformis, a hydrophyte of brackish water, and Suaeda vera, the alkali seepweed.

References: Ramsar Convention; Protected Planet®; Directorate-General for Territory and Environment Care, Bologna, Italy.

Table 2
Main data source.

Acquire date	Sensor	Path/row (Landsat) or tile number (Sentinel)
July 11, 1984	Landsat-5 TM	191/28
July 11, 1984	Landsat-5 TM	191/29
July 14, 1994	Landsat-5 TM	192/29
July 23, 1994	Landsat-5 TM	191/28
July 30, 1994	Landsat-5 TM	192/28
June 3, 2005	Landsat-5 TM	191/29
June 19, 2005	Landsat-5 TM	191/28
July 28, 2005	Landsat-5 TM	192/28
July 18, 2016	Sentinel-2A	T33TUL
July 18, 2016	Sentinel-2A	T32TQR
July 18, 2016	Sentinel-2A	T32TQQ

During June-July 2017, two field surveys were conducted on the wetlands near Venice and Ravenna, and 222 field verification points were documented. Landcover types were identified for each point, and vegetation types were recognized to genus or species level. Still, field survey data inventory is relatively limited due to the difficulties associated with land privacy and road access. Additional ancillary data, including QuickBird images and CORINE Land Cover (CLC) product, were therefore further collected. QuickBird images with 0.6 m resolution (in the panchromatic band) covering all the study areas in 2005 and 2016 were gathered to produce the additional samples and validation data. We also acquired the CORINE Land Cover (CLC) product from the European Environment Agency to help generate reliable reference data for the study area.

3. Methodology

3.1. *Quantitative analysis of landuse change*

According to the previous research and surface features of NE Italy, the landcover types of study areas were identified to fourteen classes (Table 3), including urban fabric, industrial/commercial units, mine/dump/construction sites, artificial & non-agricultural vegetated areas, arable land, permanent crops, pastures, heterogeneous agricultural areas, forests, scrub/herbaceous vegetation associations, open spaces with little vegetation, inland/maritime wetland vegetations, and water bodies (Lambin et al., 2001; Zorrilla-Miras et al., 2014).

From all 222 field verification points, 122 unchanged points were visually interpreted based on the field survey data, high-resolution image, CLC product, and temporal change of spectral feature. The unchanged points were then positioned to Landsat-5 TM and Sentinel-2A images.

Classification and Regression Tree algorithm (CART) was conducted for classifying the landcover based on the training samples produced from 122 unchanged field verification points, while the remaining 100 points were used for accuracy validation afterward. The reflectance of the Landsat or Sentinel image bands with a spatial resolution higher than 30 m were used as classification parameters. CART is a rule-based model that repeatedly splits each parent node into two child nodes, treating each child node as a potential parent node for further split (Breiman et al., 1984). Each rule set defines the conditions and recursively predicts class or variables based on sample data (Huang and Townshend, 2003; Yang et al., 2003). The regression tree model is considered to have better accuracy and predictability than that of the linear regression model for its capability to estimate the nonlinear relationships between independent and target variables (Yang et al., 2003). In this research, accuracy assessment also shows that the CART algorithm gains higher accuracy than other conventional methods, such as maximum likelihood, SVM, or Mahalanobis distance. The 14 landcover types were then clustered into five main landuse categories, i.e., artificial, agricultural, semi-natural, natural, and water bodies, for further analysis (Table 3).

Based on the 300 validation points covering all the studied sites, the accuracy of landuse classification was verified using the confusion matrix (Table 4). The accuracy verification is valid for the whole studied period since all the validation points were randomly selected from unchanged pixels. The overall accuracy of the classification results is 93.33%, and the Kappa coefficient 0.89. The individual class spatial agreement with ground truth shows the estimation of natural surfaces and water bodies, which are strongly associated with coastal wetland in the studied area, gains relatively higher accuracy.

3.2. *Extraction of coastal wetland*

According to the definition of the Ramsar Convention, wetland can spread over semi-natural/natural surfaces and water bodies, including herbage/scrub/arbor-covered areas, rivers, and lakes (Ramsar, 1994). The complex composition of wetland areas causes high heterogeneity of spectrum characteristics, which can be highly challenging for conventional supervised classification methods.

Table 3
Landuse categories and description.

Landuse category	Class description
Artificial surfaces	Urban fabric, industrial, commercial and transport units
Agricultural surfaces	Arable land, permanent crops, pastures, heterogeneous agricultural areas
Semi-natural surfaces	Scrub/herbaceous vegetation, open spaces with little vegetation
Natural surfaces	Inland/maritime wetland vegetation, forests
Water bodies	Inland/marine waters

Table 4
Confusion matrix of wetland site landuse classification.

Classification	Ground truth				
	Artificial surfaces	Agricultural surfaces	Semi-natural surfaces	Natural surfaces	Water bodies
Artificial surfaces	**9**	1	1	2	1
Agricultural surfaces	1	**65**	2	0	2
Semi-natural surfaces	0	1	**9**	0	1
Natural surfaces	1	1	1	**31**	4
Water bodies	0	0	0	1	**166**
Spatial agreement	72.00%	94.20%	75.00%	86.11%	97.36%
Kappa coefficient	0.89				
Overall accuracy	93.33%				

A classification tree model introduced by Davranche et al. (2010) was conducted to extract coastal wetland areas to reduce misidentification. By evaluating the optimal prior parameter including Normalized Difference Vegetation Index, Normalized Difference Water Index (Gao, 1996), Modified Normalized Difference Water Index (Xu, 2006), as well as the reflectance value in Landsat-5 TM/Sentinel-2A images, a binary classification tree model was implied for common reeds and submerged macrophytes respectively. Being considered robust, especially with a small number of samples, the classification tree model can provide high accuracy for wetland spatial analysis with limited ancillary data (Davranche et al., 2010; Tadjudin and Landgrebe, 1996). The resulting wetland extraction was then exported, and the misidentifications were corrected by visual interpretation based on high-resolution images and field survey data.

