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Landscape changes in the "valli da pesca" of the Venice lagoon and possible effects on the Ecosystem Services supply

Alice Stocco[1*], Lorenzo Duprè[1], Fabio Pranovi[1]

1 Environmental Sciences, Informatics and Statistics Department, Ca' Foscari University of Venice, Via Torino 155, 30170 Venezia Mestre, Italy

* corresponding author: alice.stocco@unive.it

Highlights

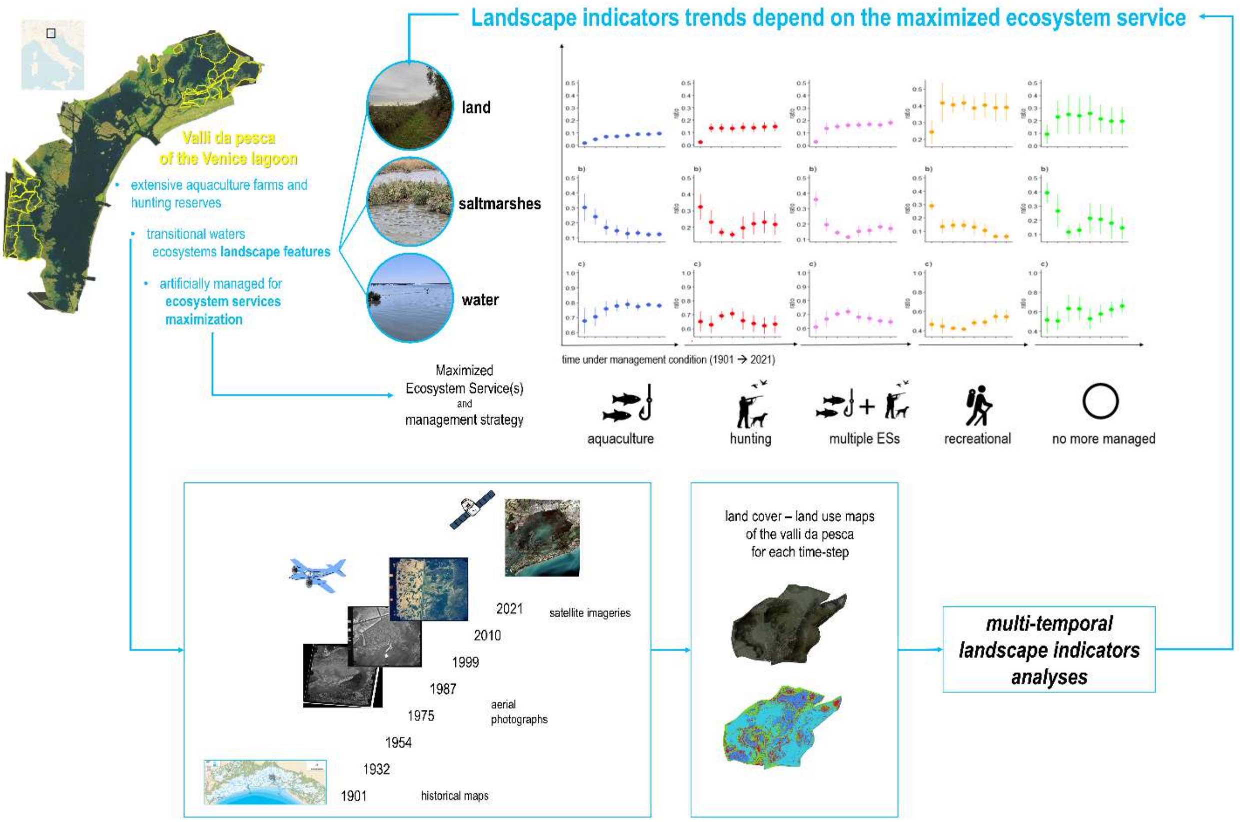
- Aquaculture and hunting reserves of the Venice lagoon changed through the years
- Remote sensing data allowed for multi-temporal landscape analyses
- Landscape indicators were effective in describing the valli da pesca evolution
- Human interventions influenced the landscape structure for maximizing different ecosystem services
- Fish production and hunting arise different landscape arrangements

Abstract

Coastal lagoons have long been subject to continuous changes caused by mutual interactions with human activities. Monitoring such changes becomes critical, particularly when modifications in landscape and land cover classes can affect their capacity to ensure Ecosystem Services (ESs). In the Venice lagoon, some confined areas called "valli da pesca" supply provisioning ESs, namely aquaculture and hunting, but also other ESs that are important for the entire lagoon, such as regulating and cultural ones. Being heavily modified ecosystems under human control, valli da pesca underwent considerable morphological evolution depending on the maximized ES and the applied management. Using remote sensing data from different sources, we reconstructed changes in land cover and landscape elements in valli da pesca over the last century. By calculating landscape indicators related to land, saltmarshes, and water, we found that landscape features were initially similar for all the valli da pesca. Then, a process began between 1975 and 1987, in which management devoted to maximizing different ESs shaped the land cover in specific patterns. This study confirms the importance of these areas in the context of the entire lagoon and require for monitoring their land cover changes. Remote sensing data represent an important source of historical data to deepen the knowledge about human-Nature interactions, for keeping trace not only of the landscape evolution but also of the dynamics in the ESs supply in response to human interventions.

Keywords: ecosystem services, landscape, land cover changes, landscape indicators, Venice lagoon, managed ecosystems, valli da pesca, remote sensing

Graphical abstract



1. Introduction

Coastal areas have long been known worldwide for their productivity. They represented the cradle of different civilizations, becoming some of the most important areas that ensure contributions to human well-being in the form of Ecosystem Services (Barbier et al., 2011; Duarte et al., 2008). Since ancient times, humans have learned how to exploit the resources of lagoons, estuaries, and coasts, modifying the environment and the landscape to their own advantage, building structures, and altering habitats (Halpern et al., 2008).

