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Analysis and management of multiple ecosystem services in social-ecological systems under a changing climate

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Summary

This thesis aims to develop new methods for the analysis and management of multiple ecosystem services (ES) in the context of climate change. Taking the Venice lagoon (Italy) as case study, it focuses on two major research challenges in the ES field of study, that are, understanding how multiple ES are co-produced and interact, and how they can be managed sustainably. These challenges are addressed first through a conceptual viewpoint based on the social-ecological systems framework, which distinguishes between ES with “direct” and “mediated” flow type: the first occur directly through some ecological functions, whereas the second require the involvement of human activities, which can generate feedbacks on the same and/or other ES. This viewpoint is then translated into a dynamic ES model, which represents multiple ES together as a single network, accounting for their interactions and for the effects of drivers of change. This represents a significant step forward with respect to current ES models, which provide static snapshots of single ES. The modeling results highlight the importance of including the ES interactions, the absence of which remarkably affects the results. Finally, the modeling application is merged with a quantitative mapping of the multiple ES delivered by the Venice lagoon, aiming at analyzing the sustainability of the ES patterns. This analysis allows to delineate management trajectories for correcting the unsustainable ES patterns and preserving the ES delivery in the face of climate change. The joint analysis of multiple ES and their interactions, along with a sustainability-driven interpretation, seems crucial for the application of ES to management challenges in the context of climate change.

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Chapter 1

Introduction

1.1. Background and motivation

Social and ecological systems are not isolated from each other: society depends on ecosystems, and ecosystems are modified by society. This integrated perspective of humans-in-nature is summarized by the concept of “social-ecological systems” (SES), which refers to nested, multilevel systems that provide essential services to society such as supply of food, fiber, energy, and drinking water (Berkes and Folke, 2000). This concept emphasizes that the delineation between social and ecological systems is artificial and arbitrary (Berkes et al., 2008; Berkes and Folke, 2000), and that the intrinsic complexity of SES requires integrated methods of analysis that adopt a systemic perspective, going beyond traditional disciplinary approaches (Binder et al., 2013). Within this context, ecosystem services (ES) are defined as the contributions of ecosystem structure and function – in combination with other inputs – to human well-being (Burkhard et al., 2012a). By emphasizing that many aspects of human well-being are dependent on ecosystems and their functioning, the ES concept aims to contribute to the sustainable management of natural resources, calling attention to the consequences that environmental degradation and biodiversity loss have for human well-being (Costanza et al., 1997; Millennium Ecosystem Assessment, 2005). The increasing importance of the ES concept is underlined by its inclusion in the EU Biodiversity Strategy to 2020 (European Union, 2011), whose Target 2 is expressly referred to ecosystem services and to their maintenance and enhancement.

ES, and the associated recently proposed concept of nature’s contributions to people (Díaz et al., 2018), are the object of a relatively young and fast-growing research field (Costanza et al., 2017; McDonough et al., 2017), whose scientific literature is dominated by (i) conceptual studies, that focus on ES classification schemes and terminology, upon which a vast consensus has not been reached yet (e.g. Haines-Young and Potschin, 2013; La Notte et al., 2017; Potschin-Young et al., 2018; Potschin and Haines-Young, 2011); (ii) methodological studies, focused on the development of different assessment methods, ranging from qualitative and quantitative ES mapping (e.g. Burkhard et al., 2012b, 2009; Burkhard and Maes, 2017; Maes et al., 2012) to economic valuation (e.g. Costanza et al., 1997; de Groot et al., 2012, 2010), and modeling techniques (e.g. Ochoa and Urbina-Cardona, 2017; Tallis and Polasky, 2009; Villa et al., 2014) (iii) descriptive applications to different study areas at various spatial scales (e.g. Nedkov and Burkhard, 2012; Ouyang et al., 2016; Stürck et al., 2015). Despite this, several crucial challenges and research frontiers still remain, mainly related to the development of interdisciplinary research approaches that are capable to address questions that go beyond the borders of single disciplines (McDonough et al., 2017), that need to be addressed in order to make this concept operational from a decision-making perspective.

This dissertation is focused on the research challenges related to the delivery of multiple ES. Indeed, SES provide different ES at the same time, the use of which interact with each other in multiple ways (Bennett et al., 2009). The management of SES faces the challenge to harmonize the exploitation and use of multiple ES, in a way that their delivery can be maintained over time. Management strategies focused on single or few ES can produce undesirable effects because they fail to capture the complexity of the system (Costanza et al., 2017; Kull et al., 2015; McDonough et al., 2017). Despite this, the majority of the studies addresses only one or few ES and does not consider feedbacks and interrelations among them (McDonough et al., 2017; Seppelt et al., 2011). This is probably due on one hand to the limited data availability, and on the other, to the limitations of current conceptual frameworks (e.g. the service cascade (Haines-Young and Potschin, 2010; Potschin and Haines-Young, 2011)), which generally do not address how multiple ES are co-produced and interact. For example, Costanza et al. (2017) highlighted that the conceptualization of ES through the service cascade is for some aspects an oversimplification, as it does not capture the complex and dynamic connections occurring between the ecosystem structures and functioning and the benefits we derive. In particular, although the involvement of anthropogenic factors in the delivery of some ES (e.g. agricultural practices and fishing effort) is recognized by several authors (Andersson et al., 2007; Bohnke-Henrichs et al., 2013; Burkhard et al., 2014; Costanza et al., 2017; Fischer and

Eastwood, 2016; Fisher et al., 2009; Jones et al., 2016; Queiroz et al., 2015) and by the ES definition itself (Burkhard et al., 2012a), a clear way to handle these anthropogenic inputs is lacking. As a result, ES assessments generally do not distinguish between the contributions that derive, sustainably, from ecosystem functions, and the contributions that, at least partially, depend on human inputs that might be unsustainable. This, combined with assessments that account for an insufficient set of ES, allows for applications of the ES concept that might be in conflict with the goals of sustainability (Schröter et al., 2017), ant that may be distorted to justify contrasting types of interventions (Kull et al., 2015).

The current ES modeling approaches (for an overview see Bagstad et al. (2013), Ochoa and Urbina-Cardona (2017) and Rieb et al. (2017)) reflect these limitations by generally treating single ES separately and failing to incorporate the interactions among ES (e.g. the widely used InVEST (Sharp et al., 2014; Tallis and Polasky, 2009)). Although these modeling tools represent a precious resource for assessing and valuing ES (Nelson and Daily, 2010) and for exploring changes in ES provision resulting from changes in the landscape (e.g. from land use change scenarios, as in Nelson et al. (2009)), they are generally conceived as static models that estimate ES at single steps in time, without taking into account the temporal dynamics of ES delivery (Rieb et al., 2017).

Within a context of changing climate, it becomes crucial to develop modeling tools that are capable to simulate the effects of this major driver of change on the multiple ES provided by SES. The links between drivers of change and ES are generally missing in most ES modeling tools (Rieb et al., 2017). Current approaches often use discipline-specific tools to simulate the effects of climate change on ecological and social variables (e.g. land use/land cover, hydrological variables, species distribution), which are then either used directly used to estimate individual ES (Hallouin et al., 2018), or used as inputs for ES models (e.g. InVEST) which are run separately for each ES in each time step (e.g. Jorda-Capdevila et al., 2019). Although these models allow for significant advancements in the understanding of the effects of climate change, they are limited by their sectoral perspective, which results in ES assessed separately, without considering the effects that interactions between ES could have on the dynamics of the system. Therefore, new dynamic modeling approaches are needed, that are capable to jointly simulate the effects of climate change (and other drivers of change) on the provision of multiple interacting ES (Rieb et al., 2017).

1.2. Objectives

The overall aim of the thesis is to provide an innovative contribution to the integrated analysis, modeling and management of the multiple ES delivered by social-ecological systems, in a context of changing climate. The proposed contributions are exemplified through applications to the Venice lagoon (Italy) case study, which represents an excellent example of complex social-ecological system in which local populations and ecosystem have co-evolved for centuries, and which is currently facing major challenges related to climate change (in particular, warming water and sea level rise).

The thesis addresses four main objectives:

- **Objective 1**: to develop a theoretical approach for the analysis of multiple ES from a social-ecological perspective, that considers both the ecological and social inputs involved in the delivery of ES and the way multiple ES interact.
  More in detail, the research questions connected to this objective are:
    1) How can the social-ecological systems framework (McGinnis and Ostrom, 2014; Ostrom, 2009) be used for the analysis of ES?
    2) Can ES be classified based on the ecological and social elements involved in their provision?
    3) What are the management implications of this theoretical approach?
- **Objective 2**: to develop a new approach for the dynamic modeling of multiple ES and their interactions under climate change scenarios.
  More in detail, the research questions connected to this objective are:

    1) How can the model account for the effects that changing ecological, social and climatic conditions on multiple ES?
    2) From a first, explorative application to the Venice lagoon case study, how can multiple ES be modeled together accounting for their interactions and dynamics?
    3) What are the added values of this integrated modeling approach?
- **Objective 3**: to analyze the spatial and temporal patterns of multiple ES from a sustainability perspective, with reference to the Venice lagoon case study.

  More in detail, the research questions connected to this objective are:
    1) What are the spatial patterns of the multiple ES provided by the Venice lagoon?
    2) What are the potential trends over time of the multiple ES provided by each lagoon's water body?
    3) Is it possible to derive an aggregated indicator that reflects the overall sustainability of the patterns of multiple ES?
- **Objective 4**: to explore the role that multiple ES, analyzed from a sustainability perspective, can play in the implementation of ecosystem-based management strategies (as the EU Water Framework Directive -WFD).

  More in detail, the research questions connected to this objective are:
    1) What are the relationships between the patterns of multiple ES, their potential trends and the ecological status defined in compliance with the WFD?
    2) How can ES contribute to overcome the issues related to the implementation of the WFD management strategies?

1.3. Outline of the thesis

The thesis is structured as follows:

Chapter 2, entitled *Analysis and management of multiple ecosystem services within a social-ecological context*, proposes a social-ecological viewpoint for the analysis of multiple ES in the light of E. Ostrom's social ecological systems framework.

Chapter 3, entitled *A Petri net modeling approach to explore the temporal dynamics of the provision of multiple ecosystem services*, turns the viewpoint proposed in Chapter 2 into a new and operational modeling approach, built using the Petri Net modeling framework. A first explorative application to the Venice lagoon case study is presented, which simulates possible management strategies aimed to maintain the provision of multiple ES under climate change scenarios.

Chapter 4, entitled *Sustainability perspectives and spatial patterns of multiple ecosystem services in the Venice lagoon: Possible roles in the implementation of the EU Water Framework Directive*, proposes an analysis of the patterns of the multiple ES in the Venice lagoon from a sustainability perspective. A quantitative mapping of the ES provided by the lagoon is presented, and the model proposed in Chapter 3 is used to explore temporal trends associated to the ES provided by the lagoon, within an explicit spatial context. The usefulness of this perspective for environmental management is discussed with reference to the implementation of the WFD, which represents a major management challenge in transitional ecosystems, in particular under the climate change scenarios.

Chapter 5 discusses the relevance of the thesis and the innovations brought within the context of ES research and integrated management of SES, and draws the overall conclusions.

