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Like little lagoons: the contribution of *valli da pesca* to the Ecosystem Services supply of the Venice Lagoon

Original Report of Research Results Article

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Like little lagoons: the contribution of *valli da pesca* to the Ecosystem Services supply of the Venice Lagoon

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Abstract

The Venice lagoon social-ecological system is characterized by a strong relationship between the natural environment and human activities. This is especially noticeable in the aquaculture and hunting reserves of the lagoon, locally known as *valli da pesca*. Previous works about Ecosystem Services (ESs) in the Venice lagoon focused on the so-called "open lagoon", overlooking the role of the *valli da pesca*. Despite being completely managed ecosystems, the *valli da pesca* have conserved typical elements of transitional water environments that the other parts of the lagoon have lost. By evaluating nine ESs using a spatially explicit approach, we found that the *valli da pesca*, despite covering 17% of the surface, are contributing for 38% of the ESs total capacity, and for 24% of the ESs total flow, in comparison to the open part of the lagoon. Moreover, the management that aims to maximize in a perspective of sustainability some provisioning ESs, such as extensive aquaculture, can positively influence the presence of factors on which other ESs capacity is also based. As a result, the open lagoon benefits from a sort of spill-over effect for lifecycle support, hunting, and cultural ESs such as tourism, information for cognitive development, and birdwatching. Such significant contributions could be endangered in the context of a lagoon subjected to increasing pressures from anthropic activities, where even adaptations to impacts, as well as to climate change and sea-level rise effects, in the long run will modify the lagoon hydrodynamics and the sea-lagoon connectivity, threatening the valli da pesca and so their ESs supply.

Keywords: Ecosystem Services, 'Side Effects', Valli da pesca, Extensive aquaculture, Waterfowls Hunting, Venice lagoon

1. Introduction

In the last decades, assessment and mapping of Ecosystem Services (ESs) have become effective methods to highlight all the contributions that humankind receives from Nature (Costanza et al. 1997; Burkhard and Maes 2017; Baró et al. 2016; MEA 2005). The ESs approach also makes evident services that would otherwise go unnoticed because they flow effortlessly to human beings (Liu et al. 2007).

Nature and humans always interact, creating complex social-ecological systems where society receives positive contributions to their well-being through the ecological processes.

In Italy, the Venice lagoon ecosystem is an emblematic example of such a complex social-ecological system.

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Since remote times, interactions between natural factors, social dynamics, and economic activities have shaped and affected its morphology and functioning (Solidoro et al. 2010). Given the complexity of these interactions, understanding spatial and temporal patterns of ESs capacity and flow (*sensu* Villamagna et al., 2013) plays a key role in environmental decision-making regarding the Venice lagoon, as suggested by Rova et al. (2015, 2019).

Previous works, however, focused on the so-called "open lagoon", composed of the principal islands and water bodies (Newton et al. 2018; la Notte et al. 2017; Rova et al. 2015; D'alpaos and D'alpaos 2021; Rova et al. 2019; Rova et al. 2022). Until now, no data have been gathered about the possible contribution to ESs by some confined, man-managed areas along the lagoon edges, called in Italian "*valli da pesca*". These areas, being considered Heavily Modified Water Bodies (HMWB) under the Water Framework Directive (European Commission 2000), are located at the interface between the land and the lagoon water and are almost completely closed, covering a total surface of approximately 97 km^2.

Like other similar environments in other coastal lagoons of the Northern Adriatic, the *valli da pesca* were established during the XIV Century as aquaculture facilities, where temporary boundaries were conceived to entrap fish without affecting water flows. Over time, the *valli da pesca* have been progressively isolated from the lagoon with permanent embankments. Nowadays, they are used especially for fish farming and waterfowl hunting and depend almost completely on human intervention for functioning, in terms of freshwater and brackish water supply, as well as for the maintenance of morphological features, resulting in an ecosystem that can be considered like an "artificial ecosystem". Quite paradoxically, the *valli da pesca*, due to their private management regime, have conserved typical elements of transitional ecosystems that the lagoon itself has instead progressively lost. Consequently, it is legit to ask whether these environments, while including and preserving brackish water basins, freshwater lakes, and saltmarshes, could act as important conservation areas, while providing ESs for the lagoon social-ecological system.

This work presents the first quantitative, GIS-based assessment of ESs in the *valli da pesca* of the Venice lagoon. On the one hand, it widens the knowledge about today's status of these ancient but poorly investigated environments, and on the other hand, it suggests some reflections about the effects of private land conservation. Furthermore, it explores the multiple ESs capacity and flow relationships emerging within these areas, and sheds light on their contribution to the whole lagoon 'ESs budget'.

2 Materials and methods

2.1 Study area

The study area is included in the Venice lagoon, the widest Italian transitional ecosystem (Fig.1). Each of the 27 *valli da pesca* that are currently still operative consists of a series of basins at different water salinity, separated from each other, and the lagoon, by means of artificial embankments, imitating the typical transitional water gradients.

Indeed, a typical *valle da pesca* receives the lagoon water that enters through a barrage, flows in the brackish lakes, and then glides towards the land. On the opposite side, some basins store freshwater inputs from inland rivers, creating a freshwater wetland area from which the water flows out to reach the major brackish basin. The mixed water then circulates in different sectors of the *valle* and finally, with the low tide,

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flows out into the lagoon (more information in Supplementary Materials I, Fig. S.M. 1.1). This creates a heterogeneous landscape with strong ecological gradients and a multitude of habitats, as much as a natural lagoon.

Among the *valli da pesca*, different types of management can be distinguished, ranging from aquaculture and hunting reserves to tourist estates. However, they all show the common trait of having a restricted access regime, making it difficult to collect data.

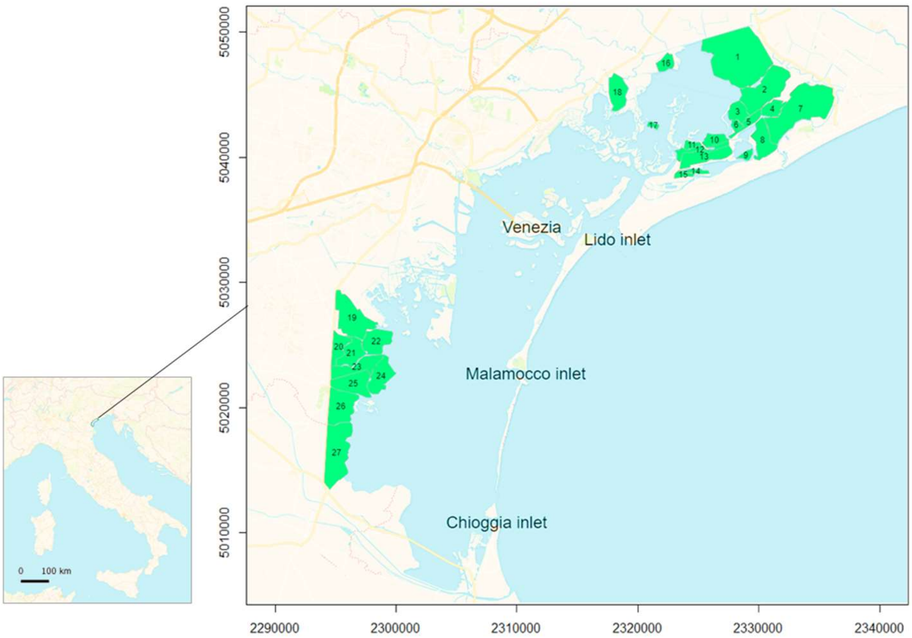

Figure 1 *Study area; 1 =Valle Dogà, 2 = Valle Grassabò, 3 = Vallesina, 4 = Valle Fosse, 5 = Valle Lio Maggiore, 6 = Valle Bianca, 7 = Valle Dragojesolo, 8 = Valle Cavallino, 9 = Valle Falconera, 10 = Valle Liona, 11 = Valle Olivara, 12 = Saline-Manciane-Sparasera, 13 = Valle Paleazza, 14 = Valle Sacchettina, 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.*

2.2 ESs' data collection, analysis, and mapping

The nine Ecosystem Services and related indicators for both capacity and flow are reported in Table 1. The ES category refers to the nomenclature of the Common International Classification of Ecosystem Services (CICES framework).