The most common anthropogenic modifications of coastal areas relate to land reclamation (Gaglio et al., 2017; Sousa et al., 2020), conversion into croplands (Tian et al., 2021; Zhan et al., 2022), deployment of aquaculture (Dias et al., 2013), and urbanization (Floerl et al., 2021; Gedan et al., 2009).

In the Venice lagoon, the larger coastal lagoon of the Mediterranean region, the long-standing interactions between human society and the ecosystem achieved many similar modifications to the landscape, through a multifaceted process of co-evolution (Gatto and Carbognin, 1981). Today, we have a fairly clear picture of this evolution thanks to numerous works focusing on the Venice lagoon from the perspective of various disciplines (Ravera, 2000; UNESCO, 1987). However, the most confined areas at the interface between the mainland and the lagoon water, called in Italian “valli da pesca”, are not as well-known.

The valli da pesca are peculiar areas confined by levees and embankments, where fresh and brackish water inputs are entirely regulated by humans, who also intentionally shaped the landscape. Born during the XIV Century to exploit fishing and waterfowl hunting, in the following decades they underwent a complex evolution that changed their numerosity, surface extent, and structure (Bullo, 1940; D’Alpaos, 2011; Laffaille, 2016).

Even if the valli da pesca are today artificial ecosystems, managed to maximize one or a few Ecosystem Services (ESs), they still provide ESs belonging to different categories along with the maximized one. Recently, they have been shown to contribute substantially to the ESs budget of the whole lagoon and act as decisive conservational areas (Stocco et al., 2023).

Despite being such an essential part of the Venice lagoon, the land cover evolution in valli da pesca has not been studied thoroughly. Indeed, all the works reconstructing the changes in the lagoon landscape on a multi-temporal scale mainly focused on the open lagoon, excluding the valli da pesca (Brivio and Zilioli, 2014; Gačić and Solidoro, 2004; Molinaroli et al., 2009).

One of the main reasons for this exclusion is that these areas include landscape features that can be smaller than 10 meters wide, resulting in difficulty in monitoring them remotely. Moreover, since the valli da pesca are privately managed, entering them for field surveys has always been difficult, making it even more unlikely to overcome this lack of data. Consequently, following their evolution has always been challenging: they can suddenly undergo artificial changes in the landscape because of management choices (Wang et al., 2021).

Even if cost-effective satellites data with a high temporal resolution, such as Sentinel and Landsat imageries, have an insufficient spatial resolution to distinguish such features on the ground (Anderson and Gaston, 2013; Casella et al., 2016), data of adequate spatial resolution come from highly detailed historical maps and aerial photos, taken during flights scheduled about 10-15 years apart. Such aerial photos are gathered and made available by the Veneto Region archive; this is an excellent opportunity to depict most interactions between human society and natural resources in the valli da pesca. This work aims to evaluate if changes in the management strategy (that is, the ES which is mainly maximized) have impacted, and how, the morphology of the valli da pesca during the last century. In particular, we assessed the land cover changes in the valli da pesca in the last century (from 1901 to 2021) and searched for possible relationships between landscape evolution and the ESs maximization.

2. Materials and methods

2.1 Study area

The 31 valli da pesca of the Venice lagoon collectively cover 97 km^2 and are located in both the Northern and Southern parts of the lagoon (Fig. 1); of these, 27 are still productive under private management.

The managers of these 27 managed valli da pesca provided information about the principal ES on which their main business relied, as well as about the periodic anthropogenic interventions and the access rules in the valle da pesca. In addition, aquaculture, hunting, and touristic activities related data were collected through 54 interviews carried out during our periodical visits to the valli da pesca. In particular, we retrieved yearly data about fish seeding, fish production, hunting catches, herbs and honey harvesting, and tourist visits. Literature review and historical maps collection were the primary sources of information for the valli da pesca that are no longer managed. We also collected data on abandoned valli da pesca through 12 interviews with the Veneto Region, local police, and ecotourism guides.

The ESs assessment and the collected data allowed for the classification of the valli da pesca into five different management groups, depending on the maximized ES (Stocco & Pranovi, submitted):

- valli da pesca devoted to fish production through extensive aquaculture (F)
- valli da pesca devoted to waterfowl hunting (H)
- valli da pesca devoted to both fish production and hunting (M)
- valli da pesca devoted to recreational ES, e.g. nature-based tourism and environmental education activities (R)
- valli da pesca no longer managed (N).

