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Research Article

Ecosystem services' capacity and flow in the Venice Lagoon and the relationship with ecological status

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Abstract

Ecosystem services (ES) are theoretically linked to healthy ecological conditions, but this relationship seems to be rather challenging to demonstrate in the real world. Therefore, shedding light on these aspects can be crucial for implementing effective ecosystem management strategies, for instance within the context of the EU Water Framework Directive (WFD) implementation. This work aims to present a spatially-explicit assessment of the ecological potential (capacity) and actual use (flow) of 12 ES in the Venice lagoon and to explore the relationships with the ecological status. Quantitative indicators of capacity and flow for each ES have been assessed and mapped and the results summarised with a set of aggregated indicators. The outcomes reveal a positive relationship between the overall capacity and flow of ES, suggesting that where the first is degraded, an overall loss of ES delivery occurs. A complex picture emerges when exploring the links with the ecological conditions, as the relationship changes with the ES and ecological status indicators considered. Structural indicators of ecological status, such as the Biological Quality Elements adopted by the WFD (assessed by MAQI and M-AMBI metrics), seem to be weakly linked with ES, while functional indicators (Kempton Q-90 diversity and secondary production) showed stronger links, especially when aggregated ES indicators are considered. Concerning different ES, it appears that the flow of the ES that are mediated by human uses (provisioning and cultural ES) is negatively related with some of the ecological status indicators. Finally, our results suggest possible limitations of the zonation adopted under the WFD, when it comes to the analysis of ES. We argue that ES could play a role in the management of the Lagoon ecosystem, as their analysis could be used to preserve the ecological functioning by managing the ‘uses’ we make of the ecosystem.

Keywords

coastal ecosystems, multiple ecosystem services, BQEs, mapping, ecosystem-based management

Introduction

The concept of ecosystem services (ES) has been conceived to highlight how the well-being of our society depends upon the functioning of ecosystems (Costanza et al. 1997, Daily 1997, Costanza et al. 2017). This linkage appears explicitly in the definition of ES, that is, “the contribution of ecosystem structure and function – in combination with other inputs – to human well-being” (Burkhard et al. 2012) and it is stressed even more in the well known “ES cascade” conceptual model (Haines-Young and Potschin 2010, Potschin and Haines-Young 2011). According to this model, in fact, ES are the result of “functions”, here referred to the capacity of the ecosystem to do something that is potentially useful to our society (Potschin and Haines-Young 2011, Burkhard and Maes 2017), which, in turn, depend upon the structures and processes of the whole ecosystem. ES, therefore, emerge from ecosystem functioning, which, in turn, is supported by a ‘healthy’ ecological condition (Daily 1997, Millennium Ecosystem Assessment 2005, Maes et al. 2012). In fact, the state of the ecosystem, with the multifaceted meaning of a 'healthy' condition, is explicitly addressed in the Mapping and Assessment of Ecosystems and their Services (MAES) conceptual framework (Maes et al. 2013). This framework, which serves as a basis for the implementation of Action 5 of the EU Biodiversity Strategy to 2020, recognises that healthy ecosystems possess the full potential of ecosystem functions and exemplifies the connection of different dimensions of biodiversity with ecosystem functions and services (Maes et al. 2012).

However, despite this theoretical clarity, the evidence about this linkage is still rather scarce in scientific literature (Maes et al. 2012, Tolonen et al. 2014) and provide an overall picture of great complexity. In Europe, two key Directives constitute the normative reference for what concerns the ecological condition of aquatic ecosystems, the Water Framework Directive (WFD, 2000/60/EC, European Commission 2000) and the Marine Strategy Framework Directive (2008/56/EC, European Commission 2008). In particular, the WFD requires the monitoring and assessment of the "ecological status", which is considered "an expression of the quality of the structure and functioning of aquatic ecosystems associated with surface waters" (European Commission 2000) and is defined mainly based on biological descriptors (aquatic flora, benthic invertebrates and ichthyofauna) classified by comparison with reference conditons. Recent works, therefore, explore if and how much the ecological status is linked with the supply of ES, reporting rather complex results. Some of them report a general agreement, in terms of both indicators (Broszeit et al. 2017) and outcomes of the monitoring (Tolonen et al. 2014), while a study at European scale (Grizzetti et al. 2019) shows that the relationship may depend on the types of ES considered, being positive for regulating and cultural ES and negative for provisioning ones. On the other hand, going beyond the metrics used to assess the WFD ecological status, a review study from Smith et al. (2017) shows that different categories of ecosystem attributes have different relationships with ES, which suggest that focusing on a single type of ecological status indicators might be limiting. Furthermore, this study identifies bundles of ES that relate with different categories of ecosystem attributes, only partially overlapping with the findings from Grizzetti et al. (2019). Finally, Spangenberg et al. (2014), analysing the reasons for the weakness of the relationship between ecological conditions and ES, highlighted that, for some ES, especially provisioning and cultural ones, the important contribution of human agency could in some way 'mask' the dependence on the ecosystem functioning.

Within this context, it becomes extremely useful to distinguish between "capacity" and "flow" of ES (Villamagna et al. 2013): the first refers to the ecosystem's potential to deliver ES, whereas the second occurs when this potential is translated into an effective production/use of the ES. The capacity, therefore, should be the component of ES more closely connected with the ecological status (Grizzetti et al. 2019, ICES 2021). Another useful distinction is the one between ES with "direct" and "mediated" flow (Rova and Pranovi 2017): in the first case, the ES flow directly depend on the ecosystem functioning, with no need of human inputs (the case of regulating and maintenance ES); in the second one, the flow is necessarily mediated by the energy investment by human society for exploiting ecosystem resources (provisioning and cultural ES). Therefore, it could be reasonable to expect that the relationship with the ecological status may be weaker (or even negative) for mediated ES, due to the human activities that intervene in the ES flow, in line with the findings by Spangenberg et al. (2014)and Grizzetti et al. (2019).

The present study intends to contribute to advance the knowledge on the ES-ecological status relationships, by focusing on the case study of the Venice Lagoon (VL), Italy (Fig. 1). With a surface area of about 550 km^2, the VL is the largest lagoon in the Mediterranean region, located in the northern Adriatic Sea. The VL is a complex example of social-ecological system, with a long history of co-evolution between environment and humans that has shaped this unique system throughout the centuries (Ravera 2000, D'Alpaos 2010). The VL has already been the object of previous ES assessments (Rova et al. 2015, Rova et al. 2019), but none of them features the distinction between capacity and flow, which we deem to be an important aspect to consider when dealing with the relationship between ES and ecological status.

The aims of this work are:

- to present a new ES assessment in the Venice Lagoon, distinguishing capacity and flow and

- to analyse possible relationships between ES and ecological status, assessed by using different indicators.

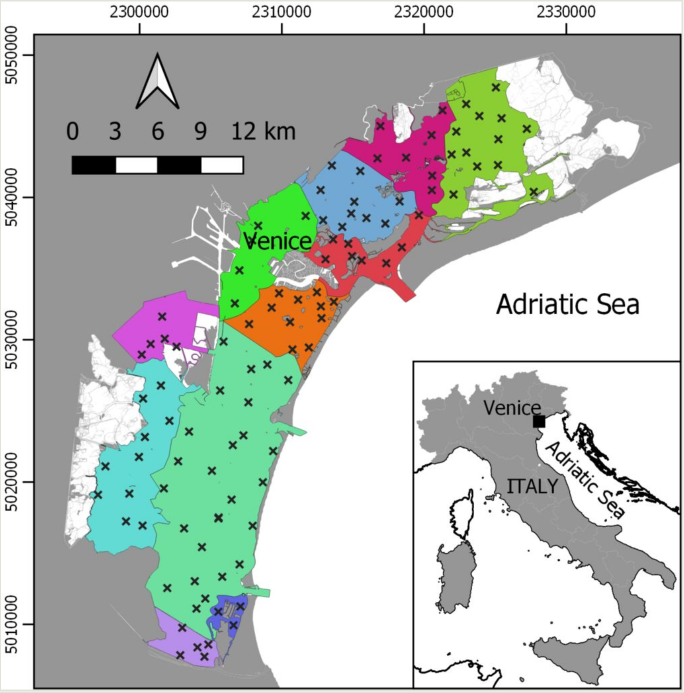


Figure 1.