Chapter 2

Analysis and management of multiple ecosystem services within a social-ecological context

This Chapter has been published as a scientific paper in the peer-reviewed journal "Ecological Indicators" (Impact Factor: 3.983).

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Abstract

The assessment of ecosystem services (ES) requires approaches that are capable to deal with the complexity of social-ecological systems (SES). A new viewpoint is proposed, in which the social-ecological perspective of Ostrom's SES framework is used to describe the flow of ES, through the identification of the social and ecological elements involved. Two types of ES flow emerge from this analysis, depending on the way in which the elements of ES supply (resource system and resource units) and demand (actors) interact: (i) a "direct flow type" in which the resource units deliver the ES through some specific ecological functions (e.g. wetlands providing carbon sequestration), and (ii) a "mediated flow type" in which the resource units become themselves the ES when "used" by means of human activities (e.g. fish harvested through fishing activities). The identification of activities is crucial to understand the interactions between ES, because of the feedbacks they produce on the ecosystem functioning and thus on the provision of the same or other ES. In addition, these feedbacks can depend on temporal aspects of ES provision. On these regards, a hypothesis is proposed according to which a time lag can exist between the ES supply-side and flow in human-modified SES. Altogether, this social-ecological analysis of ES can contribute to focus the management strategies on the control of impacting activities and on the maintenance of those processes which underpin ES' provision, thus contributing to the implementation of an ecosystem-based management of SES. These aspects are discussed in the light of the Venice lagoon example.

2.1. Introduction

Ecosystem services (ES) have gained an increasing importance in the field of sustainability science and environmental management in the past decades (Burkhard et al., 2012a; de Groot et al., 2010a, 2002; Millennium Ecosystem Assessment, 2005; Seppelt et al., 2011). ES, being defined as the contributions of ecosystem structure and function – in combination with other inputs – to human well-being (Burkhard et al., 2012a), result from the interactions between the ecological and social components of integrated social-ecological systems (SES) (Reyers et al., 2013), and thus their assessment requires an approach that takes into account the complexity of the SES by which they are generated.

The elements that make up the link between ecosystems and human well-being are often described by means of the "service cascade", a sort of production chain in which the biophysical structures and processes of the ecosystem are linked to the benefits (and values) they provide through a series of intermediate steps (Haines-Young and Potschin, 2010; Potschin and Haines-Young, 2011). A key role here is played by the anthropocentrically defined concept of ecosystem function, that is, the capacity of the ecosystem to do something that is potentially useful to people (de Groot et al., 2010b; Haines-Young and Potschin, 2010; Potschin and Haines-Young, 2011). This function is considered an ES only if a human beneficiary exists (Potschin and Haines-Young, 2011). The cascade thus stresses the role of society as the beneficiary of ES, but on the other hand it does not provide a way to represent the active involvement of humans in ES generation.

The intervention of some anthropogenic factors in ES delivery is an aspect that has been highlighted by several authors (Andersson et al., 2007; Bohnke-Henrichs et al., 2013; Burkhard et al., 2014; Fischer and Eastwood, 2016; Fisher et al., 2009; Jones et al., 2016; Queiroz et al., 2015). For instance, Fisher et al. (2009) specify that forms of capital other than natural can be required to realize benefits from ES. These "additional inputs" (*sensu* Burkhard et al., 2014) refer to the anthropogenic contributions to ES, which are recognized to be hardly separable from the ecosystem-based contributions in many human-influenced systems. The presence of additional inputs increases the complexity of ES assessments (Burkhard et al., 2014), and a clear way to handle these inputs, both conceptually and in ES assessments, is lacking.

A possible way forward is offered by the SES framework (McGinnis and Ostrom, 2014; Ostrom, 2009, 2007), aimed at providing a common language to organize findings and analyze outcomes at the SES level. According to this framework, *users* (later renamed as *actors*) extract *resource units* from a *resource system*, and this use is regulated by a *governance system* (McGinnis and Ostrom, 2014; Ostrom, 2009). The *outcomes* at the SES level are thus the result of the *interactions* among the four core variables of the SES (resource systems, resource units, governance system and actors). In a later revision of the framework, McGinnis and Ostrom (2014) open the way for its application to a broader set of situations, such as the cases in which the resources considered are ES and public goods in general.

The use of ES in environmental management, especially in the context of an ecosystem-based management, is becoming increasingly important (Agardy et al., 2011; de Groot et al., 2010a; McLeod et al., 2005). Management of SES faces the challenge to harmonize the provision and use of multiple ES in a way that they become sustainable. Management focused on single ES fails to capture the complexity of the system and can produce undesirable effects due to trade-offs between ES, that is, a situation in which increased provision of one ES can inhibit the provision of another ES (Bennett et al., 2009; Meacham et al., 2016a). Therefore, a deeper understanding of social-ecological processes involved in ES provision is required also from a management perspective, for the implementation of strategies aimed at maintaining these processes to a level that is capable to provide sustainable levels of multiple ES.

In the present work, a new viewpoint for the analysis of multiple ES, based on the SES framework, is suggested. This approach is used to: (1) describe the social-ecological elements involved in the generation/use of ES, (2) to categorize ES, and (3) to explore possible implications in terms of management of multiple ES. Finally, an example of application in the Venice lagoon is presented and discussed.

2.2. Analyzing ecosystem services through the social-ecological systems framework

2.2.1. Direct and mediated flow types

According to the SES framework, a general chain of elements is proposed, in which (1) ES depend on *resource units* that are generated by the processes of a *resource system*; (2) the ES provide benefits to some *actors,* and (3) their management is determined by the rules set by a *governance system* (Figure 1). Here the resource units correspond to the elements of the system that actually provide the ES, which, from a spatial perspective, represent the "service providing units" (*sensu* Syrbe and Walz, 2012).

The ES flow (i.e. the *de facto* used ES, Burkhard et al., 2014), results from the interaction between the ES supply-side (*resource systems* and *resource units*) and the demand-side (*actors*). Here two types of interaction are distinguished, namely *ecosystem function* and *activity*, which generate two different types of ES flow, which are named "direct" and "mediated", respectively (Figure 1A and 1B). In the "direct" flow type (Figure 1A), the resource units generate an ecological *function* that is potentially useful to actors. Here the term function is used *sensu* Potschin and Haines-Young (2011), i.e. the capacity of the ecosystem to do something that is potentially useful to people. For example, energy dissipation is a function provided by coastal vegetation (*resource unit*), that underpins the disturbance prevention ES. This function then becomes an ES when and where it is actually beneficial to some actors (e.g. residents in the coastal area), with no need of a specific human input in ES's generation. In the "mediated" flow type (Figure 1B), the interaction instead occurs in the form of an *activity* through which the resource units are "used" by actors. This *activity* is what makes beneficiaries "meet" the resource. The generation and availability of the resource units is dependent on ecosystem processes and functioning, however, the ES directly depends on resources' availability and use. Let us make the example of a forest (resource system), in which trees (resource units)

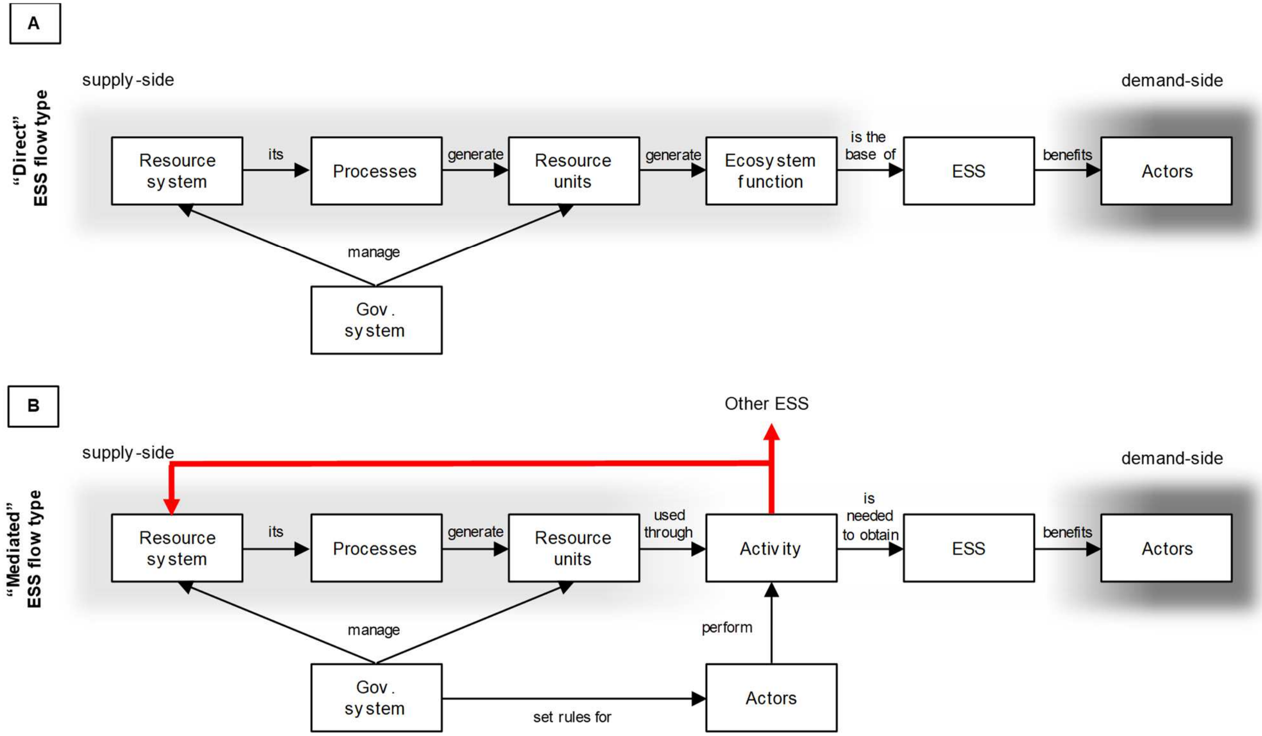

Figure 1. Ecosystem services production and use defined using the first-tier variables of the social-ecological systems framework, distinguishing between "direct" flow type (A) and "mediated" flow type (B). The background colors indicate the supply side (light grey on the left hand side), the demand side (dark grey on the right hand side) and the flow (no color). The bold red arrows in mediated flow type indicate the impacts of the activities. Abbreviations: ESS = ecosystem services; Gov. system = governance system.

provide two ES, one is the raw material “timber” (mediated ES) and the other one is erosion control (direct ES). In both cases the presence of trees depends upon ecological processes occurring in the forest, such as soil processes, water and nutrient cycling, and plant growth. However, the timber ES can be obtained only if trees are cut and timber is harvested, that is, if an activity turns the resource units into an ES. It should be noted that this exploitation can be decoupled from ecological processes up to the point that the resource is depleted (e.g. cutting rate higher than growth rate). In this situation, this ES is not sustainable, but it is still an ES until there are resource units available. In order to be sustainable, the exploitation should balance the processes that generate the resource units, and this requires to move one step back in our “production and use chain” and identify the key processes and their trends. Therefore, ecological processes are crucial also for mediated ES, but are “hidden” behind the availability of resource units. In the case of the erosion control ES, the dependence upon an ecological function (soil retention) is straightforward, the provision of the ES is directly proportional to the function and does not require any type of human input to turn the resource units into ES.

