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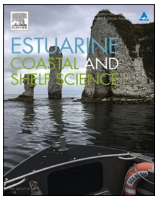

Exploring the interplay of landscape changes and ecosystem services maximization in man-managed lagoon areas

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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 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 suggests the need to monitor their land cover changes to avoid the depletion of their capacity to conserve landscape elements and the related ESs. In this task, remote sensing data represents an important source of historical data that can deepen the knowledge about human-Nature interactions, capable of tracing the landscape evolution and the dynamics in the ESs supply as responses to human interventions.

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 through 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 largest coastal lagoon of the Mediterranean region, the long-standing interactions between human society and the ecosystem caused many anthropic 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 evolution of 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 unique areas confined by levees and embankments, where fresh and brackish water inputs are entirely regulated by humans, who also intentionally shaped the landscape. Created during the XIV Century to exploit fishing and waterfowl hunting, they underwent a complex evolution in the following decades that changed their numerosity, surface extent, and structure (Bullo, 1940; D'Alpaos, 2011; Laffaille, 2016).

Even if today the valli da pesca are considered 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).

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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 m wide, resulting in difficulties 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, monitoring their evolution has always been challenging. An additional challenge is that they can suddenly undergo artificial changes in the landscape because of management choices (Wang et al., 2021).

Cost-effective satellite data with a high temporal resolution, such as Sentinel and Landsat imageries, distinguish relevant features on the ground (Anderson and Gaston, 2013; Casella et al., 2016). Data with an adequate spatial resolution comes 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 has been prioritized for maximization) 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 tourism activity 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. The primary sources of information for the valli da pesca that are no longer managed were based on literature reviews and collections of historical maps. 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 and Pranovi, 2023):

- 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).

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, last accessed on December 2022) were digitized to create categorical raster layers with three land cover classes, namely land, saltmarshes, and water.

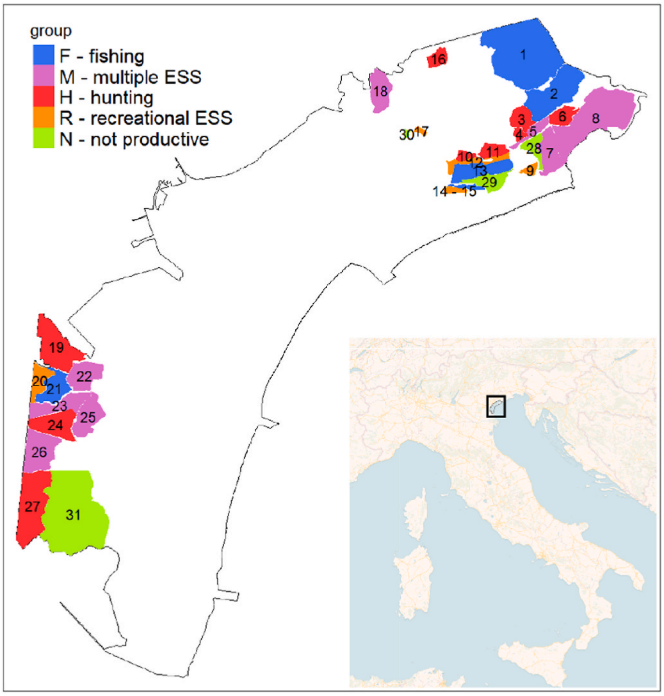

Fig. 1. The Venice lagoon and the valli da pesca. The colors of the polygons indicate the management style aiming to maximize ESs: blue stands for fish production, red for hunting, violet for multiple ESs, orange for recreational ESs, green for lack of management. 1 = Valle Dogà, 2 = Valle Grassabò, 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. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

For the following time steps, we used 148 aerial photograms from the geo-topographic database of the Veneto Region, selecting among the suitable aerial images taken in the flights carried out in 1954–1955, 1975–1978, 1987, 1999, 2010, and 2018 (S.M.).

The 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 preprocess the photos using the software GIMP 2.10.30. The preprocessing 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.

We georeferenced the corrected images with the QGIS 3.16 core GDAL Georeferencer (QGIS Association: QGIS Geographic Information System, 2022), considering 6 to 12 ground control points (GCPs) 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 Veneto Region made available in 2018. The methodology used to select the points on which to georeference the aerial images started with finding clearly visible locations in both the target and reference ortophotograph. The choice of the locations was restricted to points at the ground level or very close to the ground level, selecting among stable landmarks that have been maintained throughout the considered period, such as crossroads, concrete dams, Vinci gates, artificial channels, and corners of public squares and geometrical features on the ground (hence avoiding tall objects that could have been pointing outwards from the focal axis of the sensor that acquired the photograph). A 2nd-degree polynomial transformation algorithm was applied. After placing as many safely identified passpoints as possible, the set of GCPs that resulted in the lowest georeferencing Root Mean Square Error (RMSE) was selected to ensure the lowest overall RMSE score for the scene, aiming at reaching RMSE lower than half of the side of the image with the lower resolution. Then, the raster output of the classification was checked by inspecting that the reference ortophotograph and the target image were accurately lined up. Georeferenced 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. Near-present land cover data were obtained from very-high-resolution satellite scenes collected in 2021 by Worldview-02, Worldview-03, and GeoEye-01 on-board sensors, updated through field surveys carried out in the same year (Stocco et al., 2023). The resolution of the satellite multispectral images was 1.84 m, 1.24 m, and 1.64 m at Nadir, respectively.