3.3. *Accuracy assessment on landuse classification*

Of all the 222 unchanged field verification points, 122 points were already used as training samples for classification, and the remaining 100 points were left for accuracy assessment. However, the verification points were collected from the wetland area near Venice and Ravenna, without coverage for all the wetland sites in this research. Accordingly, additional 200 validation points were randomly created in other wetland sites. The landcover type for each validation point was visually interpreted based on the majority of the pixels in QuickBird image corresponding to one pixel of Landsat or Sentinel image. As a result, a validation dataset with 300 validation points was created covering all the wetland sites (at least 25 validation points for each site) in the study area and comprising all the landcover classes.

The confusion matrix was used for assessing the accuracy of landuse classification. Overall accuracy and Kappa coefficient were then estimated based on it. Furthermore, for assessing the accuracy of each landuse categories, individual-class spatial agreement (A_i) was calculated using the following equations (Yang et al., 2017):

$$A_i = \frac{\widehat{X}_i}{(X_i + V_i)/2} * 100\% \tag{1}$$

where X_i is the number of pixels of the class i in classification dataset, V_i is the number of pixels of the class i in the validation dataset, and $\widehat{X}_i$ is the number of pixels of the class i which has been correctly categorized.

The individual-class spatial agreement can be seen as the synthesis of producer accuracy and user accuracy, and therefore be used instead of them in this research.

3.4. Sea-level rise

For verifying the reliability of the satellite-based sea-level ECV data, the monthly sea-level records of the tide gauges documented by PSMSL (2020) were collected (Table 5, Appendix Table A2 to A9). Based on the 784 valid records, the correlation coefficient (R^2) between the sea-level ECV data and the tide gauge records is 0.62, demonstrating the reliability of the satellite-based sea-level ECV data.

To remove seasonal variation, the monthly sea-level ECV data was accumulated to form annual relative sea-level rise (RSLR) data, which was based on the mean water level change relative to the measurement in 1993. By locating the wetland sites where RSLR increased significantly, the sea-level rise impact on the coastal wetland was explored by statistical analysis and comparative study.

3.5. RSEI

The remote sensing-based ecological index (RSEI) was initially introduced for assessing the ecological status in urban areas (Hu and Xu, 2018). Recent research has proved that it is applicable for monitoring the environmental change in various regions with anthropogenic intervention (Fan et al., 2020; Hu and Xu, 2018; Ji et al., 2020; Wen et al., 2020; Xiong et al., 2021; Xu et al., 2018, 2019; Zheng et al., 2020). In this research, RSEI was experimentally employed to monitor the dynamics of the coastal wetlands in addition to landuse change analysis. Being visualizable and comparable, RSEI can avoid the error caused by the weight definition of individual characteristics by integrating four conventional remote sensing indicators, i.e., Greenness, Wetness, Heat, and Dryness. Accordingly, Greenness is evaluated by NDVI (Rouse et al., 1974), Wetness by the wetness component from the Tasseled Cap Transformation of the multispectral image, Heat by Land Surface Temperature (LST), and Dryness by Normalized differential build-up and bare soil index (NDBSI). As a combining index composed of the built-up index (IBI) and soil index (SI), NDBSI can quantify dryness caused by both artificial impervious surfaces and bare soil (Hu and Xu, 2018). After being normalized within [0, 1], the four indicators are integrated to formulate RSEI by principal component analysis (PCA). To create an RSEI image, the PCA was calculated using the ENVI PCA rotation tool (version 5.3). In this research, the percent eigenvalues of the first component of PCA (PC1) for the study years were all higher than 97%, indicating that the PC1 has explained most of the total variation of the four indicators. Instead of subjectively assigned value, the weight of each remote sensing indicators to RSEI was determined by PCA eigenvalue and contribution. Therefore, it has been considered a spatially explicit index to evaluate the ecological status and applied in recent research (Song and Xue, 2016; Xu et al., 2018).

Table 5
Basic information of the PSMSL tide gauge stations in the north Adriatic Sea.

Station ID	Station name	Location	Data period	Effective period	Number of valid records
154	Trieste	13.758472°E, 45.647361°N	1875–2019	1993–2016	288
168	Venezia	12.333333°E, 45.433333°N	1909–2000	1993–2000	96
2099	Trieste II	13.757939°E, 45.649392°N	2001–2015	2001–2015	178
2100	Venezia II	12.426528°E, 45.418219°N	2001–2015	2001–2015	88
2144	Porto Garibaldi	12.249436°E, 44.677930°N	2009–2018	2009–2016	39

4. Results

4.1. Quantification of landuse change

According to the estimation in this research, the landuse pattern was generally stable in 1984–2016 (Fig. 2 & Table 6). Across all the wetland sites, the most remarkable landuse change was the decrease of semi-natural surfaces (-12.07%) and the increase of urbanized surfaces (12.06%). Notably, natural surfaces also increased by 3.82%. The loss of semi-natural surfaces, which consists of scrub/herbaceous vegetation and open spaces with little vegetation, was due to the conversion to natural surfaces (wetlands and forests). And the increase in artificial surfaces mainly came from agricultural surfaces. Notably, large areas of natural surfaces and water bodies mutually converted from each other from 1984 to 2016 (Fig. 3).

Furthermore, the change dynamics of wetland area, extracted from semi-natural/natural surfaces and water bodies, were statistically analyzed and summarized based on the location of the wetland sites (Fig. 4). Generally, the wetland area of the two Ramsar sites (Site 1 & 2) in the FVG region decreased from 1984 to 2016. In the meantime, the artificial surfaces of Site 1 increased by 3.43 times due to the urban expansion of the adjoining Grado town (Fig. 4). However, the vegetation coverage in semi-natural/natural surfaces was relatively well preserved compared to that of Site 2, which is far away from urbanized areas. From 1984 to 1994, with the net change rate of 19.27% and 9.79%, respectively, the increasing trends of the wetland area in Site 1 & 2 were similar. From 1994 to 2005, the wetland area in both sites conspicuously reduced by 13.68% and 9.22%. Site 1 then remained stable from 2005 to 2016, while the wetland area in Site 2 continued decreasing by 7.74%, among which 1.05 km^2 of the vegetation coverage were converted to water bodies.