The activities involved in the mediated flow type can produce feedbacks directly on the resource system (red arrows in Figure 1B), resulting in negative effects on both the ES itself and/or the flow of other ES (ES trade-offs). The identification of activities and their feedbacks is thus an important aspect that should be taken into account when analyzing interactions among ES. The net result of all these interactions is the pattern of multiple ES provided by the SES, which can be understood as an *outcome* of the SES.

Finally, this perspective allows to analyze the role of the governance system in the ES delivery, which can be essentially of two types. In both flow types, the governance system should be responsible for the implementation of management measures aimed at the protection, maintenance or restoration of the resource system and units. In the case of mediated flow type, the governance system should come into play by setting rules that regulate the actors' activities, in a way that minimizes the negative effects.

The flow types that apply to the various ES groups, according to the Common International Classification of Ecosystem Services (CICES) version 4.3 (Haines-Young and Potschin, 2013), are proposed in Table 1.

2.2.2. Temporal aspects in human-modified social-ecological systems

Let us consider a SES in which society and ecosystems have co-evolved over time: in such a system, ES are provided by modified ecosystems and landscapes in which ecological and social elements are integrated. The elements of this SES are the result of processes at various temporal scales, which can influence the temporal aspects of the ES provided. With a certain degree of simplification, we can make two hypotheses about the temporal aspects characterizing ES in such systems:

- "short time scale" hypothesis (e.g. months, years), which represents the dependence of the current ES provision on the "present" state and processes of the system;
- "long time scale" hypothesis (e.g. centuries), in which the current ES provision is the direct result of "past" state and processes of the system, and this implies a sort of *time lag* between the ES supply-side and flow.

These two hypotheses are not mutually exclusive, as ES can depend upon multiple processes operating at different temporal scales. As a consequence, an ES can be characterized by a mix of the two hypotheses. The long time scale hypothesis allows to handle those ES, typically cultural ones, that are generated by a landscape in which both human and natural elements are integrated through a long-term co-evolution. Cultural ES such as aesthetic information, recreation and tourism, and information for cognitive development, most likely depend on the characteristics of the whole landscape. The SES perspective and the inclusion of a "time lagged" component allow to broaden the analysis and to take into account the contribution of those human elements, e.g. tangible and intangible cultural heritage, that are the result of a long

Table 1. Ecosystem services' flow type and temporal hypothesis that apply to the ecosystem services groups of the Common International Classification of Ecosystem Services version 4.3 (Haines-Young and Potschin, 2013). The temporal hypotheses are referred to the specific case of human-modified social-ecological systems.

Section	**Division**	**Group**	**Flow type**		**Temporal hypothesis**	
			Direct	Mediated	Short time scale	Long time scale
Provisioning	Nutrition	Biomass		x	x	
		Water		x	x	
	Materials	Biomass, Fibre		x	x	
		Water		x	x	
	Energy	Biomass-based energy sources		x	x	
		Mechanical energy		x	x	
Regulation & Maintenance	Mediation of waste, toxics and other nuisances	Mediation by biota	x		x	
		Mediation by ecosystems	x		x	
	Mediation of flows	Mass flows	x		x	
		Liquid flows	x		x	
		Gaseous / air flows	x		x	
	Maintenance of physical, chemical, biological conditions	Lifecycle maintenance, habitat and gene pool protection	x		x	
		Pest and disease control	x		x	
		Soil formation and composition	x		x	
		Water conditions	x		x	
		Atmospheric composition and climate regulation	x		x	
Cultural	Physical and intellectual interactions with ecosystems and land-/seascapes [environmental settings]	Physical and experiential interactions		x		x[1]
		Intellectual and representational interactions		x		x[1]
	Spiritual, symbolic and other interactions with ecosystems and land-/seascapes [environmental settings]	Spiritual and/or emblematic		x		x[1]
		Other cultural outputs		x		x*

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[1] Cultural ESS can be characterized by a mix of both temporal hypotheses; the long time scale hypothesis can be dominant when these ESS depend upon human-modified landscapes with integrated human and natural elements.

term interaction between society and the ecosystem and its resources. In Table 1, the temporal hypotheses that apply to the various ES are proposed. In general, the short time scale hypothesis can be considered dominant in most regulating and provisioning ES, being these ES dependent on ecological processes and functions that are roughly contemporary to the ES flow, e.g. primary production and soil functions. On the other hand, the long time scale hypothesis can be applied to cultural ES, in the cases in which these ES depend on human-modified landscapes that result from a social-ecological co-evolution spanning over long time frames. Cultural ES can be characterized by a mix of both temporal hypothesis, whose relative importance varies case by case, depending on the elements and processes that constitute the ES supply-side.

The temporal hypotheses have some implications concerning the way in which ES “respond” to present pressures and perturbations of the system, and to the feedbacks produced by the activities involved in mediated ES. For what concerns the long time scale hypothesis, the supply side depends primarily on elements “inherited” from the past SES. Therefore, under this hypothesis, ES provision is less sensitive to present pressures and feedbacks, which, instead, can affect the current ecological processes to which the short term hypothesis is referred. As a result, depending on the temporal hypotheses, the feedback between activity and ES supply-side can be present or not (Figure 2). In the case of long time scale hypothesis, the feedback is absent, but the activities involved in these ES can nevertheless impact the present SES, and thus the provision of other ES. Looking into the future, on a longer time frame, the human-modified landscape, and the time lagged ES based on it, are affected by the overall type of human-environment relationship, that is, they reflect the overall pattern of multiple resources’ and ES’ use that shape the landscape in the long term.

This approach can contribute to improve the assessment of many cultural ES, which are still understudied (Mocior and Kruse, 2016; Raudsepp-Hearne et al., 2010b), and

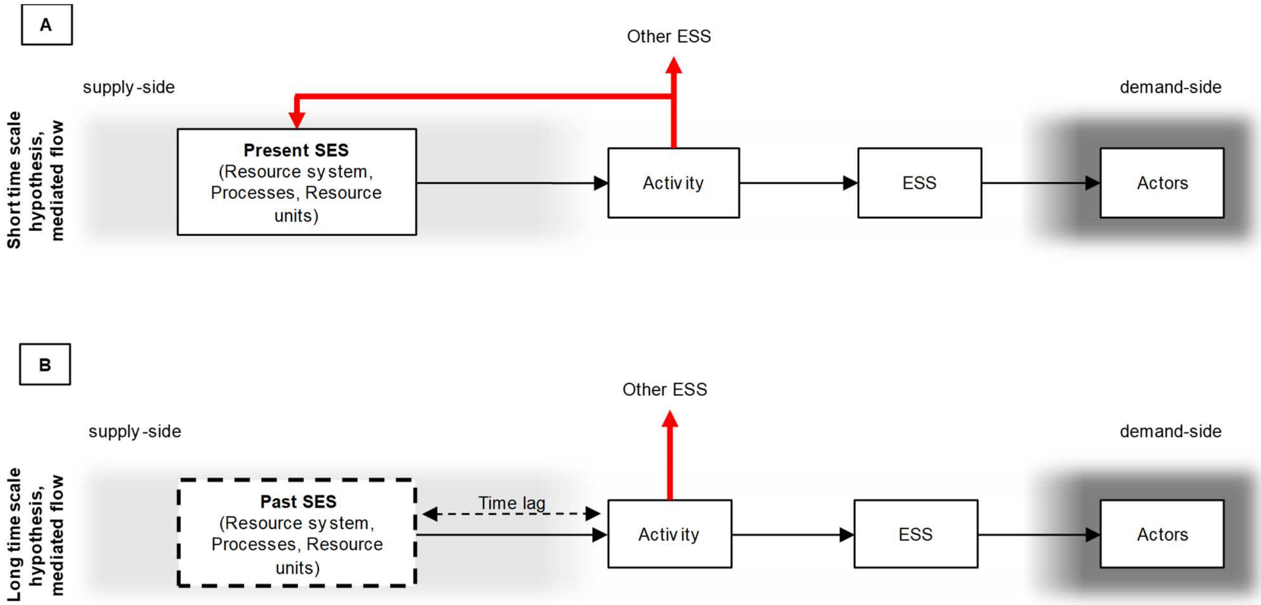

Figure 2. Short time scale (A) and long time scale ("time lagged") (B) hypotheses applied to ecosystem services with mediated flow type. In (B) the time lag occurs between the supply-side ("past SES") and the ecosystem services flow (present). The background colors indicate the supply side (light grey on the left hand side), the demand side (dark grey on the right hand side) and the flow (no color). The bold red arrows indicate the impacts of the activities. Abbreviations: ESS = ecosystem services; SES = social-ecological system.

often require a greater integration of the role of human culture in ES research (Raudsepp-Hearne et al., 2010b).

2.2.3. Management implications

According to the flow type and to the dominant temporal hypotheses, ES can be grouped in direct, mediated with short time scale and mediated with long time scale. In relation to the presence/absence of feedbacks and the interactions between ES (red arrows in Figure 1 and 2) some implications in terms of management of multiple ES arise:

- the direct flow type ES, not being dependent on human activities, are in principle able to self-sustain without any human involvement. Nevertheless, a decline of these ES can occur due to the negative impacts of external drivers and other ES' activities, and thus some management measures can be necessary to maintain or enhance the flow of these ES. This can be done either by acting on the causes of these impacts, or by protecting or restoring the elements of the supply side which are impacted.
- the mediated ES with short time scale can be perceived at the same time as impacting and impacted elements. On the one hand their activities are potentially responsible for negative feedbacks and externalities, on the other, they can undergo other ES' side-effects. As a consequence, the management of these ES should take into account the whole set of multiple interacting ES, in order to identify and manage the activities that undermine the ecological functioning of the system.
- the mediated ES with long time scale are peculiar due to the absence of feedbacks between the activity and the ES supply-side. This implies that unsustainable levels of activities may not produce a visible impact on the ES itself, but are instead likely to result in side-effects on other ES. The management of these ES is thus particularly challenging, because it requires

an integrated perspective that focuses on minimizing their impacts on other ES, and the benefits on the managed ES may not be visible.

2.3. An example from the Venice lagoon

2.3.1. Ecosystem services analyzed by flow type and temporal hypothesis

The Venice lagoon is a transitional environment located along the north-western Adriatic coast (Italy). It constitutes a representative and complex example of SES, being the man-environment linkage one of the most relevant factors shaping the characteristics of this territory throughout its history (Munaretto and Huitema, 2012; Ravera, 2000; Solidoro et al., 2010). It represents, thus, a proper case study for applying the above described approach.

The ES that are relevant for the Venetian lagoon context were selected based on Rova et al. (2015) and their classification in terms of flow type and dominant temporal hypothesis, based on authors' expertise, are shown in Table 2. The direct ES flow type applies to regulating and habitat services, whereas the mediated ES flow type applies to provisioning and cultural ones. Concerning the temporal aspects, regulating, habitat and provisioning ES are characterized by the short time scale hypothesis, whereas, among the cultural ES, some are dominated by the long time scale hypothesis and others by the short time scale one. In fact, some sub-categories of the recreation and leisure ES, i.e. recreational fishing and hunting, are dominated by processes with short temporal scale, similarly to provisioning ES. Some authors indeed classify these cultural ES as provisioning, stressing the fact that they imply the "use" of tangible resources for human nutrition (Burkhard et al., 2014; Kandziora et al., 2013). All other cultural ES are instead characterized by a long time scale, being based on the coevolution between the lagoon ecosystem and society. The "maritime transport" ES, which in the Venice lagoon depends on the network of channels, was classified as "other services" in Table 2 because it is not unanimously considered an ES (see for instance Atkins et al., (2011) vs. de Groot et al., (2010)).