Since the images gathered were sensed by both old aerial camera devices and modern sensors, they had different spectral and spatial resolutions, pixel size, and image quality. Therefore, the classification map rasters were set up aligned over a common grid with identical geographical extent and at a spatial resolution of 5 m. The temporal resolution was determined by the periodicity of the historical maps and the frequency of the photographic survey flights.

Subsequently, each one of these scenes, one per reference year, was used as input to build a categorical land cover map, in which class 1 corresponds to land, class 2 corresponds to salt marshes, and class 3 corresponds to areas covered by water. A random forest classification algorithm with a 500-trees default parameter was applied (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 within each polygon resulted 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, namely by modifying the considered variables at each split (2 for monoband images, and 3 for multispectral images). Each model accuracy was then assessed by evaluating a confusion matrix on the output categorical raster, by considering points falling in areas outside the polygons included in the training dataset. Based on the random forest models' testing results, only the output maps that resulted in at least 86% accuracy were considered (S.M. 1).

Particular attention was paid to the algorithm performance in distinguishing landmasses and saltmarshes. First, we labelled the saltmarshes as the areas surrounded by water on at least three sides, without roads or any other artificial structures, presenting scarce coverage of herbaceous halophytes. Instead, under the class "land" fell all the areas connected with the mainland, with impermeabilized soil or other structures, built-in areas, covered with trees, shrubs or grass. For RGB images the saltmarshes also had higher reflectance in the red band, whereas the land was more intense in the green band. After the random forest classification, we checked all the outputs with the relative inputs through visual photo interpretation. The workflow resulted in a land cover raster map for each considered time step (S.M. 2).

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:

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

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

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

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. Mean values of the three indicators and standard error of the mean were calculated at each time-step for each group, and a one-way ANOVA was performed to evaluate the overall differences among multiple groups. Upon detecting a statistically significant difference among the group means, specific differences were identified with post hoc multiple pairwise comparisons using Tukey's Honestly Significant Difference (HSD) test. Obtained data were analyzed with R software (R Core, 2022).

3. Results

All the groups of valli da pesca showed similar LR trends 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 always 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). Significant differences were found for all time steps when compared to the mean LR value in 1901 (ANOVA $p = 2.85 \cdot 10^{-5}$; Tukey post hoc test: 1901–1954 $p = 0.009$; 1901–1975 $p = 0.006$; 1901–1987 $p = 0.001$; 1901–1999 $p = 1.2 \cdot 10^{-4}$; 1901–2010 $p = p = 1.2 \cdot 10^{-4}$; 1901–2021 $p = 5.6 \cdot 10^{-5}$). Additionally, LR in 1932 significantly differs from LR in 2021 ($p = 0.024$).

On the contrary, the SR decreased until 1987, then slowed down towards 2021 (Fig. 2b) with no significant pairwise differences but indicating a trend (ANOVA $p = 0.09$). The WR increases with an opposite trend (Fig. 2c), also in this case with no significant difference but with a detected trend (ANOVA $p = 0.06$). For SR and WR, the heterogeneity of data decreases over time.

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), although the difference was not significant. SR decreases, reaching the lowest values in 1975, then slightly increases (Fig. 3b) but with no significantly different values. WR showed a specular trend compared with the previous indicator SR (Fig. 3c). All indicators showed higher heterogeneity than that of group F.

Group M shows trends similar to H for all the indicators but with lower heterogeneity (Fig. 4a–c). Similar to the observed pattern in Group H, LR showcased an increase from 1901 to 1932, but in this group the land extent continued to rise gradually (ANOVA $p = 0.036$; Tukey post hoc test: 1901–2021 $p = 0.026$). SR in group M had the highest value in 1901 (ANOVA $p = 5 \cdot 10^{-4}$; Tukey post hoc test: 1901–1932 $p = 0.035$; 1901–1954 $p = 0.001$; 1901–1975 $p = 2 \cdot 10^{-4}$; 1901–1987 $p = 0.003$; 1901–1999 $p = 0.003$; 1901–2010 $p = 0.015$; 1901–2021 $p = 0.008$), and recorded the lowest value in 1975, as it was showed in group H. From the following time step in 1987, SR increased until reaching a steady value in groups H and M, where hunting is practiced. However, group M presented a slightly lower SR value than group H in the last two decades.