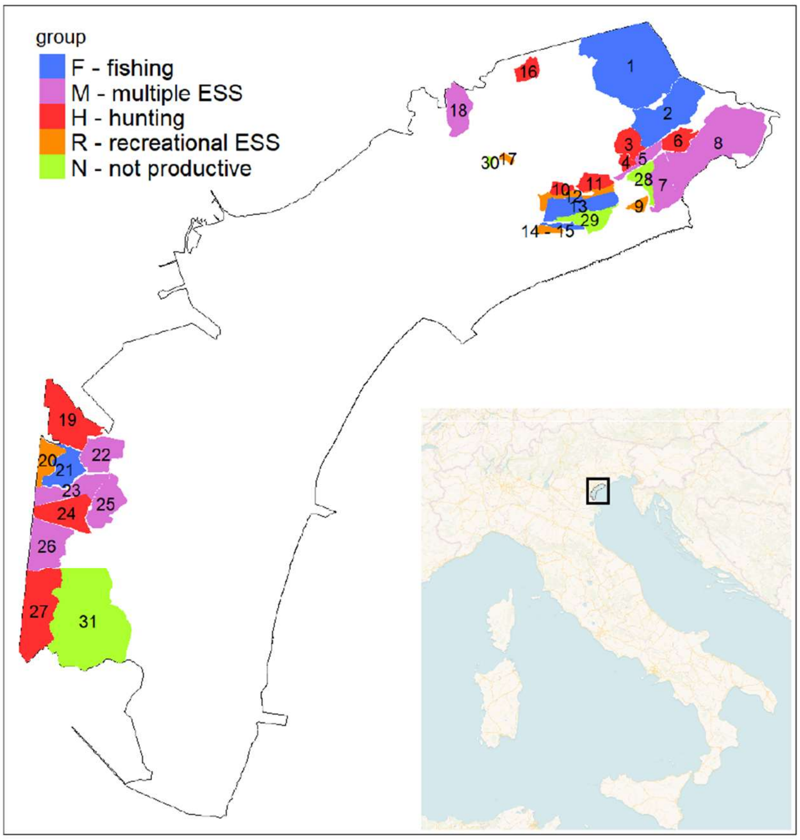


Figure 1 The Venice lagoon and the valli da pesca. The colors of the polygons indicate the management style aiming to maximize ESs: blue stands for fish production, red for hunting, violet for multiple ESs, orange for recreational ESs, green for lack of management. 1 = Valle Dogà, 2 = Valle Grassabò, 3 = Vallesina, 4 = Valle Fosse, 5 = Valle Lio Maggiore, 6 = Valle Bianca, 7 = Valle Dragojesolo, 8= Valle Cavallino, 9 = Valle Falconera, 10 = Valle Liona, 11 = Valle Olivara, 12 = Valli Saline-Manciane-Sparasera, 13 = Valle Paleazza, 14 = Valle Sacchettina, 15 = Valle Sacchetta, 16 = Valle Ca' Zane, 17 = Santa Cristina island, 18 = Valle Perini, 19 = Valle Miana-Serraglia, 20 = Valle Averto, 21 = Valle A.M.A., 22 = Valle Contarina, 23 = Valle Cornio Alto e Cornio Basso, 24 = Valle Zappa, 25 = Valle Figheri, 26 = Valle Pierimpiè, 27 = Valle Morosina-Ghebo Storto, 28 = Valle Baseggia, 29 = Valle delle Mesole, 30 = La Cura, 31 = Valle Millecampi.

2.2 Land cover and landscape indicators

Hydrographic maps of the Venice lagoon dating back to 1901 and 1932 (http://cigno.atlantedellalaguna.it/geoserver/wms) were digitized to create categorical raster layers with three land cover classes, namely land, saltmarshes, and water.

For the following time steps, we used 148 aerial photograms from the geo-topographic database of the Veneto Region, selecting among the aerial images taken in 1954-1955, 1975-1978, 1987, 1999, 2010, and 2018 (Tab. SM1 Supplementary Materials). We georeferenced the images with the QGIS 3.16 core GDAL Georeferencer (QGIS Association: QGIS Geographic Information System, 2022), considering 6 to 12 ground control points per frame projected on the national coordinate system Monte Mario – Italy zone 2 (EPSG:3004, 2021 CRS revision). All the aerial photographs were rectified on the most recent orthophoto mosaics of the study area. A 2^{nd}-degree polynomial transformation algorithm was applied.

The georeferenced photos from 1954, 1975, and 1987 had the imprint frame of the on-board camera holder, which represented an issue for the mosaicking of the photograms. To address this problem, it was necessary to pre-process the photos using the software GIMP 2.10.30. The pre-processing workflow required cropping the border of the photograms, masking the clouds and over-exposure errors, and finally desaturating them to a homogeneous value to obtain reflectance values falling in a narrow range.

Pre-processed photographs were then mosaicked together in QGIS, resulting in seven unique scenes covering the extent of the study area, with one scene for each considered year. For layers referred to years 1954, 1975, 1987, and 1999 a post-processing raster correction was performed using a pixel-based approach, limited to areas that were previously masked because they were affected by clouds or sunlight halos.

Subsequently, we obtained for each one of these scenes a land cover map with 5 meters per pixel side, in which class 1 corresponds to land, class 2 corresponds to salt marshes, and class 3 to areas covered by water, coherently with the layers referred to 1901 and 1932. To do so, we chose to apply a random forest classification algorithm (Liaw and Wiener, 2002), starting by identifying and labeling a minimum of 50 polygons of interest from which to extract the reflectance values. Obtained reflectance values of the pixels that fell within each polygon result in a matrix input for each model run. Since mosaics were mono-band or tri-band in the visible, depending on the year and the original aerial photos, we modified the classification algorithm accordingly. Based on the random forest models testing results, only the output maps that resulted in at least 86% accuracy were considered.

Finally, we obtained the land cover data for 2021 from very-high-resolution satellite scenes collected by Worldview-02, Worldview-03, and GeoEye-01 on-board sensors, updated through field surveys carried out in 2021 (Stocco et al., 2023).

Geostatistical analyses were performed on the land cover raster maps to calculate the area covered by each class within the area of each valle da pesca.

Three landscape indicators were calculated:

$$\text{land ratio (LR)} = \frac{land\ area}{total\ area}$$

$$\text{saltmarshes ratio (SR)} = \frac{saltmarshe\ \ area}{total\ area}$$

$$\text{water ratio (WR)} = \frac{water\ covered\ area}{total\ area}$$

where the area is expressed in m^2 and "total area" refers to the total area of the valle da pesca for which the calculation is made. Obtained data were analyzed with R software (R Core, 2022).