Table 2. Ecosystem services provided by the lagoon of Venice (adapted from Rova et al., 2015) classified according to Bohnke-Henrichs et al. (2013). The flow type and temporal hypothesis that apply to each ecosystem service are indicated.

Typology	**Ecosystem services**		**Flow type**		**Temporal hypothesis**	
			Direct	Mediated	Short time scale	Long time scale
Provisioning services						
	1. Sea food	1.1. Clam		x	x	
		1.2. Fish (artisanal)		x	x	
		1.3. Aquaculture		x	x	
Regulating and habitat services						
	2. Climate regulation		x		x	
	3. Disturbance prevention or moderation		x		x	
	4. Waste treatment		x		x	
	5. Coastal erosion prevention		x		x	
	6. Lifecycle maintenance		x		x	
Cultural services						
	7. Recreation and leisure	7.1. Tourism		x		x
		7.2. Recreational navigation		x		x
		7.3. Recreational fishing		x	x	
		7.4. Bird hunting		x	x	
	8. Cultural heritage and identity	8.1. Tangible cultural heritage		x		x
		8.2. Traditions		x		x
	9. Information for cognitive development			x		x
Other services						
	10. Maritime transport			x	x	

The ES “production and use chain” is reported in Tables 3-5.

The direct flow type ES depend on a variety of ecological functions, and some of them depend on more than one function, indicating the variety of mechanisms through which the ecosystem contributes to these ES (Table 3). Moving further “backwards” along the production chain, however, it is possible to group the underlying processes and resource systems essentially into three types, related to the lagoon’s morphology, primary producers and interspecific interactions in the biological community. From this it clearly emerges the ES’ “co-production”, that is, ES resulting from common structures and processes of the system.

The ES with mediated flow type and short time scale are generally mediated by some type of harvesting activity, and are based on the abundance of the target species, which in fact depends upon ecological processes with relatively short time scale; maritime transport is instead related to the lagoon’s hydrodynamics and sediment transport processes (Table 4).

Time lagged mediated ES depend completely or partially on long time scale processes, being the result of multiple processes at operating at different time scales (Dawson et al., 2010) (Table 5). This is the case for tourism, recreational navigation and information for cognitive development, which are characterized by a mix of short and long time scale hypotheses, meaning that both contemporary and time lagged components contribute to the ES’ flow. They are produced by three types of resource units, namely natural and cultural landscape (determining the sites’ attractiveness), and navigable channels (determining the sites’ accessibility). Natural landscape and navigable channels depend on relatively short time scale ecological processes, whereas cultural landscape is the time lagged component of these ES, being the result of the coevolution between lagoon and society. The cultural landscape is in fact expression of cultural heritage and identity, to which the long time scale hypothesis can be applied as it consists of (1) man-made structures that reflect past uses of lagoon resources and ES, and (2) local traditions related to the lagoon, such as venetian rowing regattas.

Table 3. Elements of the social-ecological system involved in the production of ecosystem services with “direct” flow type in the lagoon of Venice. Abbreviations: ESS = ecosystem services; LV = lagoon of Venice.

ESS	Function	Resource units	Underlying processes	Resource system	Actors	Governance system
Climate regulation	Carbon sequestration	Seagrasses and salt marshes	Productivity	Primary producers	Global population	Comitatone[2]
			Accretion, sediment deposition	Lagoon morphology		
Disturbance prevention or moderation	Tide attenuation	Emerged and intertidal structures	Bio-morphodynamic and hydrodynamic processes	Lagoon morphology	All actors in the LV	Ex Venice water Authority, Comitatone*
Waste treatment	Nutrient burial	Seagrasses and salt marshes	Productivity	Primary producers	All actors in the LV	Comitatone*
			Accretion, sediment deposition	Lagoon morphology		
	Dilution and export	Overall morphology, tidal exchange	Bio-morphodynamic and hydrodynamic processes	Lagoon morphology		
	Nutrient cycling trough the food web	Consumers	Inter-specific interactions	Lagoon communities		
Coastal erosion prevention	Biostabilization	Bottom vegetation	Productivity	Primary producers	All actors in the LV	Ex Venice water Authority, Comitatone*
	Wind energy dissipation	Emerged and intertidal structures	Bio-morphodynamic and hydrodynamic processes	Lagoon morphology		
Lifecycle maintenance	Larval transport	Overall morphology	Bio-morphodynamic and hydrodynamic processes	Lagoon morphology	-	-
	Migration, reproduction	Reproductive, migratory and nursery habitat	Bio-morphodynamic and hydrodynamic processes	Lagoon morphology		

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[2] inter-institutional committee for the safeguard of Venice and its lagoon, created under the Special Law 789/1984 (“New Interventions for the Protection of Venice”).

Table 4. Elements of the social-ecological system involved in the production of ecosystem services with "mediated" flow type and short time scale hypothesis in the lagoon of Venice. The "governance systems" column includes the local authorities in charge of adopting and enforcing regulations; existing national and international regulations are not listed. Abbreviations: ESS: ecosystem services; R&L: recreation and leisure.

ESS	Activity	Resource units	Underlying processes	Resource system	Actors	Governance system
Seafood - Clam	Harvesting effort	Clam juveniles' and adults' abundance	Larval settlement, growth	Clam population	Fishermen, consumers	Municipality
Seafood - Fish (artisanal)	Fishing effort	Fish adults' abundance	Spawning, nursery, growth	Fish community	Fishermen, consumers	Municipality
Seafood - Aquaculture	Harvest, juveniles' fishing effort	Fish juveniles' abundance	Spawning, nursery, growth	Fish community	Fishermen, consumers	Municipality
	Ponds management	Fishing ponds	Bio-morphodynamic and hydrodynamic processes	Lagoon morphology		
R&L - Recreational fishing	Fishing effort	Fish adults' abundance	Spawning, nursery, growth	Fish community	Residents	Municipality
		Navigable channels (accessibility)	Hydrodynamic processes, biostabilization	Lagoon morphology		
R&L - Bird hunting	Hunting activities	Birds abundance	Migration and reproduction	Bird community	Residents	Municipality
		Navigable channels (accessibility)	Hydrodynamic processes, biostabilization	Lagoon morphology		
	Ponds management	Fishing ponds	Bio-morphodynamic and hydrodynamic processes	Lagoon morphology		
Maritime transport	Navigation, channel dredging	Navigable channels	Bio-morphodynamic and hydrodynamic processes	Lagoon morphology	Port business, tourist business, tourists	Port Authority, Comitatone[3]

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[3] inter-institutional committee for the safeguard of Venice and its lagoon, created under the Special Law 789/1984 ("New Interventions for the Protection of Venice").

Table 5. Elements of the social-ecological system involved in the production of ecosystem services with "mediated" flow type and long time scale hypothesis in the lagoon of Venice. The grey background indicates the underlying processes with long time scale. Abbreviations: ESS: ecosystem services; R&L: recreation and leisure, SES: social-ecological system.

ESS	Activity	Resource units	Underlying processes	Resource system	Actors	Governance system
R&L - Tourism	Visiting	Natural landscape (attractiveness)	Ecological processes	Lagoon ecosystem	Tourists, residents, tourist business	Local municipalities
		Cultural landscape (attractiveness)	Coevolution between man and lagoon	Past elements of the SES		
		Navigable channels (accessibility)	Hydrodynamic processes, biostabilization	Lagoon morphology		
R&L - Recreational navigation	Navigation	Natural landscape (attractiveness)	Ecological processes	Lagoon ecosystem	Residents	Venice municipality, Veneto Region
		Cultural landscape (attractiveness)	Coevolution between man and lagoon	Past elements of the SES		
		Navigable channels (accessibility)	Hydrodynamic processes, biostabilization	Lagoon morphology		
Information for cognitive development	Environmental education activities, participation	Natural landscape (attractiveness)	Ecological processes	Lagoon ecosystem	Residents, tourists	Local municipalities
		Cultural landscape (attractiveness)	Coevolution between man and lagoon	Past elements of the SES		
		Navigable channels (accessibility)	Hydrodynamic processes, biostabilization	Lagoon morphology		
Cultural heritage and identity - Tangible cultural heritage	Conservation, appreciation	Elements of tangible cultural heritage related to the lagoon environment	Coevolution between man and lagoon	Past elements of the SES	Residents, visitors	Soprintendenza belle arti e paesaggio[4]
Cultural heritage and identity - Tradition	Involvement	Local knowledge	Coevolution between man and lagoon	Past elements of the SES	Residents	Local municipalities

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[4] local authority for the safeguard of the cultural heritage.

2.3.2. Management implications

The SES perspective and the identification of these different categories of ES can be useful to focus the management needs of the Venetian system.

Direct ES' flow occurs without the need of human interventions, but at the same time they are subject to the impacts of other ES' activities and external pressures. A dramatic example is the evolution of the lagoon's morphology, that showed a marked decrease of salt marshes' surface (more than 50% between 1927 and 2002) and deepening of tidal flats (Sarretta et al., 2010). Human activities such as channel dredging, water extraction (and subsequent subsidence), and clam fishing activities (and associated sediment resuspension) seem to have played a key role in fostering these observed changes (Sarretta et al., 2010). The important role played by the lagoon's morphology for several ES, such as coastal erosion prevention, climate regulation and lifecycle maintenance (Table 3) suggests that a negative trend of these ES is likely to have occurred in association with these morphological changes. A SES management aimed at avoiding the decline of direct ES requires, first, to understand which environmental pressures negatively affect the flow of these ES, and second, to control these pressures in a way that they not produce a decline in direct ES. It should be noted from the examples above that some of the activities involved in mediated ES can be included among these pressures (e.g. clam fishing activities). Therefore, the provision of these mediated ES should be balanced in a way that the effects produced by their activities on direct ES are minimized.

All the activities listed in Tables 4 and 5 potentially contribute to the "pressure side" of mediated ES. An advantage of the SES approach is that it allows to handle also ES which have a clear role as pressures, such as clam, maritime transport and tourism, because it provides a way to identify both their dependence on the ecosystem and their negative feedbacks on it. Considering the short time scale ES, clam harvesting and navigation on the one hand are necessary for the provision of seafood and maritime transport ES, but on the other hand, they are also recognized to negatively affect the lagoon morphology and thus other direct ES. Similarly, these activities produce negative feedbacks on “their own” ES, namely overexploitation in the case of harvesting and sediment erosion (which leads to channels siltation) in the case of navigation. Therefore, in the case of short term mediated ES, management actions need to have a double role: (1) to control the negative feedbacks aiming at maintaining the processes generating these ES, and (2) to minimize their externalities in order to maintain the processes underpinning other ES.