The wetland in Site 3, the Ramsar site in the Venetian Lagoon, maintained stability from 1984 to 2016. From 1984 to 2005, the area of wetland increased by 24.49% or 2.30 km^2. From 2005 to 2016, the wetland area slightly decreased by 0.88 km^2. Notably, the vegetation in the wetland area was hardly impacted by the rapid expansion of the village of Lova, which is just one street across the wetland area. On the contrary, in Site 4, a regional protected wetland site 5 km to the south of Site 3, the wetland area decreased conspicuously by 21.62% from 1984 to 2016, almost the highest among the studied sites. More than 40% or 2.67 km^2 of the vegetation coverage in 1984 was converted to water bodies during the following three decades.

All the other six wetland sites investigated in this research are listed by Ramsar and located in the Emilia-Romagna region. Among them, Site 5: *Valle di Gorino* is a coastal lagoon partly separated from the sea by a dune system. The wetland area in Site 5 decreased by 22.81% or 1.40 km^2 from 1984 to 2016, standing for the highest decreasing rate of all the wetland sites in this research, which was mainly due to the conversion from natural surfaces to water bodies (1.92 km^2). Site 6: *Valle Bertuzzi* and Site 7: *Comacchio & Belocchio* are both brackish, coastal lagoon uncontacted with the sea. From 1984 to 2016, the wetland area increased steadily and remarkably, by 35.35% and 45.97%, respectively, which are the highest two increasing rates of all the investigated sites. Southwards, Site 8 *Punte Alberete & Piallassa Baiona* & Site 9: *Ortazzo e Ortazzino* consists of three Ramsar sites, characterized by well-vegetated floodplain and flooded depression dissected by Po River, canal networks, and coastal dunes. With the change rate of −6.87% and −1.06%, respectively, the wetland area remained generally stable from 1984 to 2016. The loss of the wetland area was also mainly due to the conversion from vegetation to water bodies. Site 10: *Saline di Cervia* is a Ramsar site enclosing salt pans. From 1984 to 2005, the wetland area decreased by 24.75%. Afterward, the natural surfaces remarkably increased by 54.62% from 2005 to 2016. The mutual conversion between semi-natural/natural surfaces and water bodies has been the main reason for the wetland area change.

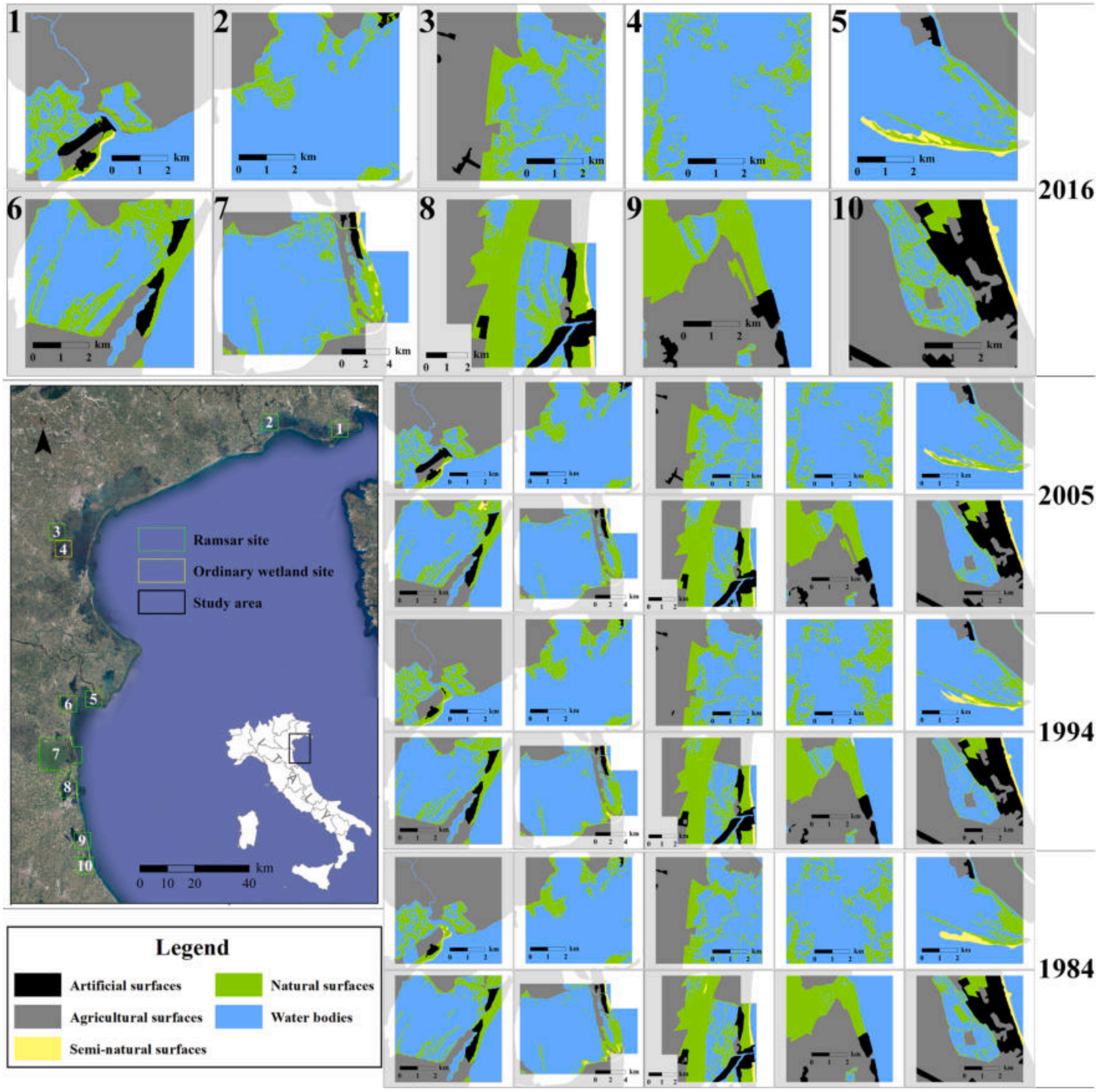

Fig. 2. Maps showing landuse in Northeast Italy in 1984, 1994, 2005, and 2016, clustered into five main categories.

Table 6
Landuse change statistics of all study areas in km^2.

