Ecosystem Services 64 (2023) 101568

Contents lists available at ScienceDirect

Ecosystem Services

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

Full Length Article

Sustainability threshold for multiple ecosystem services in the Venice lagoon, Italy

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ARTICLE INFO

Keywords:
Ecosystem services bundles
Sustainability
Transformative change
Transitional waters ecosystems
Ecosystem-based management
Ecosystem services mismatches

ABSTRACT

One of the biggest challenges for ecosystem services (ES) science is to make the concept operational for decision-making purposes. The capacity to understand the long-term sustainability of multiple ES is still limited, while being highly needed to improve the management of natural resources. This work aims to use ES, and particularly the assessment of their capacity and flow, to explore the sustainability of the ES provision in the coastal social-ecological system of the Venice lagoon, Italy, by adopting a spatially explicit approach. By applying multivariate analysis on the ES maps, a zonation is derived which reflects the different bundles of ES in the lagoon. A new approach to analyze the ES bundles is presented, which determines their degree of sustainability. Building on the rationale that not all combinations of ES are desirable for the long-term maintenance of ES capacity, a 'sustainability threshold' for multiple ES is proposed. This threshold corresponds to a balance between ES capacity and flow, and to a balance between the flow of regulating ES and the flow of ES mediated by human activities. The results show that about 53% of the lagoon's surface is exploited to a level that falls beyond the 'sustainability threshold' and thus should be considered in an unsustainable condition. This reveals the need to intervene to change the patterns of ES uses in some areas of the lagoon, to enjoy the benefits offered by the ecosystem without impairing its capacity to provide them. Some potential directions for change are discussed, moving towards a more sustainable management of the lagoon social-ecological system.

1. Introduction

It is now well established that human well-being is highly dependent on the structure and functioning of ecosystems, which are capable to provide a variety of ecosystem services (ES) at the same time (Burkhard et al., 2012a; Costanza et al., 2017, 1997; Daily, 1997; Díaz et al., 2018; IPBES, 2019; MA, 2005). In the past few decades, ES science has progressed towards a more holistic and systemic perspective, in which broad sets of ES are taken into account and jointly analyzed (Bennett et al., 2009). This is well represented by the concept of ES bundles, which are defined as sets of ecosystem services that repeatedly appear together across space or time (Raudsepp-Hearne et al., 2010). This perspective has led to acknowledge that synergies and tradeoffs among ES play an important role in determining the different combinations of multiple ES that we observe in social-ecological systems (Bennett et al., 2009; Cord et al., 2017; Lee and Lautenbach, 2016; Meacham et al., 2022; Mouchet et al., 2014; Queiroz et al., 2015; Raudsepp-Hearne et al., 2010; Renard et al., 2015; Spake et al., 2017). The way we make use of ecosystems, especially in case of intensive exploitation of few ES, can deeply affect their capacity to provide other ES, and eventually determine an overall loss of ES (Foley et al., 2005).

These well-established evidences suggest that the bundles of ES can be interpreted from a sustainability perspective. ES result from a mix of ecological and anthropogenic inputs (Burkhard et al., 2012a; Burkhard et al., 2012b; Costanza et al., 2017), the combination of which can result in more or less sustainable uses in the long term (Balvanera et al., 2022). Improving our understanding of these dynamics is necessary for a better management of natural resources (Bennett et al., 2015). This means to shift from a descriptive application of the ES concept to a judgment on the ES' sustainability, in which to evaluate whether the current levels of ES usage are compatible with the provision of multiple ES over the long term (Biggs et al., 2012; Geijzendorffer et al., 2015; Schröter et al., 2017). The importance of this shift is also shown by some of the critiques to the ES concept, which highlight that its interpretation can dramatically depart from the concept of sustainability. To cite a few, the anthropocentric and utilitarian representation of human-nature relationships (Muradian and Gómez-Baggethun, 2021), the commodification of Nature and promotion of Nature's exploitation (Schröter et al.,

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https://doi.org/10.1016/j.ecoser.2023.101568
Received 19 April 2023; Received in revised form 26 September 2023; Accepted 5 October 2023

2014b), and the fact that unsustainable uses of natural resources are often included in ES assessments (Schröter et al., 2017). According to Muradian and Gómez-Baggethun (2021), this "utilitarian environmentalism" is one of the ultimate reasons why the ES concept is failing to make the difference in reversing the current ecological crisis. Reconnecting ES with the overarching goal of sustainability can contribute to overcome these limitations, because it brings on the foreground the ethical principles to which we must appeal to achieve a transformational change (Schröter et al., 2017). This indeed represents a key frontier for ES research, which can enhance the uptake of ES studies in decision making (Bennett and Chaplin-Kramer, 2016).

To this end, the distinction between capacity, flow and demand of ES can be particularly useful because it allows to disentangle different facets of ES (Burkhard et al., 2014, 2012b; Schröter et al., 2014a; Villamagna et al., 2013). Following the definition from Villamagna et al. (2013), the *capacity* refers to the ecosystem's potential to deliver ES, the *flow* refers to their actual production or use and the *demand* refers to the amount of ES required or desired by society. ES capacity, flow and demand can be sensitive to different drivers of change and thus be mismatched over space and/or time, or be subject to different trends, with consequences in terms of sustainability (Burkhard et al., 2012b; Geijzendorffer et al., 2015; Schröter et al., 2014a; Syrbe and Grunewald, 2017; Wei et al., 2017). An example of mismatch between capacity and flow is when the ES use exceeds the capacity (unsustainable exploitation), resulting in a progressive erosion of the ecological potential underpinning the ES (Geijzendorffer et al., 2015). Despite its crucial importance in terms of sustainability, the unsustainable ES exploitation is often undetected in ES assessments, possibly due to the lack of recognition of the impacts of the anthropogenic contributions to ES flows (Geijzendorffer et al., 2015; Villamagna et al., 2014). To support this recognition, it can be useful to distinguish between ES whose flow directly depends on ecosystem functioning, with no further anthropogenic contributions (e.g. climate regulation through carbon sequestration), and ES whose flow is necessarily mediated by some kind of human activity (e.g. fish provision -through harvesting- and recreation -through visiting-) (Rova and Pranovi, 2017). While these conceptualizations provide valid support to a sustainability-driven interpretation of ES, their application to the whole bundle of ES co-produced by a social-ecological system requires further research because of the great complexity of the interactions involved.

This work aims to evaluate the sustainability of the ES provision on the basis of the assessment of the capacity and flow of multiple ES. The work has been developed using the Venice lagoon (Italy) as case study. The paper is structured around three main objectives:

- the identification of ES bundles in the Venice lagoon;
- the evaluation of the degree of sustainability of the ES bundles and the identification of a "sustainability threshold" that distinguishes between desirable and undesirable combinations of ES;
- the discussion of some possible management suggestions aimed at improving the ES sustainability.