3. Results

All the groups of valli da pesca showed similar trends of LR from 1901 to 1975 but then started to follow different trends depending on the management group (Figs. 2 – 6, a). The statistical analyses showed that trends followed by the indicators were quite gradual and did not mark significant differences between contiguous periods.

In the valli da pesca belonging to group F, the LR was the lowest in 1901 (0.02±0.005 s.e.). After that, LR increased until 1975; then, it remained around the same value (0.089 ± 0.007 s.e.) in the last decades (Fig. 2a). The SR, on the contrary, decreased until 1987, then slowed down towards 2021 (Fig. 2b). The WR increases with an opposite trend (Fig. 2c). For SR and WR, the heterogeneity of data decreases along time.

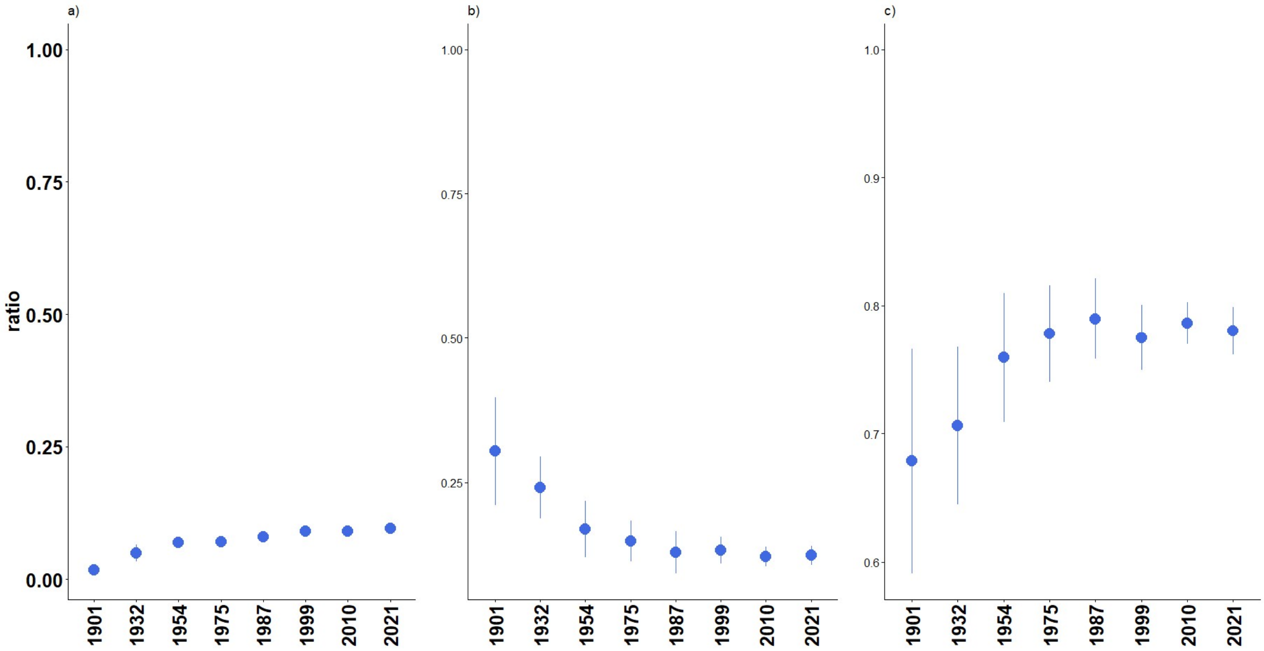


Figure 2 Landscape indicators for the valli da pesca of group F, maximizing the fish production ES. The dots represent the means, the error bars show the standard errors. a) land area to total area ratio; b) saltmarshes area to total area ratio; c) water area to total area ratio.

In the valli da pesca belonging to group H, LR is higher in 1932 than in 1901 and remained almost constant in the following years (Fig. 3a). SR decreases, reaching the lowest values in 1975, then slightly increases (Fig. 3b). WR showed a specular trend in comparison with the previous indicator SR (Fig. 3c). All indicators showed higher heterogeneity than that F group.

