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Sustainability perspectives and spatial patterns of multiple ecosystem services in the Venice lagoon: possible roles in the implementation of the EU Water Framework Directive

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Abstract:

The multiple ecosystem services (ES) co-produced by social-ecological systems include ES directly resulting from ecosystem functioning, and ES mediated by human activities, which can have negative effects on the system and on the ES provided. As a result, different patterns of multiple ES delivery can be characterized by sustainable or unsustainable trends over time, depending on the interactions occurring among ES. In this paper, a sustainability perspective was used for the identification of desirable and undesirable ES delivery patterns in the water bodies of the Venice lagoon (Italy). A set of 13 ES was quantitatively mapped for the lagoon's water bodies, and the trends of the ES provided by each water body have been explored through a modeling application. Two aggregated indicators, MED/DIR and PRESS/DIR, calculated based on the mapping outcomes, were found to be strongly associated with the modeled trends, and thus provide a synthetic indication of the potential (un)sustainability of the current ES provision. This sustainability-driven analysis paves the way for an operationalization of the ES concept in the context of the implementation of the EU Water Framework Directive (2000/60/EC). Based on the analysis of the relationships between multiple ES and ecological status, we suggest that ES could play a role in the selection of the biological quality elements, by prioritizing the metrics that are positively associated with the sustainable ES patterns. Adopting a perspective focused on sustainability, the ES concept can be used to define management trajectories that aim to reach the WFD targets through the management of unsustainable ES patterns, in the context of climate change.

1. Introduction

The concept of ecosystem services (ES) is defined as the contributions of ecosystem structures and functions – in combination with other inputs – to human well-being (Burkhard et al., 2012). It has been introduced to contribute to the sustainable management of natural resources, by calling attention to the consequences that environmental degradation and biodiversity loss have for human well-being (Costanza et al., 1997; Millennium Ecosystem Assessment, 2005). However, the delivery of some ES, generally provisioning and cultural ones, which have been categorized as “mediated” ES (Rova and Pranovi, 2017), imply the presence of additional anthropogenic inputs (e.g. fishing effort, agricultural practices, visiting activities, etc.) (Burkhard et al., 2014) that can be in conflict with a sustainable use of resources and that can have impacts on the provision of the same or other ES (Bennett and Chaplin-Kramer, 2016; Schröter et al., 2017). For this reason, the need to advance ES science to meet sustainability challenges has been recognized as a priority research area by several authors (Bennett et al., 2015; Bennett and Chaplin-Kramer, 2016; Lin, 2012; Nicholson et al., 2009; Schröter et al., 2017). Advances in this field of research include the adoption of a social-ecological systems’ perspective, that accounts for both the social and ecological factors involved in ES production (Reyers et al., 2013; Rova and Pranovi, 2017), and the mapping and analysis of how multiple ES are co-produced within social-ecological systems (Bennett et al., 2015; Meacham et al., 2016; Queiroz et al., 2015; Raudsepp-Hearne et al., 2010). However, Schröter et al. (2017) stress the need to go beyond snapshot assessments of all forms of natural resources use, by operationalizing a normative judgement of ES based on the goal of sustainability. This would allow to shift from the current and rather descriptive applications of the ES concept to more operational analyses that shed light on possible trajectories for the sustainable management of social-ecological systems.

Under this perspective and with a focus on aquatic ecosystems, a major management challenge in which the ES concept could play an important role is the implementation of the EU Water Framework Directive 2000/60/EC (WFD) (European Commission, 2000). A clear connection exists between the WFD and the delivery of ES (Giakoumis and Voulvoulis, 2018; Grizzetti et al., 2016b, 2016a; Vlachopoulou et al., 2014; Voulvoulis et al., 2017). The WFD ecological status is “an expression of the quality of the structure and functioning of aquatic ecosystems associated with surface waters" (European Commission, 2000), and thus it can be assumed to be linked to the ecosystem functions upon which ES provision is based (Vlachopoulou et al., 2014). At the same time, the ecological status is a measure of the need to reduce the anthropogenic pressures that negatively affect the ecosystem (i.e., it indicates the distance between the current and desired state), thus assuming the role of a normative indicator for policy development rather than a descriptive measure of ecological quality (Voulvoulis et al., 2017). This interpretation brings the ecological status quite close to the sustainability-driven interpretation of ES promoted by Schröter et al. (2017). Thus, a further need arises to investigate the role that ES could play in the WFD implementation. In fact, the relationship between ecological status and ES is still debated (Boon et al., 2015) and precise indications about how to apply the ES concept in the implementation of the river basin management plans are lacking (Grizzetti et al., 2016b).

The implementation of the WFD represents a major challenge at the EU level, its overall objective (achievement of good status for all EU waters) not being achieved in 2015 in about half of EU surface waters (Voulvoulis et al., 2017). The problems with WFD implementation have been attributed to a reductionist interpretation of the directive, targeting the improvement of the biological quality elements rather than managing the pressures to improve the ecological status, in other words, targeting the symptoms rather than the causes of water degradation (Voulvoulis et al., 2017). The integration of the ES concept in the WFD implementation process could contribute to overcome these limitations bringing a new integrated perspective for the definition of effective management plans (Vlachopoulou et al., 2014; Voulvoulis et al., 2017).

The objectives of our study are: (1) to analyze the spatial patterns of multiple ES to get an indication of the present and future (un)sustainability of ES provision; and (2) to use the ES patterns, "judged" in terms of sustainability, to support the implementation of environmental management strategies (as the WFD), also within the context of climate change.

The Venice lagoon (VL), Italy, a complex social-ecological system providing a broad set of ES (Rova et al., 2015) and facing several management challenges, has been chosen as case study area for our investigation. We studied how a sustainability-driven spatially explicit analysis of ES can find application in the context of the implementation of environmental strategies for the VL ecosystem, using the following three steps approach: (1) quantification and mapping of the multiple ES provided by the VL (Italy) and identification of the ES patterns that characterize the WFD water bodies, (2) analysis of the potential ES trends in each water body using a Petri nets modeling approach, (3) analysis of the relationships between ES patterns, potential ES trends and ecological status.

2. Material & Methods

2.1. Venice lagoon study area

The VL is a shallow coastal lagoon located in the northern Adriatic Sea (north-east of Italy). With a surface of about 550 km^2, it is the largest lagoon in the Mediterranean region. The VL is characterized by a mosaic of shallow habitats, that includes salt marshes, seagrasses beds, intertidal and subtidal mudflats, which are intersected by a network of channels that branch off from the three inlets that connect the lagoon to the Adriatic Sea. The management plan “Hydrographic district of Oriental Alps” (Autorità di bacino dell’Adige et al., 2010), adopted in compliance to the WFD, divides the VL into 11 water bodies (Figure 1), based on a combination of hydrological descriptors, existing pressures and chemical and ecological state. The water bodies were categorized as “polyhaline confined”, “polyhaline not-confined”, “euryhaline confined” and “euryhaline not-confined” based on their salinity and degree of confinement (polyhaline and euryhaline indicate salinity within the range 20-30 and 30-40 psu, respectively, and confined refers to the inner parts of the lagoon, delimited by salt marshes, where water exchange is low). Furthermore, three “heavily modified water bodies” have been identified, corresponding to the historical center of Venice and the fishing ponds in the northern and central-southern lagoon, which are not shown in the Figure 1 and are not included in the ES assessment due to the incomplete data available for these sites.