2. Materials and methods

2.1. Study area

The Venice lagoon is a large coastal lagoon located in North-eastern Italy, with a surface area of about 550 km^2 (Fig. 1). It is composed of a mosaic of subtidal and intertidal habitats that enclose the city of Venice and other inhabited islands, and it is a very good example of a complex social-ecological system, due to the mutual influence that humans and nature have had on each other throughout centuries. The management of the lagoon faces extremely complex challenges, to name a few, the loss of typical lagoon habitats (Fagherazzi et al., 2006; Sarretta et al., 2010; Solidoro et al., 2010), the implementation of the Water Framework Directive (WFD, European Commission, 2000) (Anelli Monti et al., 2021; Cacciatore et al., 2019), the harmonization of a variety of human activities, such as tourism, fishing and navigation (Bertocchi et al., 2020; Pranovi et al., 2013, 2004; Rapaglia et al., 2015; Scarpa et al., 2019), and the adaptation to climate change, including the protection of Venice and other residential areas from high tide events (Carbognin et al., 2010; Rinaldo et al., 2008; Tognin et al., 2021). The lagoon provides a broad set of regulating, provisioning and cultural ES, on which previous studies and data are available (D'Alpaos and D'Alpaos, 2021; Rova et al., 2022, 2019b, 2019a, 2015; Stocco et al., 2023). Despite being characterized by a good knowledge base on several topics of concern, this study area has thus several open questions on the management of local natural resources, on which this work can have a significant positive impact.

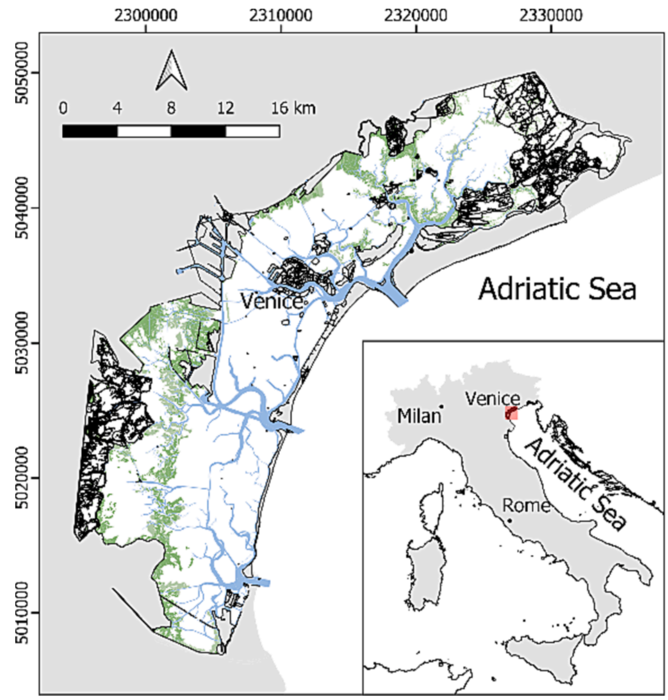

Fig. 1. The Venice lagoon study area.

2.2. Capacity and flow maps of multiple ecosystem services

This work builds upon a recent spatially explicit assessment of multiple ES provided by the Venice lagoon (Rova et al., 2022). This assessment quantifies the capacity and flow of 12 ES, which include four regulating and maintenance ES, four provisioning ES and four cultural ES (Table 1). The assessment has employed a variety of methods, including geospatial analysis of ecological data, the use of outputs from a trophic network model, and the consultation of stakeholders through questionnaires and interviews. Please refer to Rova et al. (2022) for more details on the assessment methodology. The ES were mapped on a regular grid with 250 m resolution. Capacity has been assumed equal to flow for all regulating ES, because for these ES we deemed reasonable to consider that the actual "use" corresponds to their ecological potential (Rova et al., 2022).

2.3. Aggregated indicators

A set of aggregated indicators has been calculated based on the results of the assessment on the same spatial grid with 250 m resolution. Prior to the aggregation, all ES have been scaled to a 0–1 range (min–max scaling). The aggregated indicators attempt to provide a simplified representation of the overall capacity and flow of multiple ES. Such a representation allows for focusing on the overall ES flow, to summarize how it is distributed between ES which directly depend on ecosystem

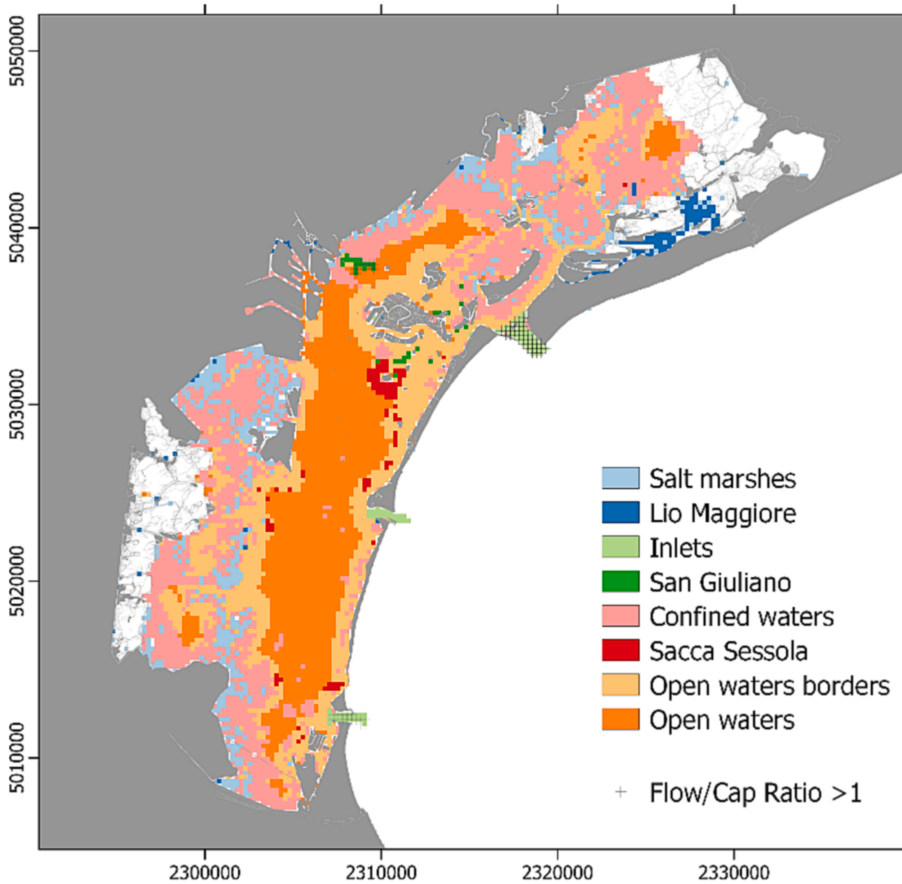

Fig. 2. Map of the zones resulting from the hierarchical cluster analysis, corresponding to different bundles of ecosystem services (ES). The pixels with Flow/Capacity ratio > 1 are also shown on the map, marked with grey crosses (corresponding, from north to south, to the areas of San Giuliano, Lido inlet and Chioggia inlet).