	Artificial surfaces	Agricultural surfaces	Semi-natural surfaces	Natural surfaces	Water bodies
1984	17.50	124.31	4.89	74.94	285.24
1994	17.54	123.99	3.62	79.18	282.55
2005	19.63	121.75	3.06	76.75	285.69
2016	19.61	121.89	4.30	77.80	283.28

4.2. Observations of sea-level rise

Sea-level rise is one of the most dominating factors that influence the environment of coastal wetlands (Mendelssohn and Morris, 2002; Morris et al., 2002). Based on the above analysis, the change of the wetland area in most study sites has a closer relationship with the mutual conversion between vegetation coverage and water rather than the expansion of artificial or agricultural surfaces. We speculate that the wetland loss in some studied sites results from sea-level rise. Further analysis was conducted to evaluate its effects on coastal wetlands quantitively.

First of all, it is necessary to reduce the uncertainty brought by the temporary tide effects. Indicated by the records from five PSMSL tide gauge stations, the tide level of the NE Italy coast shows seasonal variation. The annual high tide can be observed for all the studied years from August to November, and low tide between December and March. In this research, all the remote sensing image used as the main data source were acquired between June and July, when the monthly RSLR were generally approximate to annul RSLR. Thus, uncertainty related to seasonal RSLR fluctuation was generally excluded.

Furthermore, we downloaded another two Landsat images acquired in January 2005 and August 2005, respectively, when the year's lowest and highest tide were recorded. Trial landuse classification showed that the estimation of water bodies along the coastline could be varied as much as one pixel (30 m). In this research, all multispectral images used for landuse classification were acquired in June or July, when the tide level is well approximated to the annual mean RSLR of the corresponding year. Therefore, the misestimation caused by the temporary tide effects should be much less than one pixel. The classification results are applicable for analyzing long-term sea-level rise effects on wetland change.

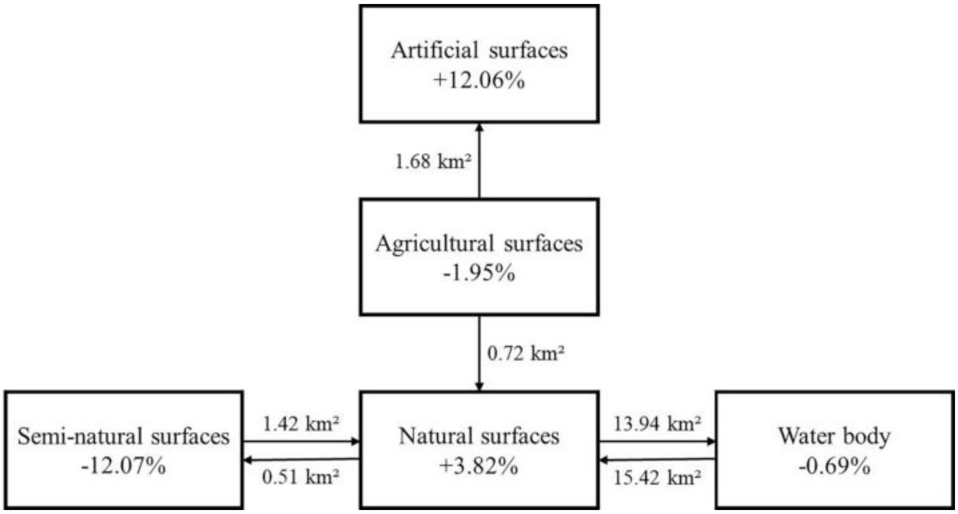

Fig. 3. Pathway of major net gains/losses of landuse in Northeast Italy from 1984 to 2016.

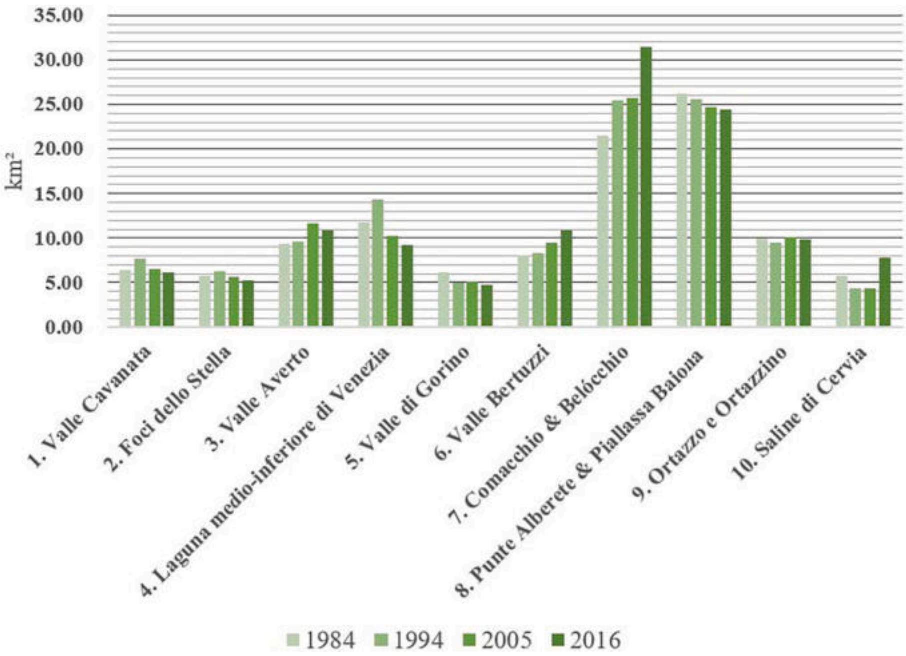

Fig. 4. Coastal wetland area change summarized by wetland sites (1984–2016).

As shown in Fig. 5, the sea level of most of the wetland sites in NE Italy has been rising since 1993, except that of Site 1, where a slight sea-level drop is observed. On the coast of Site 2, the sea level rises at a speed of 0.16 cm/yr. Southwards, much higher values are observed where sea level rises at a range of 0.42 cm/yr to 0.61 cm/yr. Among them, the coastal area of Venice has the highest value. The statistics also show that sea-level rise speed has accelerated remarkably in most coastal wetland sites since 2005. Indicated by overlay analysis, sea-level rise has close relationships with coastal wetland decrease. However, some exceptions also appear, such as Site 9 &10, where sea level rise at 0.42 cm/yr while only 3.33% of the coastal wetlands were inundated (1995–2016).