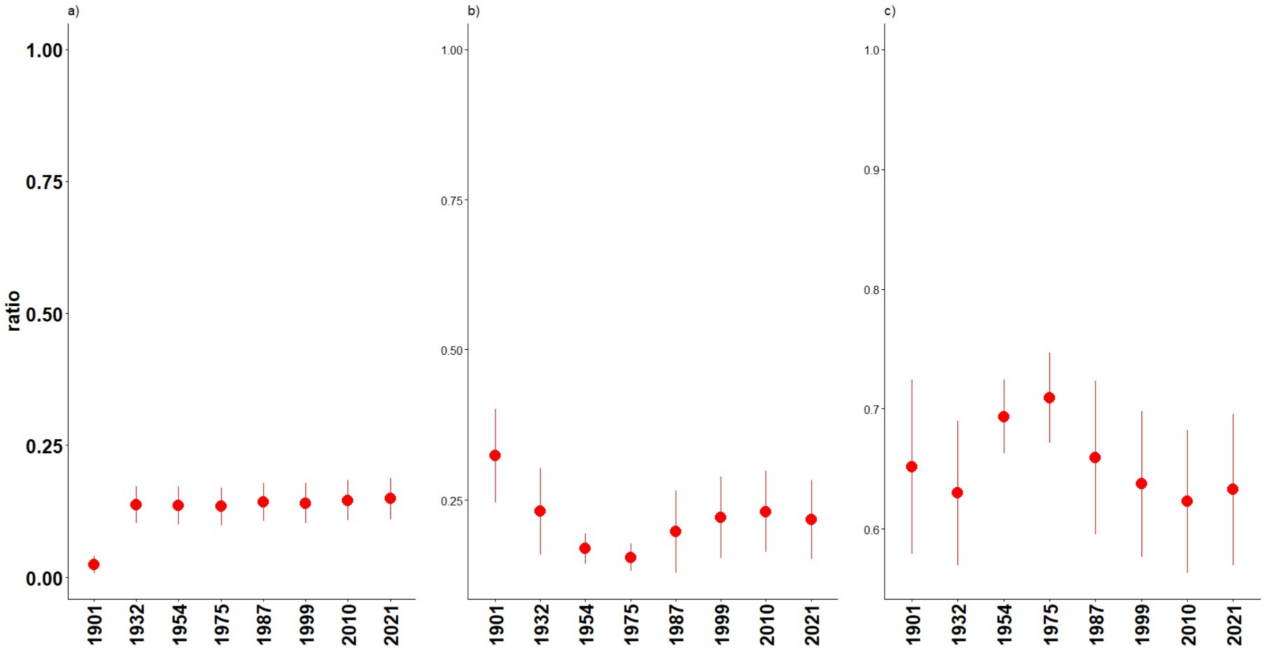


Figure 3 Landscape indicators for the valli da pesca of group H, maximizing hunting ES. The dots represent the means, the error bars show the standard errors. a) land area to total area ratio; b) saltmarshes area to total area ratio; c) water area to total area ratio.

Group M showed trends similar to H for all the indicators but with lower heterogeneity (Figs. 4a-4c). SR in group M recorded the lowest value in 1975, as showed in group H. From the following time step in 1987, SR increased until reaching a steady value in both the group H and M where hunting is practiced. However, group M presented a slightly lower SR value than group H in the last two decades.

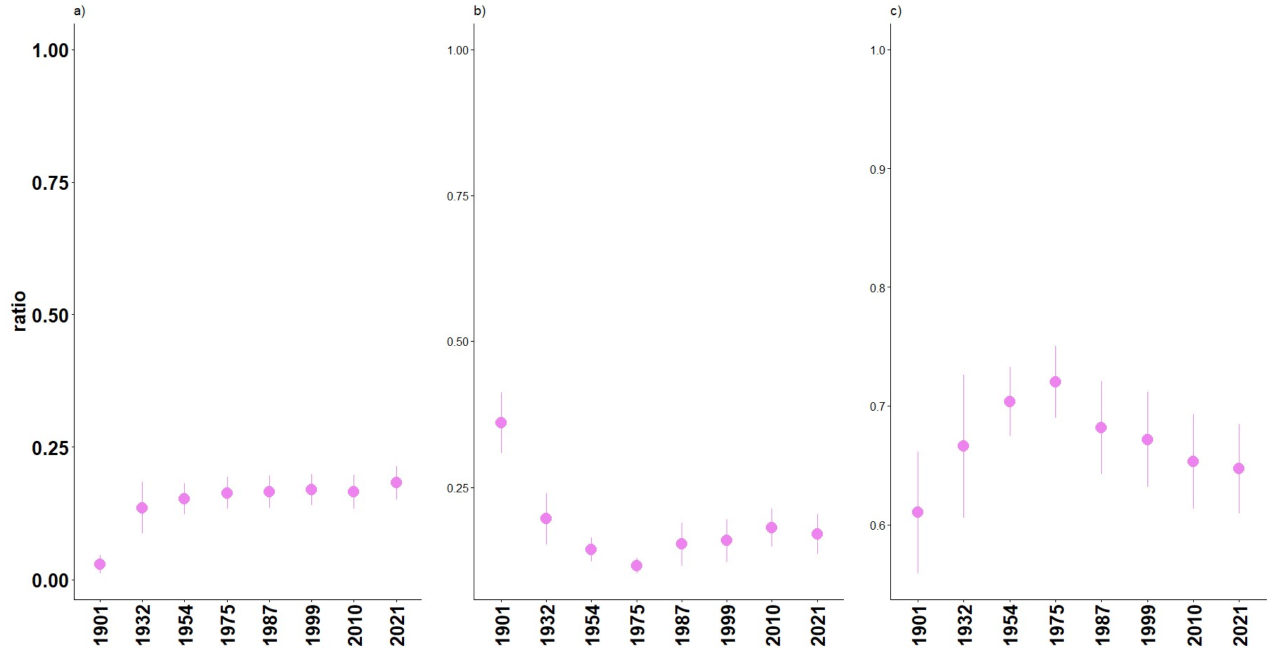


Figure 4 Landscape indicators for the valli da pesca of group M, maximizing both fish production and hunting ESs. a) land area to total area ratio; b) saltmarshes area to total area ratio; c) water area to total area ratio. The dots represent the means, and the error bars show the standard errors.

In general, group R showed higher LR than the values of groups F, H, and M. An initial increase is noticed in 1932, followed by a sort of stabilization (Fig. 5a). The SR abruptly decreased between 1901 and 1932 (from 0.38±0.14 to 0.13±0.06), and in 2010 when the SR reaches the lowest value (Fig. 5b). On the contrary, WR increased slightly going towards 2021 (Fig. 5c).