The Venice Lagoon case study area, subdivided into the water bodies identified in compliance with the Water Framework Directive (WFD). The WFD monitoring stations are marked with crosses.

Materials and methods

Ecosystem services' mapping

The assessment focuses on the quantitative mapping of 12 ES (four regulating and maintenance, four provisioning and four cultural ES) (Table 1). The selection of ES captures the most relevant functions and uses of the Lagoon, following the previous literature available for the study area (Rova et al. 2015, Rova and Pranovi 2017, Rova et al. 2019), introducing the quantification of both the capacity and flow of ES, which allows us to distinguish, for the first time in the VL, the ecological potential underpinning the ES and their actual uses. All this has required the application a variety of methods, which include the geospatial analysis of ecological data, the use of outputs from a trophic network model and the consultation of stakeholders through questionnaires and interviews (Table 1). Each indicator has been quantified and mapped on a regular grid with 250 m resolution. In the case of regulating ES, the flow has been assumed to be equal to the capacity, since for these ES, we deemed it reasonable to consider that the actual “use” corresponds to their ecological potential. In other words, the rationale of this assumption is that we deem it extremely hard to identify locations where the capacity of these ES does not turn into a flow, because of the tight interconnections between the social system and the lagoon ecosystem in the study area. More in detail, climate regulation is considered a "global non-proximal ES" (sensu Costanza 2008), meaning that the contribution of carbon sequesteration to the CO_2 regulation in the atmosphere occurs independently from the location of the sequestration processes. Regarding waste treatment, we consider that reducing the likelihood of eutrophication phenomena anywhere in the Lagoon always brings perceivable benefits, given that both pollutant sources and beneficiaries are spread in various lagoon locations (both within it and at its margins). In the case of erosion prevention, the mitigation of sediment erosion translates into ES flow by playing a role for the overall preservation of the Lagoon. In fact, wind-driven sediment resuspension is one of the main drivers of the Lagoon's morphodynamics, whose evolution is characterised by a progressive loss of intertidal features due to erosive pressures (Fagherazzi et al. 2006, Sarretta et al. 2010, Tommasini et al. 2019, Tognin et al. 2022); furthermore, by reducing resuspension in tidal flats and deposition in channels, erosion prevention directly contributes to the maintenance of channels' navigability. Finally, the nursery function played by the Lagoon as a whole is essential for the survival of stocks of marine migrant species and this function turns into a flow by supporting fishing activities that occur not only in the Lagoon, but also in the facing Adriatic Sea. Due to these reasons, the capacity and the flow of these four ES are represented by the same data (Table 1).

Table 1.

Ecosystem services assessed in the Venice Lagoon, description, capacity and flow indicators (unit of measure in brackets) and mapping methodology. Abbreviations: ES = ecosystem service, R = regulating and maintenance, P = provisioning; C = cultural.

ES category	ES	Description, indicators and mapping methodology
R	**Climate regulation**	**Description**: Capacity to sequester carbon from the atmosphere. **Capacity/flow indicator**: Carbon sequestration rate (g $C/m^2/yr$). **Methodology**: Average salt marshes' C sequestration rate calculated, based on accretion rate, sediments' bulk density and organic C concentration (from Day et al. 1998, Roner et al. 2015), applied to salt marshes distribution in the LV referred to the year 2013 (from Magistrato alle Acque). Seagrasses' C sequestration rate estimated, based on species-specific belowground production and organic C content (from Sfriso and Ghetti 1998, Sfriso et al. 2004, Sfriso et al. 2007, Sfriso and Facca 2007), applied to seagrasses distribution referred to the year 2017 (Provveditorato OO. PP. del Triveneto and SELC 2018).
R	**Waste treatment**	**Description**: Capacity to buffer excessive nutrient loads, reducing the likelihood of eutrophication phenomena. **Capacity/flow indicator**: Percentage of nitrogen loads removed through denitrification (%). **Methodology**: the N load removed through denitrification has been estimated based on residence time, according to the equation proposed by Seitzinger et al. (2006) for estuarine systems. Residence time calculated with the SHYFEM model referred to the year 2014 (Umgiesser et al. (2004), courtesy of G. Umgiesser, ISMAR-CNR).

ES category	ES	Description, indicators and mapping methodology
R	**Erosion prevention**	**Description**: Capacity to mitigate the erosion of Lagoon's sediments, contributing to the maintenance of the Lagoon's morphology and of the channels' navigability. **Capacity/flow indicator**: Sediment biostabilisation by bottom vegetation and wind fetch reduction by salt marshes (0-1 scale). **Methodology**: Sediment biostabilisation index (percentage increase in sediments' erosion threshold due to vegetation, from Amos et al. (2004) applied to seagrasses distribution referred to 2017 (Provveditorato OO. PP. del Triveneto and SELC 2018) and benthic diatoms distribution, referred to 2003 -most recent data available (Facca and Sfriso 2007). Wind fetch length calculated using the R package "waver" (Rohweder et al. 2008, Marchand and Gill 2017), with respect to Bora and Scirocco winds. The sheltering produced by salt marshes was estimated by comparing the results obtained with and without salt marshes. The indicator corresponds to the reciprocal of fetch length, normalised such that 0 ≥ 1/2000 m, and 1 ≤ 1/158 m. The two indicators have been scaled to 0-1 range and then averaged.
R	**Lifecycle maintenance**	**Description**: Capacity to sustain the species' lifecycle, with particular reference to the nursery function of the Lagoon for marine migrant species. **Capacity/flow indicator**: Biomass of juveniles of marine migrant species (t/km^2). **Methodology**: Sum of the biomass of juveniles of *Sparus aurata*, *Dicentrarchus labrax* and Mugilidae, as resulting from a trophic network model of the Venice Lagoon built with Ecopath-Ecosim-Ecospace referred to the period 2010-2015 (Anelli Monti et al. 2021).
P	**Artisanal fishing**	**Description**: Fish catches from artisanal fishing activities, which are characterised by the use of traditional fishing gears, mainly fyke nets and traps (Granzotto et al. 2001). **Capacity indicator**: Biomass of target species (t/km^2). **Capacity methodology**: Sum of the biomass of species/functional groups targeted by artisanal fishing (*Atherina boyeri*, *Crangon crangon*, Polychaeta, Decapoda, Gastropoda, Mugilidae, *Solea solea*, *Sepia officinalis*, *Platichthys flesus*, *Knipowitschia panizzae*, *Pomatoschistus canestrinii*, *Zosterisessor ophiocephalus*), as resulting from a trophic network model of the Venice Lagoon built with Ecopath-Ecosim-Ecospace referred to the period 2010-2015 (Anelli Monti et al. 2021). **Flow indicator**: Catches from artisanal fishing (t/km^2/yr). **Flow methodology**: Sum of the catches from artisanal fishing of the same species/ functional groups included in the capacity of this ES, as resulting from a trophic network model of the Venice Lagoon built with Ecopath-Ecosim-Ecospace referred to the period 2010-2015 (Anelli Monti et al. 2021).
P	**Clam harvesting**	**Description**: Catches of manila clam (*Ruditapes philippinarum*) from mechanical harvesting activities within concession areas. **Capacity indicator**: Biomass of clam (t/km^2). **Capacity methodology**: *R. philippinarum* biomass monitoring data (n. 220 monitoring stations) referred to the year 2016 (Aquaprogram 2016), interpolated on the whole lagoon area. **Flow indicator**: Catches of clam (t/km^2/yr). **Flow methodology**: *R. philippinarum* yield data and spatial extension of clam harvesting concessions referred to the year 2018 (unpublished data, courtesy of San Servolo Servizi).
P	**Recreational fishing**	**Description**: Fish catches from recreational fishing activities, mainly carried out from private leisure boats and from land. **Capacity indicator**: Biomass of target species (t/km^2).