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) with high variability in all the time steps. The SR abruptly decreased between 1901 and 1932 (from SR 0.38 ± 0.14 to 0.13 ± 0.06), and in 2010 when the SR reached the lowest value (Fig. 5b) with significant differences detected between the highest value in 1901 and those in 2010 and 2021 (ANOVA $p = 0.019$; Tukey post hoc test: 1901–2010 $p = 0.011$; 1901–2021 $p = 0.011$). On the contrary, WR

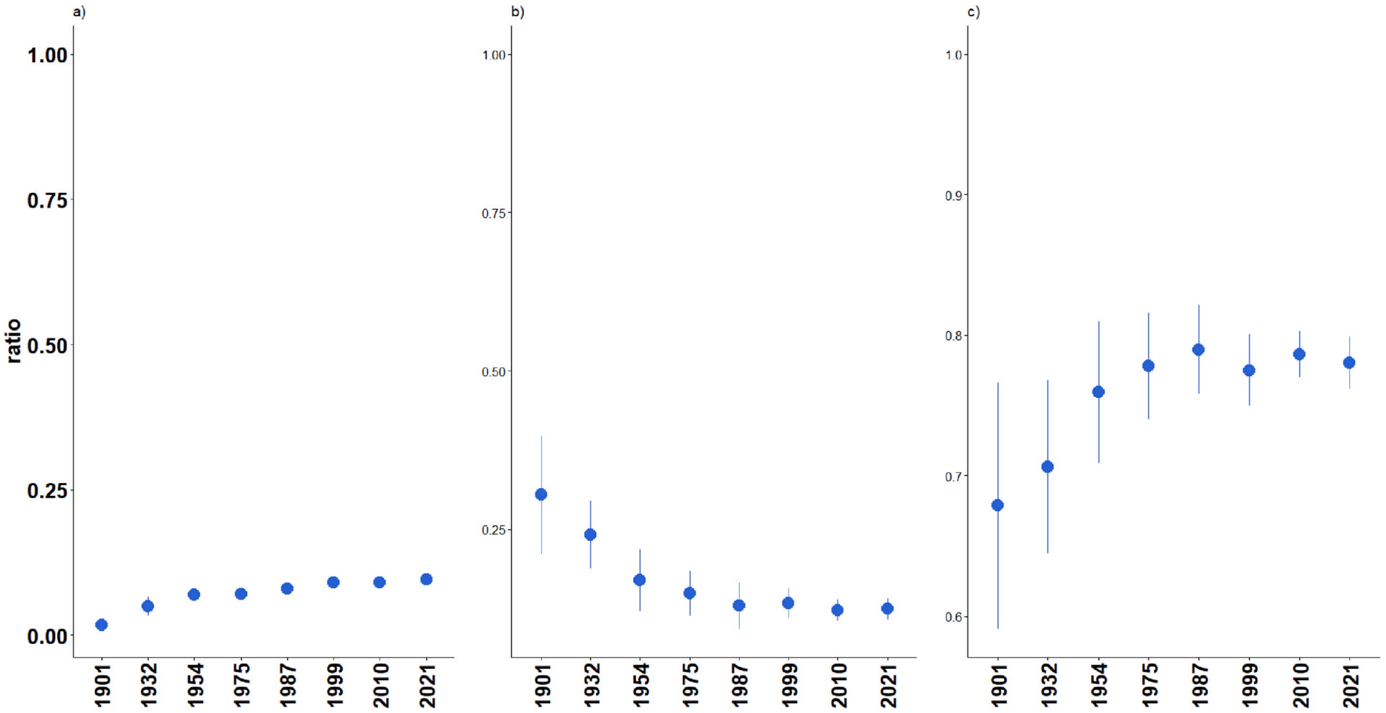

Fig. 2. Landscape indicators for the valli da pesca of group F, maximizing the fish production ES. The dots represent the means, the error bars show the standard errors. a) land area to total area ratio; b) saltmarshes area to total area ratio; c) water area to total area ratio.