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CICES section	**Ecosystem Service**	**Capacity indicator**	**Flow indicator**
Regulating & Maintenance services	Climate regulation	Carbon sequestration rate by saltmarshes and seagrasses [gC m^{-2} y^{-1}] *	
	Water purification	Percentage of Nitrogen load removed by denitrification process in brackish water [%] *	
	*According to Schröter et al. (2014) and Hein et al. (2006) capacity and flow indicators of climate regulation and water purification ESs have been considered coincident		
	Lifecycle support for fish and of avian migratory species	Attractiveness for migratory waterbirds and potentially hostable juveniles fish biomass normalized to a 0-1 scale	Number of wintering migratory waterbirds and sown juveniles fish biomass normalized to a 0-1 scale
Provisioning services	Aquaculture production	Fish biomass [kg $ha^{-1}y^{-1}$]	Harvested fish biomass [kg $ha^{-1}y^{-1}$]
	Waterbirds' hunting	Number of huntable waterbirds [n $ha^{-1}y^{-1}$]	Number of catches [n ha^{-} y^{-1}]
	Wild edible plants and honey production	*Salicornia sp*. biomass [kg $ha^{-1}y^{-1}$] Honey [kg $ha^{-1}y^{-1}$]	Harvested *Salicornia sp*. biomass [kg $ha^{-1}y^{-1}$] Harvested honey [kg $ha^{-1}y^{-1}$]
Cultural services	Tourism	Tourism attractiveness [0-1 scale]	Number of tourists [n y^{-1}]
	Information for cognitive development	Environmental education attractiveness [0-1 scale]	Number of one-day guided excursionists and students [n y^{-1}]
	Birdwatching	Birdwatching attractiveness [0-1 scale]	Mean number of active birdwatchers [n y^{-1}]

Table 1 *ESs selected for the present assessment and the adopted indicator.*

2.2.1 Regulating and maintenance ESs

The climate regulation ES has been assessed as carbon sequestration process by saltmarshes accretion (Day et al. 1998; Roner et al. 2015) and seagrasses meadows (Sfriso and Francesco Ghetti, 1998; Sfriso and Marcomini, 1999; Sfriso et al., 2007) that are present in the studied reserves.

The water purification ES is expressed as the nitrogen removal capacity of brackish lakes, in proportion to the water volume and its turnover time in each *valle da pesca*. Because of the unavailability of local data, the estimation was based on denitrification data by Ravagnan (1982), who measured the difference between the TIN in the inflowing water and outlet water in *valli da pesca* which are in all aspects managed similarly to the those considered in this case study.

According to the literature, the capacity and flow indicators of the aforementioned regulating ESs are considered coincident (Schröter et al. 2014; Hein et al. 2006a).

The lifecycle support was assessed by focusing on the migration patterns of both the fish and waterbirds. Fish lifecycle support capacity was estimated by extrapolating the distribution of mugilids fingerlings in the most confined part of the lagoon, retrieved from a spatialized foodweb model of the Venice lagoon based on functional groups (Anelli Monti et al., 2021). For migratory birds, we mapped for each one of the *valli da pesca* the favorable factors, namely saltmarshes, freshwater presence, shrubs, and herbaceous vegetation, that enhance the attractiveness for resting and molt changing (Korschgen et al., 1985; Havera et al., 1992; Arzel et

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al., 2006; Hatziiordanou et al., 2019). Fish and waterbird lifecycle support capacities were normalized on a 0-1 scale. To assess the flow for fish lifecycle support, we referred to the actual mullets' biomass sown per hectare (kg ha^{-1} y^{-1}), referring to the species *Mugil cephalus, Chelon labrosus, Chelon aurata, Chelon saliens*, and *Chelon ramada*, as officially declared by the *valli da pesca* managers. We focused on mullets because they are the only taxonomic group for which data regarding the sowing of juveniles were available and because the origin of their fingerlings was local. In contrast, for other farmed species (for example *Sparus aurata, Dicentrarchus labrax*), it is more frequent that fry often come from intensive hatcheries, not necessarily located in Northern Italy. Subsequently, we decided to not take them into account for assessing the lagoon fish lifecycle support ES. For birds lifecycle support flow, we referred to the average number of migratory waterbirds that winter within the *valli da pesca*, from the last ten years' waterbirds annual censuses (AFV 2020) The resulting indicators were combined and then normalized on a 0-1 scale.

2.2.2 Provisioning ESs

The aquaculture practiced in the *valli da pesca* is mainly extensive aquaculture. In this type of aquaculture, fish are free to move into a wide brackish basin and rely only on natural food (Costa Pierce 2002). Therefore, aquaculture capacity is represented by the potential biomass hosted by the brackish basins of each *valle da pesca* (kg ha^{-1} y^{-1}), estimated from a spatialized foodweb model (Anelli Monti et al. 2021). The flow is expressed as the average fish catches per hectare of brackish water surfaces per year (kg ha^{-1} y^{-1}), according to the 2010-2019 official data (Regione Veneto).

Waterfowl hunting was evaluated in terms of capacity using the time series of waterbird censuses from 2010 to 2019 (Associazione Faunisti Veneti). Since the census data were associated with point features, we interpolated the average number of huntable birds censused in the last ten year by Dirichlet-Voronoi tessellation for implicit surfaces to obtain the most likely spatial distribution of huntable waterbirds per hectare per year. Hunting flow was obtained from waterbird catch historical series, collected from 2010 to 2020 (Ente Produttori Selvaggina Veneto).

The food production ES focused on wild edible plants of the genus *Salicornia* growing in saltmarshes and on honey obtained from flowers of sea lavender (plants of the genus *Limonium*).

Perennial saltmarsh vegetation dominated by halophytic dwarf shrubs has been identified by visual census method in 12 patches of two different *valli da pesca* (Valle Dogà and Valle Cavallino, Figure 1 - 1, 8), and then through the identification of their predictive range in R, G, B bands reflectance values, filtered through a cut-off NDVI value calculated from aerial and satellite images (listed in Supplementary Materials II Tabs. S.M. II – 1, 2). The identified vegetation patches allowed for evaluating the capacity for edible plants, in terms of kilograms of *Salicornia* biomass that could be harvested in the *valli da pesca* per year. Considering the *Limonium* inflorescence cover in the patches (Fantinato and Buffa 2019) and the ratio between the number of sea lavender flowers and grams of honey potentially produced per unit area, the honey capacity was assessed as kilograms of honey that can be produced in the *valli da pesca*. The flow indicator refers to the kilograms of harvested plants and honey. Edible plant harvesting data were retrieved from 2020 market data (Veneto Agricoltura) and interview to local people and restaurant chefs; the amount of sea lavender honey was witnessed by five beekeepers.

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2.2.3 Cultural ESs

Tourism attractiveness was assessed by a survey carried out in the second half of 2019, addressing tourists who recreate and travel in the Venice lagoon.

To assess the tourism ES capacity, we mapped for each one of the *valli da pesca* the attractiveness factors evaluated by tourists in the questionnaires, namely saltmarshes presence, the possibility to observe birds and fauna, good water quality, and the chance to contemplate natural terrestrial habitats. Each element was weighted to depict the interest declared by the people and normalized to a 0-1 scale index.

Tourism flow was represented by the number of persons who, during a year, had passed at least one night in one of the accommodation facilities within the *valli da pesca*.

Regarding the ES information for cognitive development, the natural factors that enhance touristic attractiveness have been mapped along with the inclusivity toward the necessities of people with disabilities. The resulting map was normalized to a 0-1 scale. The flow indicator summarized data concerning the number of persons who annually attend outdoor educational activities or guided one-day trips, as reported by touristic guides and associations (ATN Laguna Sud, Cooperativa Limosa, Ente di promozione turistica di Cavallino Treporti, Oasi WWF Valle Averto).

Birdwatching ES capacity was expressed with the birdwatching attractiveness normalized map, based on the factors reported as important by 30 interviewed birdwatchers: the presence of pedestrian paths, saltmarshes presence, nesting areas in the visual field, and a high probability of observing birds. All these factors were summed and scaled to obtain a normalized attractiveness map. Birdwatching ES flow indicator was considered the mean number of active birdwatchers derived from the observers' activity trend, recorded from 2010 to 2020 in the Italian birdwatchers' database (https://www.ornitho.it/).

2.2.4 Aggregated ESs indicators

Each ES indicator was spatially assessed in the *valli da pesca* and in the open lagoon, that is all the lagoon surface which is not privately managed. The open lagoon ESs assessment was conducted accordingly with the one presented by Rova, Stocco and Pranovi (2022), and detailed in Supplementary Materials III. Once we obtained the raster layer for each indicator, for both the *valli da pesca* and the open lagoon, the results were normalized to a 0-1 scale. Finally, the indicators were aggregated to have a normalized sum of all the ESs capacities and a normalized sum of all the ESs flows, allowing quantitative spatial comparisons. In particular, we ran the algebraic sum of the normalized raster values through the core zonal statistics plugin in QGIS, by overlapping the polygons of the areas of interest on each ES normalized raster. The results were compared between the *valli da pesca* and the non-managed part of the lagoon and expressed as a percentage of the overall capacity and flow, as well as the percentage of each ES capacity and flow of the *valli da pesca* with respect to the related values found in the open lagoon. All the analyses were performed using the software R 4.1.2 (R Core team, 2021) within the RStudio 2021.09.2 environment (RStudio Team, 2021).