functions ("direct" ES, corresponding to regulating and maintenance ES), and ES whose flow is necessarily mediated by human activities ("mediated" ES, corresponding to provisioning and cultural ES) (Rova and Pranovi, 2017). The aggregated indicators are the following:

- Sum of ES capacity, corresponding to the sum of the capacity of all ES;
- Sum of ES flow, corresponding to the sum of the flow of all ES;
- Sum of Dir ES flow, corresponding to the sum of the flow of direct ES;
- Sum of Med ES flow, corresponding to the sum of flow of mediated ES;

2.4. Zonation based on ecosystem services' bundles

To identify areas of the lagoon characterized by different bundles of ES, a hierarchical cluster analysis (Euclidean distance, group-average linkage) has been performed on the capacity - flow data of the 12 ES. The individual ES maps have been used as input data for the cluster analysis, considering the value in each cell of the spatial grid as an observation. The zones identified through the cluster analysis have been mapped to obtain a geographical representation of the zonation. The data analysis has been performed using R statistical software (R core team, 2022) and QGIS (QGIS.org, 2022).

3. Results

3.1. Zonation based on ecosystem services' bundles

Fig. 1 shows the zonation of the lagoon resulting from the cluster analysis of the capacity and flow data of individual ES. The zones result from cutting the dendrogram at distance = 1.375, a threshold chosen in order to have a number of zones sufficiently high to reflect the diversity of the lagoon areas, but not so high to result in an excessive disaggregation. For this same reason, the clusters composed by a number of pixels smaller or equal to 16 (1 km^2) and without a clear geographical grouping have been excluded from the analysis (n = 4 clusters, 27 pixels in total). The resulting eight zones correspond to different bundles of ES, whose composition in terms of capacity and flow of individual ES is shown in Fig. 3. The zone Salt marshes geographically reflects the distribution of this habitat, while the zone Lio Maggiore corresponds to a semi-enclosed area located between the littoral area of Cavallino-Treporti and the nearby fishing ponds. Both these zones are characterized by relatively high regulating ES, and a high capacity for most cultural ES. The zone Inlets corresponds to the three areas of connection between the lagoon and the sea, which stand out for the high flow of recreational navigation and recreational fishing ES. The San Giuliano zone mainly corresponds to a stretch of water located between the city of Venice and the San Giuliano area in the mainland. This zone stands out for the very high flow of traditions and artisanal fishing ES. The Confined zone represents most of the submerged areas with a relatively high degree of confinement. Here several ES reach the highest or the second highest capacity among all the zones (all ES except climate regulation, clam and traditions), whereas artisanal fishing is the only mediated ES with a high flow in this zone. The Sacca Sessola zone corresponds to a small area to the south of Venice, where climate regulation and erosion prevention ES reach the highest values among the zones, along with a relatively high flow of artisanal fishing and traditions ES. The Open water borders zone mainly consists of the submerged areas close to islands and salt marshes. With respect to the others, this zone has moderate/high values of both capacity and flow for most of the ES.

Table 1
Ecosystem services assessed in the Venice Lagoon and capacity and flow indicators, with unit of measure in brackets (adapted from Table 1 in Rova et al. (2022), which includes the used assessment methodology). Please refer to Rova et al. (2022) for the assessment methodology. R = regulating and maintenance ES; P = provisioning ES; C = cultural ES.

	Ecosystem services	Capacity indicators	Flow indicators
R	**Climate regulation**	Carbon sequestration rate (g C/m^2/yr)	
R	**Waste treatment**	Percentage of nitrogen loads removed through denitrification (%)	
R	**Erosion prevention**	Sediment biostabilization by bottom vegetation and wind fetch reduction by salt marshes (0–1 scale)	
R	**Lifecycle maintenance**	Biomass of juveniles of marine migrant fish species (ton/km^2)	
P	**Artisanal fishing**	Biomass of target fish species (ton/km^2)	Catches from artisanal fishing activities (ton/km^2/yr)
P	**Clam harvesting**	Biomass of clam *Ruditapes philippinarum* (ton/km^2)	Catches of clam *R. philippinarum* (ton/km^2/yr)
P	**Recreational fishing**	Biomass of target fish species (ton/km^2)	Catches from recreational fishing activities (ton/km^2/yr)
P	**Hunting**	Huntable waterbirds distribution (Anatidae and Rallidae) (0–1 scale)	Catches from hunting activities (nr birds harvested/yr)
C	**Tourism**	Attractiveness of the lagoon environment as perceived by visitors (0–1 scale)	Number of visitors (nr of visitors/yr)
C	**Recreational navigation**	Attractiveness of the lagoon environment as perceived by pleasure-boat owners (0–1 scale)	Number of pleasure-boat trips (nr/yr)
C	**Information for cognitive development**	Attractiveness of the lagoon as perceived by visitors, accounting for the accessibility to disabled people (0–1 scale)	Number of students joining environmental education activities (nr/yr)
C	**Traditions**	Areas with bathymetry suitable for practicing venetian rowing activities (0–1 scale)	Number of venetian rowing boat trips (nr/yr)

In particular, some of highest values of tourism and recreational navigation flow are found in this zone. Finally, the Open waters zone includes most of the submerged areas with relatively low degree of confinement and far from land and salt marshes. Here the capacity of most ES is low/moderate, except for clam and traditions ES, whose capacity is higher respect to the other zones. On the other hand, here the flow of mediated ES is moderate/high respect to other zones, with clam harvesting reaching some of the highest values of flow.

Moving to the aggregated indicators, Fig. 4 shows how the sum of capacity and the sum of flow relate to each other. Overall, we observe a positive correlation between these two variables (Spearman's rho = 0.66, $p < 0.0001$), confirming that the actual "use" of ES depends upon the ecological "potential" and that the capacity is generally greater than the flow, with a Flow/Capacity ratio of 0.53 (0.44–0.61) (median, first and third quartile). This is reasonable if we consider the former as a sort of carrying capacity of the latter. However, it can be observed that few spots in the lagoon make exception to this, having a Flow/Capacity ratio greater than 1 (shown with crosses in Fig. 4). Looking at how the zones are positioned in the capacity-flow scatterplot (different colors in Fig. 4), it can be observed that they are quite differentiated in terms of overall ES capacity, overall flow and Flow/Capacity ratio, and they represent rather well the different groups of observations that are visible in the plot. Salt marshes are placed on the bottom-left portion of the scatterplot, followed by the semi-enclosed area of Lio Maggiore, a bit shifted towards greater flow. The zones Inlets and San Giuliano broadly correspond to the areas with Flow/Capacity ratio greater than one (Figs. 2 and 4), while Open waters, Confined waters and Open waters borders appear shifted along the x axis of the scatterplot, showing a progressively higher capacity. Finally, Sacca Sessola appears on the top-right portion of the scatterplot, with a high overall capacity and flow.