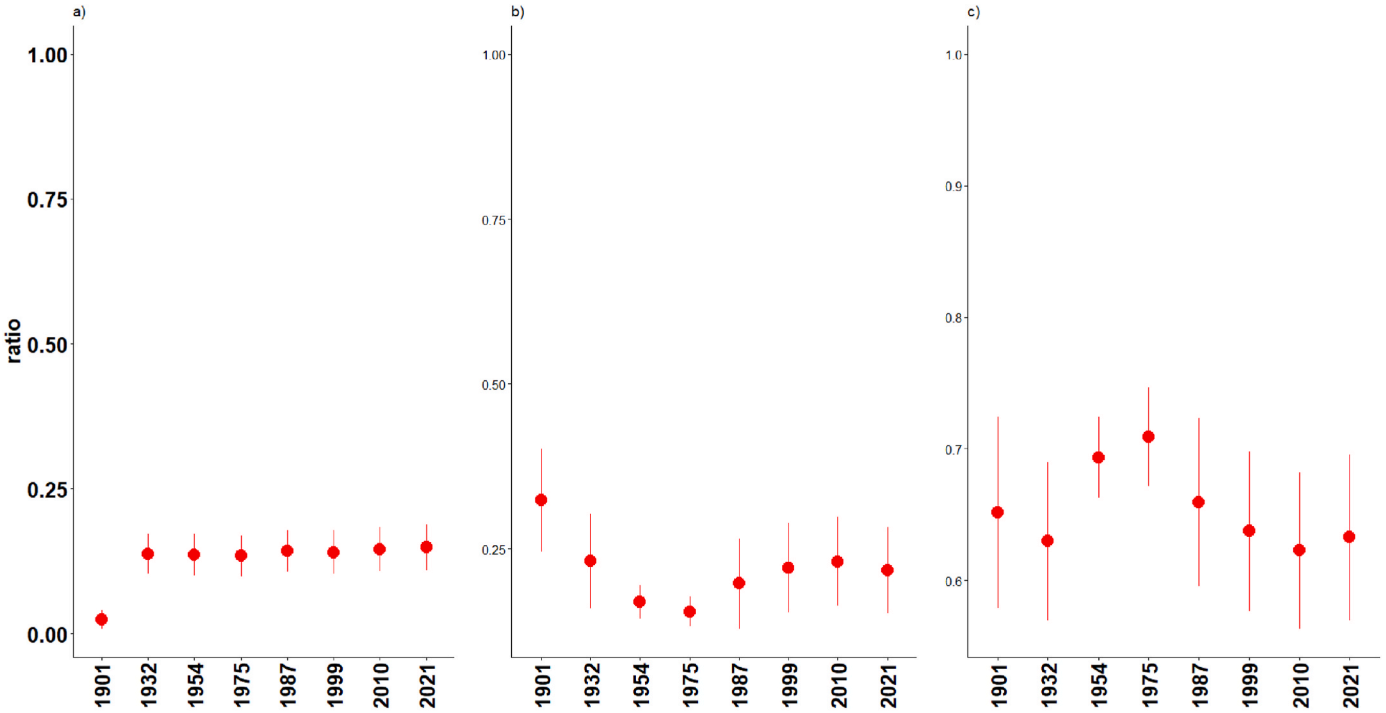

Fig. 3. Landscape indicators for the valli da pesca of group H, maximizing hunting ES. The dots represent the means, the error bars show the standard errors. a) land area to total area ratio; b) saltmarshes area to total area ratio; c) water area to total area ratio.

increased slightly going towards 2021 (Fig. 5c).

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. No significant differences were detected in the indicators among different time steps. The heterogeneity slightly decreased with time (Fig. 6c).