The VL is a good example for a social-ecological system. Since 15th century, the morphology and ecology of the lagoon have been deeply influenced by human interventions, that include, among others, the diversion of rivers, the construction of sea defenses, the development of an extended industrial pole (Porto Marghera) and the dredging of artificial channels (D'Alpaos, 2010; Pignatti and Seminara, 2009; Ravera, 2000; Sarretta et al., 2010). On the other hand, the Venetian settlements and their cultural heritage have been shaped by the lagoon ecosystem since the evolution of the Venice Republic, resulting in the unique lifestyle and landscape that we can observe in recent times. With about 6.4 million tourist overnight stays in the year 2014 (Comune di Venezia (2015)) and about 20 million same-day visitors estimated per year, tourism is currently the main economic sector of the area, and a major socio-economic pressure, if compared to the number of residents (about 56000 in 2014) living in the historical center of Venice (Comune di Venezia, 2018). The VL system is facing several urgent management challenges, ranging from the implementation of the WFD, which requires reaching a good ecological status in all the water bodies, to the protection of Venice from the impacts of high tides, which are increasing due to relative sea level rise driven by climate change and anthropogenic factors. A system of mobile barriers at the lagoon inlets (MOSE system (Consorzio Venezia Nuova, 2018)), aimed to protect Venice from flooding, is currently under construction and is expected to be completed in 2019. The barriers, raised during high tide events, would separate the lagoon from the sea. The operationalization of the MOSE will shift the system to a situation in which the water exchanges between lagoon and the sea can be actively controlled, and is expected to be a key adaptation measure in response to relative sea level rise.

2.2. Ecosystem services mapping

A set of 13 ES has been mapped in the VL using quantitative biophysical indicators (Table 1). The ES have been selected based on Rova et al. (2015) and Rova and Pranovi (2017), and include five regulating, four provisioning and four cultural ES. The indicators have been designed in agreement with marine and coastal ES literature (e.g. Bohnke-Henrichs et al., 2013; Hattam et al., 2015), and have been adapted to reflect the specific characteristics of the case study area. Indicators, mapping methodology, data sources and mapping units are reported in Table 1. In case of regulating ES, the indicators quantify the outputs of ecosystem functions, which were estimated based on a combination of ecological, morphological and hydrological data. In case of provisioning and cultural ES, the indicators were quantified using a combination of ecological and socio-economic data, that reflect the human activities through which the ES are delivered, which in turn depend on the structure and processes of the lagoon ecosystem. Along with service-specific data, the mapping makes use of shapefiles and GeoTiff of lagoon habitats and morphology (salt marshes, seagrasses, intertidal mudflats, channels, and islands from Comune di Venezia et al. (2018) and benthic diatoms from Facca and Sfriso (2007)). The mapping is referred to the year 2015, data are referred to the same year or to a period as close as possible, depending on availability. The spatial units used for mapping are the WFD water bodies (Figure 1). The mapping procedure has been carried out at a 250 m spatial resolution, and subsequently, for all indicators, average values for each water body have been calculated. The mapping results have been normalized on a scale ranging between 0 and 1. Data analysis and mapping were conducted using R statistical software (R Core Team, 2017) and QGIS (QGIS Development Team, 2017).

2.3. Ecosystem services modeling in water bodies

2.3.1. Modeling approach

An explorative modeling application has been implemented to analyze the potential ES trends that are associated to each water body. The Petri net model proposed by Rova et al. (*in press*) has been used to reproduce the patterns of multiple ES that characterize each water body, and to simulate their temporal trends. The model is based on Ostrom's social-ecological systems framework (McGinnis and Ostrom, 2014; Ostrom, 2009), and is built using the Petri net approach (Esparza and Nielsen, 1994; Girault and Valk, 2003; Murata, 1989). The application to the VL case study allows a dynamic modeling of the same set of 13 ES mapped in this study. The general structure of the model distinguishes between ES with direct and mediated flow type (*sensu* Rova and Pranovi, 2017): ES with direct flow type, generally corresponding to regulating ES, are provided directly through ecosystem functions occurring independently of human inputs; ES with mediated flow type, generally corresponding to provisioning and cultural ES, are instead provided through human activities that "use" the resource (Table 1). In the model, direct ES are quantified through the simulation of ecosystem functions which in turn depend on the systems' ecological resources (e.g. for climate regulation ES, the carbon sequestration function provided by seagrass and salt marshes habitats). On the other hand, mediated ES result from the simulation of human activities, which generally depend on the systems' resources and on the presence of the actors performing the activities (e.g. for seafood ES, the model simulates the fishing activities, which are performed by fishermen and consume target fish species). These activities can be modulated by management actions (e.g. fishery management) enforced by the governance system. Furthermore, the negative externalities produced by some of these activities (e.g. side-effects of fishing practices on habitats) are modeled as a "consumption" of the impacted elements by the activities themselves. The overall topology of the network has been designed to represent the multiple ES altogether, along with their interactions and the cause-effect relationships with drivers of change. This modeling application has no ambition to provide quantitative ES projections but aims to explore the potential trends that are associated with each water body, based on the habitat configuration and on the current pattern of multiple ES. Negative trends indicate potentially unsustainable conditions, in which the provision of multiple ES may not be maintained over time.

2.3.2. Models setup and simulations

In this work, a separate model has been built up for each water body (11 models in total), whose initial conditions have been set up based on the distribution of resources (habitats, fauna, channels and cultural heritage) and actors across the water bodies. Based on these input variables, the model calculates the delivery of ES in each water body. The following data and assumptions were used to estimate the model's inputs for each water body: spatial data about lagoon habitats and morphology (salt marshes, seagrasses, intertidal mudflats, and channels from Comune di Venezia et al. (2018) and benthic diatoms from Facca and Sfriso (2007) were used to calculate the amount of habitats and channels in each water body. The spatial distribution of the fisheries and hunting yields, as obtained for ES mapping purposes (see Table 2), were used to estimate the amount of fauna (target fish species, clam and birds) in each water body. Cultural heritage and traditional knowledge were assumed to be proportional to the relative surface area of each water body. The actors involved in provisioning ES (artisanal, recreational and clam fishermen, and hunters) were estimated by assuming that half of the actors carry on their activities in the northern lagoon (Palude Maggiore, Dese, Tessera, Lido and Marghera) and half in the central-southern lagoon (Sacca Sessola, Centro-Sud ,Teneri, Millecampi, Val di Brenta and Chioggia). These proportions differ in the case of clam fishermen, whose estimated proportion are 20% in the northern lagoon and 80% in the central-southern lagoon. These estimates broadly reflect the distribution of the yields in these two portions of the lagoon. The actors involved in cultural ES (tourists, boat owners, users of environmental education activities and residents) were estimated based on the socio-economic data collected for mapping the distribution of these ES (see Table 2). The values assigned to the input variables in the 11 models are reported in Appendix. Based on these inputs, each model calculates the patterns of multiple ES delivery that result from the initial conditions in each water body. These patterns drive the evolution of the simulations, along with the external drivers included in the modeled scenarios (next paragraph). The comparison between the ES resulting from the models' initial conditions and the ES patterns resulting from the current ES assessment, in each water body, are reported in Appendix.