According to the long time scale hypothesis, time lagged ES are generally less sensitive to negative feedbacks, although they reflect the overall pattern of human-environmental relationships in the long term. In case of ES to which both temporal hypotheses apply, on the one hand, the short term component implies the possibility of a negative feedback between the activities and their own ES, but on the other, the importance of this feedback is “attenuated” by the long term component of the ES: a landscape with degraded ecological state (short term component), such as the water bodies in the immediate surroundings of Venice, might be nevertheless attractive because of its co-evolved character (long term component). This means that a control of the activities may not seem an urgent matter from the perspective of a single ES, making the role of an integrated perspective even more crucial for the identification of management needs. This becomes clear if we look at tourism or recreational navigation: although they respond weakly to a change in state of the ecosystem or to an excessive number of visitors, some management is needed to control the negative effects of high tourist or navigation pressure on other ES.

2.4. Conclusions

The approach proposed in this paper allows to identify the role played by social-ecological elements in the generation and use of multiple ES. Overall, this integrated view suggests that ES can play a role in the implementation of an ecosystem-based management of SES. First, the knowledge deriving from the analysis of multiple ES leads to the identification of the ecological processes and functioning to be used as management targets, that is, those processes and functioning that underpin ES provision. This means that ES can help to set management targets that focus on ecosystem processes and functioning, rather than only on ecosystem structures. Second, the added value brought by a SES perspective is that it allows to integrate social elements (such as actors, activities and governance systems) in the ES analysis. In particular, it helps to clarify their role both as elements involved in ES generation and as pressures on the system. An analysis such as that sketched here for the Venice lagoon sets the basis for further research on multiple ES interactions, aiming at supporting the implementation of ecosystem-based management.

Chapter 3

A Petri net modeling approach to explore the temporal dynamics of the provision of multiple ecosystem services

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Authors' contributions: Rova, S.: conceptualization, methodology, analysis and writing. Meire, P., Müller, F., Simeoni, M., Pranovi, F.: supervision and reviewing.

Abstract

The representation of the temporal dynamics of ecosystem services (ES) is a crucial research frontier in the field of ES modeling. In fact, most current ES models focus on static ES assessments, that need to be repeated with different inputs per time step to explore potential changes in ES. Here, we present a new approach for the dynamic modeling of multiple ES, based on the Petri Net modeling framework. The key features are: (i) multiple ES are modeled together as a single network, using a social-ecological systems (SES) perspective; (ii) the model accounts for the interactions occurring among ES, by distinguishing between the ES whose provision is mediated by some type of human input, which can produce some side-effects on the system, and those that are generated directly through ecosystem functions and do not generate side-effects; (iii) the model can reproduce the effects of changing drivers on the elements of the SES. These features allow to use the model to explore how ES can evolve over time under different "what-if" scenarios. The importance of considering the ES interactions is tested, showing that failing to include them in the model remarkably affects the results. Due to its complexity, the model should be used as an exploratory tool, focusing on the analysis of the general trends of multiple ES provision, rather than on the generation of quantitative projections. A first conceptual application to the Venice lagoon, Italy, is presented, in which the trends of 13 different ES are simulated. This application shows the potential of the model in exploring the development produced by climate change and socio-economic pressures, and the effects of a set of possible management actions. This modeling approach can contribute to generate new perspectives on the dynamic modeling of multiple ES and on the integrated management of SES.

3.1. Introduction

Ecosystem services (ES) emerge from the complex interactions occurring between ecosystems and humans, within the context of interconnected social-ecological systems (SES) (Fischer and Eastwood, 2016; Ostrom, 2009; Reyers et al., 2013). SES are complex adaptive systems characterized by complex processes, feedbacks and trade-offs which cannot be captured if social and ecological systems are studied separately (Levin et al., 2013; Liu et al., 2007). Therefore, the study of SES and the ES that they produce requires system-based methods of analysis that account for their complexity (Bennett et al., 2015; Reyers et al., 2013).

Several ES modeling tools exist (e.g. Boumans et al., 2015; Jackson et al., 2013; Sharp et al., 2014; Tallis and Polasky, 2009; Villa et al., 2014), that provide useful tools for the assessment of multiple ES and for generating ES predictions under various scenarios (for a review see Bagstad et al., 2013; Ochoa and Urbina-Cardona, 2017; Rieb et al., 2017). However, current ES models lack to account for some key elements of complexity, with respect to three main aspects: space-time ES dynamics, link with human well-being and the role of technology in enhancing and/or substituting ES (Rieb et al., 2017). With respect to the temporal dynamics, in fact, most of the current ES modeling approaches focus on the static prediction of the ES provision, providing a snapshot referred to a single step in time (Rieb et al., 2017). As a result, trends are often explored by running the models multiple times with different inputs (e.g. Rukundo et al., 2018; Xu et al., 2018), often based on land use data (e.g. Lautenbach et al., 2011; Stürck et al., 2015), rather than by modeling the ES dynamics. The global unified metamodel of the biosphere (GUMBO) (Boumans et al., 2002), and the Multiscale Integrated Models of Ecosystem Services (MIMES) (Boumans et al., 2015) are ES models based on system dynamics, which are designed to simulate the dynamics of multiple ES. However, the lack of documentation and methodological support has hindered their application in scientific studies so far (Ochoa and Urbina-Cardona, 2017).

This paper presents a new approach for modeling the temporal dynamics of the provision of multiple ES. It builds upon the social-ecological viewpoint for ES analysis proposed in Chapter 2, turning it into a dynamic model using Petri nets (Girault and Valk, 2003; Murata, 1989). A previous application of Petri nets to ES exists (Fongwa et al., 2010), aimed at providing a decision-support system for agro-forest landscapes, which supported the choice of Petri nets as modeling framework for this work. Petri nets, in fact, are characterized by a graphical structure that facilitates the communication of the modeling work to stakeholders, and furthermore they allow the modeler to fully specify the model structure, functions and parameters, and to represent a variety of different ecological and social processes and interactions. A first, conceptual application to the Venice lagoon, Italy, is presented, that represents a set of 13 ES provided by the lagoon SES. The Venice lagoon is an excellent example of complex SES, in which nature and humans have coexisted for centuries, with a co-evolution which has resulted in profound modifications of both the lagoon ecosystem and the habits of the local society (D'Alpaos, 2010; Ravera, 2000; Solidoro et al., 2010). This deep linkage between social and ecological aspects, and the urgent threats related to climate change have posed the challenge to develop a new ES modelling approach, flexible enough to represent the peculiar characteristics of the Venice lagoon SES, and capable to dynamically simulate the production of multiple ES under different scenarios.

In particular, this manuscript addresses three main research questions: (1) How can multiple ES be modeled together accounting for their interactions and dynamics? (2) From a first, explorative application to the Venice lagoon case study, how might the current drivers of change and climate change pressures affect the multiple ES delivered by the lagoon? (3) Can we use the model to explore which management actions could be effective in maintaining the provision of ES over time?

3.2. Materials and methods

3.2.1. Modeling approach

The structure of the model has been developed by making use of the tiered structure of Ostrom's SES framework (Ostrom, 2009), based on four core subsystems (resource system, resource units, actors and governance system) and their interactions (McGinnis and Ostrom, 2014; Ostrom, 2009). This allows to include both ecological and social elements involved in ES' delivery. The model reflects the approach proposed in Chapter 2, which has been translated into the general Petri Net structure shown in Figure 3 (please see below for a brief introduction to Petri nets). The model makes a distinction between ES with direct and mediated flow types (*sensu* Chapter 2), that is, it differentiates between ES provided directly through ecosystem functions, occurring independently of human inputs (direct flow type), and ES whose provision is mediated by human activities that "use" the resource (mediated flow type). For example, climate regulation is a direct ES, as it depends e.g. on coastal habitats' carbon sequestration function (Figure 3A), whereas seafood is a mediated ES because it necessarily depends on fishing activities (Figure 3B). Activities are performed by actors (e.g. fishermen) and can be regulated by the governance system (e.g. a fishery management institution). The crucial difference between these two types of ES is that the flow of direct ES does not consume resources and does not generate negative effects on the system, whereas the activities of the mediated ES can (and often do) consume the resource units upon which they depend, and, most of all, can generate negative side-effects on other resources (externalities). For example, fishing activities can produce negative impacts on coastal habitats, thus affecting the provision of other ES. The modeling of the activities and their impact on the system is the key characteristic of the present approach, which allows to represent not only how multiple ES are produced but also the way they interact with each other.

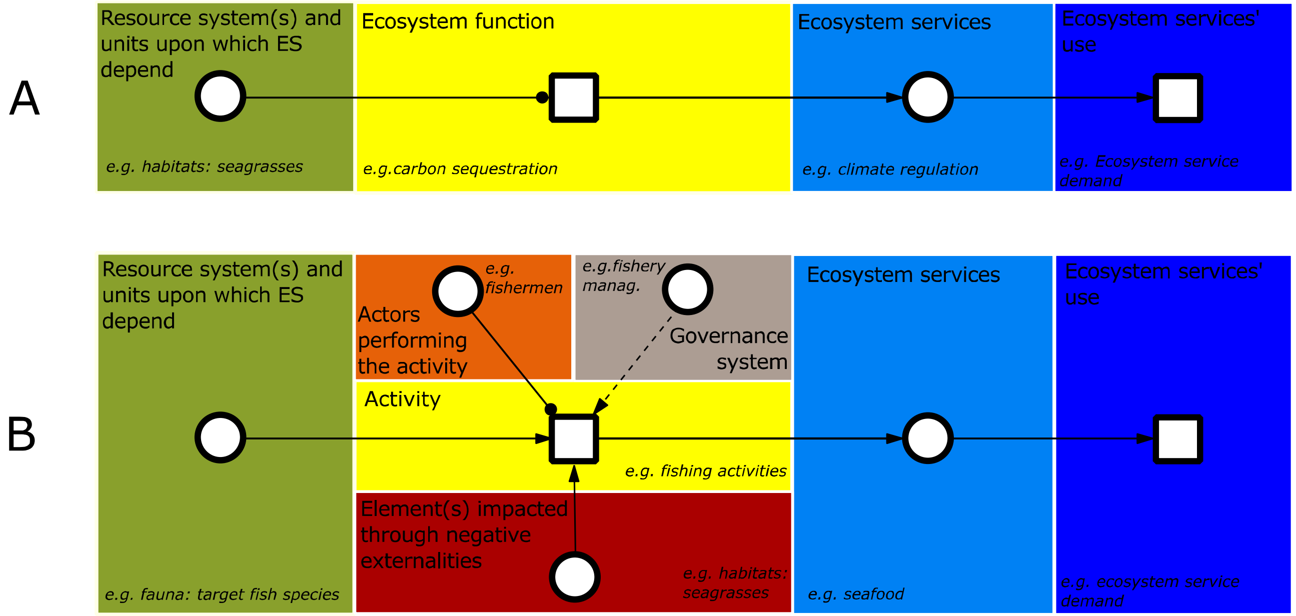

Figure 3 General Petri net structure developed for modeling ecosystem services (ES) with direct flow type (regulating ES, A) and with mediated flow type (provisioning and cultural ES, B). Circles = places (i.e. elements of the system); squares = transitions (ecosystem functions, activities, interactions); solid arrows = normal arcs (i.e. transitions consume the elements in the input places); solid lines ending with a circle = read arcs (i.e. elements in the input places are needed but not consumed by the transition); dashed arrows = modifier arcs (i.e. input places can modify the rate of the transition but are not a precondition for the transition).