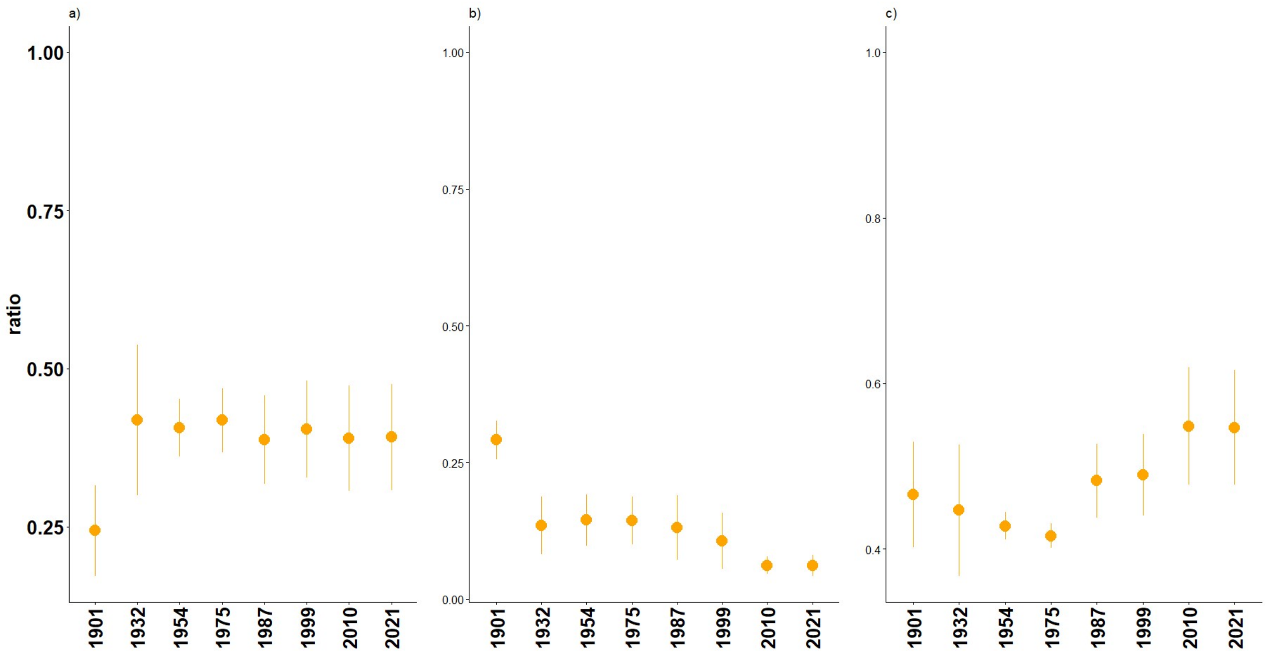


Figure 5 Landscape indicators for the valli da pesca of group R, that abandoned fishing and hunting while maximizing recreational ESs. a) land area to total area ratio; b) saltmarshes area to total area ratio; c) water area to total area ratio. The dots represent the means, and the error bars show the standard errors.

In group N, an increase in LR can be seen from 1901 to the following years, when LR seems to stabilize (Fig. 6a). Although showing a wide heterogeneity, SR followed a decreasing trend especially from 1901 to 1975; after a momentary increase in 1987 SR continued on its decreasing trend (Fig. 6b). The WR shows a quite specular path to SR, with an increase toward 1954-1975 followed by a decrease in 1987, when the upward trend of WR occurs again. The heterogeneity slightly decreased with time (Fig. 6c).

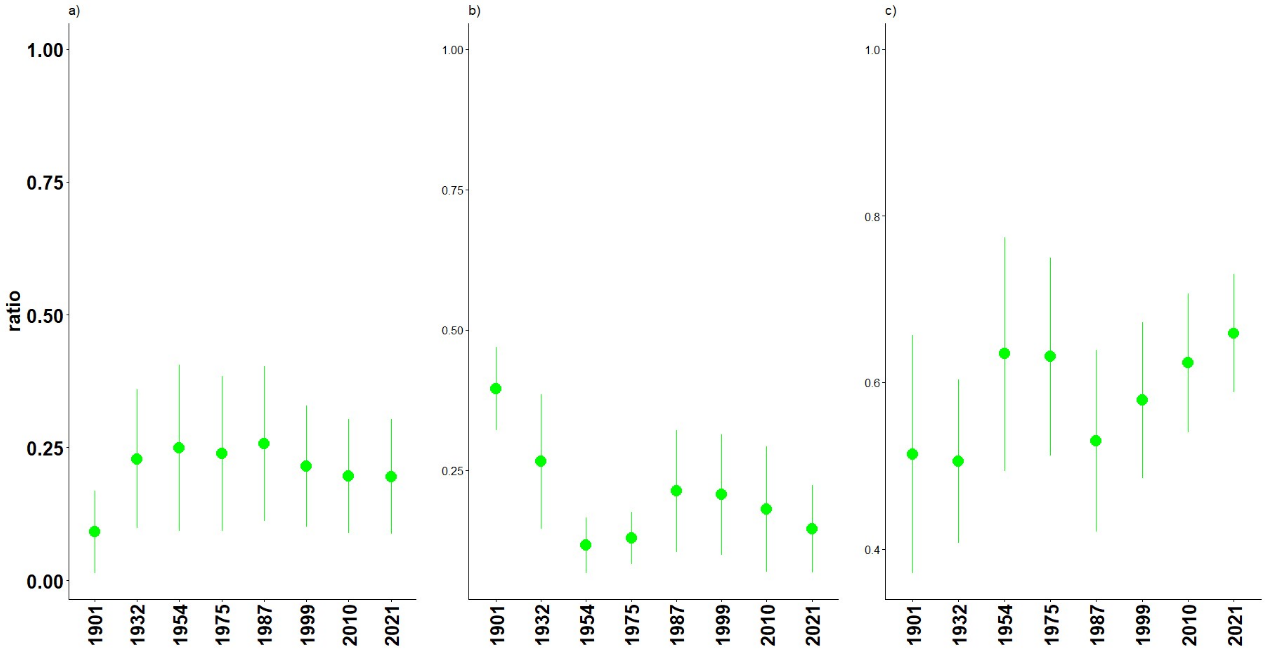


Figure 6 Landscape indicators for the valli da pesca of group N, which are not managed. a) land area to total area ratio; b) saltmarshes area to total area ratio; c) water area to total area ratio. The dots represent the means, and the error bars show the standard errors.