2.3 ESs spatialization

In order to assess all the considered ESs with a spatially explicit approach, remote sensing imageries of the study area were collected and analyzed to obtain the land cover/land use map (LULC) on which ES mapping was based.

A machine-learning, scalable gradient-boosting decision trees XgBoost algorithm (Chen and Guestrin 2016) was used to classify land cover classes from multispectral and hyperspectral remote sensing data. Very High-Resolution multispectral satellite scenes (VHR), collected by Worldview-02, Worldview-03, and GeoEye-01 constellations, were granted by the European Space Agency Services via the "ESA On-Demand Restricted Data Access program" (see Supplementary Materials II for details).

For some uncovered areas, satellite tiles were pan-sharpened and mosaicked in a custom composition of RGB + NIR raster stack, along with AGEA aerial photograms at 20 cm resolution, granted by Regione Veneto.

The classification was performed on the multi-band images through the tuning of the XgBoost algorithm and was assessed with an accuracy test, resulting in a mean of 96% correct class prediction.

The classification and the following spatialization tasks have been performed with the open-source software QGIS 3.16 (QGIS Association: QGIS Geographic Information System, 2022), R 4.1.2 (R Core, 2022), and RStudio 2021.09.2 (RStudio Team, 2022).

3 Results

The assessment results are summarized in Table 2. The spatial distribution of each ES capacity and flow are illustrated in Supplementary Materials IV.

	Capacity			Flow		
Ecosystem service	Measure unit	Mean ± s.d.	Values range	Measure unit	Mean ± s.d.	Values range
Climate regulation	gC m^{-2} y^{-1}	60.86 ± 54.60	10.00 ÷ 245.00	gC m^{-2} y^{-1}	60.86 ± 54.60	10.00 ÷ 245.00
Water purification	% removed nitrogen	9.37 ± 11.67	0.00 ÷ 34.61	% removed nitrogen	9.37 ± 11.67	0.00 ÷ 34.61
Lifecycle support	0-1 scale	0.58 ± 0.23	0.30 ÷ 0.73	0-1 scale	0.31 ± 0.24	0.00 ÷ 1.00
Aquaculture	kg ha^{-1} y^{-1}	60.79 ± 59.99	0.00 ÷ 119.92	kg ha^{-1} y^{-1}	29.83 ± 34.77	0.00 ÷ 159.13
Hunting	n ha^{-1} y^{-1}	29.56 ± 36.56	0.02 ÷ 376.67	n ha^{-1} y^{-1}	6.12 ± 4.77	0.00 ÷ 20.94
Wild hedible herbs & honey production	edible plants kg ha^{-1} y^{-1}	0.20 ± 0.37	0.00 ÷ 2.03	edible plants kg ha^{-1} y^{-1}	0.00 ± 0.00	0.00 ÷ 0.00
	honey kg ha^{-1} y^{-1}	0.11 ± 0.01	0.00 ÷ 0.11	honey kg ha^{-1} y^{-1}	0.03 ± 0.10	0.00 ÷ 0.45
Tourism	attractiveness, 0-1 scale	0.49 ± 0.14	0.06 ÷ 1.00	tourists n y^{-1}	7.86 ± 34.07	0.00 ÷ 20.00
Information for cognitive development	attractiveness, 0-1 scale	0.30 ± 0.12	0.04 ÷ 0.89	students n y^{-1}	102 ± 470	0.00 ÷ 3640.0
Birdwatching capacity	attractiveness, 0-1 scale	0.33 ± 0.23	0.00 ÷ 1.00	birdwatchers n y^{-1}	1.47 ± 5.99	0.00 ÷ 38.67

Table 2 *Capacity and flow results in the* valli da pesca.

Overall, in the *valli da pesca* the highest values for carbon sequestration were detected in the areas where both saltmarshes and seagrasses are present, reaching values up to 245 gC$m^{-2}y^{-1}$. The mean carbon sequestration has been estimated at 60.86±54.60 gC$m^{-2}y^{-1}$, for a total amount of 2448 tonC y^{-1}, or 8982 tons of CO_2y^{-1} (Supplementary Materials IV, a). The water purification ES is represented by an average removal of 9.37% (±11.67%) of the nitrogen loadings; the greater the extent of the brackish lakes in the *valli*, the higher results the removal capacity. However, it must be noticed that this average estimate may likely be influenced by the water quality of the river water entering the *valli da pesca* (Salvetti et al. 2008; Bettiol et al. 2005) and must be considered as a first estimate of the average value for this ES.

Regarding lifecycle support, the capacity indicator is homogenously distributed with a mean of 0.58 (±0.23), while the flow indicator shows a mean of 0.31±0.24 (Supplementary Materials IV, c-d).

The aquaculture capacity of the study area results in a mean of 60.79±59.99 kg per hectare per year, but the flow of this ES varies greatly between different *valli da pesca* (Supplementary Materials IV, f) because it is influenced by several factors, both natural and social. Fish production is related to fish sowing, which in turn depends on wild fry availability; moreover, fish sowing is dependent on both fish survival to the previous years and precedent production. Based on the 2014-2019 period, the average total quantity of juveniles sown per year was 6'867'213, with a value per *valle da pesca* ranging between 26'000 and 2'793'033 individuals. On this basis, the mean sowing value was 1'227 (±958) juveniles per hectare per year. Thus, when faced with an average production of the whole area of 29.83 (±34.77) kg ha^{-1} y^{-1}, we must distinguish that the *valli da pesca* carrying out semi-intensive aquaculture show a value of 70.55 ± 23.78 kg ha^{-1} y^{-1} (e.g., *valli da pesca* n. 2, 22, 24), while those practicing only extensive aquaculture drop to a mean of 15.45 ± 16.35 kg ha^{-1} y^{-1}.

Regarding waterfowl hunting, during the period 2010-2019, about 280'000 huntable waterfowls have been wintering inside the *valli da pesca*, where a yearly average of 29.56 ± 36.56 huntable waterfowls per hectare were hosted. The highest number of waterfowls was consistently recorded during 2010-2019 in the *valli da pesca* n. 1, 7, 8, 19, 25, 26, and 27, while in the *valli da pesca* from n. 10 to n. 15, most exposed to nautical and tourist traffic, the number of censused waterfowls was lower (Supplementary Materials IV, g).

Regarding the hunting flow, in 2010-2019 the average catch was estimated at 38'404 (±7299) waterfowls per year, considering the total surface of the *valli da pesca*. On average, 6.12 ± 4.77 waterbirds ha^{-1} y^{-1} have been caught in the considered period. These catches were homogeneously distributed, with a maximum value of 20 catches ha^{-1} y^{-1} in the most confined *valli da pesca* 3, 4, 5, 6, 26, 27 (Supplementary Materials IV, h).

Although a homogeneous potential for provisioning edible wild plants and honey has been estimated in the *valli* area, harvesting occurs almost exclusively in the saltmarshes located in the open part of the lagoon, except from three *valli da pesca* – n. 5, 6, 8 – which host beehives (Supplementary Materials IV, j). Harvesting of *Salicornia* and other edible herbs has not been reported in the *valli da pesca* saltmarshes, apart from tiny quantities in occasional occurrences.

Tourism capacity results in all the areas with a mean attractiveness of 0.49 ± 0.14 (Supplementary Materials IV, k); nevertheless, very few of them are open for touristic trips, and not even regularly, which restricts the flow for tourism as well as for other cultural ESs (Supplementary Materials IV, l). The flow of tourists is limited to few *valli da pesca* in the Northern lagoon, involving Valle Lio Maggiore (5), Valle Cavallino (8), Valle Falconera (9), Valle Sacchetta (15), and Santa Cristina (17).

The capacity and flow for the ES information for cognitive development cover an even narrower extent: only the WWF Oasis Valle Averto (20), Valle Olivara (11), and Valle Liona (12) have a capacity higher than 0.5 (Supplementary Materials IV, m), but it resulted that the 3'154 students per year, who visit the *valli da pesca* for educational purposes, take part into guided tours in *valli da pesca* n. 12, 20, 23, 24 (Supplementary Materials IV, l).

Finally, the overall attractiveness for birdwatching is evenly distributed (Supplementary Materials IV, o) but the ES flow is not homogeneous and confirms that the Northern part of the lagoon is the most frequented for such outdoor activities, with 72 active birdwatchers – who spend a mean of 84.41 ± 21.36 hours per year birdwatching – converging in the nearing of the area n. 5, 11, 12 (Supplementary Materials IV, p).