In this work, colored continuous Petri nets are used to model multiple ES. Petri nets are graphical and mathematical modeling tools, represented as directed, weighted, bipartite graphs (see Murata (1989), Girault and Valk (2003)and Esparza and Nielsen (1994) for surveys on Petri nets and their properties). They consist of two kinds of nodes: places, generally representing conditions, items or resources (drawn as circles), and transitions, generally representing events or (re)actions (drawn as boxes). In this work, places are used to represent ES, resource systems, actors and governance system (e.g. seafood ES, fish stock, fishermen and fishery management institution), whereas transitions represent the interactions among the elements of the SES (i.e. processes, ecosystem functions and activities) (Figure 3).

Directed arcs, drawn as arrows, connect nodes of different type, so that transitions have a certain number of input places (preconditions, items needed for the action) and outputs places (postconditions, items produced). For example, fish and fishermen are inputs for the fishing activity, that generates the seafood ES. Different types of arcs are used to represent different types of relationships between a transition and its input places. In particular, normal arcs (drawn as solid arrows) imply that the transition consumes the resources contained in the input places (e.g. the fishing activity removes fish from the stock); “read arcs” (drawn as solid lines ending with a circle) imply that the resources in the input place are needed but not consumed (e.g. the fishing activity requires the fishermen, but does not consume them, or, similarly, in case of direct ES, the carbon sequestration function depends on habitats but does not consume them); “modifier arcs” (drawn as dashed arrows) imply that the input places are not needed to enable the transition but can modify its rate (e.g. a fishing management institution is not a precondition for fishing to take place, but can modify its rate). For what concerns the negative externalities produced by the activities, they are represented by weighted arcs (with weights different form one) connecting the impacted resources with the impacting activity. The weights quantify the magnitude of these side effects, e.g. for the fishing activity, the amount of habitat consumed per unit of fish caught. In this way, the model can represent the loss of habitats connected with the fishing activity, and thus the trade-off occurring between seafood ES and other ES delivered by the impacted habitats.

In continuous Petri nets (Heiner et al., 2008), a non-negative real number (called “mark”) is specified for each model variable, representing its “amount”, e.g. the stock of resources available. The arrangement of marks over the net (a vector called “marking”) specifies the overall system state. Furthermore, rate functions, which can be any kind of mathematical function and express the "speed" of the transformation from input to output places (Heiner et al., 2010), are assigned to all transitions. For example, the rate of the fishing activity represents the amount of seafood harvested per each time step, calculated as a function of fish stock, fishermen and governance system. The rate functions are translated and solved as differential equations when the model simulations are run.

Finally, colored Petri nets (Jensen, 1997), were chosen for this work because they allow a compact model representation. “Colorsets” (sets of one or more colors), which are associated to places, specify, in a tiered-structure based on the SES framework, the different types of element (e.g. habitats, fauna, actors, etc.) involved in the model. This allows to group and overlay (folding) the portions of the net that represents ES whose generation involves the same types of elements, resulting in a compact model structure.

All the modeling work has been developed using the Petri net tool Snoopy (Heiner et al., 2012; Snoopy, 2017).

3.2.2. Application to the Venice lagoon.

The application to the Venice lagoon, Italy (Figure 4) provides a representation of a set of 13 ES produced by the lagoon SES (Table 6), and their interactions. The model includes the ES which have been found to be relevant for the VL in previous studies (Rova et al., 2015; Chapter 2), and for which a scientific understanding is currently available .The main effort in the building of the model was put in obtaining a topology

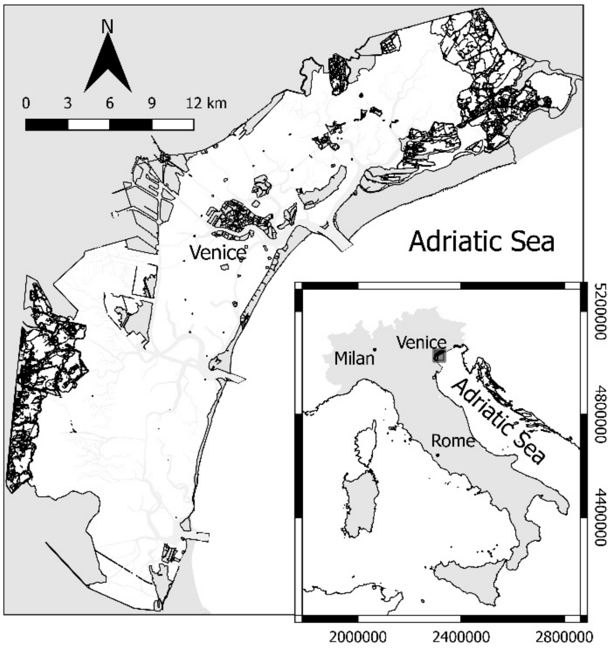

Figure 4. Case study area: the Venice lagoon (Italy).

Table 6. Ecosystem services (ES) included in the model and their indicators. More details on the modeling of each ES are provided in Appendix A.

ES category	ES	Indicator
Regulating	Climate regulation	Amount of carbon sequestered by seagrasses and salt marshes habitats
	Waste treatment	Self-depuration capacity indicated through the amount of nitrogen removed through denitrification
	Erosion prevention 1	Areas in which salt marshes provide a sheltering effect with respect to wind driven erosion
	Erosion prevention 2	Sum of habitats' biostabilization capacity, that reduces the bottoms' susceptibility to erosion
	Lifecycle maintenance	Sum of habitats' nursery role
Provisioning	Artisanal fishing	Yield from artisanal fishing activities
	Recreational fishing	Yield from recreational fishing activities
	Hunting	Yield from recreational bird hunting activities
	Clam harvesting	Yield from mechanical clam harvesting activities
Cultural	Info. for cognitive development	n. of visitors through environmental education activities
	Traditions	n. of people practicing traditional activities
	Tourism	n. of visitors to the lagoon (historical center of Venice excluded)
	Navigation	n. of recreational boats' passages

able to catch the multiple ES, their interactions and the cause-effect relationships with drivers of change, with no ambition of being quantitatively calibrated.

3.2.2.1. Ecosystem services model structure

The workflow starts with the identification of the model variables, which have been organized according to the tiered structure of the SES framework: based on the core-subsystems of the SES framework (resource systems and units, actors, governance system) and ES, the types of elements that compose the system have been specified (colorsets), along with the elements belonging to each of them (colors within each colorset) (Table 7). The ES have been analyzed and characterized based on (i) the type of ES flow (direct/mediated), (ii) the resource systems upon which the ES depend, and (iii) the generation of negative externalities, according to the logical flow depicted in Figure 5. The ES with similar characteristics have been grouped together, resulting in six ES “topological” groups, which share a similar net topology (Figure 5). Therefore, by taking advantage of the features of colored Petri nets, a “folded” net structure has been developed for each “topological” group, resulting in six folded ES subnets (Figure 5). Each folded subnet is based on the general structure of Figure 3, but incorporates the specific features of each”topological” group. The folded subnets are a compact way to graphically represent the net structure of the ES belonging to each “topological” group, as if they were stacked together. Within each subnet, each ES has a specific combination of elements involved (the colors of the places’ colorsets) and specific parameters for the transitions’ rate functions. The “unfolding” of the net returns the topology for each ES, which is summarized in Table 8 and more extensively described in Appendix A.

In general, regulating ES follow the general structure developed for the direct flow type ES (Figure 3A), whereas provisioning and cultural ES follow that of a mediated flow type ES (Figure 3B). Then, each subnet presents some variations that account for the specific characteristics of the ES “topological” group. Provisioning 1 ES’ subnet (Figure 6B), which refers to low impact fishing and hunting activities, does not include places impacted through negative externalities. In the model, these activities were

Table 7. Colorsets (italics) and colors (numbered elements) representing the social-ecological system's (SES) elements involved in the model

Resource systems (colorsets) and resource units (colors within the colorsets)			
Habitats	*Fauna*	*Channels*	*Resources deriving from past states of the SES (Heritage)*
- 0 Salt marshes - 1 Seagrasses - 2 Bare (intertidal) - 3 Benthic diatoms - 4 Macroalgae	- 0 Target fish species - 1 Clams - 2 Birds	- 0 Channels	- 0 Density of cultural heritage - 1 Traditional knowledge

ES categories (colorsets) and ES (colors within the colorsets)		
Regulating ES	*Provisioning ES (*)*	*Cultural ES*
- 0 Climate regulation - 1 Waste treatment - 2 Erosion prevention 1 - 3 Erosion prevention 2 - 4 Lifecycle maintenance	- 0 Artisanal fishing - 1 Recreational fishing - 2 Clam harvesting - 3 Hunting	- 0 Tourism - 1 Navigation - 2 Information for cognitive development - 3 Traditions

Governance system (colorset) and management fields (colors within the colorset)
Governance system
- 0 Tourism - 1 Navigation - 2 Artisanal fishing - 3 Recreational fishing - 4 Clam harvesting - 5 Hunting - 6 Salt marsh maintenance - 7 Seagrass maintenance - 8 Bare (intertidal) maintenance - 9 Benthic diatoms maintenance - 10 Macroalgae maintenance - 11 Channel dredging - 12 Lagoon-sea exchanges

Actors (colorset) and types of actors (colors within the colorset)
Actors
- 0 Residents - 1 Artisanal fishermen - 2 Recreational fishermen - 3 Clam fishermen - 4 Hunters - 5 Users of environmental education activities - 6 Tourists - 7 Boat owners

(*) Recreational fishing and hunting are here classified as provisioning ES as they yield tangible products, but can be also assimilated to cultural ES due to their recreational importance.

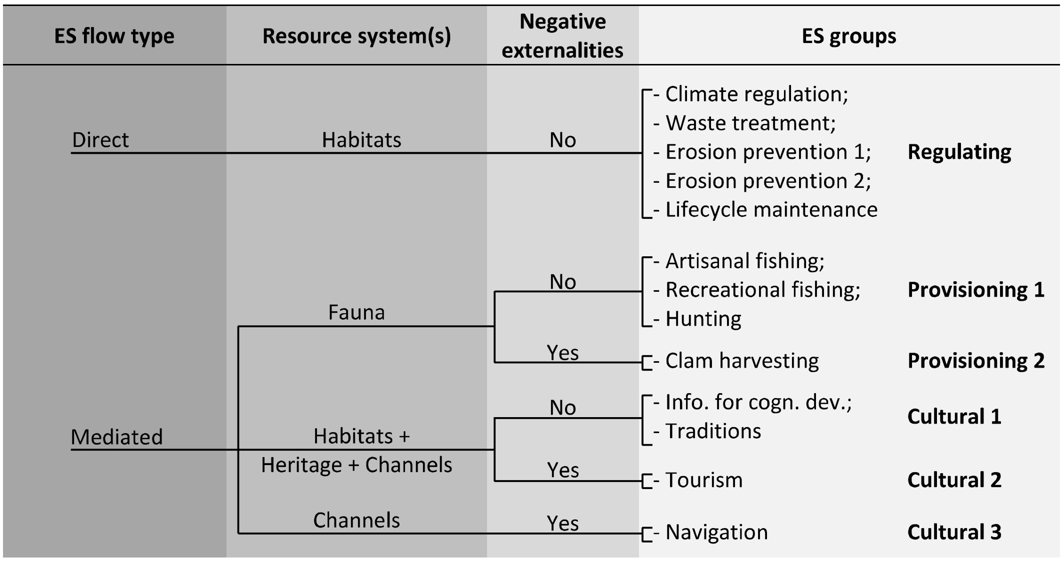

Figure 5. Logical flow diagram for the definition of the ecosystem services (ES) “topological” groups

Table 8. Unfolding of the places involved in the generation of each ecosystem service (ES). Abbreviations of the ES "topological" groups: R, regulating; P1, provisioning 1; P2, provisioning 2; C1, cultural 1; C2, cultural 2; C3, cultural 3.