4. Discussion

In this work, we used remote sensing data from different sources and based onf different technologies to assess the evolution of the land cover in the valli da pesca of the Venice lagoon in the last century, focussing on the possible relationship between ESs maximization and the landscape arrangement.

By using historical maps, aerial photographs, and high-resolution satellite optical imageries, it was possible to demonstrate that at the beginning of the 20th century, the morphological structure, that is the areas covered by land, saltmarshes, and water, was similar for all the valli da pesca of the Venice lagoon.

The abrupt change un LR between 1901 and 1932 is explainable mainly by the land reclamation process, dating back to 1920-1927 (D'Alpaos, 2010; Sarretta et al., 2010) that caused a deep modification in land use in the study area, confirming that land reclamation is one of the processes that mainly affected northern Italy coastal lagoons in the past (Fontolan et al., 2012; Gaglio et al., 2017).

In the following years, the building of terrain levees and embankments changed the landscape proportions in all the valli da pesca; from 1922 to 1943, the land area increased due to a decree law that allowed, and even financed, the transformation in terrain levees of the thin fences made of swamp reeds (Bullo, 1940; D'Alpaos, 2010; Gatto and Carbognin, 1981). In that period, however, noticeable portions of saltmarshes were lost in all the valli da pesca until 1975, regardless of the management group they belonged, following the same decreasing trends described for the open lagoon (Madricardo and Donnici, 2014; Molinaroli et al., 2009; Sarretta et al., 2010).

A change in the law in 1973 started a process for which the managers of the valli da pesca could implement substantial changes to the landscape elements, so the development trends have become distinctive of each management group. In a long process, started during the last years of the Seventies, all the valli da pesca were provided with bold perimeter structures reinforced with ripraps well above the high tide elevation (Basurco, 2001; D'Alpaos, 2010; Finotello et al., 2019). This change explains the little spike in 1975 for the LR. Moreover, the freshwater and brackish water inputs began to be fully regulated by employing outlet works. Thus, all the water inputs fell completely under human control, and the valli da pesca became "regulated artificial ecosystems".

In the 80's, different management strategies of the valli da pesca were established (Laffaille, 2016), according to the need to maximize different ESs, highly influencing the evolution of the landscape, especially after 1987.

For instance, the increase of land in the valli da pesca of group F is linked to the construction of artificial, rectangular boundaries of the fishponds, built for protecting fish during winter. The managers of the valli da pesca of group F seemed to lose interest in conserving saltmarshes: such observation is concordant with the urgency to maximize the volume of water where to carry out aquaculture. Therefore, SR decreased due to a continuous loss of saltmarshes as time passed under this type of management.

On the other hand, in groups H and M, where hunting is preferred to aquaculture, the saltmarshes have been restored and preserved between 1987 and 2021, being regarded as crucial elements for attracting waterfowl in terms of places to rest and shelter (Arzel et al., 2006; Cherkaoui et al., 2017; Liang et al., 2015; Rizzo and Battisti, 2009). Therefore, the need to preserve suitable habitats to attract waterfowl to shoot at has led to maintaining these landscape elements. However, the higher heterogeneity shown by groups H and M indicates that each valle da pesca underwent different interventions and that no shared management was applied, even if they all aim to maximize the same ES. This heterogeneity could be linked to the willingness to attract huntable species that require different habitat characteristics (Adair et al., 1996; Ma et al., 2010; Velasquez, 1992). For instance, dabbling ducks and diving ducks need different water levels, the former preferring shallow lakes punctuated with bare shoals and saltmarshes, the latter preferring deeper and wider lakes surrounded by reed beds (Colwell and Taft, 2000; Isola et al., 2000).

A different situation can be identified for group R, where the land-covered area was already higher than in the other group since 1901. After the land reclamation in 1920-1940, it increased to twice its initial value. We could hypothesize that such a high ratio has driven the future evolution of the valli da pesca belonging to group R, perhaps leading their managers to maximize the recreational ESs for which these valli da pesca were suitable instead of fishing and hunting. Consequently, the cessation of the need to maintain habitats to attract fish and birds has led to overlooking the importance of saltmarshes (Fontolan et al., 2012).

Finally, in group N, the land cover trend continued to be the same as in the open lagoon (Carniello et al., 2016; Sarretta et al., 2010). In this case, the heterogeneity among data is more remarkable than that of the managed groups because each valle da pesca belonging to group N has a different origin and has seen the ceasing of the management in different time steps.

Our findings show that the trends in landscape indicators in the valli da pesca of the Venice lagoon are related to the type of management implemented and, consequently, to the maximized ES. The maximization of one (or a few) ES(s) turns out to be effective in making the valli da pesca landscape more similar to each other when belonging to the same management group, and rather different when compared to the ones belonging to a different management strategy group. Indeed, as soon as the management started to modify the landscape to maximize the potential of its own valle da pesca to provide the desired ES, this caused the same changes in the landscape for all the valli da pesca that are managed to maximize that specific ES.