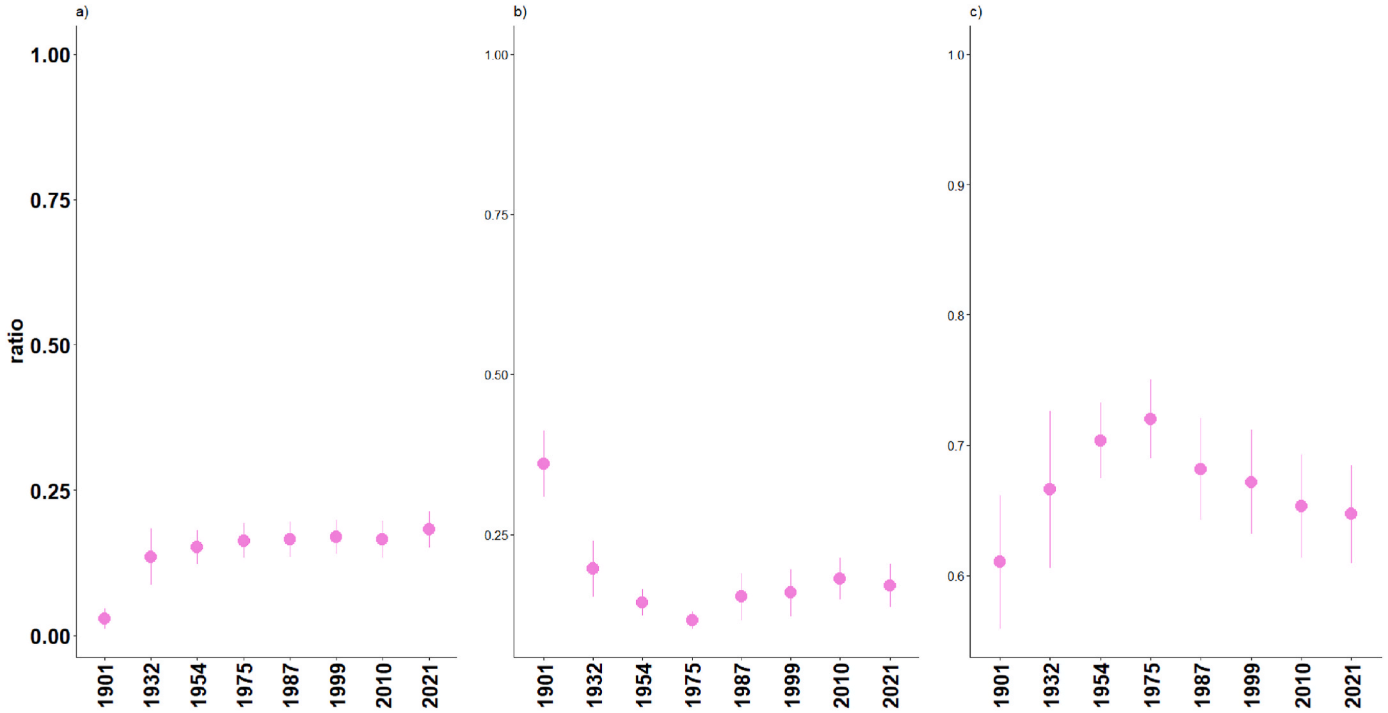

Fig. 4. Landscape indicators for the valli da pesca of group M, maximizing both fish production and hunting ESs. a) land area to total area ratio; b) saltmarshes area to total area ratio; c) water area to total area ratio. The dots represent the means, and the error bars show the standard errors.