Table 3 shows how much the total ESs capacity and flow assessed in all the *valli da pesca* is comparable to that observed in the open, not privately managed part of the lagoon. The most important contributions from the *valli da pesca* to the ESs supply of the open lagoon are noticeable for lifecycle support, aquaculture, hunting, information for cognitive development, and birdwatching.

Ecosystem service	***% vs. lagoon capacity***	***% vs. lagoon flow***
Climate regulation	12.79	12.79
Water purification	12.50	12.50
Lifecycle support	23.93	25.78
Aquaculture	12.79	31.68
Hunting	99.8	65.76
Wild hedible herbs	6.46	0.00
Honey production	83.48	1.82
Tourism	27.22	0.01
Information for cognitive development	25.97	23.88
Birdwatching	21.57	13.66

Table 3 *Proportion of capacity and flow assessed in the* valli da pesca *compared to each ES capacity and flow in the open lagoon.*

3.4 Aggregated ESs indexes analyses

Figure 2 and figure 3 show the normalized maps for the aggregated indicators of all the ESs capacity and the flow intensities, respectively. The sum of all the capacities shows that the highest values have been registered inside the valli da pesca which maximize both aquaculture and hunting (Fig. 2 n. 1, 2, 4, 26, 27).

As regards the sum of all the flows, the highest values have been recorded especially where provisioning and cultural ESs flows are the highest as well, e.g., Valle Grassabò, Valle Lio Maggiore, and Valle Dragojesolo (Fig. 3 n. 2, 5, 7).

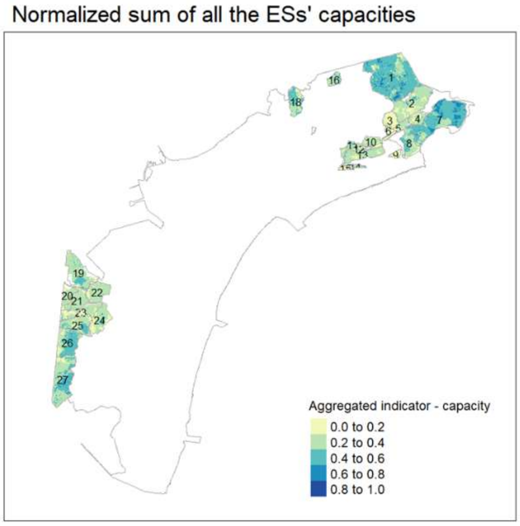

Figure 2 *Spatialized total capacity indicator, as the sum of all the ESs' capacities*

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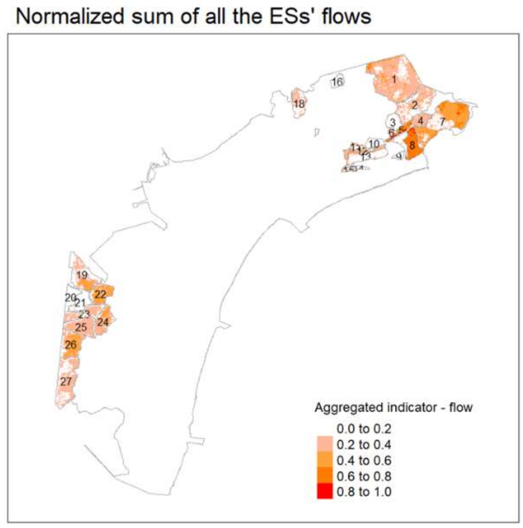

Figure 3 *Spatialized total flow indicator, as the sum of all the ESs' flows*

In general, the extension of the area where the sum of all the ESs' capacity is higher than the sum of all the ESs' flow is 71.1 km². In contrast, the area where the sum of all the assessed ESs' flow results greater than the sum of all the ESs' capacity is 23.4 km² (Fig. 4)

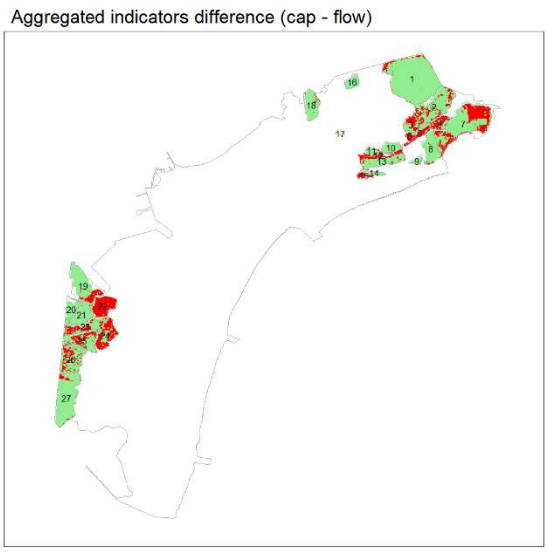

Figure 4 *Spatialized capacity – flow difference (C-F). Green = C > F; red = C < F.*

Spatialized capacity — flow difference (C–F). Light-colored areas, C > F; dark-colored areas, C < F

Discussion

The lagoon of Venice is a complex social-ecological system with a historical link between natural habitats and human activities, which is particularly strong for the *valli da pesca*. Despite being "artificially maintained", the *valli da pesca* conserved the typical features and related ecological processes of transitional environments that the open lagoon has progressively lost, especially due to erosion and relative sea level rise (Day et al. 1998;

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Madricardo and Donnici 2014). For these reasons, it would be interesting to analyze the possible role of the *valli da pesca* in terms of ESs.

The ESs approach has already proven to be effective in visualizing and assessing the contribution to people of similar man-managed ecosystems, and in suggesting sustainable management strategies as well (Gaglio et al. 2019; Aschonitis et al. 2016; Weitzman 2019; Walton et al. 2015). In this study, we proposed for the first time the assessment of multiple ESs in the *valli da pesca* of the Venice lagoon to better understand their possible ecological role within the context of the entire lagoon environment. Obtained results highlighted a non-negligible contribution of the *valli da pesca* to the entire supply of ESs of the Venice lagoon.

Regarding carbon sequestration, for instance, about 12% of the CO_2 sequestered every year by the lagoon is due to saltmarshes and seagrasses located inside the *valli da pesca*, where these habitats are preserved by different impacts, erosion, and trampling. Also, the mean water purification through denitrification is higher inside the boundaries of the *valli da pesca* than in the outer part of the lagoon. Indeed, it has been estimated that the open lagoon can remove about 10.08% of nitrogen loadings (Rova et al. 2022) but no area reaches the maximum values recorded in some lakes located inside the *valli da pesca*. These findings are in accordance with those of other studies that have focused on water management for extensive aquaculture (Walton, Vilas, Coccia, et al. 2015; Gamito 1997). This result, however, should inspire further research. Indeed, extensive aquaculture is today prevalent in *the valli da pesca,* meaning that fish feed on the available food they naturally find in the *valle da pesca* without the need to add feed artificially. In addition, the density of fish is such that the brackish lake ecological processes can process naturally dead organic matter and nutrient loadings, avoiding the risk of eutrophication (Anras et al. 2010; Costa Pierce 2002). If things are going to change, the denitrification process would also be influenced by several factors, including the water quality of the rivers entering the *valli da pesca*, and the organic matter loading that can increase in response to eventual higher densities of fish and waterbirds inside the lakes. Thus, the denitrification process is worthy of further experimental field studies. New data and models about this aspect, along with an exploration of the most likely future trends, may prove extremely useful to better depict this regulating ES not only at the local scale but also for other similar Heavily Modified Water Bodies, such as in the Po River Delta, in the Marano lagoon or other areas along the Adriatic coasts.

The most confined parts of the lagoon were identified centuries ago as the most suitable places for fish farming and hunting purposes, as confirmed more recently for fish (Cavraro et al. 2017; Brigolin et al. 2014) and waterfowl (Arzel et al., 2006; Scarton and Bon, 2009; Guillemain et al., 2013). Within this context, the ES lifecycle support provided by the *valli da pesca* turned out to be quite significant compared to the open lagoon, confirming the important ecological role still played by these areas despite the presence of levees and embankments. However, the naturally recruited fish is not sufficient for meeting the *valli* requirements, to the point that today the aquaculture ES in the *valli da pesca* of the Venice lagoon depends on personal, social, and economic factors, which lead the owner to decide whether and how much fish to sow. As a consequence, the practice of fishing wild fry in the lagoon and then sowing them inside the *valli da pesca* is the only method that grants the biomass actually hosted by each area. From such a point of view, besides enhancing aquaculture productivity, this tradition could be seen as a good practice, capable of maintaining some species' presence in the long run. On the one hand, fry fishery is strictly regulated and controlled, being entrusted to only a very few licensed operators who annually update the quota that can be caught in order not to affect lagoon fish population dynamics (Fortibuoni et al. 2014; Granzotto et al. 2001).