ES category	ES	Description, indicators and mapping methodology
P	**Recreational fishing**	**Capacity methodology**: Sum of the biomass of species/functional groups targeted by recreational fishing (*Sparus aurata*, *Dicentrarchus labrax*, *Solea solea*, *Sepia officinalis*, *Platichthys flesus*), as resulting from a trophic network model of the Venice Lagoon built with Ecopath-Ecosim-Ecospace referred to the period 2010-2015 (Anelli Monti et al. 2021). **Flow indicator**: Catches from recreational fishing (t/km^2/yr). **Flow methodology**: Total catches per capita (kg/fisherman/fishing trip), fishing effort (no. of fishing trips/person/year) and main fishing grounds estimated from a survey of recreational fishermen active in the VL (no. 127 questionnaires collected in the year 2019, more details in Suppl. material 1). The average individual behaviour has been applied to the total number of fishermen active in the VL, estimated based on available data (Provincia di Venezia 2014), local fishing associations, interviews to sports fishing federation (FIPSAS) and expert judgement.
P	**Hunting**	**Description**: Catches of wintering birds from hunting activities, targeting mainly species belonging to Anatidae and Rallidae families. **Capacity indicator**: Wintering birds' distribution (Anatidae and Rallidae) (0-1 scale). **Capacity methodology**: Estimate based on the number of huntable wintering birds of the families Anatidae and Rallidae from census data, considering the average of the period 2010-2019 (no. 38 monitoring stations) (Associazione Faunisti Veneti 2019). Data from monitoring stations located within hunting grounds have been considered representative of the respective area, while for the rest of the lagoon, the census data have been interpolated (nearest neighbour). The census observations are not referred to a precise surface and, thus, the data cannot be expressed as a density. Therefore, the outcome has been scaled to a 0-1 range (min-max scaling) to obtain a dimensionless indicator that reflects the expected relative distribution of bird abundance. **Flow indicator**: Catches from hunting activities (no. birds harvested/yr). **Flow methodology**: Catches in hunting reserves were derived from hunting registries, considering the average of the period 2010-2019. For the rest of the Lagoon, catches were estimated, based on the total catches per capita (no. birds/ person/hunting trip), the hunting effort (no. of hunting trips/person/year) and the proportion of hunters active in the Lagoon outside the hunting farms, which have been estimated from interviews to hunters active in the VL (no. 84 hunters interviewed). The total number of hunters corresponds to the members of the local hunting association ("Ambito Territoriale di caccia VE5") in 2020 and the location of hunting blinds in the Lagoon has been obtained from the local hunting regulation plan (Regione Veneto 2019).
C	**Tourism**	**Description**: Visits carried out in the Lagoon and its islands, including both private visits with public transport and organised boat tours (excluding mass tourism in the City of Venice). **Capacity indicator**: Attractiveness of the environment as perceived by visitors (0-1 scale). **Capacity methodology**: The relative importance of different environmental factors of attractiveness has been obtained from a survey addressed to the visitors of the lagoon (no. 517 questionnaires collected in 2019, more details in Suppl. material 1). The spatial distribution of the environmental factors (water quality, possibility to observe elements of lagoon landscape -salt marshes-, presence of birds, presence of beach, presence of natural terrestrial habitats) has been mapped and then scaled on a 0-1 range. The overall natural attractiveness has been obtained through a sum of the individual factors, weighted by their relative importance. Furthermore, we asked visitors to express the relative importance attributed to natural environment with respect to cultural heritage.

ES category	ES	Description, indicators and mapping methodology
C	**Tourism**	**Flow indicator**: Number of visitors (nr/yr). **Flow methodology**: Number of people visiting the Lagoon in the year 2019, excluding the historical centre of Venice, obtained from stakeholders operating in the tourism and transportation sectors (public transport company AVM-ACTV S.p.a., 17 private navigation companies - the major ones operating in this sector and nine ecotourism associations). The maps represent the itineraries of the trips enjoyed by visitors, thus representing the fluxes of people visiting different lagoon areas.
C	**Recreational navigation**	**Description**: Recreation in the Lagoon by pleasure-boat owners. **Capacity indicator**: Attractiveness of the environment as perceived by pleasure-boat owners (0-1 scale) **Capacity methodology**: The relative level of appreciation of different Lagoon areas has been obtained from a survey to recreational boaters, active in the Lagoon (no. 233 questionnaires collected in 2019, more details in Suppl. material 1). We identified and mapped three types of areas on a gradient from the inlets to the internal areas (areas nearby the inlets, intermediate “urbanised” areas and internal areas), which differ by type of landscape, intensity of water traffic and speed limits. The maps were scaled on a 0-1 range and then summed using as weights the respective level of appreciation by boaters. **Flow indicator**: Number pleasure-boats trips (nr/yr) **Flow methodology**: The fluxes of pleasure-boats have been estimated, based on the average behaviour of boaters, as obtained from a survey (no. 233 questionnaires collected in 2019, more details in Suppl. material 1) and the number of boats present in different areas of the Lagoon. The survey allowed us to obtain the average frequency of trips (no. trips/boat/year) and the areas visited as a function of the location of the homeport. The number of pleasure-boats hosted in different areas of the Lagoon has been estimated, based on official data from the Venice Municipality, interviews to the owners of marinas and analysis of remote sensing data. The fluxes of pleasure-boats in different channels and areas of the Lagoon were mapped by combining these two types of information.
C	**Information for cognitive development**	**Description**: Environmental education activities carried out in the Lagoon and its islands by students of every level (guided tours, naturalistic excursions and educational workshops, excluding cultural visits to the City of Venice). **Capacity indicator**: Attractiveness of the Lagoon as perceived by visitors, accounting for the accessibility to disabled people (0-1 scale). **Capacity methodology**: The map is obtained by averaging the attractiveness map produced for the capacity of tourism ES and a map of accessibility for disabled people, characteristic that is necessary for the organisation of educational activities with schoolchildren and students. The rationale is that not all the Lagoon is accessible to disabled people and, thus, considering educational activities, the attractiveness of inaccessible areas is much lower. The accessibility map (0/1 scale, meaning not accessible/accessible) includes areas reachable by land and areas with landing places and itineraries that are accessible for disabled people. **Flow indicator**: Number of students joining environmental education activities (nr/yr). **Flow methodology**: The number of students of every level who practise environmental education activities in different areas of the Lagoon (guided tours, naturalistic excursions, educational workshops) has been mapped, based on data and interviews to the six major ecotourism cooperatives and associations that offer environmental education activities to students in the area).

ES category	ES	Description, indicators and mapping methodology
C	**Traditions**	**Description**: Recreation in the Lagoon through venetian rowing activities ("voga alla veneta"). Venetian rowing is an ancient local rowing technique tailored to the characteristics of the Venice Lagoon ecosystem, in which rowers are standing and facing forward on traditional boats with flat bottom, allowing a safe navigation also in shallow waters. Originally developed for transportation within the Lagoon, it is nowadays practised as a recreational activity that allows the enjoyment of the Lagoon ecosystem also outside the navigable routes. **Capacity indicator**: Areas with bathymetry suitable for practising venetian rowing activities (0/1 scale). **Capacity methodology**: The average bathymetry suitable for venetian rowing activities has been obtained from interviews with rowing associations. The map of suitable areas corresponds to all the Lagoon areas with bathymetry ≥ 90 cm (0/1 scale, corresponding to unsuitable/suitable, respectively), excluding the inlets. **Flow indicator**: Number venetian rowing boats trips (nr/yr). **Flow methodology**: The number of boat trips with traditional venetian rowing boats has been estimated, based on interviews to all venetian rowing associations active in the lagoon (no. 31 associations). From each association, we obtained the average number of boat trips per day in spring-summer and autumn-winter periods and the areas where the trips occur.

Aggregated indicators of ecosystem services

A set of aggregated indicators has been calculated, based on the results of the assessment (Table 2), on the same spatial grid (250 m resolution). Before the calculation of aggregated indicators, all ES have been scaled to a 0-1 range (min-max scaling), in order to ensure comparability between the different units used for the single ES. The distinction between direct and mediated flow (*sensu* Rova and Pranovi 2017) represents an intermediate level of aggregation, which has been chosen because we believe that the human inputs that intervene in the flow of provisioning and cultural ES ("mediated" ES) could be key drivers affecting the relationship with ecological status. The sum of ES capacity and flow instead represent a full level aggregation that attempts to synthesise the overall capacity and flow of multiple ES.

Table 2.

Aggregated indicators of ecosystem services (ES).

Aggregated ES indicator	Description
Sum of ES capacity	Sum of the capacity of all ES.
Sum of ES flow	Sum of the flow of all ES.
Sum of Dir ES flow	Sum of the flow of direct ES (i.e. regulating and maintenance ES).
Sum of Med ES flow	Sum of flow of mediated ES (i.e. provisioning and cultural ES).