A business as usual (BAU) scenario has been simulated for each water body. This scenario includes the major current social and ecological trends that characterize the VL, viz, increasing tourists, decreasing residents, unbalanced consumption of salt marshes and increasing seagrasses. In addition, the effects of climate change pressures have been explored with a climate change (CC) scenario, that incorporates, in addition to the BAU trends, the effects of relative sea level rise (+50 cm by the end of the 21st century) and temperature increase (+1°C by the end of the 21st century), and simulates the functioning of the MOSE system.

For each water body, the simulations have been interrupted when any of the resources becomes depleted or, in case of positive evolution, until any of the resources increases by 50% (which are the boundaries within which the model behavior is considered reliable). This results in simulations of different duration, ranging between 4 and 80 t steps. The model calculates the ES trends throughout the simulation, which have been summarized as percentage difference between the end of the simulation and the initial conditions. These outputs have been divided by the duration of the simulations in order to make the outputs comparable despite the different durations, and are thus expressed as ES percentage variation per time step. The results have been aggregated as average of all ES trends, which summarizes the overall ES trend, and provides indications concerning the sustainability of the ES patterns, that is, whether the they allow for the maintenance of ES provision over time (equitable intergenerational distribution (Schröter et al., 2017)). All the modeling work has been developed using the Petri net tool Snoopy (Heiner et al., 2012; Snoopy, 2017).

2.4. Data analysis

The patterns of multiple ES in each water body are visualized using star plots. A set of aggregated indicators have been calculated to allow a direct comparison between water bodies. These indicators, built upon the distinction between ES with direct and mediated flow type (*sensu* Rova and Pranovi, 2017, Table 1), are (i) sum of all ES, (ii) sum of direct ES, (iii) sum of mediated ES and (iv) ratio between the sum of mediated and the sum of direct ES (MED/DIR). Furthermore, three among the mediated ES are characterized by the production of major negative externalities: clam harvesting, due to the impacting mechanical harvesting techniques (cfr. Pranovi et al., 2004), and tourism and recreational navigation due to the intense related navigation activities. To reflect this, the ratio between the sum of these “pressure” ES and the sum of direct ES (PRESS/DIR) has also been calculated.

A Principal Component Analysis (PCA) has been carried out to allow a multivariate analysis of the patterns of multiple ES characterizing each water body. The analysis was performed using the PRIMER 6 software.

The relationships between the patterns of multiple ES, the potential ES trends obtained with the models under the BAU scenario (aggregated as average percentage variation per time step) and the water bodies’ ecological status were analyzed through a correlation analysis (Spearman’s rho and associated p-value). The data about the ecological status, assessed in compliance with the WFD, are referred to the monitoring period 2013-2015 (ISPRA-ARPAV, 2016). The biological quality elements used for the definition of the ecological status in the VL are benthic macro-invertebrates and macrophytes, assessed through the metrics M-AMBI (Borja et al., 2009; Muxika et al., 2007) and MAQI (Sfriso et al., 2014, 2009), respectively. The overall status in each water body is defined based on the biological quality element with the lowest classification (“one-out-out-all” approach).

Data analysis was conducted using R statistical software (R Core Team, 2017).

3. Results

3.1. Patterns of multiple ecosystem services in the WFD water bodies

The spatial distribution of ES in the VL water bodies is presented in Figure 2. Among regulating ES, climate regulation is higher in confined water bodies, in which most of the salt marshes are located, and in Centro-Sud, which includes about 90% of seagrass beds. Erosion prevention 1 (wind fetch reduction) shows a similar distribution driven by salt marshes but is instead low in Centro-Sud. Waste treatment, erosion prevention 2 (biostabilization) and lifecycle maintenance generally increase with the degree of confinement but show distinct distributions within the confined water bodies. Provisioning ES show different spatial arrangements, artisanal fishing is broadly distributed throughout the lagoon, clam harvesting is concentrated in the central and southern parts of the lagoon (Val di Brenta and Centro-Sud), where most of the concessions are located, recreational fishing is mostly concentrated in the water bodies nearby the inlets, whereas hunting is mostly practiced in the confined water bodies in the northern and southern parts of the lagoon. Cultural ES are instead characterized by quite similar distributions, mostly concentrated in the surroundings of the historical center of Venice.

The star plots (Figure 3) display the patterns of multiple ES that characterize each water body. These patterns can be better interpreted based on the results of the PCA relative to the first two principal components (which explain 43% and 17% of the variance, respectively) (Figure 4). The PCA plot, and specifically the first principal component, clearly distinguishes between confined water bodies (on the right-hand side of the graph) and not-confined water bodies (left-hand side of the graph). The confined water bodies (top row in Figure 3) in fact show quite similar patterns, generally dominated by regulating ES and hunting. Among them Dese appears more separated in the PCA plot, being characterized by higher levels of some cultural and provisioning ES. Not-confined water bodies are less clustered in the PCA plot, and in fact present more diversified patterns. The patterns of Chioggia and Lido, which present low scores for both principal components, reveal their “urban” character (they are close to the cities of Chioggia and Venice, respectively), characterized by cultural ES and recreational fishing (bottom row in Figure 3). The patterns of Centro-Sud and Sacca Sessola indicate lower overall levels of ES provision, while Marghera and Tessera present quite diversified patterns: Marghera is focused on three ES (artisanal fishing, information for cognitive development and traditions), whereas Tessera provides a broad set of cultural and regulating ES.

The spatial distribution of aggregated indicators is shown in Figure 5. The highest overall ES provision is found in the confined water bodies and in those located to the northern part of the lagoon (Tessera, Dese, Lido, Val di Brenta, Teneri, in decreasing order). In particular, confined areas of the lagoon provide higher levels of direct ES, whereas mediated ES are higher in the surroundings of the historical center of Venice, which is mostly due to the spatial distribution of cultural ES. The MED/DIR ratio summarizes the different distribution of these two categories of ES, with mediated ES prevailing over direct ES in the surroundings of the cities of Venice and Chioggia. The PRESS/DIR ratio shows that the ES that produce negative externalities prevail in Chioggia and Lido, followed by Sacca Sessola and Val di Brenta. Interestingly, these two ratios are in good agreement with the PCA, showing a clear decreasing trend along the first principal component. This suggests that these aggregated indicators capture the variability of the patterns of multiple ES quite well.

3.2. Potential ecosystem services trends

The results of the models’ simulations under the BAU scenario, aggregated as average of all ES trends, are presented in Figure 6A. Six of the 11 water bodies, mostly corresponding to the not-confined water bodies, exhibit a potential negative trend. Negative trends indicate patterns of ES provision at risk of declining over time, the expected decline being faster in the cases with more negative trends. It should be noted that the most negative trends (Lido, Val di Brenta and Tessera) correspond to the water bodies with the highest levels of overall ES provision: this suggests on the one hand the unsustainability of the patterns of multiple ES provision that currently characterize these water bodies, and on the other hand the need to intervene with appropriate management strategies to prevent a massive loss of ES.