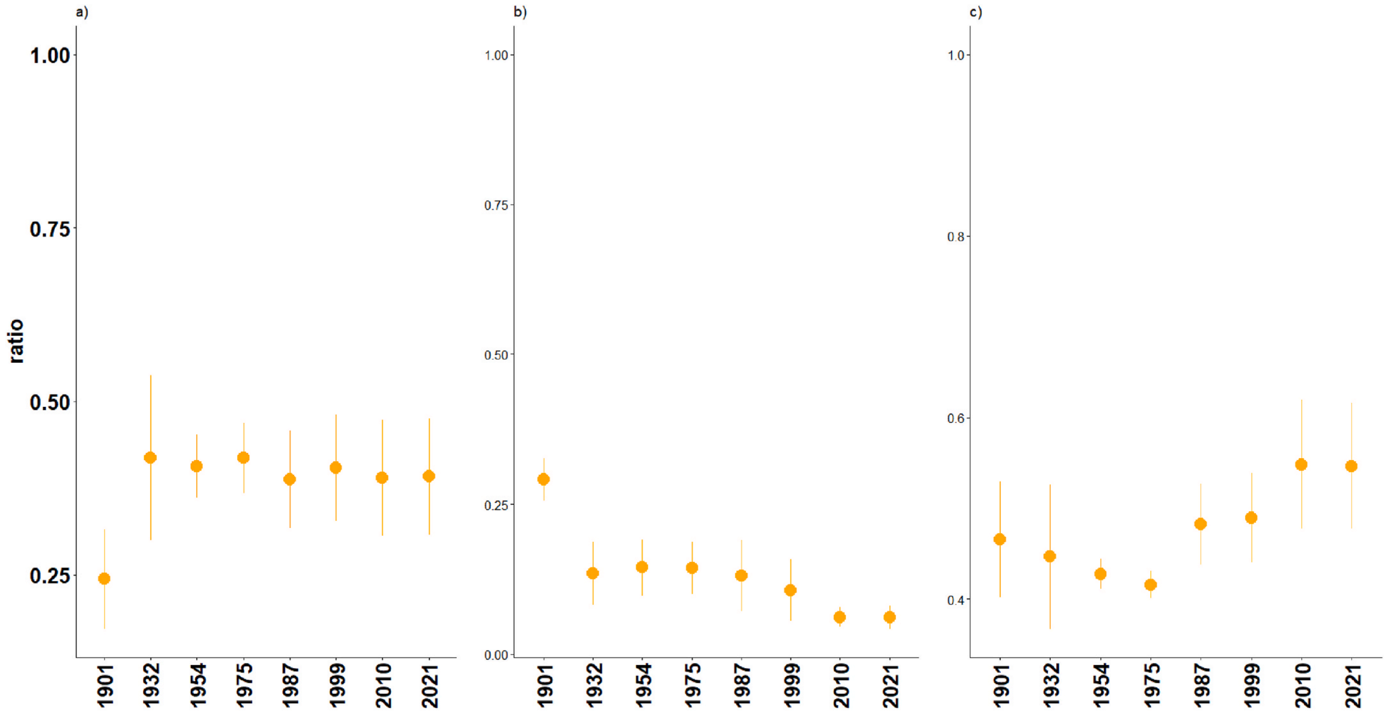

Fig. 5. Landscape indicators for the valli da pesca of group R, that abandoned fishing and hunting while maximizing recreational ESs. a) land area to total area ratio; b) saltmarshes area to total area ratio; c) water area to total area ratio. The dots represent the means, and the error bars show the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

4. Discussion

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

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

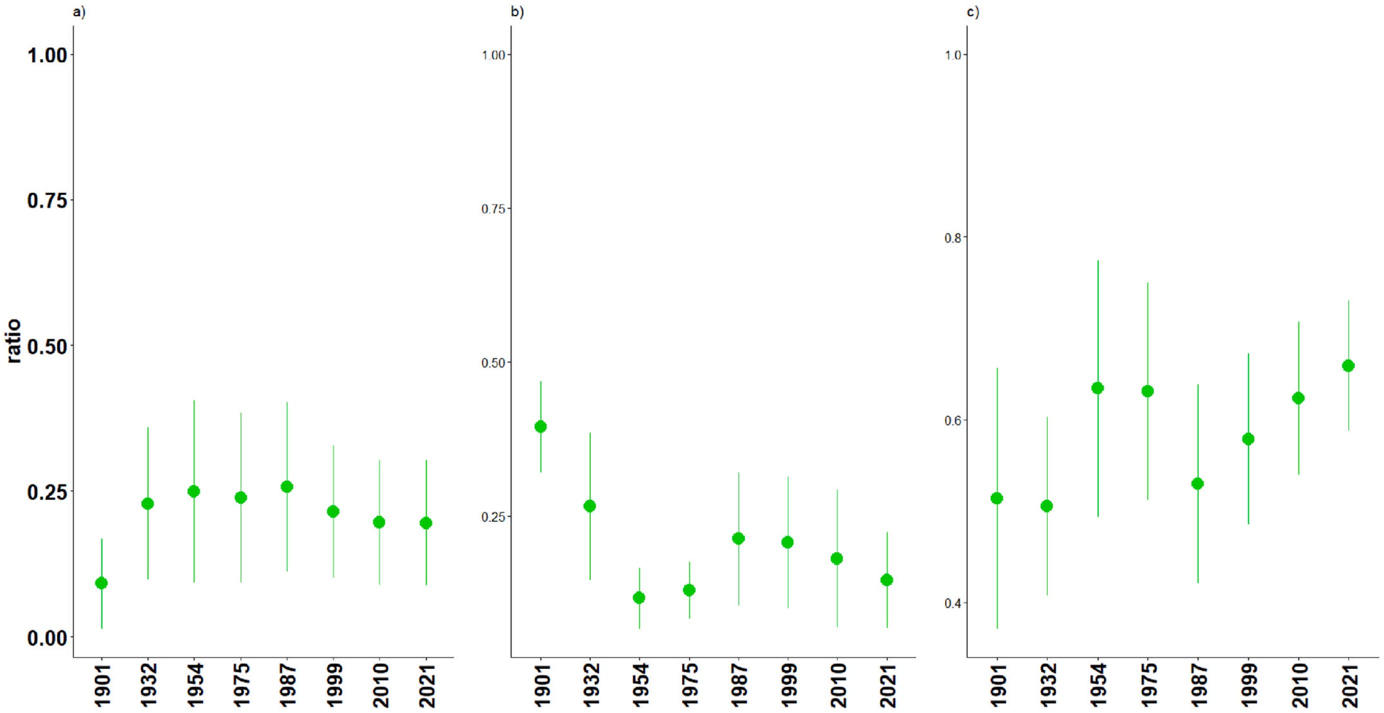

Fig. 6. Landscape indicators for the valli da pesca of group N, which are not managed. a) land area to total area ratio; b) saltmarshes area to total area ratio; c) water area to total area ratio. The dots represent the means, and the error bars show the standard errors.

The abrupt change in LR between 1901 and 1932 is largely explainable 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- This supports that land reclamation is one of the main processes that has significantly affected the morphological composition of northern Italian coastal lagoons in the past (Fontolan et al., 2012; Gaglio et al., 2017).