On the other hand, since fish migration and the recruitment processes taking place in the open lagoon play a fundamental role in sustaining fish lifecycle (Lanzoni et al. 2021; Scapin et al. 2022; Cavraro et al. 2017) and the aquaculture ES in the *valli da pesca,* we could also affirm that the aquaculture ES in the *valli da pesca* could positively affect the regulating ES of lifecycle support in the entire lagoon. As happens for waterbirds, the persistence of suitable habitats in the *valli da pesca* depends on human maintenance, which in turn depends on economic resources from the provisioning ESs incomes. This generates positive feedback that raises considerations about how a provisioning ES can also support other ESs belonging to a different category, in agreement with the findings of other authors (Liquete et al. 2016; Grizzetti et al. 2019)

The extensive aquaculture practiced today in the *valli da pesca*, moreover, can be considered quite sustainable, considering that the production value of 60 kg ha^{-1} y^{-1} falls in the range of 45 - 110 kg ha^{-1} y^{-1} reported by (Koutrakis et al. 2007) for extensive aquaculture in Mediterranean lagoon, but is quite lower than 150 kg ha^{-1} y^{-1} expected for a desirable production in a typical Italian *valle da pesca*, according to Ravagnan (1982) and Shang (1982).

Since the aquaculture ES in the *valli da pesca* is getting less worthwhile in the last decade, as shown by the data, other activities have started to play a key role. Among them, the most important is waterfowls hunting, which also depends on both natural and anthropogenic factors. To say to what extent the great capacity of bird attraction is granted by the *valli da pesca* environment itself, or whether it is due to management choices, is difficult. Indeed, to attract waterfowl and increase hunting opportunities the managers regulate water regimes, construct mild sloping islands, take care of windbreak hedges made of reeds and tamarisks, and often spread millet or grains.

The management which aims to maximize hunting ES is possibly influencing the capacity and the flow of this ES not only inside, but also outside the boundaries of the *valli da pesca*. Our assessments found that most huntable waterfowl censused in the lagoon are reaching for the *valli da pesca* during their migration, where they rest, feed, and breed as well (at least some species). Such evidence is in accordance with other authors, who reported about the high importance of the *valli da pesca* for waterbird populations, whereas the lagoon is losing suitable habitats (Scarton 2017; AFV 2020) Also, the waterfowls hunting flow in the lagoon results strongly related, for timing and catches as well, to the flow happening inside the *valli*. As a comparison, the hunting flow in the lagoon is estimated from 12'635 to 12'770 catches per year and takes place just in proximity of the allowed hunting blinds, where the catches have a mean of 4.44 ± 1.56 per hectare per year. Even if the distribution of this flow is homogeneous in the whole lagoon, the highest values have been detected in the blinds between contiguous *valli da pesca*, in the North-Eastern and Southern parts of the lagoon. Indeed, waterfowl hosted inside the valli da pesca, while moving across different *valli da pesca* or from a *valle da pesca* to another place just outside, represent the "stock" on which not only the *valli da pesca* hunters, but also the "open lagoon" hunters rely.

Another example of driving relationships between different ESs is the substantial contributions of the *valli da pesca* to the ESs that depend on the consistency of the birds presence. For example, the management which aims to attract the highest possible number of huntable waterfowls is possibly also dragging the attractiveness for cultural ESs, especially for birdwatching. Accordingly, many aquatic birds are attracted into the *valli da pesca* managed environment and this also can increase the overall capacity, as bird movements between the *valli da pesca* and the open lagoon create a positive side-effect in increasing attractiveness to birdwatchers, tourists, and hikers even outside the *valli da pesca* boundaries.

However, despite the high overall capacity for all cultural ESs in the *valli da pesca*, the flow is strongly shaped by accessibility and inclusiveness, ending up with flow occurring just on a few areas. Nevertheless, this restricted flow should not be read as totally negative: the *valli da pesca* are seen as extremely attractive especially for the preservation of lagoon landscapes and fauna in a quiet and uncrowded space. This consideration should make one think carefully about whether, how, and how often the *valli da pesca* could be open for touristic and educational visits. Similar considerations have also been aroused on different environments by other authors (Villamagna et al., 2015; Drescher et al., 2017; Drescher and Brenner, 2018), who proposed to give more support to private natural areas for enhancing conservation and educational purposes, provided that excursionists' entrances must be controlled.

Management initiatives that also take these perspectives into account should seek to harmonize with the current situation of the *valli da pesca*, seeing that the difference between capacity and flow aggregated indexes shows that the majority of the *valli da pesca* display a total capacity higher than the total flow (figs. 2, 3, 4). Just a few zones with the highest flows of mediated ESs (*sensu* Rova and Pranovi 2017) stand out amongst other areas: in fact, some *valli da pesca* where hunting ES' flow is, on average, more important than the aquaculture production display an aggregated flow index slightly higher than the ESs' capacity. This may be because waterfowls hunting relies on a moving resource so that the catches in one *valle da pesca* can affect the waterfowls which have been censused in another *valle* and, consequently, represent the capacity assessed on a different place, but not strictly linked to it.

The analysis of the contribution of the *valli da pesca* sub-system to the whole transitional ecosystem confirms that the *valli da pesca* are highly significant to the whole Venice lagoon. The comparison of the ESs' aggregated index between the open part of the lagoon and the *valli da pesca* brings out that the latter, despite covering just 17% of the total lagoon, play an important role in terms of ESs contributions: 38% of the capacity and 24% of the flow in comparison to the open lagoon capacity and flow, respectively.

This non-negligible contribution to ESs, habitats, and landscape features conservation, makes the *valli da pesca* a good example of effective ecosystem-based management of Heavily Modified Water Bodies, representing a good example to set up sustainable management for similar productive areas in the Mediterranean.

Like little lagoons that are artificially managed, the *valli da pesca* are regulated by a private regime that, on the one hand, denies the access and minimizes cultural ESs flow, but on the other hand, conserves the landscape, the ecological processes and ESs provided by them. The open lagoon receives from them the benefits of a spill-over effect, especially for lifecycles support, aquaculture, hunting, and birdwatching ESs. For these ESs, the *valli da pesca* provide ESs that benefit a wider community, spread into a larger spatial scale than that the ES are generated at. In addition, the *valli da pesca* act as a buffer area between the land and the open lagoon, in particular for climate regulation and water purification, as the results of carbon sequestration and nitrogen removal show.

The role of *valli da pesca* as buffers and as conservation opportunities also leads us to consider how important it might be to restore a buffer strip between the land and the lagoon, which has been lost in some areas. As the *valli da pesca* proved to be effective in maintaining saltmarshes, reed meadows and ecological

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gradients, similarly it might be useful to consider ecological restoration efforts in areas that are most affected by the transfiguration of the original lagoon landscape (Feola et al., 2022).

Since the connection between the lagoon and *valli da pesca* persists, we must consider the possible evolution of such interconnected systems as a whole. The lagoon now subjected to manifold pressures from anthropic activities (Fortibuoni et al. 2015; Zucchetta et al. 2021; Anelli Monti et al. 2021; Solidoro et al. 2010) that are likely going to increase (Jennerjahn and Mitchell 2013). The adaptations to such impacts, as well as to climate change and sea-level rise effects, in the long run, might modify the lagoon hydrodynamics and the sea-lagoon connectivity, threatening the *valli da pesca* and so their ESs supply (Solidoro et al. 2010; Cristiano and Gonella 2020).

Eventually, we suggest that decisions about the MOSE barrier functioning must be well pondered to not put the *valli da pesca* at risk of being endangered. Considering that the *valli da pesca* are continuing to exchange energy and matter with the lagoon, such equilibria can be at risk in the context of a "regulated lagoon". The MOSE system (with its mobile barriers at the inlet) controls the marine water flow to mitigating the effect of climate change and sea-level rise on cultural heritage, but could conversely threat the daily exchange of water in the most confined part of the lagoon, and the *valli* waterfronts as a consequence.

Indeed, it is very important to preserve the cultural heritage of the historic center of Venice and the islands so as not to lose cultural ESs and economic activities flowing from them. Nevertheless, we are facing the possibility that the lagoon will remain closed for longer periods of time. According to Umgiesser (2020) and Lionello et al. (2021), the period of closure of the mobile barriers is very likely to grow up to 3 weeks per year by the end of 2050, and up to 2 months per year by 2080. This would mean affecting the sea-lagoon connectivity, the lagoon hydrodynamics, and landscape evolution patterns, as several studies have already argued (Ghezzo et al. 2010; 2011; Pérez-Ruzafa et al. 2019). Such a perspective could put the *valli da pesca* at risk: lower connectivity with the sea can affect the fish fry availability for the aquaculture ES even more than today. In addition, a lower frequency of exchanges through the inlets is expected to worsen the water quality, nutrient concentration (Solidoro et al. 2005), and microcirculation (Ghezzo et al. 2010) involved in the processes on which the regulating ESs are based.