ES group	ES	Habitats resource units	Fauna resource units	Channels resource units	Heritage resource units	Actors	Governance system's management fields	ES
R (Fig. 6A)	Climate regulation	Salt marshes Seagrasses						
R (Fig. 6A)	Waste treatment	Seagrasses Benthic diatoms Bare (intertidal) Macroalgae						
R (Fig. 6A)	Erosion prevention 1	Salt marshes						
R (Fig. 6A)	Erosion prevention 2	Seagrasses Benthic diatoms Macroalgae						
R (Fig. 6A)	Lifecycle maintenance	ALL						
P1 (Fig. 6B)	Artisanal fishing		Target fish species			Artisanal fishermen	Artisanal fishing	
P1 (Fig. 6B)	Recreational fishing		Target fish species			Recreational fishermen	Recreational fishing	
P1 (Fig. 6B)	Hunting		Birds			Hunters	Hunting	
P2 (Fig. 6C)	Clam harvesting	Seagrasses (*) Benthic diatoms (*)	Clams	Channels (*)		Clam fishermen	Clam harvesting	Lifecycle maintenance (*)
C1 (Fig. 6D)	Info. for cognitive development	ALL		Channels	Density of cultural heritage	Users of environmental education activities		
C1 (Fig. 6D)	Traditions	ALL		Channels	Traditional knowledge	Residents		
C2 (Fig. 6E)	Tourism	Salt marshes(*) Seagrasses(*) Bare (intertidal)(*) Benthic diatoms(*)		Channels (*)	Density of cultural heritage	Tourists	Tourism	
C3 (Fig. 6F)	Navigation	Salt marshes(*) Seagrasses(*) Bare (intertidal)(*) Benthic diatoms(*)		Channels (*)		Boat owners	Navigation	

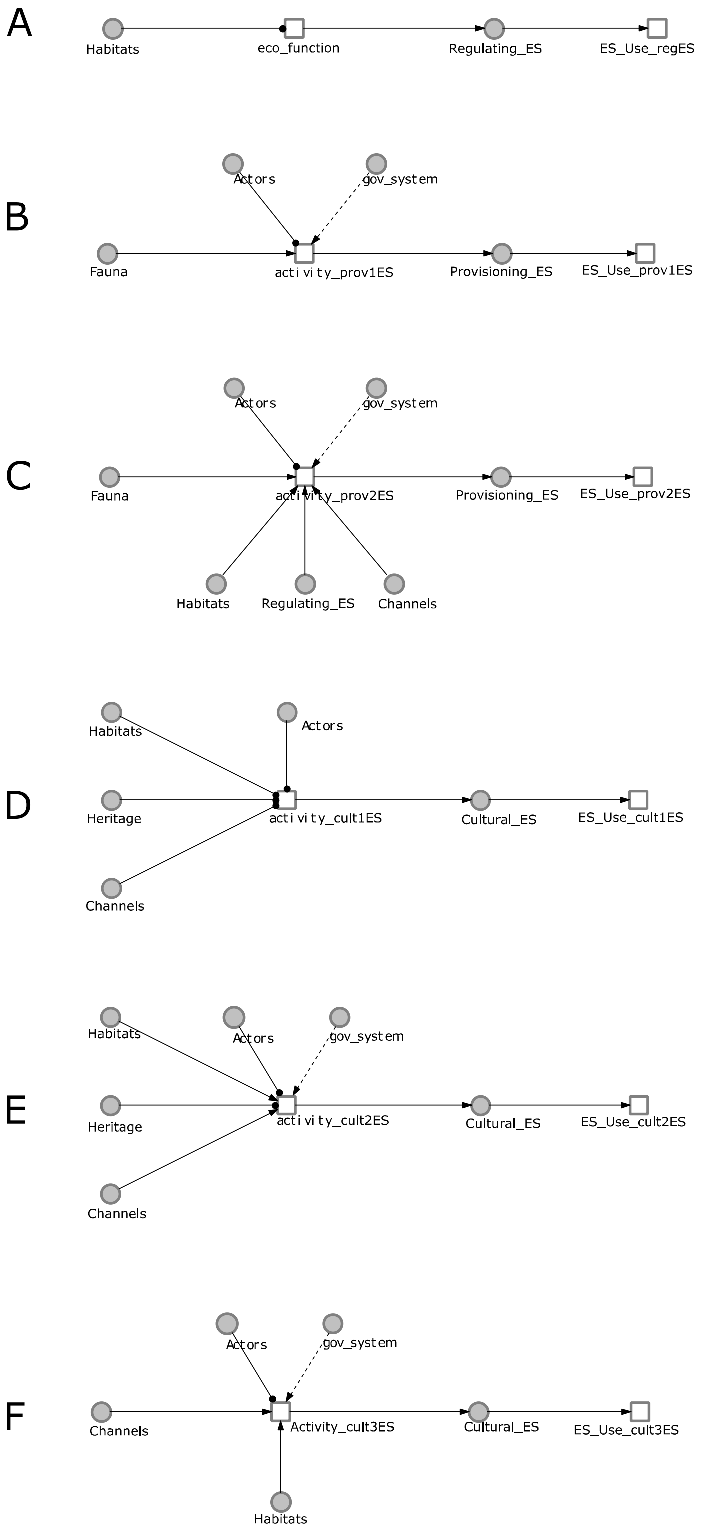

Figure 6. Graphical structure of the six ecosystem services (ES) subnets (regulating ES (A), provisioning 1 ES (B), provisioning 2 ES (C), cultural 1 ES (D), cultural 2 ES (E), cultural 3 ES (F)). Circles = places; squares = transitions; solid arrows = normal arcs; solid lines ending with a circle = read arcs; dashed arrows = modifier arcs

assumed to produce no externalities because the side effects that they produce on other resources (other than the exploited ones) are extremely low if compared to the habitats' degradation, enhanced channels' siltation and disturbance to the nursery function that are instead caused by the mechanical harvesting activities involved in provisioning 2 ES (clam harvesting, Figure 6C) (cfr. Pranovi et al., 2004, 2003). Cultural 1 and 2 ES (Figure 6D-E), have been modeled to be dependent on habitats, heritage and channels, which reflect natural attractiveness, cultural attractiveness and accessibility, respectively. The difference between these two "topological" groups concerns the negative externalities. Cultural 2 ES (tourism) produces severe side effects related to the intensive navigation activities through which visiting occurs, that cause degradation of habitats and enhanced channels siltation. Cultural 1 ES are instead characterized by slower navigation modes (rowing and sailing boats, or slow motorboats used for educational excursions) whose negative impacts can be considered negligible compared to tourism. Cultural 3 ES (navigation, Figure 6F) depends mainly on the presence of channels and, similarly to tourism, causes channels' siltation and habitats' degradation.

For what concerns the graphical representation of the model, please note that Figures 6, 7 and 8 (which are described in this section, section 3.2.2.2 and 3.2.2.3 respectively) compose together the overall model structure, which has been split in different portions for visualization purposes; the nodes in grey ("logical nodes") appear multiple times as graphical copies of a single node, logically identical.

3.2.2.2. Underpinning ecological and social processes

The model includes, with a certain degree of simplification, the ecological processes and the anthropic interventions upon which the presence of resource units depend, and can simulate the social trends of actors' populations. Due to its complexity and variety of variables and processes included, the model provides a simplified representation of ecological and social processes: an effort was made to design a model structure that applies a relatively homogeneous degree of simplification to all processes, to avoid having an imbalance between the detailed representation of some aspects and simplification of others. This section describes the folded net structure representing these processes. A more detailed description is provided in Appendix A.

Habitats are generated through ecological processes that depend on the extent of each habitat and are modulated by fauna (target fish species and birds) (Figure 7A). This modulation reflects the feedback of higher levels of the tropic network on habitats. Furthermore, habitats can be the object of management actions controlled by the governance system, aimed at their maintenance and/or reconstruction. In addition, the model accounts for the positive effect of the environmental sensibilization deriving from the information for cognitive development and tradition ES. This reflects the environmental friendly behavior of the people that have been exposed to these ES.

Channels' presence and navigability are determined by two factors in the model (Figure 7B). The first is self-regulation capacity, that represents the effects of channels' hydrodynamics on sedimentation. It is influenced by the erosion prevention 1 and 2 ES, which contribute to prevent siltation. The second factor are channel dredging activities, regulated by the channel dredging governance system.

The abundance of fauna depends on population growth (Figure 7C). Growth depends on the abundance of the fauna resource units, and is modulated by the lifecycle maintenance ES, reflecting the key role played by the spawning, nursery and nesting functions for the maintenance of these resources.

An actors' growth transition (Figure 7D) allows for the specification of social trends regarding actors, in particular residents and tourists.

The model does not include processes that "produce" cultural heritage and traditions. These resources derive from past states of the SES, and result from the long-term coevolution between society and ecosystem. These processes are not modeled as they have a time scale far longer than that of the other processes considered (please refer to Chapter 2 for a more thorough discussion of these aspects).

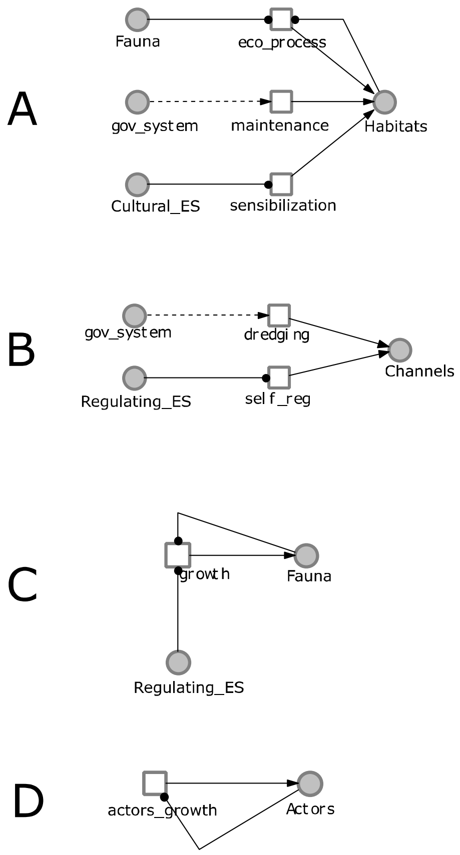

Figure 7. Graphical structure of the subnets representing the processes generating the resource units (habitats (A), channels (B) and fauna (C)), and actor's growth (D). Circles = places; squares = transitions; solid arrows = normal arcs; solid lines ending with a circle = read arcs; dashed arrows = modifier arcs.

3.2.2.3. Effects of drivers of change

The model simulates the effects of the relative sea level rise (RSLR) and temperature increase driven by climate change, and the effects of the mobile barriers at the lagoon inlets (MOSE system (Consorzio Venezia Nuova, 2018)), which are expected to be completed in 2019 in order to defend Venice from flooding (Figure 8).