Indicators of ecological status

For what concerns the ecological status of the Lagoon, on one side, we used the two biological quality elements (BQE) suggested by the WFD (MAQI and M-AMBI); on the other, two functional indicators extracted by a food web model (Kempton Q-90 index and Secondary Production).

The WFD requires that the ecological status of transitional waters environment, as the VL, is assessed by monitoring macrophytes and benthic macroinvertebrates, by using the metrics MAQI (Macrophyte Quality Index, Sfriso et al. 2009) and M-AMBI (Multivariate-AZTI Marine Biotic Index, Muxika et al. 2007), respectively. MAQI is an index based on the composition of the macrophyte community, specifically developed for the transitional environments of the Mediterranean ecoregion (Sfriso et al. 2009). M-AMBI is a multivariate indicator that integrates the AMBI index (Borja et al. 2000), which reflects the proportion of species with different sensitivity to disturbance, with the Shannon-Wiener Diversity Index and Species Richness (Muxika et al. 2007, Borja et al. 2009).

Kempton Q is a community diversity index which measures the slope of the cumulative species abundance curve (Kempton and Taylor 1976). Its Q-90 version has been specifically adapted for application to the outcomes of trophic web models, considering functional groups similarly to species for the scope of the index calculation and referring to the slope between the 10th and the 90th percentiles of the curve (Ainsworth and Pitcher 2006). Secondary Production is the net biomass increase of consumers in the community over a period of time (year) (Golley 1968, Alvarez-Borrego 1994) and, thus, is a measure that reflects the sum of energy flowing across the different trophic levels of the ecosystem. Both indicators have been calculated using the outcomes of a spatially explicit trophic web model developed for the VL (Anelli Monti et al. 2021). The model, and, thus, the two indicators, are spatialised on the same grid used for the ES mapping (250 m resolution).

This set of indicators covers different aspects of the Lagoon ecosystem health, following the recommendation of previous studies (e.g. De Leo and Levin 1997, Smith et al. 2017): MAQI and M-AMBI reflect the status of specific compartments of the ecosystem, while Kemption Q and Secondary Production complement them by reflecting structural and functional characteristics of the Lagoon ecosystem as a whole. This allows us to investigate how ES are related to these different aspects of the health of the Lagoon. MAQI and M-AMBI, being the normative reference for the ecological status in the VL, allow us to explore what could be the relationship between the implementation of the WFD and the ES supply and management, both in terms of possible dependence of the ES capacity on the ecological status and in terms of possible impacts of the ES flow on it. Kemption Q and Secondary Production complement the analysis, shedding light on if and how these relationships could change when more holistic and functional aspects of ecosystem health are considered.

The monitoring of the BQE occurs in 103 monitoring stations distributed across the Lagoon (Fig. 85 for MAQI and 75 for M-AMBI), whose values are averaged at the “water body” level, that is, the management units defined by the management plan “Hydrographic district of Oriental Alps" (Autorità di bacino dell'Adige Piave Brenta-Bacchiglione et al. 2010), in compliance with the Directive (Fig. 1). The plan identifies 11 water bodies, with a size ranging between about 4 and 135 km^2, defined, based on a combination of hydrological descriptors, existing pressures and chemical and ecological states (Fig. 1). Three "heavily modified water bodies" have also been identified, corresponding to Venice downtown and the 'valli da pesca', semi-enclosed areas located in the Northern and Central-Southern Lagoon (in white in Fig. 1). These water bodies are not included in this work due to the incomplete data currently available for these sites.

Fig. 2 shows the distribution of the four ecological status indicators. For what concerns the two BQE, the status is referred to the monitoring period 2017-2019 (Regione Veneto 2020).

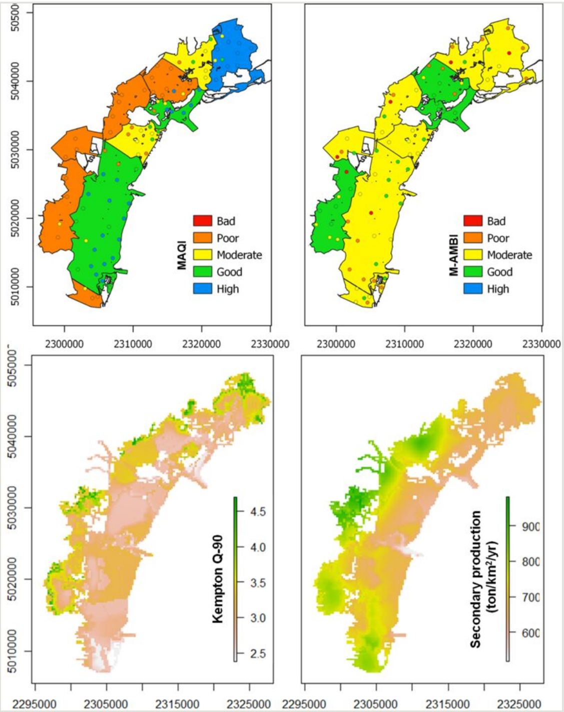


Figure 2.

Maps of the ecological status indicators considered in this study: **A)** MAQI; **B)** M-AMBI; **C)** Kempton Q-90 and **D)** Secondary Production.

Relationships between ES and ecological status indicators

In order to be able to capture different nuances of the relationship between ecological status and ES, we have considered both the capacity and flow of individual ES and the aggregated ES indicators described above. Their relationships with each of the four ecological status indicators (MAQI, M-AMBI, Kempton Q-90 and Secondary Production) have been tested using Spearman's rank correlation and subsequent significance test, adjusted for multiple comparisons using Holm's correction (considering each ecological status indicator as a separate set of tests).

We have chosen to evaluate these relationships under two different spatial settings: by considering the water bodies adopted by the Directive and by disregarding them, in order to broaden the analysis beyond these spatial units given the greater variation in size that characterises them. The BQE values in water bodies were calculated as the average of the data from the sampling stations falling within each water body, according to the methodology required by the WFD. For the other ecological status indicators (Kempton Q-90 and Secondary Production), as well as for individual ES and aggregated ES indicators, in order to have a number of observations per water body comparable to that of the BQE, the data were subsampled in the locations corresponding to the BQE monitoring stations. The average values in the water bodies were calculated on the basis of this subsample. To test the relationship between ecological status indicators and ES without considering the subdivision of the Lagoon into water bodies, we used as samples the values of ecological status and ES corresponding to the locations of the BQE monitoring stations, without averaging the data by water body.

Finally, we have tested the relationship between the aggregated ES' capacity and flow, by calculating the Spearman's rank correlation (and subsequent significance test) between the sum of capacity and the sum of flow. In this case, the test has also been repeated under different spatial settings:

1. by considering all the pixels of the Venice Lagoon's submerged and intertidal areas, therefore making use of the full dataset available. The fishing ponds were excluded because of the lack of data. Due to their marginal position and their almost complete segregation, the ES they provide are likely to differ at least partially from those of the open Lagoon and, thus, require a dedicated study.
2. by considering the average value in each water body, similarly to what the WFD requires for the BQE, that is, first subsampling the data on the locations of the BQE monitoring stations and then averaging the data of the stations located in each water body.
3. by disregarding the water bodies and using the data subsampled on the locations of the BQE monitoring stations.

These two latter settings are equal to those used to analyse the ES-ecological status relationship.

All the analyses have been carried out in R statistical software (R Core Team 2020).

Results

Ecosystem services' assessment and capacity and flow relationship

The maps of ES capacity and flow in the VL are shown in Figs 3, 4, 5.

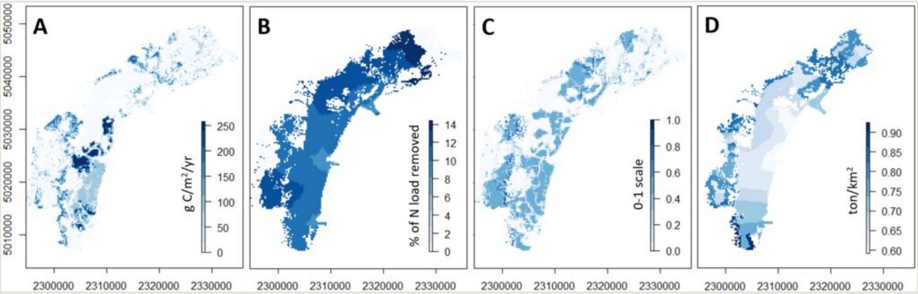


Figure 3.