Further analysis shows that sea-level rise is just one of the two necessary conditions for coastal wetland loss, while the other is the amount of insular wetland (Fig. 6). In this research, all the coastal wetlands are classified as insular or continental wetlands based on their location. Multiple correlation analysis was conducted on Site 1, 2, 5 & 4, where more than 20% of the coastal wetlands were inundated. In these areas, the inundation proportion of wetlands (P_w) is in a linear correlation with annual RSLR and the proportion of the insular wetland in the entire wetland area (P_i). The fitting formula is:

$$P_w = 0.111*RSLR + 0.325*P_i + 0.221 \tag{2}$$

With R^2 of 0.85, the multiple correlation analysis shows both RSLR and P_i are significantly positively correlated with wetland inundation. The fitting formula also reasonably explained the inundation proportion difference among wetland sites with commensurate RSLR. In Site 5 & 4, where 53% and 84% of the wetlands can be found in isles, the wetland inundation proportion can be 20 ~ 30% higher than that of adjacent sites with few insular wetlands, such as Site 1, 3, 6, 7 & 8. In these areas, the correlation coefficient between annual RSLR and P_w is merely 0.04, indicating sea-level rise has brought less influence to continental wetlands.

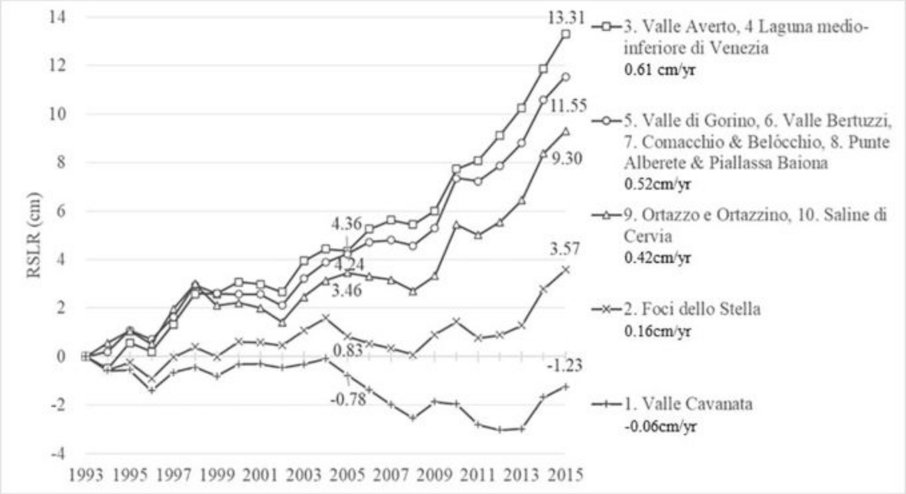

Fig. 5. Relative sea-level rise record aggregated from monthly sea-level ECV data.

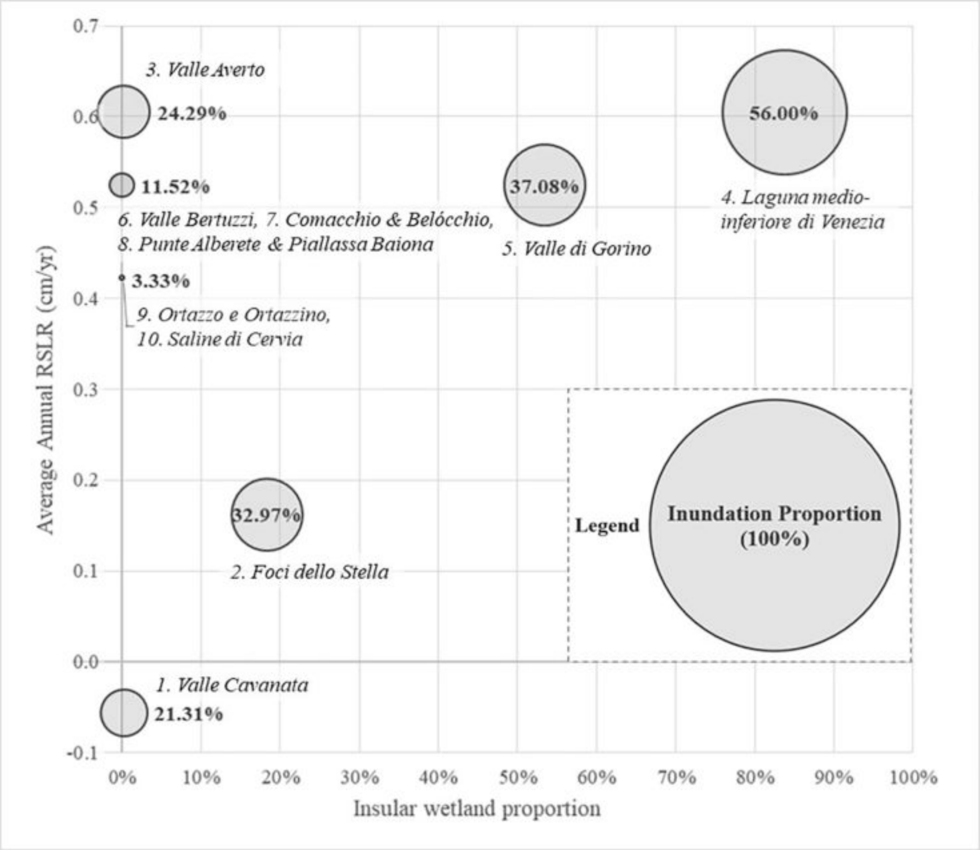

Fig. 6. Wetland inundation proportion analysis correlated with location and sea-level rise.

4.3. Exploratory data analysis of RSEI

The average RSEI value of the total study area slightly decreased from 0.390 to 0.361 from 1984 to 2016, while the median value also decreased from 0.335 to 0.308. In the meantime, the standard deviation (STD) increased from 0.232 to 0.277, indicating the growing spatial variation of the environmental status (Table 7).

The changes of RSEI were further statistically analyzed and summarized by the wetland sites (Fig. 7). The RSEI of Site 1, 6, 7, 8, 9 & 10 increased or remained stable during 1984–2016. Meanwhile, the RSEI of Site 2, 4 & 5 decreased conspicuously with the natural surfaces

Table 7
Statistics of RSEI.