In light of our results, it must be carefully considered that losing the *valli da pesca* might represent an issue for the entire community because of their contribution to conserving habitats and providing regulating, provisioning, and cultural ESs. This trade-off perspective takes great importance, especially in the light of future scenarios, including climate change, subsidence, and management of health problems, which claim a responsible attendance of the lagoon.

Conclusions

This work has shown, by using quantitative indicators, the spatial distribution of ESs capacity and flow within the managed *valli da pesca* of the lagoon of Venice. The multiple ESs approach enhanced the areas where capacity and flow have the highest values. It also revealed that the capacity is not always and everywhere fully granted to translate itself in a flow towards the local population due to different accessibility and availability of some places. Therefore, the comparison between different areas of the same wide ecosystem highlights that,

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although the capacity of the provided ESs tends to be overall high, a multiplicity of social and behavioral factors influence the relative flows.

In this context, confirmation of the usefulness of assessing the value of ESs in ecosystem management is given (Costanza 2006), especially when a trade-off must be accomplished between the moral duty to preserve and emphasize regulation and support services, and the need to build on the economic revenues that come from provisioning ESs. This dynamical network stimulates to continue the research with a modeling approach, which could consider behavioral, social, and economic factors that act as fulcrums for decision-making.

Increasing the knowledge about the *valli da pesca* and other similar socio-ecological systems can help to enlighten not only the relationships between ESs, landscape, and management choices, but also to rethink the interaction between the environment, the society, and the institutions involved in the Venice lagoon ecosystem.

The assessment of ESs, such as lifecycle support, hunting, and birdwatching, showed that the open side of the lagoon is often strictly related to the management of the most confined areas, corroborating the hypothesis that the *valli da pesca* play an important role in defining the ESs pattern of the whole lagoon of Venice. Indeed, the *valli da pesca* represent a buffer between the aquatic ecosystem of the lagoon and its land boundaries, mitigating anthropogenic pressures; in addition, their provisioning and cultural ESs also show a series of positive side-effects in the open lagoon.

Thus, it is of great importance to take them into account to fully comprehend the Venice lagoon ecosystem, especially when investigating the effects under different health, social and economic scenarios, as well as when facing climate change and sea-level rise.

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Supplementary materials I

Scheme of a valle da pesca

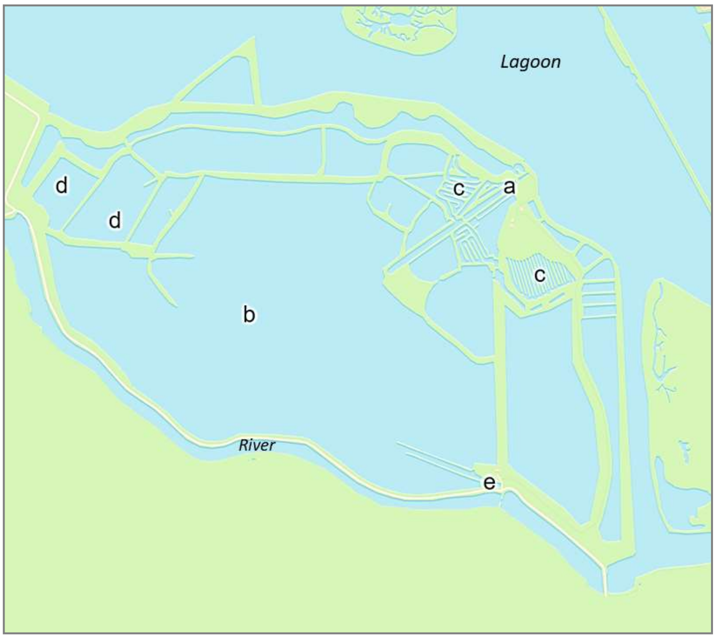

Figure S.M. I - 1 *Sketch map of a* valle da pesca *structure. a) brackish water inlet; b) brackish lake; c) winter fishponds; d) freshwater lakes; e) freshwater intake.*

Supplementary materials II

Remote sensing images

The following tables list the remote sensing images analyzed in this work. Very High-Resolution (VHR) satellite imageries have been granted by the European Space Agency (ESA) via the ESA On-Demand Restricted Data Access program (Tab. S. M. II - 1). Aerial photograms has been granted by Regione Veneto, "Direzione Pianificazione Territoriale, U.O. Pianificazione territoriale strategica e cartografia" (Tab. S. M. II - 2).

Satellite scenes

Collection data	*Satellite/sensor*	*bands*	*resolution*	*clouds coverage*	*off-nadir:*
2019/07/01	WV 02	8-bands	40 cm	0.0%	13.0°
2019/01/10	WV 02	8-bands	40 cm	1.0%	12.6°
2019/11/07	WV 03	8-bands	32 cm	0.0%	8.1°
2018/11/29	GE 01	4-bands	51 cm	0.0%	26.7°

Table S. M. II - 1 VHR satellite imageries characteristics

Collection data	*Flight name*	*bands*	*resolution*
2018	REVEN 2018	3-bands (RGB)	20 cm
2019	AGEA REVEN	3-bands (RGB)	20 cm

Table S.M. II - 2 Aerial photograms characteristics

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Supplementary materials III

ESs assessment methodology

ES category	ES	Assessment methodology	
		Valli da pesca	Lagoon
Regulating & maintenance	**Climate regulation** Carbon sequestration rate by saltmarshes and seagrasses [gC m-2 y-1]	*Capacity/flow methodology* The spatial distribution of saltmarshes in the valli da pesca has been achieved with a machine learning classification of very high-resolution satellite and aerial imageries (listed in table S. M. II - 1), with calibration points collected during field work. Average saltmarshes' carbon sequestration rate based on literature data (Day et al. 1998; Roner et al. 2015) The spatial distribution of seagrasses meadows has been achieved by photointerpretation of very high-resolution satellite imageries (WV-2A, GeoEye), with the support of UAV aerial imageries and visual census field surveys data collected during periodical visits within the valli da pesca. Seagrasses' C sequestration rate based on species-specific belowground production and organic C content (Sfriso, Facca, and Ceoldo 2004; Sfriso and Francesco Ghetti 1998b; Sfriso, Facca, and Ceoldo 2007; Sfriso and Facca 2007; 2007) According to the literature, capacity and flow indicators of regulating ESs have been considered coincident (Schröter et al. 2014; Hein et al. 2006b).	*Capacity/flow methodology* The saltmarshes spatial distribution in the open, not privately managed part of the lagoon has been retrieved from the saltmarshes map achieved in 2003 by Magistrato alle Acque. Average saltmarshes' carbon sequestration rate based on literature data (Day et al. 1998; Roner et al. 2015) The seagrasses distribution refers to the seagrasses map in 2017 (Provveditorato OO. PP. del Triveneto; SELC, 2018). Seagrasses' C sequestration rate based on species-specific belowground production and organic C content (Sfriso and Facca 2007; Sfriso, Facca, and Ceoldo 2007; 2004; Sfriso and Francesco Ghetti 1998b) According to the literature, capacity and flow indicators of regulating ESs have been considered coincident (Schröter et al. 2014; Hein et al. 2006b).
Regulating & maintenance	**Water purification** Percentage of Nitrogen load removed by denitrification process in brackish water [%]	*Capacity/flow methodology* Nitrogen removal capacity of the brackish lakes estimated in proportion to the lake extension and the turnover time of the volume of water in the saltwater basin, based on experimental data about denitrification measured by Ravagnan (1982) in other valli da pesca managed in the same way as the valli da pesca considered in this study. According to the literature, capacity and flow indicators of regulating ESs have been considered coincident (Schröter et al. 2014; Hein et al. 2006a).	*Capacity/flow methodology* N load removed through denitrification estimated based on residence time, according to the equation proposed by Seitzinger et al., (2006) for estuarine systems. Residence time calculated with SHYFEM model (Umgiesser et al. 2004) referred to the year 2014 (courtesy of G. Umgiesser, ISMAR-CNR). According to the literature, capacity and flow indicators of regulating ESs have been considered coincident (Schröter et al. 2014; Hein et al. 2006a).