If the potential effects of climate change are considered (Figure 6B), we see that most of the water bodies that were characterized by sustainable patterns under the BAU scenario (most confined water bodies) shift to a negative trend under the CC scenario. If the concern under the BAU scenario was mostly focused on not confined water bodies, the potential effects of CC pose at risk also the ES provided by confined water bodies. The negative effects of CC seem to be larger on these water bodies than in not confined ones. This might be explained the fact that (i) the habitats which are most likely to be negatively affected by climate change (salt marshes and intertidal mudflats) are mainly located in confined areas, and (ii) the general conditions of not-confined water bodies are already so compromised that the negative effects of climate change are relatively less important.

3.3. Relationships between ecosystem services patterns, trends and ecological status

Table 2 summarizes the results of the correlation analysis performed to explore the relationships of the ES patterns with the ES trends and ecological status.

For what concerns the relationship between ES patterns and potential ES trends, the underlying question is whether it is possible to derive an aggregated indicator that reflects the overall sustainability of the pattern of multiple ES. The MED/DIR and PRESS/DIR ratios seem to provide quite good indications on these regards. In fact, direct ES are positively correlated with the overall trend, whereas mediated ES are negatively correlated. Consequently, the MED/DIR and PRESS/DIR ratios are strongly negatively correlated with the modeled trends. These aggregated indicators could therefore provide a synthetic indication concerning the possible good/bad evolution of the ES provision. In particular, all the water bodies that show a potential negative trend are characterized by a MED/DIR ratio greater than 1, that is, a prevalence of mediated ES, and vice versa, all the water bodies with a sustainable trend have a MED/DIR ratio lower than 1, that is, a prevalence of direct ES. The multivariate analysis (PCA) provides some additional indications on these regards: the first principal component, which corresponds to a decreasing gradient of MED/DIR and PRESS/DIR ratios, and which discriminates well between water bodies with different degrees of confinement, is significantly positively correlated with the ES trends. This suggests a rather strong association between water body types, ES patterns and ES trends. Different water body types could therefore benefit from tailor-made management strategies aimed at a sustainable ES provision.

Moving to the link between ES patterns and ecological status, in general, our analysis has not identified strong relationships between the patterns of multiple ES and the biological quality elements that concur to define the ecological status of the VL water bodies. If the aggregated ES indicators are considered, both MAQI and the overall classification present a negative (not significant) association with the sum of all ES and with the sum of direct ES. No relevant associations (rho < 0.4) were found with M-AMBI. However, if only provisioning ES are considered, a significant positive correlation emerges between the sum of these ES and M-AMBI, suggesting a stronger linkage between the ES that directly depend upon fauna and the status of macro-invertebrates. As the other aggregated indicators, provisioning ES are negatively correlated with MAQI and the overall classification. Some additional indications emerge from the PCA, that reveals a positive correlation (not significant) between the first principal component and M-AMBI. It also suggests, in agreement with the previous cases, a negative association between the first principal component and both MAQI and the overall ecological status classification (Figure 4).

No relationships were found between the potential ES trends and the ecological status. This was indeed expected given the weak relationships found between ES patterns and the biological quality elements.

4. Discussion

4.1. Multiple ecosystem services and sustainability

This work presents the first quantitative and spatially explicit assessment of the multiple ES provided by the VL. Previous works assessing the ES of this complex social-ecological system include a qualitative mapping of seven ES (Rova et al., 2015), an expert-based assessment in multiple lagoons (Newton et al., 2018) and two valuation studies related to the island of S. Erasmo (Alberini et al., 2005) and sport fishing activities (Alberini et al., 2007). With respect to previous studies, this spatially explicit assessment of a comprehensive set of ES provides an important contribution because it allows to identify the spatial patterns of ES co-produced by the social-ecological system (Bennett et al., 2015; Meacham et al., 2016;

Queiroz et al., 2015; Raudsepp-Hearne et al., 2010; Sun et al., 2018). In order to highlight the potential applications of this analysis to concrete management challenges, such as the WFD implementation, the mapping has been based on the WFD water bodies.

If individual ES are considered, the spatial distribution of direct (regulating) ES seems to be mostly driven by the ecological characteristics of the water bodies (e.g. for climate regulation the habitat's distribution -structures- and their carbon sequestration -function-). Instead, for mediated (provisioning and cultural) ES the spatial distribution is influenced by the anthropogenic factors (e.g. proximity to urban areas) that determine the spatial arrangements of human activities involved in these ES. This influence seems to be greater for cultural ES than provisioning ones. This considerations can be linked to a different balance between ES capacity and flow (Burkhard et al., 2014; Liquete et al., 2016; Schröter et al., 2014; Tomscha et al., 2016) in direct and mediated ES. In the case of direct ES, the flow (that is, the actually "used" ES) is generally coincident with the capacity (that is, the ES that can be potentially provided by the ecosystem), being directly related to ecosystem functioning. On the other hand, in case of mediated ES, the human inputs involved in ES provision can mask the link between capacity and flow, potentially leading to ES flows that exceed the capacity of ecosystems to provide ES, producing unsustainable situations deriving from excessive ES use (Liquete et al., 2016).

If we shift to a multiple ES perspective, the relative proportions of different ES determine the (un)sustainability of the observed patterns, which is related to the different types of interactions (synergies and trade-offs) occurring among ES (Bennett et al., 2009; Foley, 2005; Raudsepp-Hearne et al., 2010; Rodríguez et al., 2006). Here we have explored the sustainability of the ES patterns in the VL water bodies by analyzing the associated potential ES trends, that reveal if the ES patterns allow for equitable intergenerational distribution (Schröter et al., 2017). The results show a general association between water body type, ES pattern and ES trend. The water bodies characterized by a low degree of confinement present mostly unsustainable ES patterns, dominated by mediated ES. Confined water bodies are instead characterized by more sustainable ES patterns, dominated by direct ES. The MED/DIR ratio and the PRESS/DIR ratio were found to provide a synthetic indication of the unsustainability of the multiple ES provision. A higher ratio is associated to a possible negative evolution of ES over time, due to the impacts of an excessive ES use. Therefore, ES patterns unbalanced towards the provision of mediated ES seem most likely to be unsustainable.

In operational terms, which management recommendations can be drawn for the VL from an ES perspective? The interpretation of the ES patterns in the light of the normative goal of sustainability (Schröter et al., 2017) allows to sketch a sort of management trajectory. Management strategies should aim at “correcting” the unsustainable patterns found in most not-confined water bodies, rather than simply attempting to increase the overall ES provision. This “correction” consists in balancing the provision of direct and mediated ES, which, graphically speaking, would correspond to shifting the water bodies’ patterns towards the right-hand side of the PCA graph (Figure 4). This could be achieved with a combination of measures aimed at reducing pressures and at maintaining/restoring the ES capacity through habitat conservation and restoration. An improvement in this sense would preserve (or even improve) the ecosystem functioning over time, along with the associated ES provision.