	Average	Median	STD
1984	0.390	0.335	0.232
1994	0.357	0.330	0.219
2005	0.363	0.315	0.246
2016	0.361	0.308	0.277

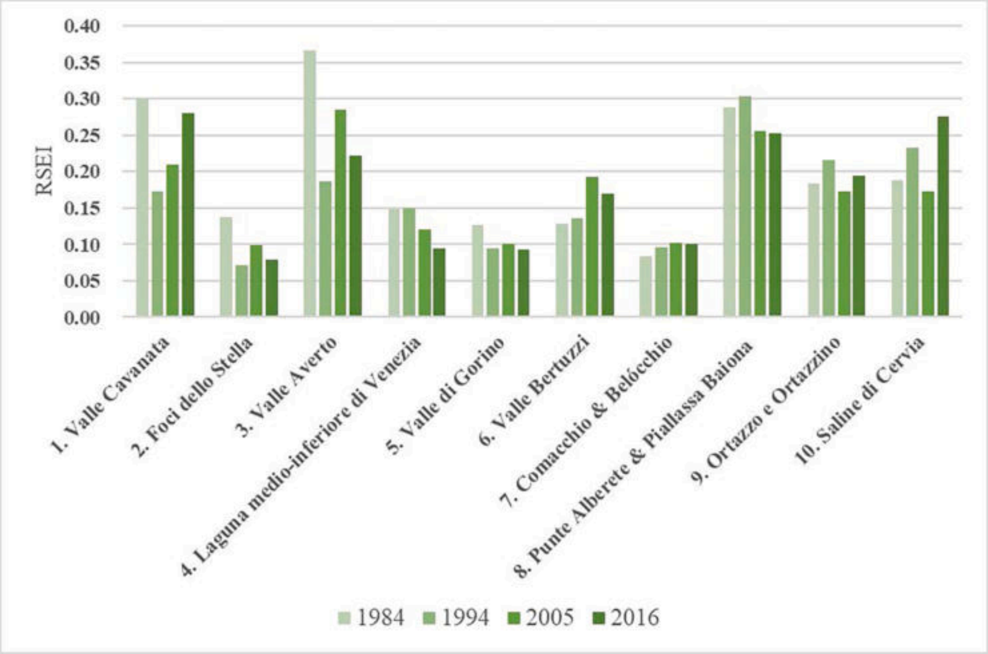

Fig. 7. Change of average RSEI summarized by wetland sites (1984–2016).

continuously converted into the water bodies. In most of the wetland sites, the change of RSEI is strongly correlated with the natural surface change. The relationship can be quantified by correlation analysis, with an R^2 reach 0.679 (Fig. 8). it is also notable that the change of RSEI is more fluctuant than that of natural surface area, which shows more details in the environment change process.

Specifically, the natural surface area of Site 6, 7 & 10 increased by 29.43% or more from 1984 to 2016, resulting in a significant improvement of the RSEI. In Site 1, 8 & 9, where the natural surface area has been generally stable, the change of RSEI is also inconspicuous. In Site 2, 4 & 5, where natural surface area decreased by at least 21.41%, the RSEI correspondingly remarkably decreased, revealing the deterioration of the environment in those areas. Without the protection from Ramsar or state natural reserve, Site 4, which is located in the Venetian Lagoon, suffers one of the most significant decreases of RSEI and natural surface area among all the studied sites. Notably, the other wetland site in the Venetian Lagoon, Site 3, also see a remarkable RSEI decrease from 1984 to 2016. However, unlike other sites, it does not result from the change of natural surface areas but was caused by contiguous anthropogenic activities in Venice. This noticeable trend also reflects environmental polarization phenomena which will be detailly discussed in the next section. Altogether, there are four wetland sites with remarkable RSEI decrease. It is worth mentioning that three of them (Site 3, 4 & 5) are threatened by a high speed of relative sea-level rise (above 0.5 cm/yr).

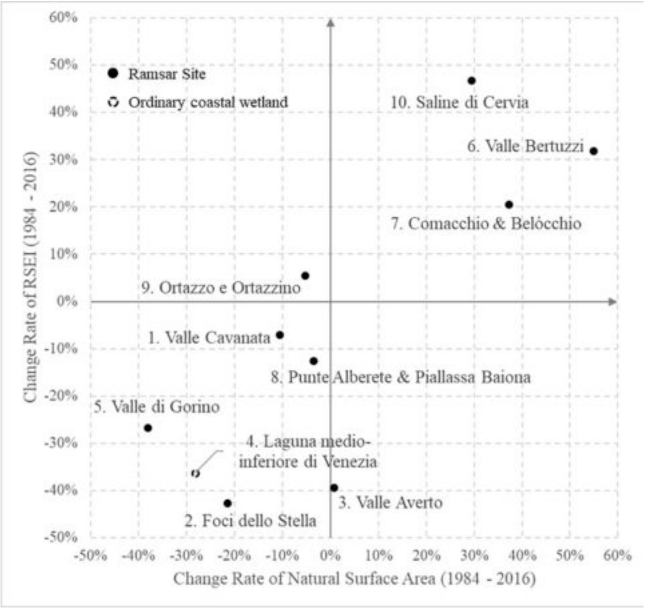

Fig. 8. Scatter plot on the change rate of natural surface area and RSEI (1984–2016).

5. Discussions

The results of this research show the effects of the influential factors, including landuse change and sea-level rise, on the coastal wetland environment in Italy. However, these adverse effects can be alleviated due to the conservation policy implemented by the public sector or NGOs. Although RSEI was initially developed for urban areas, the components of the index profoundly reflect the fundamental conception of the pressure-state-response (PSR) model, which is one of the most widely used environmental frameworks applicable for various landscape (Fan et al., 2020; Hu and Xu, 2018; Ji et al., 2020; Wen et al., 2020; Xiong et al., 2021; Xu et al., 2018, 2019; Zheng et al., 2020). Therefore, the change of RSEI can quantitively reflect the strength and effectiveness of the protection policy in wetland areas of NE Italy.