Capacity/flow of direct (regulating) ecosystem services (**A**: climate regulation; **B**: waste treatment **C**: erosion prevention **D**: lifecycle maintenance).

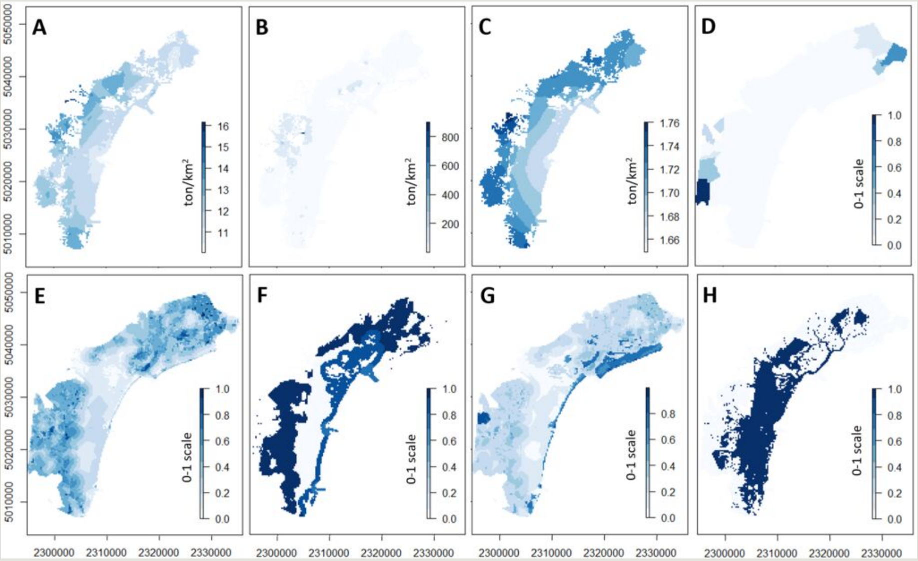


Figure 4.

Capacity of mediated (provisioning and cultural) ecosystem services (**A**: artisanal fishing; **B**: clam harvesting; **C**: recreational fishing; **D**: hunting; **E**: tourism, **F**: recreational navigation; **G**: information for cognitive development; **H**: traditions).

The carbon sequestration rate for salt marshes and seagrass meadows ranges between 64 and 258 g C/m^2/yr, while for waste treatment, we estimate that denitrification processes can remove about 12% of nitrogen loads. Erosion prevention shows the important role played by salt marshes and seagrasses to prevent sediment erosion and thus to maintain the Lagoon morphology, while the lifecycle maintenance map shows that juveniles' biomass is greater in the northern part of the Lagoon, which is characterised by a a greater surface of intertidal and shallow areas (Fagherazzi et al. 2006, Sarretta et al. 2010) and which receives more freshwater inputs (Zuliani et al. 2005, Sarretta et al. 2010), creating chemical-physical gradients stronger than in other parts of the Lagoon. The capacity of provisioning ES tends to be higher in confined areas of the Lagoon, but it is important to point out that this is a static representation of a dynamic resource which, in the case of fish species, moves across the Lagoon and from/to the sea on a seasonal basis. The capacity of most cultural ES also tends to be greater towards the internal parts of the Lagoon, due to the more diversified landscape that characterises these areas, being the typical lagoon landscape, the most appreciated natural factor of attractiveness. Overall, the Lagoon ecosystem is considered very relevant by the visitors interviewed, which attributed the same level of importance to the natural environment and to cultural heritage (please see the results of the survey in Suppl. material 1).

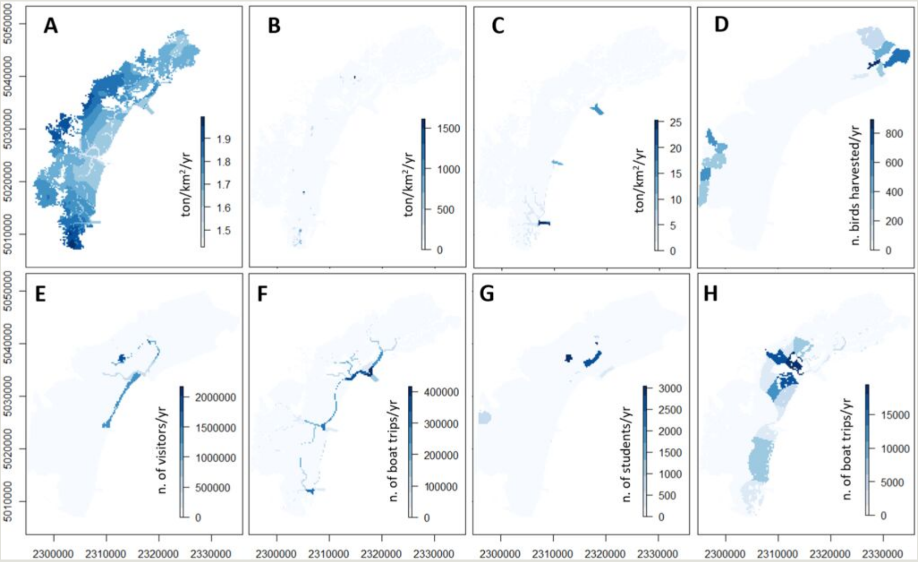


Figure 5.

Flow of mediated (provisioning and cultural) ecosystem services (**A**: artisanal fishing; **B**: clam harvesting; **C**: recreational fishing; **D**: hunting; **E**: tourism; **F**: recreational navigation; **G**: information for cognitive development; **H**: traditions).

We estimate that total catches of artisanal fishing are equal to almost 700 tonnes/yr, while clam harvesting amounts to about 1900 tonnes/yr, concentrated in the small areas directly managed by fishers. It should be noted that harvest of clam in these areas often exceeds the capacity, because clam juveniles are usually re-allocated there from other areas of the Lagoon, for growing. We estimate that catches from recreational fishing amount in total to about 140 tonnes/yr, mainly concentrated at the three inlets, while for hunting, the greatest share of catches occurs in the hunting farms and a smaller share in the hunting blinds located in the confined areas of the Lagoon. Finally, for what concerns the flow of cultural ES, we estimate a total flow of visitors to the northern Lagoon as high as 2.4 million visitors/yr, while for recreational navigation, we estimate that fluxes of leisure boats can be as high as 400,000 boat trips/yr in the most congested channels located in front of the inlets. Environmental education in the Lagoon has been enjoyed by almost 14,000 students in a single year, the majority of which have visited areas located in the northern part of the Lagoon. The fluxes of venetian rowing boats are as high as nearly 215,000 boat trips/yr in total, mainly concentrated around Venice downtown where most of the rowing associations are located.

The maps of the ES aggregated indicators are shown in Fig. 6. The Sum of capacity and Sum of flow represent the overall "multifunctionality" and "multiple uses" of the Lagoon, respectively (Fig. 6 A and B). Emerged land is characterised by very low values of both indicators, which is due to the fact that the assessment only partially captures the ES provided by these areas. It can be noticed that some portions of the central part of the Lagoon (surrounding the Malamocco-Marghera Channel), present low levels of both capacity and flow, suggesting that a degradation of the ecological potential also produces lower ES uses. For what concerns the flow, the maps of direct and mediated ES (Fig. 6 C and D) highlight the different spatial patterns that characterise the two, the first having a distribution that reflects the presence of habitats and morphological features of the Lagoon, the second being strongly influenced by the proximity to Venice downtown.

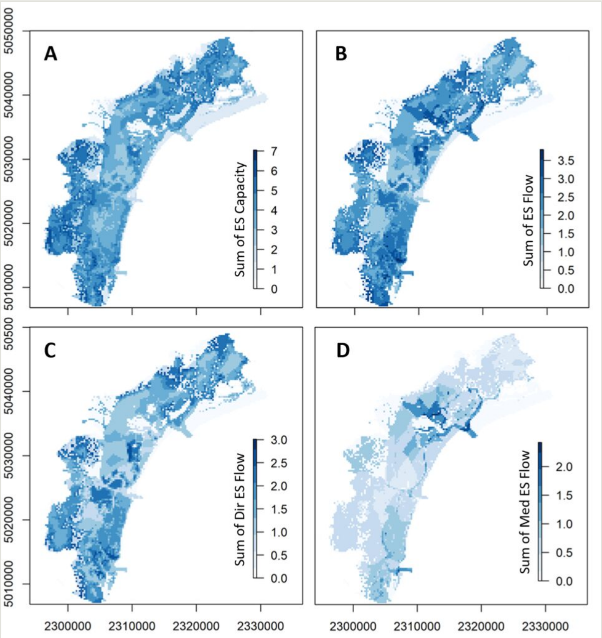


Figure 6.