The consideration of the effects of climate change introduces additional sources of pressures on the system, which cannot be directly controlled and thus require adaptation measures to be implemented. The MOSE system focuses on the protection of the historical center of Venice from the effects of relative sea level rise, but is not sufficient to prevent the negative effects on the multiple ES provided by the VL (Rova et al., *in press*). The negative effects produced by the CC scenario on the confined water bodies indicate that, although the ES pattern is sustainable in these areas, interventions aimed at maintaining/restoring the most vulnerable habitats (intertidal habitats) are needed to counterbalance, at least partially, the effects on lagoon ecosystem and its functioning.

4.2. Ecosystem services and WFD implementation

In general terms, ecological status and ES are assumed to be positively associated, being the ecological status a prerequisite for ecosystem functions, upon which ES provision depends (Vlachopoulou et al., 2014). However, the results of our analysis show rather puzzling relationships (and lack of relationships) between ES and the metrics used to define ecological status in the VL. As can be seen from the PCA graph (Figure 4), M-AMBI and MAQI indicate contrasting trajectories with respect to the patterns of multiple ES: M-AMBI can be seen to increase towards the more sustainable ES patterns of confined water bodies, whereas MAQI and the overall classification point towards the not-confined water bodies characterized by unsustainable ES patterns.

This discrepancy might at least partially depend on the fact that, if on the one hand the common denominator between the ES and ecological status is the functioning of the ecosystem, on the other hand this functioning is poorly or only partially reflected by the indicators used for the assessment of ecological status and ES. For what concerns the ecological status, the metrics used to assess the biological quality elements are “structural” indicators based on the composition of the biological community (Borja et al., 2013; Vlachopoulou et al., 2014), and are characterized by several limitations in terms of poorly understood response to multiple stressors and problematic definition of reference conditions (Borja et al., 2013), that may weaken their linkage with the ecological functioning. Concerning ES, indicators of mediated ES can be decoupled from ecosystem functioning due to the masking effect of human inputs involved in ES provision.

On the other hand, it is worth highlighting that the assessment of biological quality elements in transitional environments can be particularly challenging: different metrics can produce contrasting results due to the unclear response to natural and anthropogenic stressors, and due the difficult identification of reference conditions (Elliott and Quintino, 2007; Reyjol et al., 2014). In the VL, the M-AMBI and MAQI metrics show rather contrasting classifications across the water bodies, and furthermore, if a comparison between the first (2010-2012) and the second (2013-2015) monitoring cycles is made, the two metrics do not show a consistent response to the changes in the system (there are water bodies in which both metrics improve, others in which one improves and the other get worse, and vice-versa) (ISPRA-ARPAV, 2016). This behavior, combined with the “one-out-out-all” approach in the definition of the overall ecological status (which has been heavily criticized by several authors (Borja et al., 2013; Borja and Rodríguez, 2010; Hering et al., 2010)) has resulted in a generally “flattened” classification, in which all water bodies are classified either as poor or moderate status (ISPRA-ARPAV, 2016). This situation does not allow to recognize where interventions are really needed. Overall, this situation hinders the definition of effective management strategies, leaving the WFD implementation at a standstill.

ES could play an important role in fostering the WFD implementation, through the application of a systemic thinking that puts more emphasis on ecosystem functioning, going beyond the reductionist focus on “structural” biological quality elements. These have in fact been identified as essential advancements needed for a more effective implementation of the WFD (Vlachopoulou et al., 2014; Voulvoulis et al., 2017). Desirable ES patterns, characterized by a provision of ES over the long term, are patterns in which the pressures, including those created by the provision of mediated ES, are balanced in a way that does not impair the ecosystem functioning. Unsustainable patterns, characterized by high MED/DIR and PRESS/DIR ratios, are instead those where the “uses” (mediated ES and more specifically those producing major pressures) are disproportionate with respect to the functioning and thus need to be reduced. This type of ES analysis gets very close to the “systemic” meaning of ecological status: they both aim at ecosystems characterized by uncompromised ecological functioning and sustainable level of anthropogenic pressures. This could lead to a possible way to solve the issues related to definition of the ecological status and to the “one-out-out-all principle”. ES, judged from a sustainability perspective, could play a role in the selection of the biological quality elements that concur to determine the ecological status: *the biological quality elements and their metrics could be selected such that they positively resonate with the sustainable patterns of multiple ES provision*. In the VL case study, the negative relationship found between the overall ecological status classification and ES (and especially direct ES) suggests that the way the ecological status is currently defined in the VL might not be adequate, as in fact is reflected by the current impasse in the WFD implementation. In this situation, the ES analysis provides support for the prioritization of one of the two conflicting biological quality elements, thus possibly contributing to get over the management impasse. The relationships found between ES and the biological quality elements seem to support the use of M-AMBI, which seems to be in a better agreement with the sustainability of the ES patterns. However, the rather weak relationships found warn to take this indication with caution: further research should be done to assess the agreement between ES indicators and the metrics that can be used to assess the biological quality elements, with a particular attention to metrics that merge structural and functional aspects, and possibly at a higher spatial resolution. Overall, this approach would promote a WFD implementation that embraces the broader and “systemic” aims of the directive, and at the same time, due to the focus on social-ecological systems, provide a more direct link with possible management trajectories.

5. Conclusions

The analysis of multiple ES from a sustainability perspective allows to shift from a descriptive application of the ES concept to a more operational application, in which desirable and undesirable patterns of multiple ES are distinguished. The findings of this work suggest that a first indication concerning the (un)sustainability of the patterns of multiple ES can be obtained by applying the aggregated indicators MED/DIR and PRESS/DIR ratios. Higher ratios seems in fact associated to a possible negative evolution of ES over time, due to the impacts that the human activities involved in the provision of mediated ES produce on ecosystem functioning. In particular, in the VL case study, the MED/DIR ratio presents values greater than one in all the water bodies with potentially negative ES trend over time, suggesting that an ES provision unbalanced towards mediated ES is most likely to be unsustainable. Furthermore, the association between the modeled ES trends and the water bodies’ degree of confinement suggests that different management strategies are appropriate for confined and not-confined water bodies, the first needing interventions to enhance the resilience to climate change impacts, the latter requiring a “correction” of the ES patterns towards more sustainable ones, through the reduction of anthropogenic pressures and habitats’ conservation and restoration.

This sustainability-driven interpretation of ES integrates the concepts of ecosystem functioning and anthropogenic pressures and thus gets very close to the targets of the WFD (high functioning and no or low pressures). Therefore, the patterns of multiple ES, judged from a sustainability perspective, could play a role in the implementation of the WFD by (i) supporting the selection of the biological quality elements (and metrics) that concur to determine the ecological status, through the identification of the metrics that are positively associated with the sustainable ES patterns and (ii) supporting the definition of management trajectories that aim to reach the WFD targets through the management of unsustainable ES patterns.