In the years following this reclamation period, 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 of the thin fences made of swamp reeds into terrain levees (Bullo, 1940; D'Alpaos, 2010; Gatto and Carbognin, 1981). In this period, however, noticeable portions of saltmarshes were lost in all the valli da pesca, and this trend continued until 1975, regardless of the management group to which the valli belonged. This follows the same decreasing trends described elsewhere 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 phase during which the managers of the valli da pesca could implement substantial changes to the landscape elements. At this point, the development trends became distinctive for each management group type. In the process initiated during the last years of the Seventies, all the valli da pesca were gradually provided with solid 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 upward spike in LR visible in 1975. 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 80s, different management strategies of the valli da pesca were established (Laffaille, 2016), according to the need to maximize different ESs. This development highly influenced the evolution of the landscape, especially after 1987.

For instance, the increase of land coverage 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 Group F managers seem to have been uninterested in conserving saltmarshes: this observation is concordant with their perceived urgency to maximize the volume of water suitable for aquaculture. It is also linked with the increasingly frequent use of artificial sowing of juvenile fish, that has made it optional to maintain saltmarshes nursery areas and freshwater flows that were previously crucial for attracting the fingerlings during their natural migrations. 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 hunt 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 strategy was applied, although 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 ratio has already been higher than in the other groups since 1901. After the land reclamation that occurred from 1920 to 1940, the LR 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 those related to fishing and hunting. Consequently, the cessation of the need to maintain habitats to increase the natural recruitment of fish juveniles and attract migratory birds to rest has led to overlooking the importance of saltmarshes in the valli da pesca that are no longer deeply interested in conserving the processes related to fish and birds lifecycles (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 experienced the cessation 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. This result aligns with those reported by other authors who assessed the effects on the landscape of wetland management (Zhao et al., 2021), especially when dwelling on aquaculture ES maximization (Kelly, 2001; Maltby, 1991; Saha and Paul, 2021; Schneiders et al., 2012). In a more general context, the dependence between landscape changes and management strategies is also confirmed by similar conditions and dynamics detected in other coastal ecosystems subjected to different interventions for management implementation, to the point that such considerations become essential in the context of restoration ecology (Guo et al., 2022).

An additional consideration to focus on is that, according to our findings, the maximization of one (or a few) ES(s) led to a notable homogenization of the valli da pesca landscape when belonging to the same management group, while they showed distinctiveness when compared to those valli da pesca belonging to a different management strategy group. Indeed, as soon as the management approach 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 tailored management strategy successfully increased each valle da pesca ability to provide the prioritized ESs. However, this effectiveness was contingent upon multiple valli da pesca within the same lagoon area sharing identical management priorities, thereby following similar ecological gradients and processes over time. Conversely, by the 1980s, the individual regulation and partial isolation of each valle da pesca caused them to operate independently and diverge from neighboring areas. This shift proved counterproductive, as the originally synchronized features and processes, namely saltmarshes integrity and coordinated freshwater inputs that were present in the past across confined lagoon areas, were crucial for attracting fish fry and waterfowl towards the valli da pesca (Cavraro et al., 2017; Flaherty et al., 2013; Fortibuoni et al., 2014; Zucchetta et al., 2021).

The "de-synchronization", caused by different interventions, along with the reduction of the fish stocks in the entire Venice lagoon, 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, 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 interventions caused unexpected feedback with the life-cycle support ES.

Also, other unforeseen feedbacks 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 groups H and M can help maintain a high supply for regulating ESs (Stocco et al., 2023; Stürck et al., 2015) and provisioning ESs. 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. Considering the strong influence of human activities on the structure and functions of coastal ecosystem (Sahavacharin et al., 2022) and transitional waters ecosystems, where all the landscape elements are interrelated (Pinto et al., 2021), it is crucial to avoid the potential loss of landscape heterogeneity supporting ecological processes and biodiversity by adopting a system-thinking approach. Changes in a single element can disturb the balance of the entire ecosystem and may also disrupt broader ecological connectivity due to a decline in the quantity and quality of habitats, as has been acknowledged worldwide (Venter et al., 2016).

If the changes in an ecosystem result in a reduced capacity to provide regulating services, the indirect effects can also affect other ESs through decreased resilience of food-webs and ecological functions. Therefore, trade-offs among services must always be carefully evaluated when the ambition of managing an ecosystem exists.

This viewpoint aligns with the concept, as recently elucidated by Elliott (2023), that ecosystem management should focus on preserving the health of the whole natural system, because it is from the processes that result from a healthy ecosystem, with a robust and resilient structure, that the society can obtain ESs in the form of goods and benefits.