Ecosystem services' (ES) aggregated indicators in the Venice Lagoon. **A**: Sum of ES Capacity; **B**: Sum of ES Flow; **C**: Sum of Direct ES Flow; **D**: Sum of Mediated ES Flow.

The relationships between the sum of capacity and sum of flow, in the different spatial settings considered, are shown in Fig. 7. Considering the submerged and intertidal pixels, we observe a high correlation between these two variables (Fig. 7A, Spearman's rho = 0.66, $p < 0.0001$) and the same occurs if we subsample the data on the locations of the WFD monitoring stations (Fig. 7B, Spearman's rho = 0.50, $p < 0.0001$). If instead the average values in the water bodies are considered, the relationship becomes not significant (Fig. 7C, Spearman’s rho = 0.25, p = 0.45). Additionally, we can observe that the overall flow is generally about half of the overall capacity, with a flow/capacity ratio of 0.53 (0.44-0.61) (median, first and third quartile) considering all pixels, 0.54 (0.49-0.61) considering the subsample on the WFD monitoring stations and 0.55 (0.50-0.61) considering the average values in water bodies.

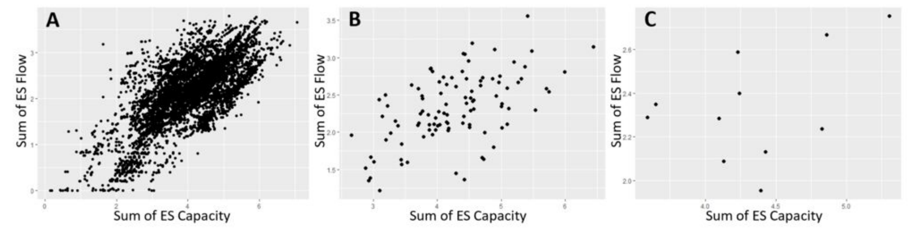


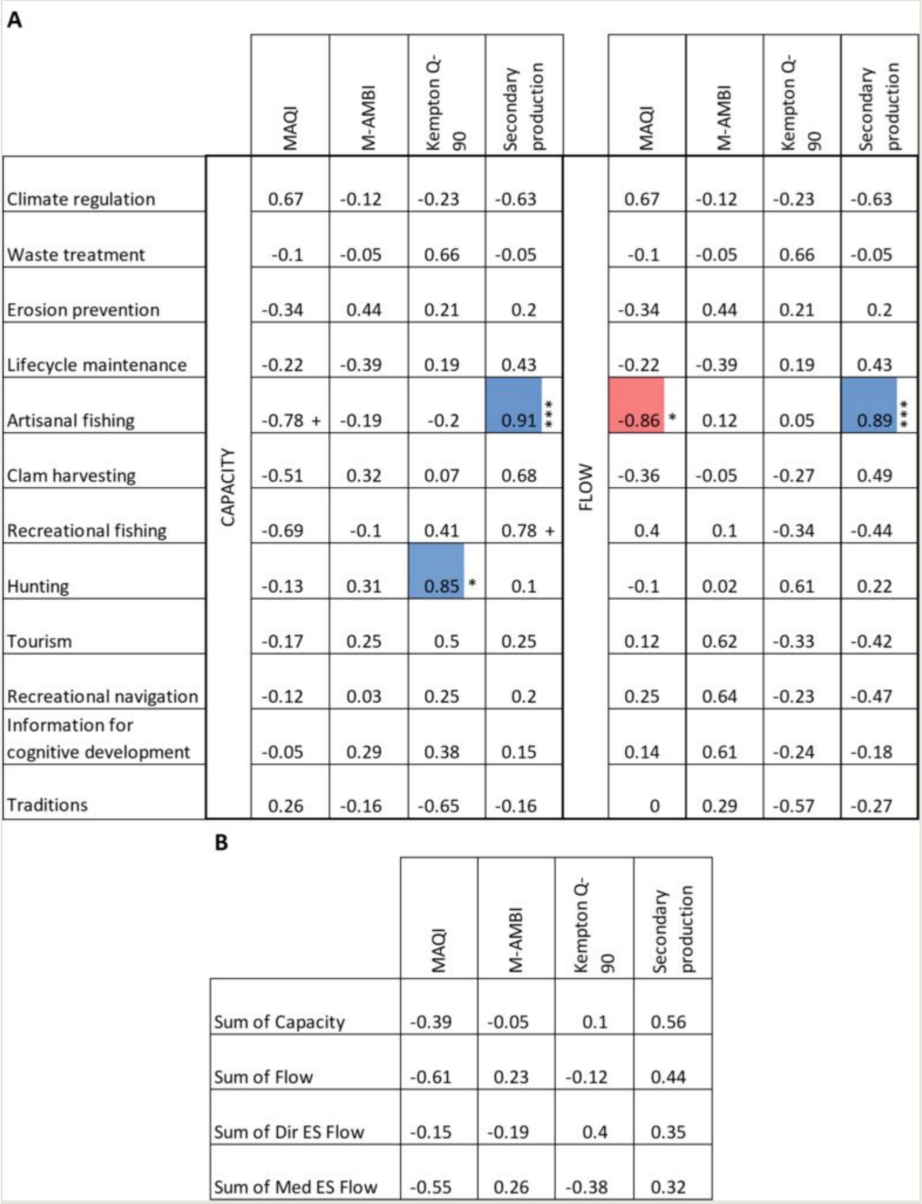
Figure 7.

Scatterplot between the sum of ecosystem services’ (ES) capacity and the sum of ES flow, considering **(A)** submerged and intertidal pixels; **(B)** data subsampled in the WFD monitoring stations and **(C)** average values in the water bodies defined in compliance with the Water Framework Directive (WFD).

Relationship between ecosystem services and ecological status

Fig. 8 shows the correlations between the indicators of ecological status (MAQI, M-AMBI, Kempton Q-90 and Secondary Production) and ES, considering the average values per water body, following the methodology adopted by the WFD. Concerning the BQE, only MAQI and artisanal fishing flow showed a significant (negative) relationship, while no significant relationships with aggregated indicators have been found. Regarding the other ecological status indicators, some significant positive relationships emerge with respect to the capacity and flow of provisioning ES (Kempton Q-90 with hunting capacity and secondary production with artisanal fishing capacity and flow), while no significant relationships are found with aggregated indicators.

Fig. 9 shows the correlation between ES and ecological status indicators, calculated without averaging the data by water body. MAQI is significantly negatively related with the capacity of most provisioning ES (artisanal fishing, clam harvesting and recreational fishing) and with the flow of artisanal fishing, while it is positively correlated with climate regulation. In terms of aggregated indicators, the only significant relationship is the negative one with the flow of mediated ES. The results for M-AMBI do not show any significant relationship also at this level of analysis. Kempton Q-90 is characterised by a positive significant relationship with waste treatment and a negative one with traditions’ capacity. In terms of aggregated indicators, it is positively related with the sum of the flow of direct ES and negatively with the flow of mediated ES. Finally, Secondary Production is positively related with the capacity of all provisioning ES and with the flow of one of them (artisanal fishing). For what concerns the aggregated ES indicators, the results show a positive relationship with nearly all of them, with the exception of the sum of direct ES flow.