3.2. *Lags in time and/or space*

The pixels with Flow/Capacity ratio greater than one correspond to three distinct sites of the lagoon, namely, Lido inlet, Chioggia inlet, and a shallow area in front of San Giuliano (Fig. 2). These areas are also identified by the cluster analysis as the Inlets and San Giuliano zones (Fig. 4). By looking at the capacity and flow of individual ES, it emerges that each of these sites has a peculiar pattern of ES. Lido inlet has a high flow for recreational navigation and recreational fishing, while the capacity of these ES is respectively moderately-high and low. The flow of both these ES is linked to the fact that the inlets are nodes of connection between the lagoon and the sea, and thus are highly used by boaters to reach the sea, and by fishermen to catch fish while it migrates from the sea to the lagoon and vice versa. For the same reason, Chioggia inlet has a very high flow of recreational fishing and a relatively low capacity for the same ES. Finally, the small area facing San Giuliano stands out for a single ES, Tradition, being highly used for rowing (ES flow) but not suitable for this activity considering the low bathymetry (ES capacity). This sounds like a nonsense but indeed it is not: crossing this unsuitable area is common for many users because it allows to quickly reach some nearby areas which are very suitable for this activity.

These patterns can be interpreted in the light of an hypothesis on the spatiotemporal lags in ES, where "lag" refers to the distance in time and/or space between the ES capacity and the flow. Three types of lags have been identified: spatial, temporal, and mixed spatial and temporal (Table 2).

3.3. *Classification of the ecosystem services' sustainability*

A new approach is proposed here that classifies the ES bundles in terms of sustainability and management needs. In this perspective, the target would be to manage the social-ecological system in a way that the flow of multiple ES is provided without eroding the ES capacity, so to preserve the potential to provide ES in the future. The idea is that the analysis of ES capacity and flow could be used to evaluate the degree of sustainability of the ES provision in different portions of the study area, and could thus contribute to identify which type of interventions are needed.

The approach is based on the combined use of the zonation and aggregated indicators. While the zonation provides the geographical dimension, the aggregated indicators are combined together to classify the sustainability of the ES bundles, following the scheme presented in Fig. 5. First, for the Sum of Capacity, Sum of Flow, Sum of Dir ES capacity and Sum of Med ES Flow, it is checked whether each zone presents values that are high, low, or on average with respect to the rest of the lagoon. To do so, a pairwise Mann-Whitney *U* test is run for each zone against all the other zones altogether. Each zone is classified as "High" if the test is significative and the median of the zone is higher than that of the whole lagoon, "Low" if the test is significative and the median of the zone is lower than that of the whole lagoon, and "Average" if the test is not significant. Then, capacity-flow and direct-mediated indicators are merged into two "combined" color scales, as illustrated in Fig. 5, where the level of environmental sustainability increases from red to green to blue. Finally, the two color scales are combined in a sort of 'one-out, all-out' approach to obtain an overall 'sustainability gradient', as shown in Fig. 5. The rationale is that, from an environmental perspective, the degree of sustainability can be linked to the balance between capacity and flow of ES, and to the balance between the flow of direct (regulating and maintenance) and mediated (provisioning and cultural) ES. The ES capacity represents the 'potential' to provide ES, and the flow of direct ES the 'regulation' capacity of