In light of the results of this study case, monitoring the valli da pesca through multi-temporal remote-sensing data proved to be a promising long-term investment, especially when keeping track of the changes occurring in the landscape elements. Along with the strengths, of course, it's also important to acknowledge the limitations of the study, since the available aerial images, their spatial resolution, and the employed classification methods to obtain the landscape indicators might have introduced some uncertainties. The quality issues of some older aerial images, along with the 5 m resolution of the land cover map, for instance, could have limited the precision in detecting the decadal landscape changes, potentially impacting the accuracy of the monitoring. Although acceptable when considering the evolution of landscape indicators trends, it may be a limiting factor when it comes to monitoring the dynamics of the extent and the detection of tipping points, especially if the analyses also aim to focus on assessing the social-ecological system resilience.

Furthermore, it is crucial to note that while our study links ES supply to specific land cover classes, this association might not fully capture the complexities of ESs, as various interacting factors beyond land cover alone can influence them. Variations in ecological processes, temporal dynamics, and the intricate interplay of multiple landscape elements could influence the provision of ESs, which may not be completely accounted for solely based on land cover classes area, and may be influenced by non-linear dynamics that may be triggered under certain conditions, such as a rapidly eroded saltmarsh that, due to abrupt shifts (Fagherazzi et al., 2006), may be no longer able to provide its ecological processes and ESs.

Therefore, while our study provides valuable insights into the potential effects of landscape changes on ESs, the results should be interpreted with caution due to the complexity of the dynamics underlying the ES supply.

While requiring further studies to account for the high level of detail needed to encompass all the complex interactions between the ecosystem structure, the ecological processes, and the ecosystem services, this study confirmed that landscape management aimed at maximizing one ES may indeed exclude the interventions needed for other ESs, thus causing instability in the ESs balance of these areas and, consequently, in the ESs supply of the whole lagoon system, to which the valli da pesca belong.

Seeing that the valli da pesca management strategies have the potential to enhance or mitigate the loss of landscape elements in the Venice lagoon, monitoring these areas is as important as monitoring the whole lagoon, in order to prevent the degradation of the landscape elements, ecological functions, and the essential ESs related to them. The same type of multi-temporal monitoring approach, involving the analysis and the reconstruction of landscape changes in relation with the management conditions or the pressures and the impacts that the system undergoes, holds the potential to be applied to other aquatic ecosystems, particularly those characterized by a strong interplay between the ecosystem and socioeconomic systems.

For instance, a similar framework based on remote sensing data and ESs assessment could be extended to the entire Venice lagoon scale and generalized to other coastal lagoons, taking advantage of the increasing availability of technologies and methods to keep track of changes in landscape and ecosystem structures. Changes in land cover and land use, or alterations in the proportion of different land classes, are indeed increasingly considered valuable meta-indicators to define the current landscape status, monitor changes, regulate pressures, and ultimately assist in making informed decisions in complex development scenarios (Collin, 2011).

Moreover, considering the whole spectrum of ecosystem services with a spatially explicit approach in areas subjected to aquaculture or other productive reasons can help appreciate these areas and guide decision-makers toward sustainable management strategies (Barletta et al., 2023; Brito et al., 2023). This would ensure that any ecosystem is not solely managed with a strong emphasis on productivity but also considering the other ESs that are generated in synergy.

5. Conclusions

The multiple interactions between humans and the Venice lagoon have led to centuries of human-driven manipulation of the ecosystem, altering landscape structure and ecosystem functions. Studying the land cover change during the past century in the valli da pesca helped in understanding their evolution, allowing 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 similar landscape indicator trends. When private management came into play between the 70 and the 80s, they moulded the landscape elements, giving different importance to distinct features based on their relationship to the ES they aimed to maximize.

The interplay between landscape indicators and the supply of ecosystem services, as evidenced in this study, confirms a strong connection between the specific combinations and proportions of landscape elements within a transitional waters ecosystem and their ability to provide ecosystem services even beyond the local spatial scale and the current time frame. This confirms that the valli da pesca are areas important to the entire lagoon, capable of conserving landscape elements and biodiversity thanks to maintaining habitats that support several species' life cycles. These aspects make the valli da pesca highly valuable because they can help the lagoon ecosystem mitigate the adverse effects of climate change through their contribution in terms of the persistence of landscape elements and ESs supply.

Due to the valli da pesca being completely managed and under man's control, it is crucial to monitor the valli da pesca. Changes in these areas could trigger 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 be done to understand the dynamics of the valli da pesca, as field data is still scarce. However, since aerial orthophotographs and remote sensing images proved to be very informative, it would be well worth considering putting effort into regularly collecting and analyzing these images using the proposed landscape indicators, which were found to be effective in depicting the landscape structure of these areas and its evolution. This proposed approach can be of great help for monitoring the landscape changes happening in the valli da pesca, especially when related to management choices, in order not to lose the ecosystem services related to the persistence and resilience of landscape elements that have proven to be crucial in providing fundamental ecological processes.

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CRediT authorship contribution statement

Alice Stocco: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lorenzo Dupré:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Fabio Pranovi:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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