Three typical studied sites, namely Site 7, 3 & 4, are selected for further discussion. The studied Site 7 covers one of the first natural reserves in Italy, the Sacca di Bellocchio I, which was established in 1972 with only 1.63 km^2. Followed by the designation of the Ramsar Sites (Sacca di Belócchio in 1976, Valli residue del comprensorio di Comacchio in 1981) and four more state natural reserves, the protected area Comacchio & Belócchio rapidly expanded to 112.00 km^2 until 1984. With the establishment of the Po Delta regional park, a large reserve crossing the province of Ferrara and Ravenna regulated by the Ministry of the Environment and local government, the protected area expanded to 120.00 km^2 in 1988 (Fig. 9, Fig. 10a). Indicated by the rising RSEI, the ecological quality of this area improved despite the fact that the

Fig. 9. Hunting prohibition and access restriction in the Po Delta regional park (photo by Jin Wang).

northern part of the wetland site was impacted by the intense urbanization of Lido di Spina during this period which involved the construction of roads and banks. In 1995, with the adoption of the Habitats Directive (92/43/EEC) by the European Union, two Sites of Community Importance covering 85.03% of the area were designated to protect the threatened, rare plant species. Afterward, the ecological quality in the wetland site continuously improved from 1994 to 2005. It remained stable since the withdrawal of vast areas of arable land and economic vegetations (poplar groves) in the southern part after 2005 to create ponds and grasslands with patches of shrubs managed for wild flora.

As an integral part of the well-known World Heritage Site "Venice and its lagoon", the studied Site 3 is considered international environmental significance (Coccon and Baldaccini, 2017; Franco et al., 2006; Pillai, 2003). However, the implementation of reserve measures was relatively lagging compared to other studied wetland sites. In February 1989, about 2 km^2 of the wetland area in the Valle Averto was designated as a Ramsar site. In May 1993, the protected area expanded to 5.0 km^2 to establish a natural reserve managed by the World Wildlife Fund (WWF). Historically, extensive fish farming has long been influencing the coastal environment in this area. And mass tourism has further escalated the anthropogenic impact through various ways, including coastal transport infrastructure, cruise ships and ferries, intertidal trampling/collection disturbance, and coastal ecotourism (Davenport and Davenport, 2006). From 1984 to 1994, together with about seven to eight million tourists visiting Venice per year (MONTANARI and MUSCARÀ, 1995), the RSEI dropped noticeably from 0.397 to 0.186, indicating an environmental degradation in the wetland site (Fig. 10b). After 1995, WWF replanted local plant species and maintained the local flora (OASI, 2016). The Board of the Veneto Region then designated the Valle Averto a Site of Community Importance "Lower Middle Lagoon of Venice" (Codice IT3250030), under the protection by the Habitats Directive (92/43/EEC) of the EU. Indicated by the change of RSEI, recovery of the ecological quality appeared in the coastal wetland site as a result of the WWF and government efforts to preserve a biodiversity oasis just a few kilometers from the city of Venice.

It is worth mentioning that the Site of Community Importance "Lower Middle Lagoon of Venice" also covers another studied site with large areas insular wetland near Venice, Site 4, which is not designated to any reserve until 1995 (Fig. 10c). To date, the Habitats Directive (92/43/EEC) by the EU is the only effective environmental directive for this area. In Site 4, nearly half of the wetlands have low elevation and are highly vulnerable to inundation under future sea-level rise (Carniello et al., 2009; Torresan et al., 2012). Without robust protection, the ecological status degraded continuously with the sea level rise impact on the insular coastal wetland (as shown in Figs. 5, 6, 7, 8, and Fig. 11). Similarly, the results in this research show large areas of insular wetlands in other studied sites (whether or not in a protected area) were also under the risk of inundation. Compared with continental wetlands, the reservation of insular wetlands is equally important but more challenging due to its low accessibility and elevation.

The results of this research show that reservation policy and legislation can be particularly effective for the coastal wetland in the continental reserve area. For decades, the process of urbanization in the adjacent areas has brought slight impacts on the wetland in most studied sites. However, the environmental polarization phenomena appear and worth more attention. Strengthened by the current reservation policy, polarization phenomena were spatially reflected by increasing artificial/natural surfaces and decreasing agricultural/semi-natural surfaces. Outside the reserve, anthropogenic activities are unrestricted, leading to the expansion of artificial impervious surfaces. In contrast, most traditional production activities, such as hunting, fish farming, artisanal salt manufacturing, were prohibited or strictly limited inside the reserves. Recent research has discussed border effects due to the contrasting landcover type inside and outside the natural reserves (Bailey et al., 2016; Jusys, 2016; Zorrilla-Miras et al., 2014). Strict conservation policies to constrain the local user's access and discontinue the traditional uses would affect ecosystem services and cause a loss of local knowledge. Conversely, regulated traditional economic activities such as aquaculture, apiculture, etc., can simultaneously improve the wetland environmental status and sustainable socioeconomic development (Sousa et al., 2020).

In this research, with the expansion of artificial/natural surfaces and the reduction of agricultural/semi-natural surfaces, the overall standard deviation of RSEI rises from 0.232 (1984) to 0.277 (2016), indicating the increasing spatial environmental variations and the fostered polarization effects over time (Table 7). Within the studied Site 8, two Ramsar sites and one state natural reserve locates closely adjacent to the port area and Marina di Ravenna, where beach resorts overspread. The natural reserves are subject to severe anthropogenic pressure both for the seaside tourism flow and the presence of buildings and infrastructures. Inside the reserve area, the mixture of complex habitats, differentiated, superimposed plant communities with high ecological value made it even more vulnerable under the risk of further degradation. Rather than a solid enclosed border, buffer zones with partial restrictions shall help alleviate the impact on the wetland reserves. Regulated traditional uses can be permitted in adjacent areas of the reserves, providing valued benefits to neighboring rural communities. However, in buffer zones, the intensity of aggressive anthropogenic activity should be strictly limited or at least maintained at the present state, giving an added layer of protection to the protected area itself.