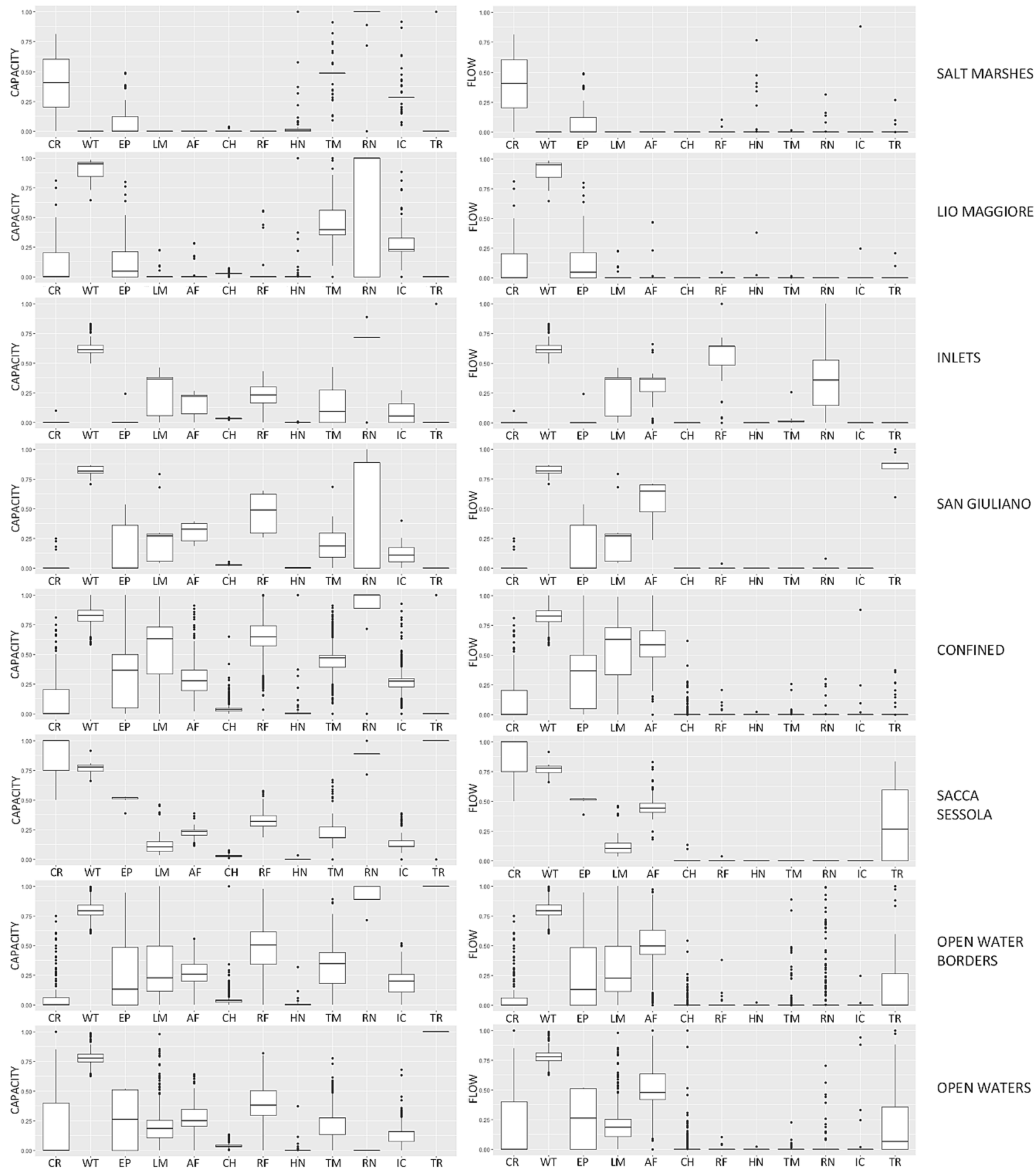

Fig. 3. Capacity (left column) and flow (right column) of ecosystem services (ES) in the different zones of the Venice lagoon. Abbreviations: CR = climate regulation, WT = waste treatment, EP = erosion prevention, LM = lifecycle maintenance, AF = artisanal fishing, CH = clam harvesting, RF = recreational fishing, HN = hunting, TM = tourism, RN = recreational navigation, IC = information for cognitive development, TR = traditions.

ecological processes. Both can be seen as a sort of ‘reservoir’ of the ecosystem’s functionality for the present and future. Therefore, in a sustainable situation, a high level of ES flow should necessarily be sustained by a high level of capacity. If a high ES flow occurs without a high capacity, the uses of the ecosystem might exceed the ecological potential, and thus resulting unsustainable. On the other hand, the flow of mediated ES, which requires some human activity, inevitably implies some type of impact on the ecosystem. These impacts should be moderated, not to occur at the expense of the ecological “regulation” capacity. Therefore, in a sustainable condition, the flow of mediated ES should coexists with a high flow of direct ES. Instead, if a high flow of mediated ES occurs without a high flow of direct ES, this can be

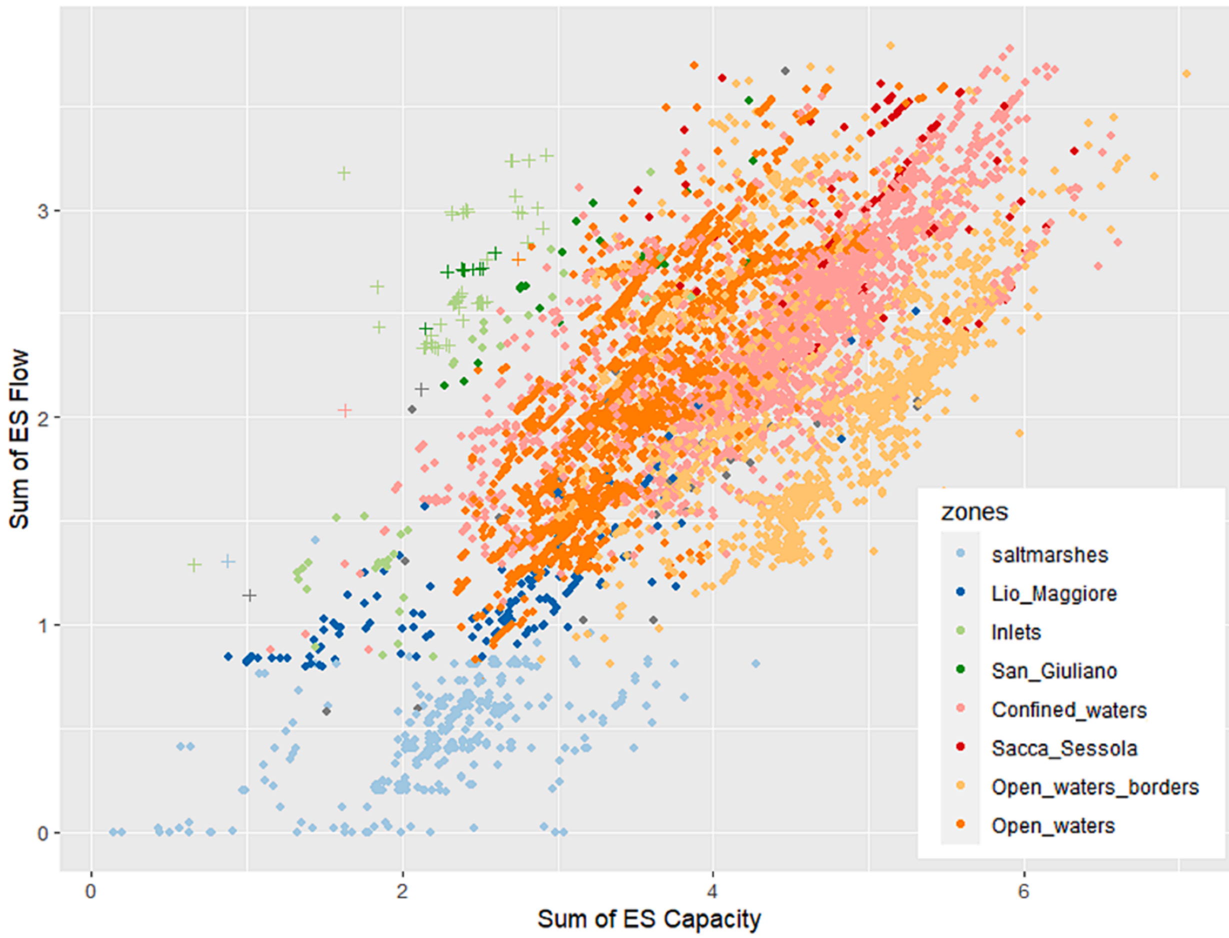

Fig. 4. Scatter plot of the Sum of ES Capacity and the Sum of ES Flow, colored according to the zones resulting from the cluster analysis. The pixels with Flow/Capacity ratio > 1 are marked with crosses
(adapted from Rova et al., 2022)

indicative that the activities might be deteriorating the regulation capacity, thus being unsustainable.

Given this interpretation from a sustainability perspective, a 'sustainability threshold' is proposed, corresponding to a green level for both color scales (Fig. 5). This condition can be considered acceptable from a management perspective because it represents a balance between the actual use of ES (flow) and their ecological potential (capacity), and particularly, a balance between the ES which require potentially impacting human activities (mediated ES) with those directly deriving from the ecological functioning (direct ES). Overall, ES bundles that satisfy this condition are more likely to satisfy societal and economic needs within the boundaries of environmental sustainability, because the human uses of the ecosystem coexist with the ecosystem functionality that underpins them.

Fig. 6 reports the results of this classification, applied to the zones of the VL presented in section 3.1. Fig. 7 maps the overall sustainability of the ES bundles in the VL. The classification of four zones (Open waters, Open water borders, Inlets and San Giuliano) falls beyond the "sustainability threshold", meaning that the corresponding ES bundles are unsustainable. These four zones correspond in total to about 53 % of the lagoon's surface.