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Figures

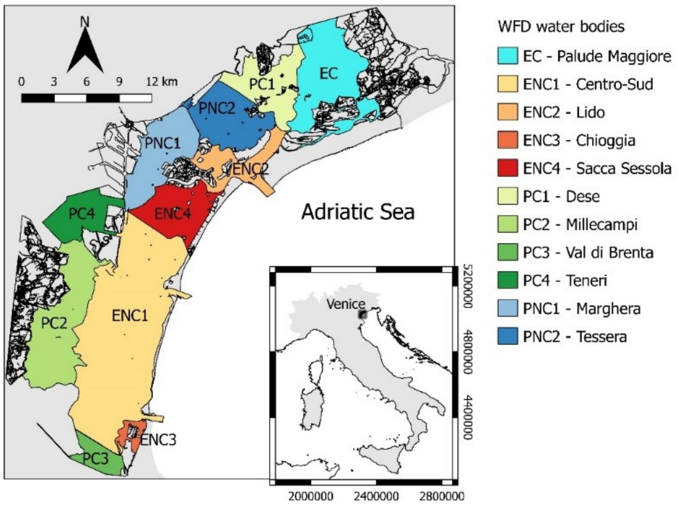

Figure 1. Venice lagoon (Italy) study area, subdivided into 11 water bodies defined in compliance with the Water Framework Directive. The heavily modified water bodies are not shown. Abbreviations: EC= euryhaline confined; ENC=euryhaline not-confined; PC=polyhaline confined; PNC=polyhaline not-confined.

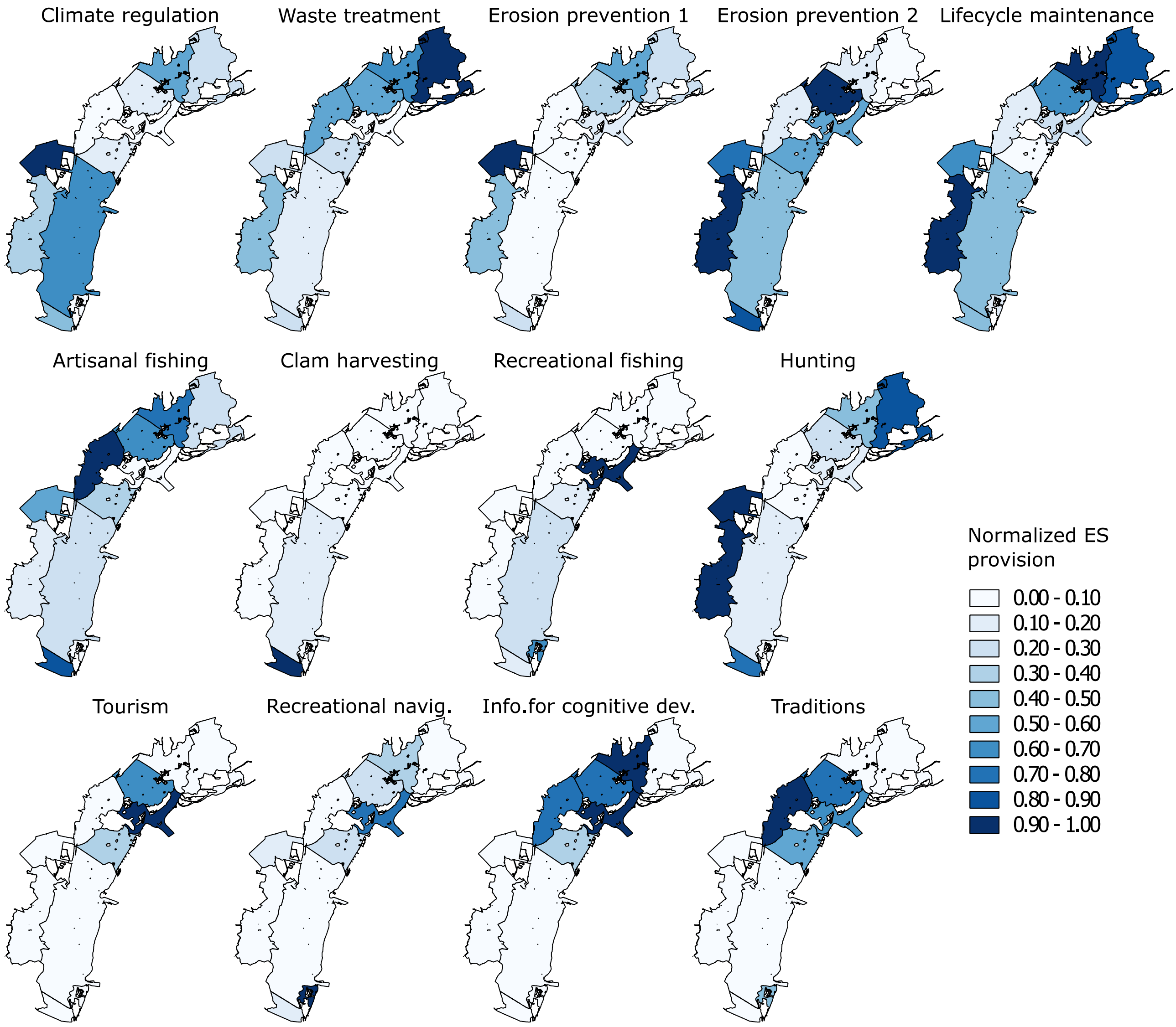

Figure 2. Maps representing the spatial distribution of each ES (top row: regulating ES; middle row: provisioning ES; bottom row: cultural ES). in the Venice lagoon water bodies. The level of ES provision has been normalized on a 0-1 scale.