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ES category	ES	Assessment methodology	
		Valli da pesca	Lagoon
Regulating & maintenance	**Lifecycle support** 0-1 scale	Capacity methodology Attractiveness for migratory waterbirds related to the presence of waterbirds lifecycle support factors (saltmarshes, freshwater presence, shrubs, and herbaceous vegetation) that enhance the suitability for resting and molt changing (Korschgen et al., 1985; Havera et al., 1992; Arzel et al., 2006; Hatziiordanou et al., 2019), retrieved from aerial imageries photo interpretation and geospatial layers data. Estimated distribution in the most confined part of the lagoon of juveniles fish biomass [kg ha-1y-1] of the foodweb group "Mugilidae", retrieved from a spatialized foodweb model of the Venice lagoon (Anelli Monti et al. 2021a) Fish and waterbirds lifecycle support capacities were normalized to a 0-1 scale, then aggregated. *Flow methodology* Waterbirds: Average number of migratory waterbirds [n ha-1y-1] wintering in the valli da pesca, according to the last ten years' waterbirds annual censuses (AFV 2020). Fish: Fry biomass [kg ha-1y-1] sown in the valli da pesca for the species Mugil cephalus, Chelon labrosus, Chelon aurata, Chelon saliens and Chelon ramada according to the official management data. Waterbirds and fish lifecycle support capacities were normalized to a 0-1 scale, then aggregated.	*Capacity methodology* Attractiveness for migratory waterbirds related to the presence of waterbirds lifecycle support factors (saltmarshes, freshwater presence, shrubs, and herbaceous vegetation) that enhance the suitability for resting and molt changing (Korschgen et al., 1985; Havera et al., 1992; Arzel et al., 2006; Hatziiordanou et al., 2019), retrieved from aerial imageries photo interpretation and geospatial layers data. Estimated distribution of juveniles fish biomass [kg $ha^{-1}y^{-1}$] of the foodweb group "Mugilidae", retrieved from a spatialized foodweb model of the Venice lagoon (Anelli Monti et al. 2021a) Fish and waterbirds lifecycle support capacities were normalized to a 0-1 scale, then aggregated. *Flow methodology* Waterbirds: Average number of migratory waterbirds [n $ha^{-1}y^{-1}$] wintering in the open and not privately managed part of the lagoon, according to the last ten years' waterbirds annual censuses (AFV 2020). Fish: Fry biomass [kg $ha^{-1}y^{-1}$] distribution estimated in the lagoon, retrieved from a spatialized foodweb model of the Venice lagoon (Anelli Monti et al., 2021). Waterbirds and fish lifecycle support capacities were normalized to a 0-1 scale, then aggregated.
Provisioning	**Fish production** Fish biomass [kg $ha^{-1}y^{-1}$]	*Capacity methodology* Potential fish biomass hosted by each *valle da pesca* (kg ha^{-1} y^{-1}), estimated basing on an Ecopath-Ecosim with Ecospace spatialized foodweb model (Anelli Monti et al. 2021a). *Flow methodology* Average fish catches per hectare of brackish water surfaces per year (kg ha^{-1} y^{-1}) in the valli da pesca, according to the 2010-2019 official data (Regione Veneto).	*Capacity methodology* Sum of the biomass of fish functional groups targeted by artisanal fishing, calculated by an Ecopath-Ecosim with Ecospace spatialized foodweb model (Anelli Monti et al. 2021). *Flow methodology* Average fish catches from artisanal fishing per hectare of water per year (kg ha^{-1} y^{-1}), calculated by an Ecopath-Ecosim with Ecospace spatialized foodweb model (Anelli Monti et al. 2021).
Provisioning	**Waterfowl hunting** Number of huntable waterbirds [n $ha^{-1}y^{-1}$]	*Capacity methodology* Mean number of huntable waterbirds per hectare per year wintering in the valli da pesca, according to the time series of waterbirds censuses from 2010 to 2019 (Associazione Faunisti Veneti, 2020), spatially interpolated by Dirichlet tessellation. *Flow methodology* Average number of waterbirds catches calculated on 2010 - 2020 hunting registries data of the *valli da pesca*, spatialized considering the effective hunting reserve area.	*Capacity methodology* Mean number of huntable waterbirds per hectare per year wintering in the open part of the lagoon, according to the time series of waterbirds censuses from 2010 to 2019 (Associazione Faunisti Veneti, 2020),spatially interpolated by Dirichlet tessellation *Flow methodology* Estimated considering the catches per capita (n. birds/person/hunting trip), the hunting effort (n. of hunting trips/person/year) and the proportion of active hunters in the lagoon outside the hunting farms. Data were gathered through 84 interviews to hunters and by asking the total number of hunters active in the lagoon to the "Ambito Territoriale di caccia VE5" in 2020. Spatial distribution based on the location of the hunting blinds in the lagoon (Regione Veneto, 2019), weighted by the average effective shotgun range.
Provisioning	**Wild herbs & honey**	*Capacity methodology* Kg of *Salicornia spp.* biomass that could be harvested in the *valli da pesca*, per year, estimated from the	*Capacity methodology* Kg of *Salicornia* biomass that could be harvested in the lagoon, per year, estimated from the vegetational patches

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ES category	ES	Assessment methodology	
		Valli da pesca	**Lagoon**
		vegetational patches distribution in the valli da pesca retrieved with both visual census method and through the identification of their predictive range in R, G, B bands reflectance values, filtered through a cut-off NDVI value calculated from aerial and satellite imageries (listed in Supplementary Materials II). Kg of honey potentially produced per unit area in the valli da pesca, considering the *Limonium sp.* inflorescence cover in the patches (Fantinato and Buffa 2019) and the ratio between the number of sea lavender flowers and the grams of honey that can be obtained from them. *Flow methodology* Kg of harvested edible plants reported by 2020 market data (courtesy of Veneto Agricoltura), by interviewed local people and restaurant chefs. Kg of produced sea-lavender honey witnessed by 5 interviewed beekeepers.	distribution in the open lagoon retrieved with both visual census method and through the identification of their predictive range in R, G, B bands reflectance values, filtered through a cut-off NDVI value calculated from aerial and satellite imageries (listed in Supplementary Materials II). Kg of honey potentially produced per unit area in the lagoon, considering the *Limonium* inflorescence cover in the patches (Fantinato and Buffa 2019) and the ratio between the number of sea lavender flowers and the grams of honey that can be obtained from them. *Flow methodology* Kg of harvested edible plants reported by 2020 market data (courtesy of Veneto Agricoltura), by interviewed local people and restaurant chefs. Kg of produced sea-lavender honey witnessed by 5 interviewed beekeepers.
Cultural	**Tourism**	*Capacity methodology* Tourism attractiveness map, assessed by a survey carried out in the second half of 2019. Spatialization achieved by considering the attractiveness factors evaluated by tourists in the questionnaires, namely saltmarshes presence, the possibility to observe birds and fauna, good water quality, and the chance to contemplate natural terrestrial habitats in the *valli da pesca*. Each element was weighted to depict the interest declared by people and normalized to a 0-1 scale index. *Flow methodology* Number of people who, during a year, have passed at least one night in one of the accommodation facilities within the *valli da pesca*.	*Capacity methodology* Tourism attractiveness map, assessed by a survey carried out in the second half of 2019. Spatialization achieved by considering the attractiveness factors evaluated by tourists in the questionnaires, namely saltmarshes presence, the possibility to observe birds and fauna, good water quality, and the chance to contemplate natural terrestrial habitats in the lagoon. Each element was weighted to depict the interest declared by people and normalized to a 0-1 scale index. *Flow methodology* Number of people visiting the lagoon in the year 2019, excluding the historical center of Venice, obtained from tourism and transportation operators (public transport company AVM-ACTV S.p.a., 17 private navigation companies, 9 ecotourism associations).
Cultural	**Information for cognitive development**	*Capacity methodology* The natural factors that enhance touristic attractiveness assessed by a survey carried out in the second half of 2019 have been mapped along with the inclusivity for the necessities of people with disabilities. The resulting map was normalized to a 0-1 scale. *Flow methodology* Number of persons that yearly attend outdoor educational activities or guided one-day trip in the valli da pesca, as reported by the valli da pesca managers, 6 touristic guides and 6 major ecotourism associations.	*Capacity methodology* The natural factors that enhance touristic attractiveness assessed by a survey carried out in the second half of 2019 have been mapped along with the inclusivity for the necessities of people with disabilities. The resulting map was normalized to a 0-1 scale. *Flow methodology* Number of persons that yearly attend outdoor educational activities or guided one-day trip in the lagoon, as reported by 6 touristic guides and 6 major ecotourism associations.
Cultural	**Birdwatching**	*Capacity methodology* Birdwatching attractiveness normalized map, scaled 0-1, based on the factors reported as important by 30 interviewed birdwatchers, namely the presence of pedestrian paths, saltmarshes presence, birds nesting areas in the visual field, and high probability for observing birds. All these factors were summed up to obtain a normalized attractiveness map. *Flow methodology* Average number of active birdwatchers [n y^{-1}] calculated from the observers' activity trend, recorded from 2010 to 2020 in the Italian birdwatchers' database (https://www.ornitho.it/).	*Capacity methodology* Birdwatching attractiveness normalized map, scaled 0-1, based on the factors reported as important by 30 interviewed birdwatchers, namely the presence of pedestrian paths, saltmarshes presence, birds nesting areas in the visual field, and high probability for observing birds. All these factors were summed up to obtain a normalized attractiveness map. *Flow methodology* Average number of active birdwatchers [n y^{-1}] calculated from the observers' activity trend, recorded from 2010 to 2020 in the Italian birdwatchers' database (https://www.ornitho.it/).