4. Discussion

Global decline in nature leads to decline of ES worldwide (IPBES, 2019), calling for immediate action to improve environmental sustainability. Understanding the long term (un)sustainability of different combinations of ES can reconnect ES with the sustainability principles, by providing a substantial advancement in the management of natural resources (Bennett et al., 2015; Bennett and Chaplin-Kramer, 2016; Schröter et al., 2017). On a global level, differences have been reported between the trends of the ES potentials (declining), the flow of regulating ES (declining), the realized production of several material commodities (increasing) and the experiential use of cultural ES (increasing for wealthy and urbanized populations) (Brauman et al., 2020). These diversified trends suggest the need to focus on the preservation of the ecological potential underpinning the ES and of the flow of regulating ES, because their decline is undermining the provision of all ES for future generations. These different trends can be at least partially explained by the tradeoffs existing between different ES, for example between provisioning and regulating ES, for which negative interactions have been frequently reported in literature (Aryal et al., 2022; Cord et al., 2017). The anthropogenic contributions needed to make use of the ES with mediated flow (*sensu* Rova and Pranovi, 2017), such as land use change, biomass harvest, visitation activities (Balvanera et al., 2022), are likely to be responsible for these tradeoffs by generating negative environmental impacts that affect the provision of other ES (Smith et al., 2017). Within this context, the classification of ES sustainability presented in this work contributes by allowing to distinguish sustainable and unsustainable bundles of ES. While capacity and flow maps represent a static snapshot of the social-ecological system, their classification can provide hints about the underlying trends. The lack of balance between the flow of direct and mediated ES has been shown to be correlated with negative modeled trends of ES provision (Rova et al., 2019b).

Table 2
Types of lag between ecosystem services' (ES) capacity and flow.

Type of lag	Description	Examples in the Venice lagoon
Spatial	The ES flow is spatially disjoint from the capacity.	High flow in places which are crucial nodes of connection with areas of high capacity. This is the case of recreational navigation at the lagoon inlets: navigation is high at the inlets because they connect the lagoon with the sea.
Temporal	The ES flow is temporally disjoint from the capacity. This can occur over relatively short time scales (e.g. days, seasons), but also over much longer ones (e.g. decades or even centuries).	High flow in places where the cultural heritage is connected with past uses of the ecosystem. This is the case of tourism in the islands of the lagoon (e.g. Burano), where the presence of cultural heritage reflects the ES of the lagoon in the past centuries (protection, connection with the sea, fishing)
Mixed spatial and temporal	The ES flow is both spatially and temporally disjoint from the capacity.	High flow in places which are crucial nodes of connection with areas of high capacity, but where the flow can be shifted in time with respect to the processes upon which the capacity is based. This is the case of recreational fishing at the inlets: inlets are crossed for both feeding and nursery purposes by marine migrant species. Fishing (flow) is mainly concentrated in the natural bottlenecks of these migrations, the inlets. The capacity occurs in the internal areas of the lagoon, which are used as feeding or nursery areas, and can be shifted of days to months respect to the flow, depending on the types of migrations.

Similarly, an ES flow that goes beyond the ES capacity can be indicative of an underlying degradation that would lead to a progressive loss of ES (Balvanera et al., 2022; Geijzendorffer et al., 2015; Schröter et al., 2017). Therefore, the approach presented in this work, with its attempt to synthesize the main factors that lead to unsustainable situations, can contribute to the much needed operationalization of the ES concept towards sustainability (Abson et al., 2014; Bennett et al., 2015).

What are the implications from a management perspective?

First, a sustainability-driven interpretation of the ES patterns is meant to provide a judgment on how much they are aligned with the normative goal of sustainability (Schröter et al., 2017). By doing so, it helps to translate the overarching goal of environmental sustainability into more concrete *targets* in terms of ES. This, along with the adoption of a systemic approach, can indeed contribute to improve the policy targets (Reyers et al., 2013). From an ES perspective, it is here proposed to rebalance the ES patterns in a way that a high flow is backed by a high capacity, and that provisioning and cultural ES are used while securing at the same time the flow of regulating ES.

Second, the geographical application of the sustainability classification allows to evaluate *where* management needs are greater. The results are indeed consistent with some situations of concern already reported in the study area, in particular in the central-southern areas of the lagoon, where the morphology is currently undergoing a severe degradation because of the strong erosive patterns (Fagherazzi et al., 2006; Sarretta et al., 2010). These areas in fact also appear to have the lowest level of ES sustainability: the capacity is relatively low respect to the flow, which in turn is unbalanced towards mediated ES at the expenses of regulating ES. The zonation based on ES could become operative from a management point of view, for example, by complementing the water bodies adopted in compliance with the WFD (European Commission, 2000). By merging the WFD's water bodies with the zonation based on ES, it would be possible to distinguish areas that share similar combinations of ES, similar levels of ES sustainability and thus similar management needs.

Finally, the zones' classification suggests some broad trajectories for the interventions needed to achieve a more sustainable ES provision. Four main types of interventions can be suggested:

(1) To reduce the anthropogenic pressures in the areas where excessive uses threaten the ES capacity and the flow of regulating ES (red classes of the sustainability gradient), or to modify the existing activities to reduce their impacts. A careful consideration of the potential impacts of human activities on ES capacity and on regulating ES flow is necessary, especially before any additional pressure is allowed in these areas. In this regards, the recognition of the ES provided by the study area and the spatially explicit assessment of their capacity and flow (Rova et al., 2022) provide a new comprehensive knowledge base against which the potential impacts of human activities should be evaluated. Additionally, also lags between ES capacity and flow should be taken into account when planning for interventions that act on the ES flow to preserve the capacity. Building on previous studies (Costanza, 2008; Fisher et al., 2009; Rova and Pranovi, 2017; Serna-Chavez et al., 2014; Syrbe and Grunewald, 2017; Syrbe and Walz, 2012), we point out that, in particular cases, some spatial and/or temporal mismatches between the capacity and flow of ES inevitably arise from the geographical, ecological and/or historical characteristics of a social-ecological system. As a consequence, these lags "shift" in time and/or space the focus and the effects of potential management actions, requiring the adoption of a broad systemic perspective. For example, spatial lags imply that reducing the pressures in correspondence to the sites of the lagged flow may not directly affect the capacity. The maintenance of the capacity in these cases instead requires interventions in other sites, which can only be identified if the lag is properly recognized and understood.