A

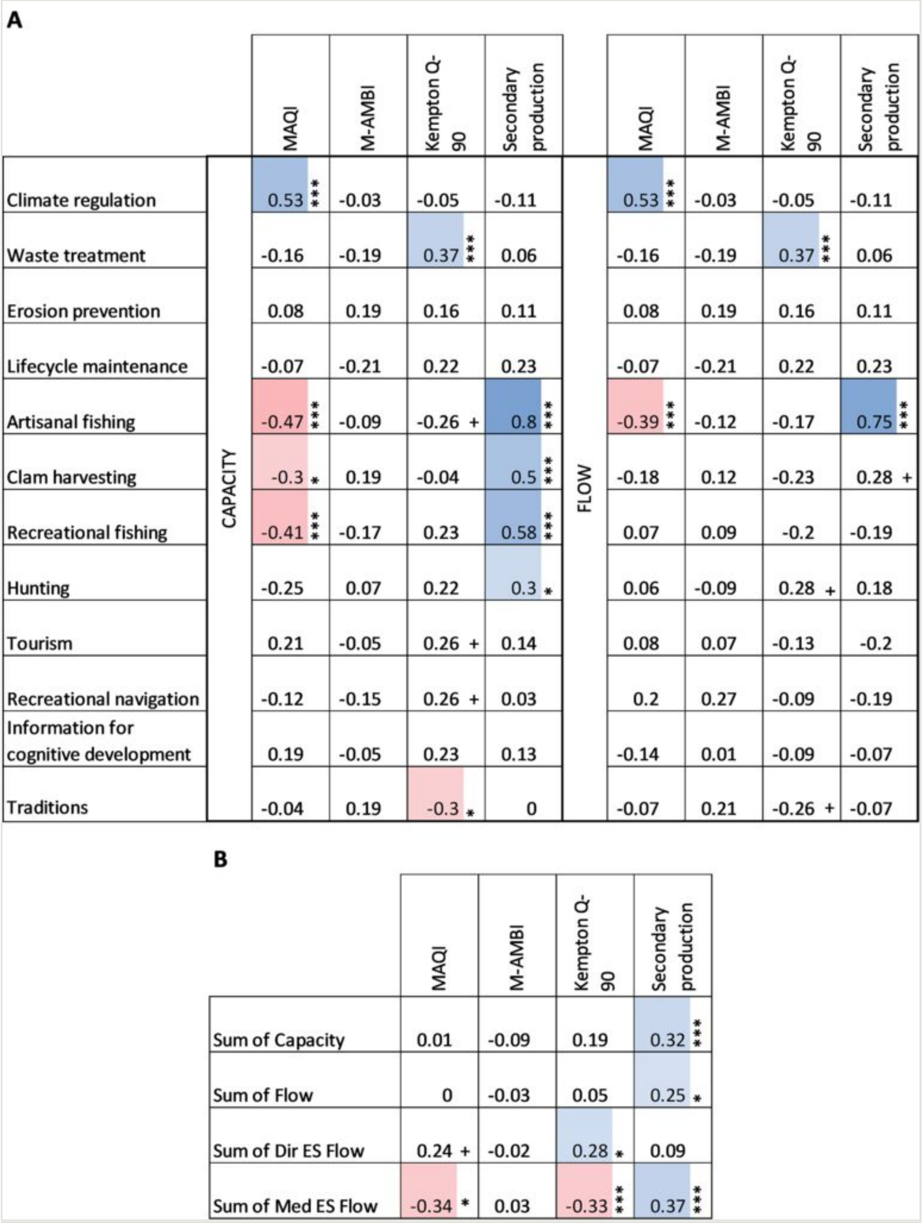
	CAPACITY				FLOW			
	MAQI	M-AMBI	Kempton Q-90	Secondary production	MAQI	M-AMBI	Kempton Q-90	Secondary production
Climate regulation	0.67	-0.12	-0.23	-0.63	0.67	-0.12	-0.23	-0.63
Waste treatment	-0.1	-0.05	0.66	-0.05	-0.1	-0.05	0.66	-0.05
Erosion prevention	-0.34	0.44	0.21	0.2	-0.34	0.44	0.21	0.2
Lifecycle maintenance	-0.22	-0.39	0.19	0.43	-0.22	-0.39	0.19	0.43
Artisanal fishing	-0.78 +	-0.19	-0.2	0.91 ***	-0.86 *	0.12	0.05	0.89 ***
Clam harvesting	-0.51	0.32	0.07	0.68	-0.36	-0.05	-0.27	0.49
Recreational fishing	-0.69	-0.1	0.41	0.78 +	0.4	0.1	-0.34	-0.44
Hunting	-0.13	0.31	0.85 *	0.1	-0.1	0.02	0.61	0.22
Tourism	-0.17	0.25	0.5	0.25	0.12	0.62	-0.33	-0.42
Recreational navigation	-0.12	0.03	0.25	0.2	0.25	0.64	-0.23	-0.47
Information for cognitive development	-0.05	0.29	0.38	0.15	0.14	0.61	-0.24	-0.18
Traditions	0.26	-0.16	-0.65	-0.16	0	0.29	-0.57	-0.27

B

	MAQI	M-AMBI	Kempton Q-90	Secondary production
Sum of Capacity	-0.39	-0.05	0.1	0.56
Sum of Flow	-0.61	0.23	-0.12	0.44
Sum of Dir ES Flow	-0.15	-0.19	0.4	0.35
Sum of Med ES Flow	-0.55	0.26	-0.38	0.32

Figure 8.

Spearman's rank correlation between ecological status indicators (MAQI, M-AMBI, Kempton Q-90 and Secondary Production) and ES (**A**: capacity and flow of single ES, **B**: ES aggregated indicators), computed using the water bodies as spatial units. Symbols near the correlation coefficient represent the significance level (+: p-value < 0.1; *: p-value < 0.05; **: p-value < 0.01; ***: p-value < 0.001), adjusted for multiple comparisons using Holm's correction. Significant correlation coefficients (p-value < 0.05) are coloured in blue or red, representing positive and negative correlations, respectively.



A

	CAPACITY				FLOW			
	MAQI	M-AMBI	Kempton Q-90	Secondary production	MAQI	M-AMBI	Kempton Q-90	Secondary production
Climate regulation	0.53 ***	-0.03	-0.05	-0.11	0.53 ***	-0.03	-0.05	-0.11
Waste treatment	-0.16	-0.19	0.37 ***	0.06	-0.16	-0.19	0.37 ***	0.06
Erosion prevention	0.08	0.19	0.16	0.11	0.08	0.19	0.16	0.11
Lifecycle maintenance	-0.07	-0.21	0.22	0.23	-0.07	-0.21	0.22	0.23
Artisanal fishing	-0.47 ***	-0.09	-0.26 +	0.8 ***	-0.39 ***	-0.12	-0.17	0.75 ***
Clam harvesting	-0.3 *	0.19	-0.04	0.5 ***	-0.18	0.12	-0.23	0.28 +
Recreational fishing	-0.41 ***	-0.17	0.23	0.58 ***	0.07	0.09	-0.2	-0.19
Hunting	-0.25	0.07	0.22	0.3 *	0.06	-0.09	0.28 +	0.18
Tourism	0.21	-0.05	0.26 +	0.14	0.08	0.07	-0.13	-0.2
Recreational navigation	-0.12	-0.15	0.26 +	0.03	0.2	0.27	-0.09	-0.19
Information for cognitive development	0.19	-0.05	0.23	0.13	-0.14	0.01	-0.09	-0.07
Traditions	-0.04	0.19	-0.3 *	0	-0.07	0.21	-0.26 +	-0.07

B

	MAQI	M-AMBI	Kempton Q-90	Secondary production
Sum of Capacity	0.01	-0.09	0.19	0.32 ***
Sum of Flow	0	-0.03	0.05	0.25 *
Sum of Dir ES Flow	0.24 +	-0.02	0.28 *	0.09
Sum of Med ES Flow	-0.34 *	0.03	-0.33 ***	0.37 ***

Figure 9.

Spearman's correlation between ecological status indicators (MAQI, M-AMBI, Kempton Q-90 and Secondary Production) and ES (**A**: capacity and flow of single ES, **B**: ES aggregated indicators), computed without using the water bodies as spatial units. Symbols near the correlation coefficient represent the significance level (+: p-value < 0.1; *: p-value < 0.05; **: p-value < 0.01; ***: p-value < 0.001), adjusted for multiple comparisons using Holm's correction. Significant correlation coefficients (p-value < 0.05) are coloured in blue or red (representing positive and negative correlations, respectively).