Table S.M. III - 1 *ESs assessment methodologies applied in this study.*

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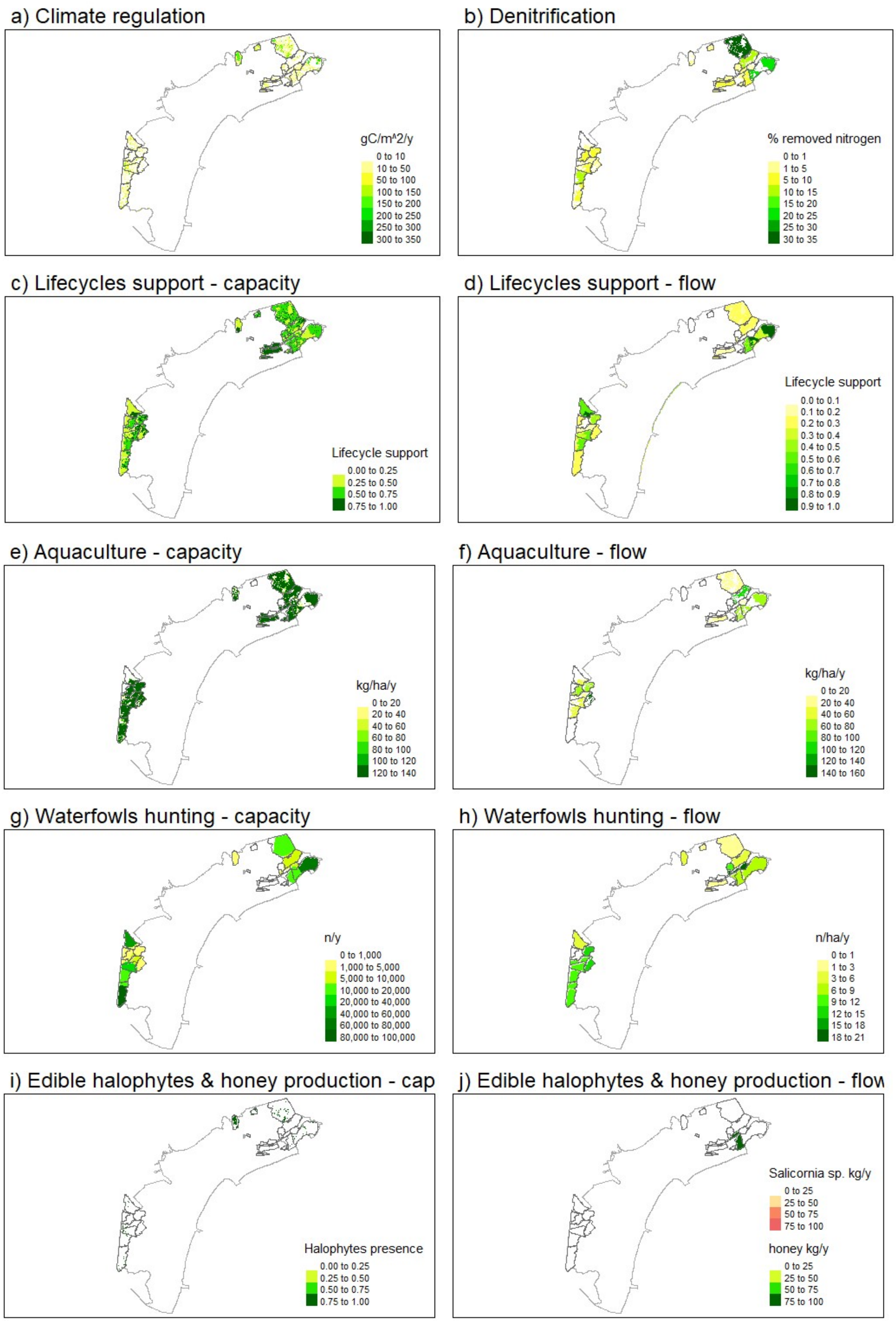
Supplementary materials IV



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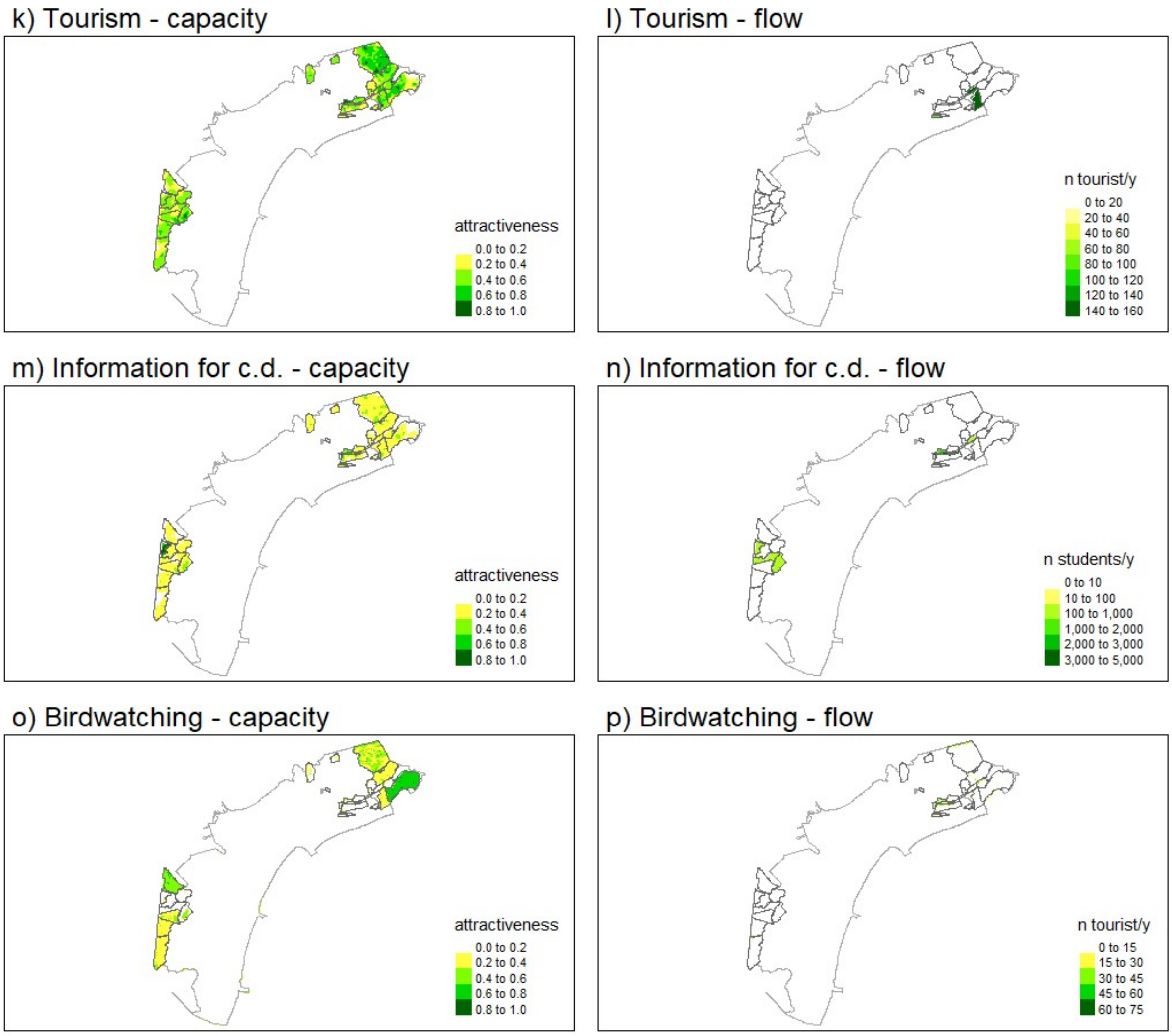

Fig. S.M. IV *Results of the ESs assessment. a), b), c), d) refer to regulating and maintenance ESs. e), f), g), h), i), j) refer to provisioning ESs. k), l), m), n), o), p) refer to cultural ESs.*