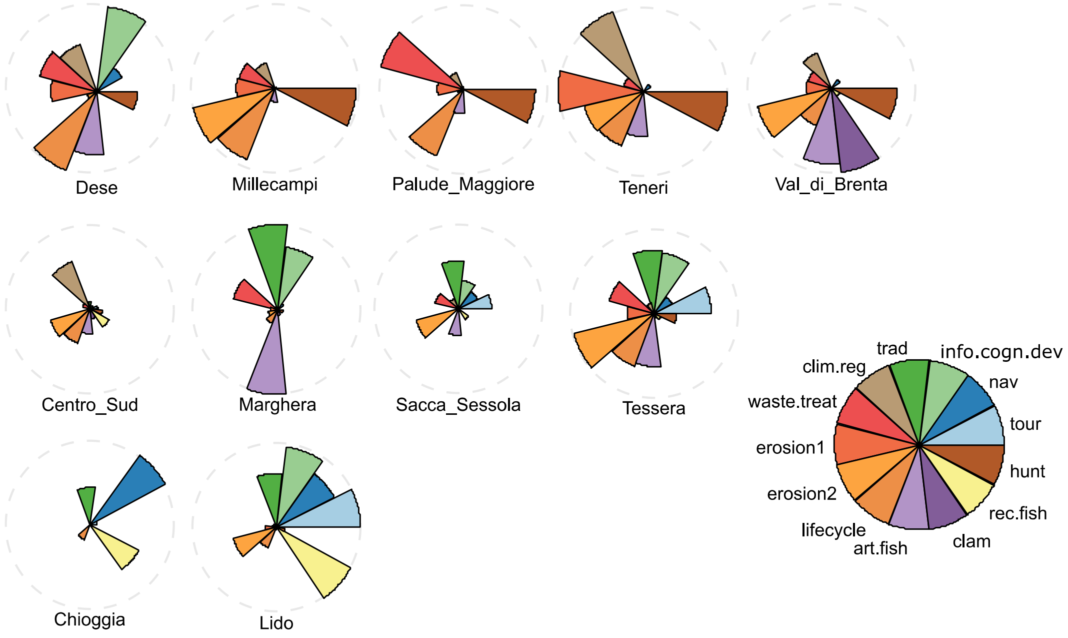

Figure 3. Star plots representing the pattern of multiple ecosystem services (ES) in each water body (top row: confined water bodies; middle and bottom rows: not-confined water bodies). The length of the sectors in each star represents the provision of the corresponding ES, according to the legend on the bottom-right of the figure. ES are normalized on a scale ranging from 0 (which correspond to the center of the star) to 1 (which corresponds to the dashed grey circle delimiting each star). Abbreviations: clim.reg = climate regulation; waste.treat = waste treatment; erosion1 = erosion prevention 1; erosion2 = erosion prevention 2; lifecycle = lifecycle maintenance; art.fish = artisanal fishing; clam = clam harvesting; rec.fish = recreational fishing; hunt = hunting; tour= tourism; nav = recreational navigation; info.cogn.dev = information for cognitive development; trad = traditions.

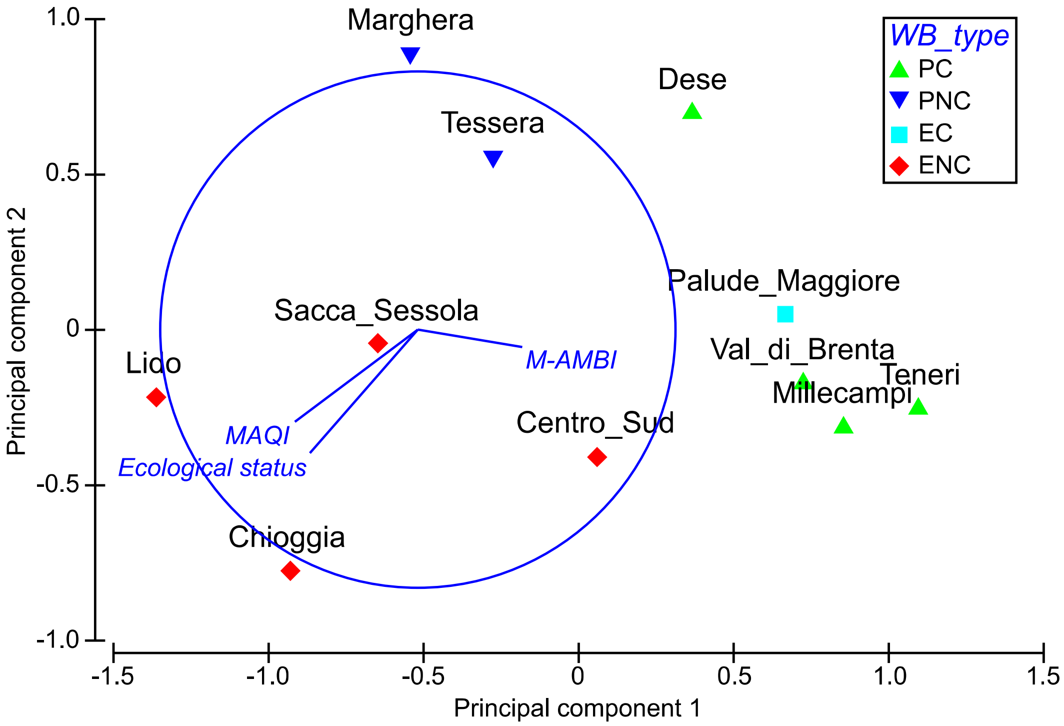

Figure 4. Plot of the Principal Component Analysis of the patterns of multiple ecosystem services in the Venice lagoon water bodies. The blue vectors represent the correlation (Spearman's rho) between the WFD biological quality elements (and overall ecological status) and the ordination axes, the blue circle representing rho=1. Different symbols represent different water body types (EC= euryhaline confined; ENC=euryhaline not-confined; PC=polyhaline confined; PNC=polyhaline not-confined).

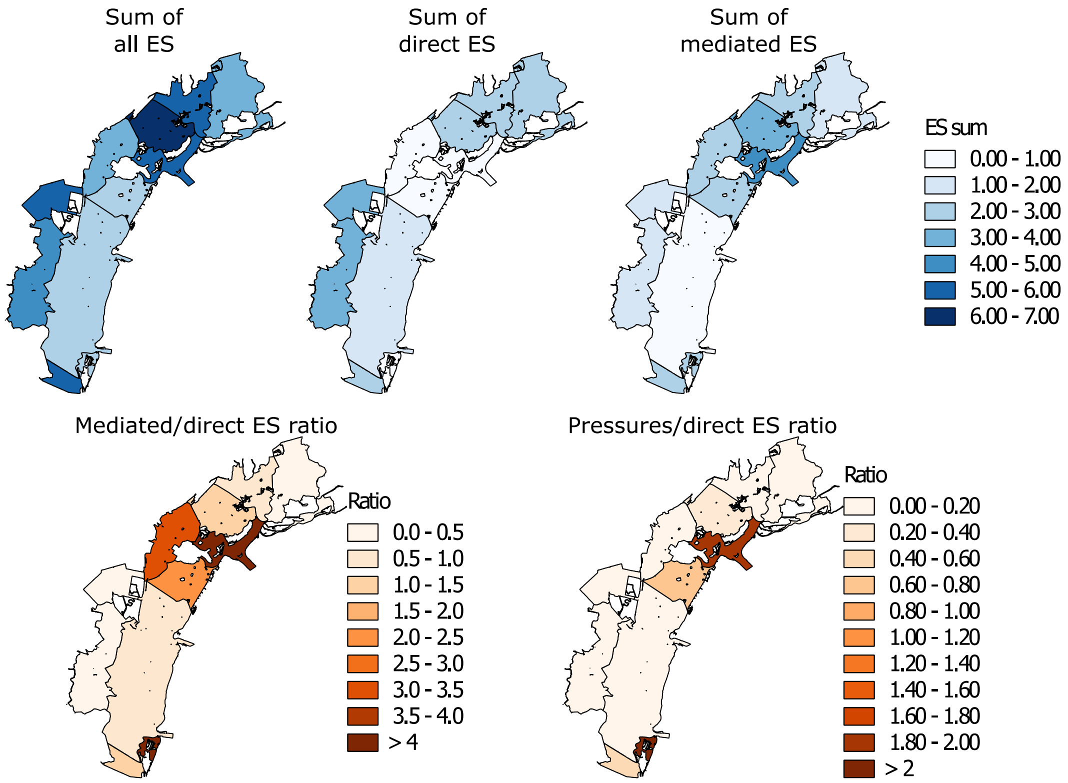

Figure 5. Spatial distribution of the aggregated ecosystem services (ES) indicators.