This result concords with other authors who assessed the effects of wetland management on the landscape, especially when dwelling on aquaculture ES maximization (Kelly, 2001; Maltby, 1991; Saha and Paul, 2021; Schneiders et al., 2012).

In the Venice lagoon, such an approach did work appropriately for each one of the valli da pesca, when analyzed alone. However, they have performed well in providing ESs as long as they shared the same ecological gradients and processes timeline, in terms of structure and functionality. When, around the 80'ies, each one of the valli da pesca began to be regulated and partially isolated from the lagoon, it likewise began to be self-reliant and to detach its dynamics from the one of the other valli da pesca that surrounded it. This turned out to be quite counterproductive because it was thanks to the saltmarshes and the synchronized freshwater inputs, initially found in all the confined areas of the lagoon, that the fish fry and the waterfowl migrate towards the valli da pesca (Cavraro et al., 2017; Flaherty et al., 2013; Fortibuoni et al., 2014; Zucchetta et al., 2021).

The "de-synchronization" of the interventions, and the reduction of the fish stocks, could be among the reasons why, in the last decades, only a low quantity of fry spontaneously migrated inside the valli da pesca, as reported by the managers. In a situation where the lagoon fish struggle to overcome the pressures on the lagoon ecosystems (Zucchetta et al., 2021), the ecological connectivity and the movements of the fish may have been affected even more by anthropogenic modifications in the lagoon borders. The presence of levees and barriers in front of the fringing saltmarshes, as well as the loss of plentiful freshwater inputs, could have negatively influenced the ability of fingerlings to reach the confined areas where they can find refuge and nourishment (Cavraro et al., 2017; Flaherty et al., 2013; Huisman et al., 1979; Zucchetta et al., 2021). Consequently, the valli da pesca managers needed to increase the artificial sowing of fish fry to maintain the aquaculture ES, because their management caused unexpected feedback on the life-cycle support ES.

Also, other feedback may represent a matter of concern because the loss of landscape elements might result in the risk of losing ESs related to them (Grizzetti et al., 2019; Rova et al., 2022). For example, the tendency to conserve saltmarshes in the groups H and M can help in maintaining a high supply for regulating ESs (Stocco et al., 2023; Stürck et al., 2015) and provisioning ESs as well. On the contrary, the replacement of saltmarshes with consolidated and built-up land, as shown in group R, may result in the loss of ESs that are significant on a broader scale.

In light of the results, monitoring the valli da pesca through multi-temporal remote-sensing data can be an excellent long-term investment, especially when keeping track of the landscape elements changes. Landscape management aimed at maximizing one ES may indeed exclude interventions needed for other ES, thus causing drawbacks in the ESs balance of these areas and, consequently, in the ESs balance of the whole lagoon system to which the valli da pesca belong.

Seen that the valli da pesca management can mitigate the loss of landscape elements in the Venice lagoon, monitoring these areas is as important as monitoring the whole lagoon to prevent harms to landscape elements, ecological functions, and the essential ESs related to them.

5. Conclusions

The multiple interactions between humans and the Venice lagoon led to centuries of human-driven manipulation of the ecosystem, which has altered landscape structure and ecosystem functions. Studying the land cover change since the past century in the valli da pesca helped in understanding their evolution, allowing for the identification of the trends followed by landscape elements and the related land cover change.

Owing to the multi-temporal analyses performed, we found that after a period of similarity in the landscape indicators trends, the private management came into play to mold the landscape elements, giving different importance to distinct features based on their relationship to the maximized ES.

The mutual relationship between landscape indicators and ESs supply confirms that the valli da pesca are areas important to the entire lagoon, being capable of conserving landscape elements, such as the saltmarshes, and habitats supporting the life cycle of several species. These aspects make the valli da pesca to be highly considerable because they can help the lagoon ecosystem in mitigating the negative effects of climate change through their contribution in terms of ESs supply.

However, due to their being completely managed and under men's control, it is important to monitor the valli da pesca. Changes in them could trigger the put in place of functional and morphological adaptations that, on the one hand, can be customized and effective for each one of the valli da pesca, but on the other hand, could prove to be detrimental to the system as a whole.

Much work remains to do to understand the dynamics of such areas since field data are still scarce. However, since aerial orthophotographs and remote sensing imageries proved to be very informative, it will be well worth considering putting effort into regularly collecting and analyzing them through the calculation of the proposed landscape indicators, that were effective in depicting the landscape structure of these areas and its evolution. They can be of great help for monitoring the landscape changes in the valli da pesca, especially when related to management choices, in order not to lose benefits and services related to the consistency of meaningful landscape elements.

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Author Contributions: (according to CRediT taxonomy)

Stocco Alice: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Coding, Writing - original draft, Writing - review & editing.

Duprè Lorenzo: Data curation, Formal analysis, Investigation, Methodology, Writing - review & editing.

Pranovi Fabio: Conceptualization, Funding acquisition, Project administration, Supervision, Validation, Writing - review & editing.

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Supplementary material

Table SM1 Data of the flights whose aerial images have been used in this work upon request to the Aerophotography Collection of the Veneto Region.

Flight related code	year	cruising altitude [m]	band(s)	Study area coverage [%]
1954-1955 GAI	1954-1955	5000	1	100
1975 ReVen Benedetti	1975	2600	1	75
1978 ReVen Benedetti	1978	6000	1	100
1987 ReVen	1987	3000	3, R-G-B	100
1999 ReVen Veneto Centrale	1999	2500	3, R-G-B	100
2010 ReVen Area Venezia VA 18	2010	1680 - 3030	3, R-G-B	100
AGEA orthoimage 20 cm [2018]	2018	NA (likely 1600-3000)	3, R-G-B	100