6. Conclusion

The Adriatic coast of the NE Italy is a representative area holding high ecological value in the Mediterranean. In this research, we have monitored the environmental change (1984–2016) of the coastal wetland in ten study sites covering all the Ramsar sites and most of the

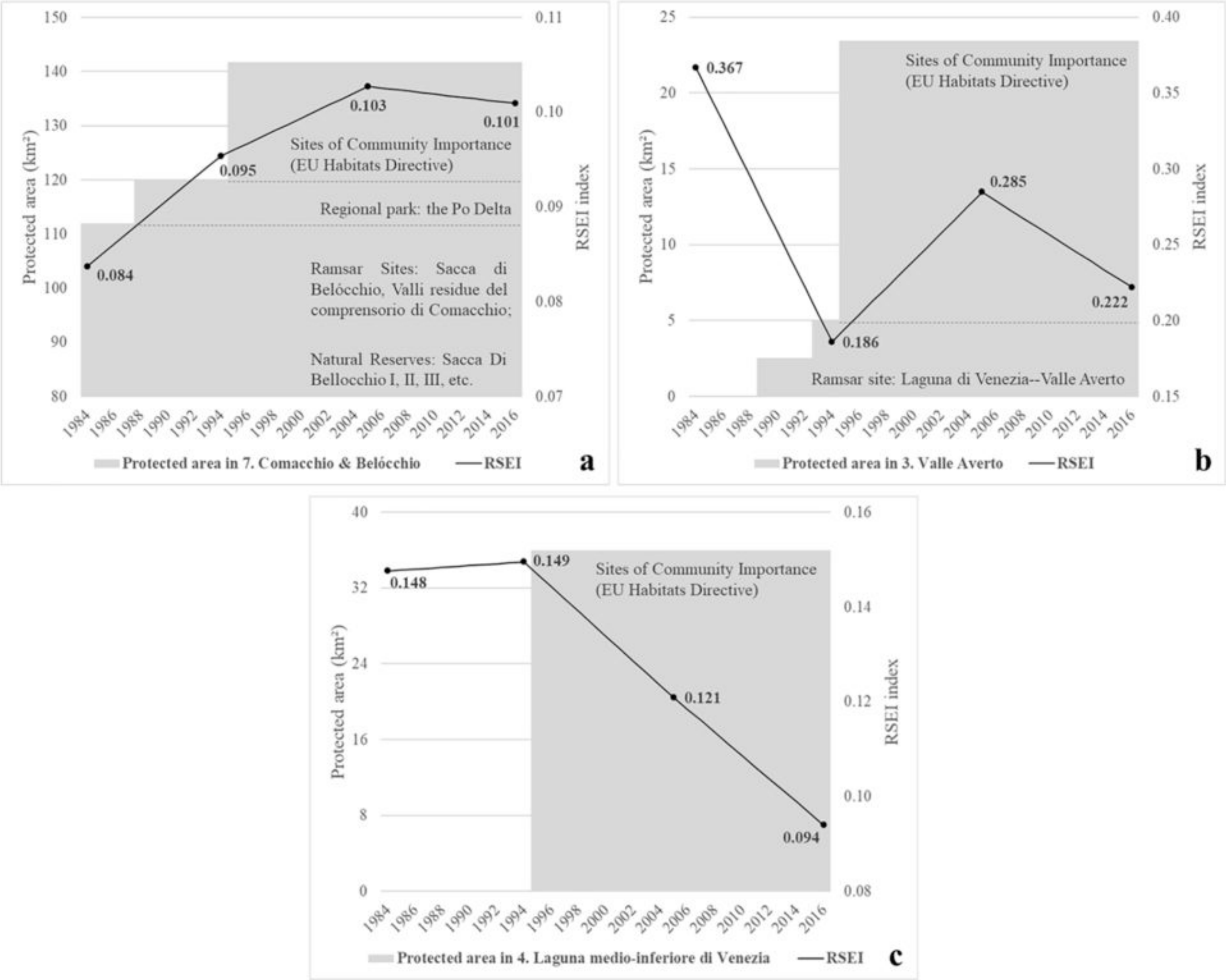

Fig. 10. Protected area and RSEI index of Site 7 (a), Site 3 (b) and Site 4 (c) during the studied period.

Fig. 11. Low-elevation insular coastal wetland in the Venetian lagoon (photo by Jin Wang).

natural reserve in the NE Italy. The change of the coastal wetland environment in this area is associated with a series of the influential factors, which have been quantitatively analyzed by this research. Generally, the landcover of the coastal wetland sites remained stable despite the continuous anthropogenic disturbance due to the robust reservation policies. However, wetlands located in the insular area are subject to more severe inundation impacts. As the sea-level rise shall be an inevitable trend, the survival of insular wetlands with low elevation will become more challenging in the future. The existing reservation directives and regulations should be amplified to preserve and restore the insular wetland vegetations actively. Across the continental coastal wetland sites, environmental polarization effects have been strengthened by strict reservation policy and contiguous aggressive anthropogenic activities, subsequently intensifying the anthropogenic pressure along the border and increasing the vulnerability of the reserve. In these areas, buffer zones should be established for the continental wetland reserves to alleviate the polarization effects.

Generally, RSEI provided reasonable and quantitative estimation for coastal wetland environmental conditions in NE Italy. However, the remote sensing-based index may not be perfectly appliable in particular areas. Besides, more specific factors, such as manufacturing, ship wake energy, and bottom elevation of sediment, can be elicited in future research to explore further the anthropogenic and natural effects on the coastal wetland. Moreover, mapping the vegetation type in the studied wetland sites with high accuracy will also help provide a deeper understanding of the environmental change in coastal areas for future related research.

CRediT authorship contribution statement

Jin Wang: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Writing - original draft, Writing - review & editing. **Jinsong Chen:** Funding acquisition, Resources, Supervision. **Ya Wen:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision. **Wei Fan:** Methodology, Visualization, Writing - review & editing. **Qiannan Liu:** Validation, Writing - review & editing. **Paolo Tarolli:** Investigation, Resources, Project administration, Supervision, Writing - review & editing.

Declaration of Competing Interest

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

Acknowledgements

We are grateful to Sonia Silvestri, University of Bologna for comments and revision of the manuscript. This work was supported by the Strategic Priority Research Program of the Chinese Academy of Sciences [XDA19030301]; the NSFC-Guangdong Joint Foundation Key Project [U1901219]; the National Natural Science Foundation of China [42001365]; the Fundamental Research Foundation of Shenzhen Science and Technology Program [KCXFZ202002011006298].

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2021.107906.

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