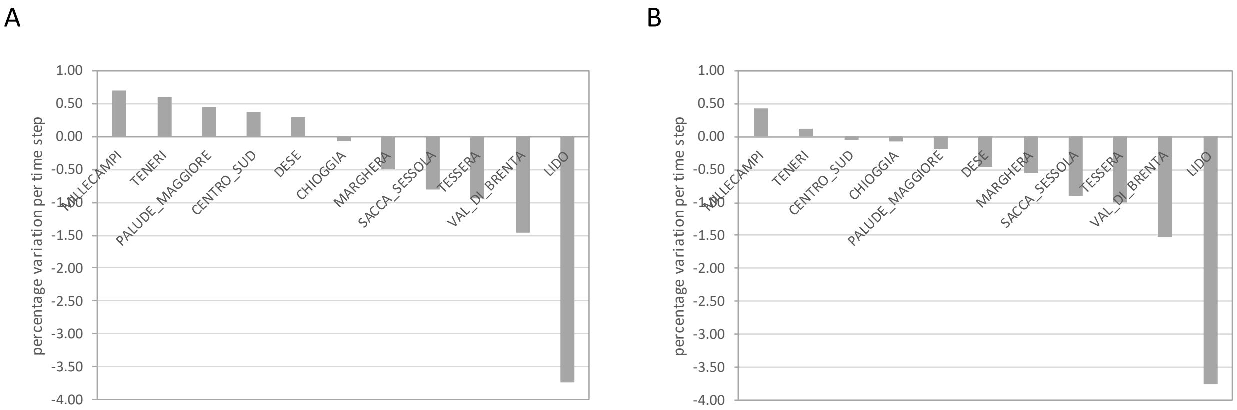

Figure 6. ES trends resulting from the models’ simulations under the BAU and CC scenarios (A and B respectively). The results are expressed as average of all ES trends, expressed as percentage variation per time step, with respect to the initial conditions.

Tables

Table 1. Ecosystem services (ES) assessed in this study, indicators, mapping units, methods and data sources

Ecosystem service	Flow type	Indicator	Unit	Methods and data sources
REGULATING SERVICES				
Climate regulation	Direct	Carbon sequestration rate	ton C/km2/yr	Average salt marshes’ C sequestration rate calculated based on accretion rate, sediments’ bulk density and organic C concentration (from Day, 1998; Roner et al., 2015). Seagrasses’ C sequestration rate estimated based on species-specific belowground production and organic C content (from Sfriso et al., 2007, 2004; Sfriso and Facca, 2007; Sfriso and Ghetti, 1998)
Waste treatment	Direct	Percentage of nitrogen load removed through denitrification	%	N load removed through denitrification estimated based on residence time, according to the equation proposed by Seitzinger et al. (2006) for estuarine systems. Residence time calculated with SHYFEM model (Umgiesser et al., 2004, courtesy of G. Umgiesser, ISMAR-CNR).
Erosion prevention 1	Direct	Wind fetch reduction by salt marshes (expressed as degree of sheltering of open waters)	sheltering of open waters (scale 0-1, where 0 no sheltering, 1 complete sheltering)	Wind fetch length calculated using the R package “waver” (Marchand and Gill, n.d.; Rohweder et al., 2008), 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, normalized such that 0 ≥ 1/2000 m, and 1 ≤ 1/158 m.
Erosion prevention 2	Direct	Bottom vegetation's biostabilization capacity	biostabilization index (%)	Biostabilization index (percentage increase of sediments' erosion threshold due to vegetation, Amos et al., 2004) applied to seagrasses and benthic diatoms habitats, based on data from Amos et al. (2004).
Lifecycle maintenance	Direct	Habitats' nursery role	scale 0-1, where 0 no habitats with nursery role, 1 all habitats with highest nursery role	Qualitative estimation of the affinity of marine migrant fish species for the lagoon habitats (salt marshes’ creeks, seagrasses, macroalgae and subtidal with *Ruditapes philippinarum* (mapping from Bergamin, 2017)), based on Franco et al. (2006b, 2006a).
PROVISIONING SERVICES				
Artisanal fishing	Mediated	Yield from artisanal fishing activities	ton/km2/yr	Yield estimated based on fishing effort (n. of traps/ km^2) and catches per unit of effort (g/ trap/day), from data referred to the year 2015 (unpublished data, courtesy of P. Franzoi and M. Zucchetta, Ca’ Foscari University of Venice).

Ecosystem service	Flow type	Indicator	Unit	Methods and data sources
Clam harvesting	Mediated	Yield from mechanical clam harvesting activities	ton/km2/yr	*R. philippinarum* yield data and spatial extension of clam harvesting concessions referred to the year 2015 (unpublished data, courtesy of R. Ruggeri, G.R.A.L. Gestione Risorse Alieutiche Lagunari).
Recreational fishing	Mediated	Yield from recreational fishing activities	ton/km2/yr	Yield estimated based on the average seasonal yield per fishermen, the number of fishermen and the spatial distribution and use of fishing areas (Provincia di Venezia, 2014a).
Hunting	Mediated	Yield from hunting activities	n. of birds harvested/km2/yr	N. of birds harvested estimated based on the n. of hunters, the n. of birds that can be harvested per hunter, according to local regulations, and the location of hunting farms and hunting blinds (Provincia di Venezia, 2014b).
CULTURAL SERVICES				
Tourism	Mediated	Number of visitors in the lagoon's islands (historical center of Venice excluded)	n. of visitors/km2	N. of visitors per island estimated based on the fluxes of non-local users of public transport. The data cover the islands served by public transport (Burano, Certosa, Chioggia, Lido, Mazzorbo, Murano, Sant'Erasmo, Torcello and Vignole). Unpublished data, courtesy of G. Santoro, AVM-ACTV S.p.a.
Recreational navigation	Mediated	Number of boat trips with leisure boats	n. of boat trips/km2	N. of boat trips in 2008 (MAV-CVN, 2009) mapped based in the quantitative and qualitative description of fluxes in COSES (2007, 2002) and MAV-CVN (2009).
Information for cognitive development	Mediated	Number of people joining environmental education activities	n. of visitors/km2	N. of visitors and destinations estimated based on interviews to cooperatives of environmental education.
Traditions	Mediated	Areas where traditional venetian rowing activities are practiced	proportion of venetian rowing areas (0-1 scale)	Areas used for venetian rowing activities estimated based on the location of the rowing associations.

Table 2. Results of the correlation analysis (Spearman's rho) between ecosystem services (ES) patterns and potential ES trends, and between ES patterns and ecological status. Rho with absolute value < 0.4 are not reported. Level of significance: † p-value < 0.1; * p-value < 0.05; ** p-value < 0.01. Abbreviations: PC1 = first principal component of the PCA.

	Potential ES trends	**WFD Biological quality elements and ecological status**		
	Average of all ES trends	M-AMBI	MAQI	Overall classification
Sum of all ES			-0.52	-0.48
Sum of direct ES	0.54†		-0.49	-0.42
Sum of mediated ES	-0.84**			
MED/DIR ratio	-0.77**			
PRESS/DIR ratio	-0.83**			
PC1	0.65*	0.40	-0.48	-0.42
Sum of provisioning ES		0.67*	-0.43	