(2) To incentivize sustainable forms of ES use in the areas where the capacity is not fully expressed and/or the flow of regulating ES is high. The high ecological potential of some areas of the lagoon (blue classes of the sustainability gradient) can reasonably allow for some expansion of human uses, offering space for new economic opportunities, provided they are respectful of the ecosystem and its functioning. This means not replicating and expanding existing unsustainable uses but rather to adopt and/or create sustainable practices, taking inspiration from both the past and the future. Inspiration form the past, because local traditional knowledge and practices often contain the key for a long-term sustainable exploitation of the ecosystem (Berkes et al., 1994, 2000; Gómez-Baggethun et al., 2012, 2013; Stori et al., 2019). Local examples from the Venice lagoon are traditional artisanal fishing practices, with their low impact and highly selective gears (Granzotto et al., 2001), the management of the lagoon's fishing ponds ("valli da pesca"), where traditional practices for extensive aquaculture and hunting maintain a high overall ES capacity (Stocco et al., 2023), or traditional venetian boats, crafted by local artisans and meant for a slow navigation in the lagoon. Inspiration from the future, because creativity and innovation can generate new business and new forms of economic development in harmony with the ecosystem. New interesting windows of opportunity can be generated also when innovation is merged with traditional knowledge, adapting ancient practices to the current context and needs (Gómez-Baggethun et al., 2013). Some relatively recent local examples are the development of slow tourism businesses such as fishing tourism, or the creation of

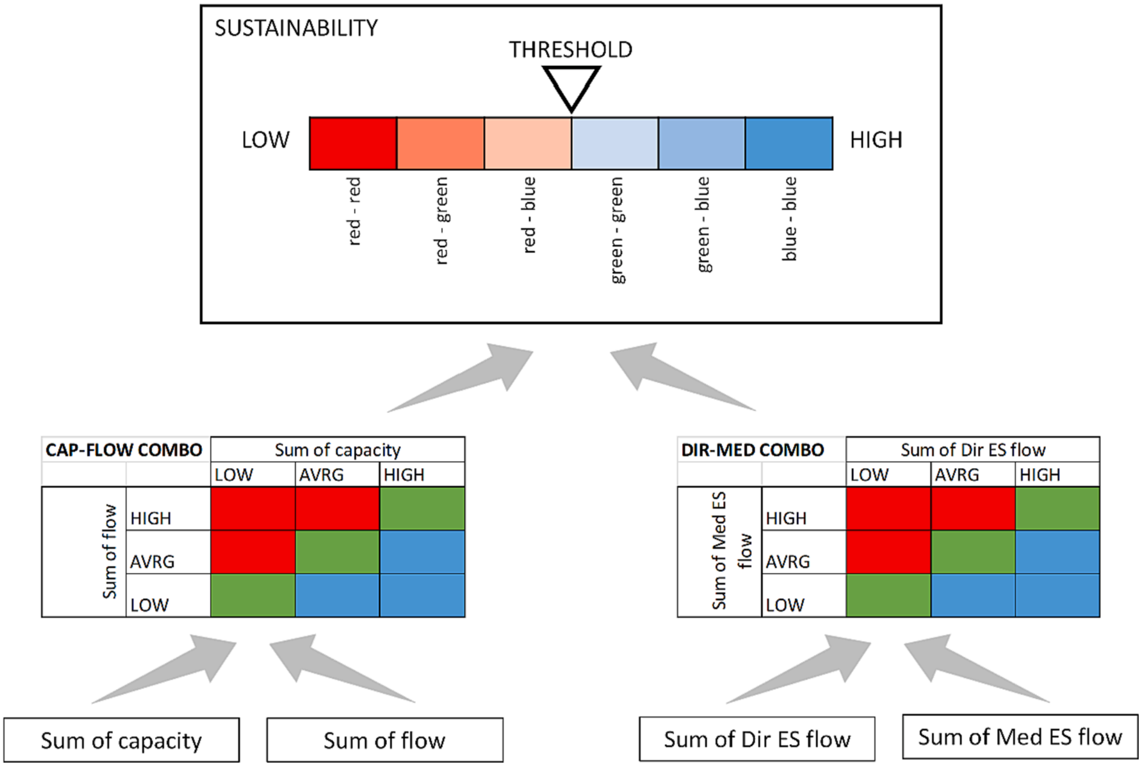

Fig. 5. Conceptual scheme of the classification of the sustainability of multiple ecosystem services.

Zone	Sum of ES Capacity	Sum of ES Flow	COMBO CAP FLOW	Sum of Dir ES flow	Sum of Med ES flow	COMBO DIR MED	Sustainability
Salt marshes	*LOW*	*LOW*	(green)	*LOW*	*LOW*	(green)	(light blue)
Lio Maggiore	*LOW*	*LOW*	(green)	*LOW*	*LOW*	(green)	(light blue)
Inlets	*LOW*	*AVRG*	(red)	*LOW*	*HIGH*	(red)	(red)
San Giuliano	*LOW*	*HIGH*	(red)	*AVRG*	*HIGH*	(red)	(red)
Confined waters	*HIGH*	*HIGH*	(green)	*HIGH*	*AVRG*	(blue)	(medium blue)
Sacca Sessola	*HIGH*	*HIGH*	(green)	*HIGH*	*HIGH*	(green)	(light blue)
Open waters borders	*HIGH*	*AVRG*	(blue)	*LOW*	*HIGH*	(red)	(light red)
Open waters	*LOW*	*AVRG*	(red)	*AVRG*	*HIGH*	(red)	(red)

Fig. 6. Classification of the ecosystem services bundles in each zone, according to the scheme presented in Fig. 5.

traditional boats powered by electric engines. Overall, enhancing the ES sustainability can also imply new opportunities that seize, but not harm, the potential that the lagoon ecosystem has to offer.

(3) To increase ES capacity through ecological restoration, especially where it is relatively low and threatened by human activities (red classes of the sustainability gradient). This should go in parallel with the pressures' reduction envisaged in point 1, necessary to create the conditions for successful restoration interventions. Successful examples of different types of ecological restoration have recently been implemented in the Venice lagoon thanks to different EU Life projects, such as Life REFRESH (Feola et al., 2022; Life REFRESH, 2022), Life SERESTO (Life SERESTO, 2018; Sfriso et al., 2021) and Life VIMINE (Barausse et al., 2015; Life VIMINE, 2019). The unsustainable zones that emerge from this work, as well as the recognition of spatiotemporal lags, could help to design the future agenda of restoration upscaling in the lagoon in three main ways: first by highlighting the areas where interventions are most needed (the zones with red classification), second by understanding which ES are particularly lacking in those areas, and third by recognizing that interventions should also be able to provide the ES capacity that is needed to "feed" the areas with lagged ES flow. By combining this information with the know-how acquired in the Life projects cited above, new large scale restoration interventions could be planned in which Nature-based solutions are specifically designed to provide multiple ES (Keesstra et al., 2018; Sánchez-Arcilla et al., 2022).