Discussion

This study presents a comprehensive and spatially-explicit assessment of the ecological potential underpinning the ES (ES capacity) and their actual use (ES flow) in the VL. The assessment of both these aspects of ES delivery represents a crucial advancement of this assessment with respect to previous ones (Rova et al. 2015, Rova et al. 2019). This distinction is considered to be a key step for understanding the sustainability of ecosystem use (Schröter et al. 2014), especially in the cases where the unit of measure of capacity and flow is comparable (most provisioning ES) and we can estimate how much of the overall capacity is actually used. For example, artisanal fishing activities harvest annually about 1/7 of the biomass available and this ratio becomes almost 1/5 for recreational fishing, highlighting how this recreational activity represents a pressure fully comparable to the commercial one. Assessing the ES capacity also allows us to identify the key structures and functions of the ecosystem upon which the ES' use depends. For example, this assessment reveals the high degree of appreciation of the lagoon landscape by the people – over 2 million per year - who visit the islands of the Lagoon outside Venice downtown. Nature is ranked equally important to cultural heritage, highlighting the key contribution of the ecosystem to tourism, which is the main economic sector of the area (counting in total about 5.5 million overnight stays (Città di Venezia 2020) and 22 million excursionists (Bertocchi et al. 2020) per year). Our results also provide the first estimate of the contribution of VL habitats to the regulation of CO_2 concentrations in the atmosphere. In particular, our estimates for salt marshes and seagrasses habitats' carbon sequestration, which are comparable with data from literature on similar habitats (Chmura et al. 2003, Duarte et al. 2005), sum up to a carbon sequestration rate of about 20 x 10^3 tonnes C/yr for the whole Lagoon. This value is comparable with the carbon sequestration reported in another Mediterranean lagoon of similar size (Eid and Shaltout 2013).

Considering the aggregated ES indicators, we can first of all observe that the overall capacity and flow appear to be positively related. This is consistent with expectations given the definition of the ES concept (Burkhard et al. 2012), confirming that the actual use of ES depends upon the ecological structures and processes of the ecosystem that make up the ES potential. This means that, in general, where the ecological potential is degraded, also the ES flow is compromised, as exemplified by the areas in the central lagoon where both the aggregated capacity and flow tend to be low. These areas are in fact characterised by a particularly severe sediment erosion resulting in the degradation of the Lagoon morphology (Sarretta et al. 2010), suggesting that losing the typical lagoon characteristics implies also losing the multiple benefits we can derive from it. In general, our results show that the overall capacity is generally greater than the overall flow, the latter being on average about half of the first. This is reasonable if we consider the ES potential as a sort of carrying capacity for the ES use, in agreement with the definition of these concepts (Villamagna et al. 2013). Therefore, our results suggest that, on average, we are using about half of this overall carrying capacity. However, besides the average value, from the scatterplot, we can observe that some areas are characterised by a Flow/Capacity ratio close to one or even greater. This "saturation" might reveal areas where the ES uses are particularly high with respect to the carrying capacity of the ecosystem. A further analysis of these areas would be required to provide useful hints from a management perspective.

This rich assessment dataset allows us to capture the different nuances of the relationship between ES and ecological status. In particular, our results highlight three main findings: there is a general lack of relationship between the BQE and ES, both in terms of single ES and aggregated indicators, when they are evaluated at the water body level according to the WFD; the same occurs if we change indicators of ecological status, but not the spatial level of assessment; a series of relationships emerge if we do not consider the water bodies as spatial units of the assessment and they are rather different amongst the different ES (in terms of capacity/flow indicators and ES categories) and ecological status indicators. This underlines the complexity of this relationship, in agreement with previous studies (Spangenberg et al. 2014, Grizzetti et al. 2019).

When considering different ecological status indicators, we can recognise that they belong to three different "categories" of indicators, according to Müller (2005). The two BQEs (MAQI and M-AMBI) are "*sectoral*" indicators, based on specific ecosystem compartments, reflecting a traditional, rather reductionistic, approach (Müller 2005); Kempton Q-90, instead, depicts a more integrated "*structural*" characteristic of the ecosystem, being a measure of the diversity of the whole community (Kempton and Taylor 1976, Ainsworth and Pitcher 2006); Secondary Production, finally, represents a "*functional*" ecosystem indicator, summarising the energy flow from primary producers across the consumers' trophic levels. From our results, we can observe that the relationships with ES capacity and flow change amongst these categories of ecological status indicators and, particularly, the number of positive correlations tends to increase as we broaden our perspective on the ecological status, switching from sectoral to structural and finally functional indicators. Sectoral indicators appear to be poorly linked with ES, which is possibly due to the conceptual "distance" between the compartments that they represent and the processes and functions upon which the ES depend. This is particularly true if we consider the macroinvertebrates compartment, for which we do not identify any significant relationship with ES at any of the tested settings. Both MAQI and Kempton Q-90 relate negatively with the aggregated flow of provisioning and cultural ES ("mediated ES" *sensu* Rova and Pranovi 2017). In line with the findings from Spangenberg et al. (2014), this may be due to the fact that these indicators are more sensitive to the impacts of human activities than critical for the provision of these ES, whose flow depends on substantial human inputs. Kempton Q-90 is also found to be positively related with regulating ES ("direct ES" *sensu* Rova and Pranovi 2017), suggesting that the provision of these services is linked with the biodiversity of the whole community. Finally, Secondary Production is positively related with most of the ES aggregated indicators, suggesting that the ecosystem functionality that it represents is closely linked with the ES potential and use.

Our results highlight a scarcity of significant correlations when considering the average values per water body, if compared with the outcomes obtained disregarding these spatial units, both in terms of capacity-flow and ES-ecological status relationships. It seems that using the water bodies as spatial units of analysis hinders the detection of the relationships found using other spatial settings. This could suggest that this zonation could represent a limitation when it comes to the analysis of ES, not being able to fully capture the functional characteristics of the Lagoon ecosystem and, thus, the spatial patterns of ES. This becomes an issue if, in agreement with previous literature (Blackstock et al. 2015, Grizzetti et al. 2016, Carvalho et al. 2019, Rova et al. 2019), we argue that ES could play a role in the management of aquatic environments, in particular within the context of the WFD implementation. The partial failure in the achievement of the Directive's goals (Voulvoulis et al. 2017) indeed calls for new approaches for the management of surface waters. We believe that ES could not "only" be used to prove the benefits resulting from an improved ecological condition, but could represent a basis for the development of new management strategies, being, on one hand, dependent on the ecosystem conditions and, on the other hand, being closer to human uses of the ecosystem that can be directly targeted by management actions. In other words, ES, when capacity and flow are distinguished, could represent a "bridge" between what we want to achieve (a good ecological status and a high ES capacity) and what we can manage (the uses of the ecosystem -ES flows-), a perspective that we believe deserves attention in future research. From this perspective, our results suggest that the zonation of the Lagoon into the water bodies adopted in compliance with the WFD could represent an obstacle to the ambition of using ES for deriving and applying new management solutions, at least at the local scale of analysis adopted in this study.

Conclusions

The assessment of ES capacity and flow brings a relevant advancement with respect to the previous knowledge on ES in the VL. In particular, on an aggregated level, the flow of multiple ES in the Lagoon is shown to be positively related to the overall ecological potential and, on average, about half of this aggregated potential is expressed as a flow. This suggests that the ES capacity is acting as a sort of carrying capacity for the ES flow: where this carrying capacity is degraded, we observe an overall loss of ES uses. Furthermore, the relationship with ecological status reveals a picture of great complexity. In terms of indicators, the relationship changes depending on the ES and on the ecological status indicators considered. In particular, the number of positive links increases as we move from more sectoral indicators (M-AMBI and MAQI) to a more integrated structural indicator (Kempton Q-90 diversity), to a more functional indicator (Secondary Production). This suggests that ES are more closely linked with indicators that reflect functional characteristics of the ecosystem as a whole rather than to indicators that represent the structural characteristics of isolated compartments of the ecosystem. From a spatial perspective, our results suggest some possible limitations of the WFD water bodies, as most of the relationships fail to emerge when we consider these spatial units of analysis. This zonation seems not to be able to capture the patterns of ES in the Lagoon, hindering the analysis from an ES perspective. We argue that ES, thanks to their capacity to "bridge" ecosystem properties and human uses, could play a role on the management of the Lagoon, possibly also with regards to the definition of spatial units to be used for management purposes.

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Supplementary material

Suppl. material 1: Annex doi

Authors: Rova S., Stocco A., Pranovi F.
Data type: MS word document
Brief description: Information about the surveys conducted to assess the tourism, recreational navigation and recreational fishing ES.
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