(4) To preserve ES capacity through ecological conservation measures, especially where capacity is currently high or on average (blue classes of the sustainability gradient). The implementation of conservation (and also restoration) measures requires the involvement of citizens and, more in general, of local stakeholders. The plurality of values that people attach to Nature,

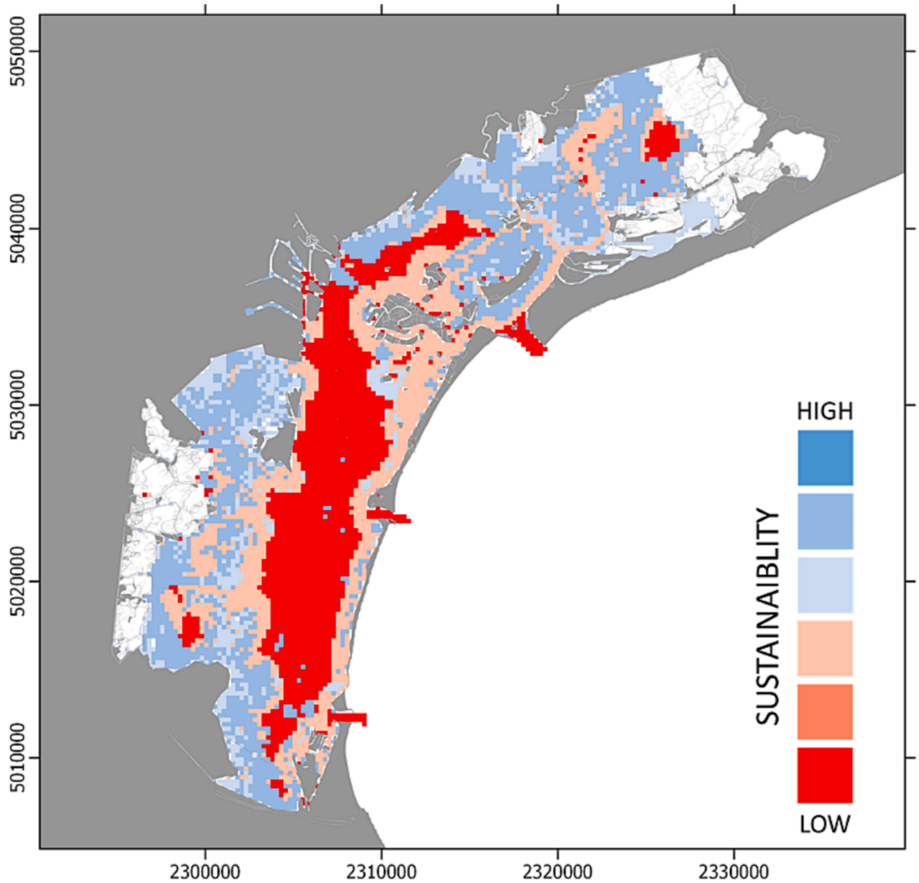

Fig. 7. Classification of the sustainability of the ecosystem services bundles in the Venice lagoon.

especially relational ones, can be used as a leverage to reconnect people with Nature and to ground Nature's conservation on the people's care for the ecosystem (Abson et al., 2017; Chan et al., 2016; Mattijssen et al., 2020; Muradian and Gómez-Baggethun, 2021). Therefore, conservation and restoration actions should be explicitly planned through and for widespread stakeholders' participation. By appealing to the emotional bonds and to the empathy and altruism of people, and by bringing, physically, people back to Nature, it is possible to foster a transformational change that allows a true legitimation of conservation and restoration initiatives.

Concerning the methodological limitations of the work, it is important to point out that the absolute values of the aggregated indicators (Sum of Capacity, Sum of Flow, Sum of Dir ES capacity and Sum of Med ES Flow) depend on the characteristics of the ES assessment (set of ES, indicators, methods). These characteristics can thus affect the overall results. Therefore, for a meaningful application of the sustainability classification proposed here, the following necessary conditions can be identified: (1) the set of ES considered has to be evenly distributed across the main categories of ES (regulating and maintenance, provisioning and cultural), and (2) the set of ES must be broad, being as representative as possible of the diverse interactions occurring between the ecosystem and society. Furthermore, as no reference values currently exist, the methodology has been designed to evaluate the aggregated indicators in relative terms (i.e. they are classified as low/medium/high with respect to the median value in the study area), considering their values within the boundaries of the same ES assessment. As a consequence, the approach presented here allows to identify the zones with higher and lower degree of sustainability within a certain study area, but it does not allow to directly compare the ES sustainability in different case studies, if the characteristics of the ES assessments are different.

As future steps, to address the limitations outlined above, it would be extremely interesting to test the applicability of the approach to other case studies, with different ecosystems, sets of ES, challenges, spatial settings and scales, to evaluate whether it is possible to identify general patterns and thresholds for the aggregated indicators considered, that can be linked with the overall sustainability. Additionally, the proposed zones, as well as targets and management trajectories, need to be discussed with stakeholders and decision-makers. Stakeholders' ecological knowledge could be incorporated in the zonation and be used to refine it. Furthermore, their knowledge and the different importance they attribute to ES could help to define the specific management interventions and to prioritize conservation and restoration actions (Barausse et al., 2022). This exchange is fundamental to incorporate the perspectives and needs of different stakeholder groups and to frame the outcomes in a way that can be embedded in the language, priorities and tasks of decision-makers.

5. Conclusions

This work shows that the level of sustainability of different ES bundles can be evaluated by looking at the balance between the overall ES capacity and flow, and at the balance between the flow of regulating ES and the flow of ES mediated by human activities. The combination of these two criteria can be indicative of whether the current ES uses are compatible with the provision of multiple ES over the long term. By applying the classification to the different ES bundles found in the Venice lagoon, it results that more than half of the lagoon's surface falls beyond the "sustainability threshold", meaning that the ES bundles found in those areas should be considered unsustainable and require some interventions. These outcomes can support the planning of large scale nature restoration projects, by suggesting the areas and the ES that need to be restored. Interestingly, by distinguishing sustainable and unsustainable situations, new windows of opportunity can also be opened. New sustainable activities can be developed to valorize the high ES capacity of some areas without producing its decline, for example by combining traditional local knowledge and innovation, respectful of the lagoon ecosystem. Overall, this classification allows to assign a judgment on the different ways in which our society makes use of the ecosystem, in the light of the sustainability principle, and to spot some broad management trajectories, in a geographically explicit way. This can facilitate the uptake of ES science in the decision-making process.

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.

Acknowledgements

This scientific activity has been performed within the Research Program Venezia2021, coordinated by CORILA, with the contribution of the Provveditorato for the Public Works of Veneto, Trentino Alto Adige and Friuli Venezia Giulia. This publication was supported by the European Union - Next Generation EU - Project ECS000043 - Innovation Ecosystem Program "Interconnected Northeast Innovation Ecosystem (iNEST)," CUP H43C22000540006. We sincerely thank the reviewers for their insightful comments which helped to improve the manuscript.

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