RSLR (Figure 8A) has been assumed to produce three major effects on the lagoon SES: a negative impact on salt marshes and bare (intertidal) habitats (Marani et al., 2007; Rizzetto and Tosi, 2011), and seagrasses (Saunders et al., 2013); a negative impact on residents and an effect on cultural heritage that is initially positive (increased attractivity) and then negative, as the RSLR increases. The negative effects on residents and cultural heritage are related to the flooding of urban areas, which increases with increasing water level, as shown by the altimetric charts of the historical center of Venice (Comune di Venezia, 2018a). The frequency and severity of high tides is expected to increase with RSLR (Carbognin et al., 2010), thus exacerbating the flooding events. The initial positive effect on cultural heritage has been assumed here to account for the increased tourist attractivity of the flooded urban areas.

The MOSE system consists of a system of gates, installed on the bottom of the three lagoon's inlets, which will be raised during high tide events (>110 cm with respect to Punta della Salute tide gauge), temporary separating the lagoon from the sea. The frequency of high tides is expected to increase with RSLR, and so the frequency of the MOSE closures (Carbognin et al., 2010; Umgiesser and Matticchio, 2006). In this model, the yearly frequency of closures is calculated as a function of RSLR, according to the trends estimated by Carbognin et al. (2010) (Figure 8A). It has been assumed to produce both social and ecological effects: on the one hand, it balances the effects produced by RSLR on residents and cultural heritage, and on the other hand, because of the modified lagoon-sea exchanges related to the inlets' closure, it negatively affects submerged habitats, lifecycle maintenance and channels' self-regulation capacity.

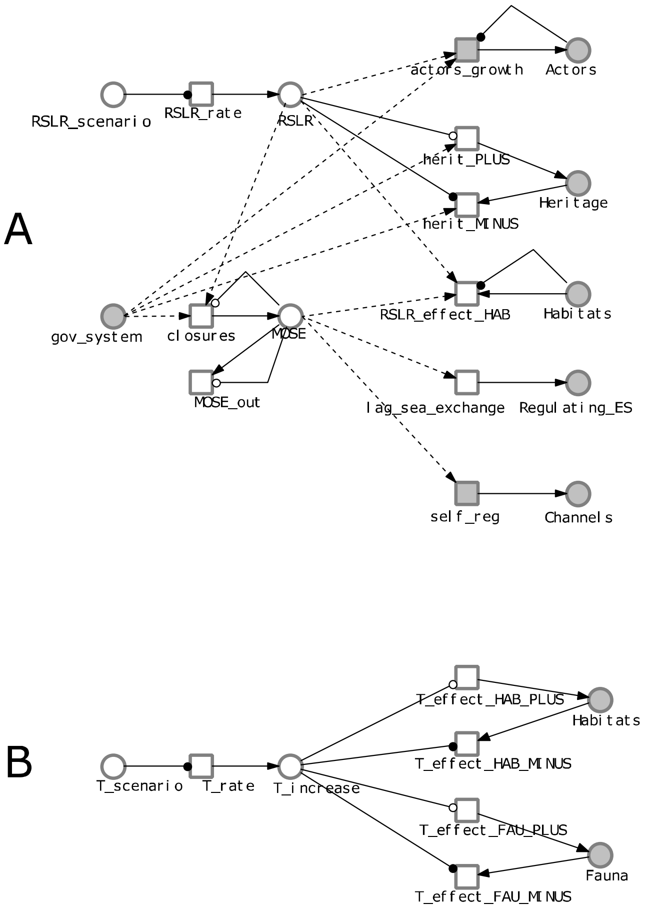

Figure 8. Graphical structure of the subnets modeling the effects of relative sea level rise (RSLR) and MOSE system (A) and of temperature (T) increase (B). The following additional model variables were added to model these effects: RSLR_scenario: specifies the RSLR scenario (none, +15 cm, +25 cm and +50 cm by the end of the 21st century); RSLR: RSLR at each time step; MOSE: n. of MOSE closures per year at each time step; T_scenario: specifies the T scenario (none, +1°C by the end of the 21st century); T_increase: T increase at each time step. For a detailed description of how these subnets work please refer to Appendix A. Circles = places; squares = transitions; solid arrows = normal arcs; solid lines ending with a circle = read arcs; dashed arrows = modifier arcs.

The effects of temperature increase on habitats and fauna (Figure 8B) have been modeled according to the following assumptions. Target fish species have been assumed not to change at low levels of temperature increase (simulating the effects of species substitution), and to be negatively affected at higher levels (Pranovi et al., 2013). Seagrasses have been assumed to be positively affected at low levels of temperature increase, and negatively affected at higher levels of temperature increase, which seem to reduce seagrasses growth when occurring concurrently with a reduced light availability, as that caused by RSLR (Bulthuis, 1987). A similar behavior has been assumed for clams, as high values of temperature increase seem to become a stress factor for this species (Munari et al., 2011; Velez et al., 2017).

A more detailed description of the modeling of the effects of these drivers is provided in Appendix A.

3.2.2.4. Rate functions and parameters

The rate functions of all transitions are reported in Table A1 (Appendix A). Wherever possible, functions widely used in ecology (e.g. logistic population growth) were used, where not possible, the functions reflect the authors' hypothesis on the modeled processes. The model's initial conditions, functions' parameters and arc weights (Tables A2, A3, A4 of the Appendix A, respectively) are built up to reproduce the realistic proportions between the modeled variables and the relative magnitude of the processes occurring in the lagoon system. Overall, the model setup was tuned to represent an ideal configuration of the Venice lagoon SES in which all variables are in steady-state. The steady state is a hypothetical perfectly equilibrium situation, in which all variables are constant over time: no growth function is specified for actors, no climate change pressure occurs, and resources' consumption perfectly balances their generation rate. As a result, the ES provision is constant over time too. Moving from this condition, the behavior of the model was tested by performing a set of simulations in which all the model parameters were changed one at a time by ±10% and ±25%. The analysis was repeated iteratively while tuning the parameters, in a sort of sensitivity analysis, until a satisfactory model behavior was obtained, that broadly reflected the processes and variables' interactions observed in the lagoon. The results of these simulations, relative to the final version of the model, are reported in Appendix B. Furthermore, we have tested the sensitivity of the model with a limited number of combined variations of model variables, with a focus on the governance system's variables (about 150 combinations, including combination of two, three, four and five variables, with positive and negative variations). Under these conditions the model showed an overall consistent behavior, with no ecological nonsenses, and a sensitivity in the same order of magnitude than that obtained with single variations.

3.2.2.5. Scenarios

- A **Business as usual (BAU)** scenario, that features the deviations from the steady state that characterize the current situation of the Venice lagoon. These deviations are: (i) increasing tourists, (ii) decreasing residents, (iii) unbalanced consumption of salt marshes, (vi) increasing seagrasses. These deviations take place simultaneously and for the entire simulation period. The corresponding variations in the input parameters are specified in Tables A2 and A3 (Appendix A).
- Three **Business as usual + Climate change (CC)** scenarios, that incorporate climate change pressures into the BAU scenario. The simulations include tree RSLR scenarios (15 cm, 25 cm and 50 cm RSLR by the end of the 21st century) combined to one temperature scenario (1°C temperature increase by the end of the 21st century), resulting in three CC scenarios (named CC_15, CC_25, CC_50, respectively).
- Three **Business as usual + Climate change + MOSE (CC_MOSE)** scenarios, in which the functioning of the MOSE system has been combined with the three CC scenarios (resulting in three CC_MOSE scenarios named CC_MOSE_15, CC_MOSE_25, CC_MOSE_50 respectively).
- **Additional management options** scenarios, that feature additional management strategies tested under BAU and CC_MOSE scenarios. These

strategies include single and combined variations of all governance systems' management fields (except for MOSE, which is already active under MOSE_CC scenarios), aimed at exploring if and how it is possible to balance the negative effects of these scenarios on ES. For the management fields related to the mediated ES' activities (tourism, navigation, artisanal fishing, recreational fishing, clam harvesting and hunting, which directly modulate the respective activities' rates), a variation of -50% has been used. For the management fields related to habitats maintenance and channels dredging, which represent the yearly maintenance rate expressed as proportion of the resources' initial condition, a variation of +1% has been used.

All simulations have been run until the end of the century.

3.2.2.6. Aggregated indicators of ES provision

The model outputs illuminate the trends of all its variables over time. To summarize and compare the effects of the various scenarios on the multiple ES, two aggregated indicators have been developed and computed based on the ES state at the end of the century:

- Sum of direct ES' percentage variations with respect to initial conditions (**ΔDir**);
- Sum of mediated ES' percentage variations, excluding tourism, with respect to initial conditions (**ΔMed-T**).

Tourism ES was not included in ΔMed-T because, being the major driver of change in the BAU scenario, it was expected to show a distinct trend. Therefore, its variation has been considered separately.

3.2.2.7. Testing the effects of excluding the interactions among ecosystem services

To sum up, the multiple ES included in the model interact, either directly or indirectly, in the following ways:

a) consumption of the same resource units (i.e. artisanal and recreational fishing activities insisting on the target fish species);

b) negative effects generated by some of the activities of the mediated ES (i.e. negative effects of clam harvesting, tourism and navigation ES);
c) positive effects of some ES on the resource systems (i.e. the environmental sensibilization deriving from the information for cognitive development and tradition ES, and the effect of erosion prevention ES on channels' self-regulation);
d) ecological feedbacks (i.e. fauna influencing the habitats' processes, and lifecycle maintenance ES influencing the growth of fauna).

The importance of having these interactions included in the model was tested by analyzing the effects that their exclusion has on the model results. To do so, three additional model configurations were created, which neglect the ES interactions partially or completely:

- a configuration without the positive and negative side effects produced by ES (points (b) and (c) above) ("NO_ES_sideEffects”). This configuration represents a model that mainly ignores the interactions deriving from “social” aspects of ES delivery (i.e. the consequences of human activities);
- a configuration without the ecological feedbacks (point (d) above) (“NO_EcoFeedbacks”). This configuration, on the other hand, represents a model that ignores the interactions deriving from the “ecological” aspects of ES delivery (i.e. the feedbacks between ecological elements);
- a configuration without both (“NO_ALL”).

The first source of interaction listed above (point (a)) could not be excluded because it would require eliminating one of the two fishing ES. For details on the setup of these configurations, please refer to Appendix A. The BAU and CC_MOSE scenarios were run with each of these configurations to compare the different outcomes.

3.3. Results

3.3.1. Business as usual, climate change and MOSE scenarios

Figure 9 shows the relative variation over time of the 13 ES considered in this study, under the BAU scenario. The massive loss of ES indicates that the BAU is an unsustainable scenario, even without considering the potential effects of climate change. Management actions are thus necessary to prevent the decline of ES over time. A trade off can be observed between tourism ES, whose marked increase is driven by the growing number of tourists assumed as BAU's major driver, and all the other ES, which are instead characterized by a general declining trend, except for erosion prevention 2. This trend shows that the model is capable to represent the feedbacks of socio-economic drivers (increase of the number of visitors and decrease of residents) on the lagoon ecosystem and on the ES it produces. The aggregated indicators ΔDir and ΔMed-T, and tourism variation (Figure 10) synthetically represent these trends.

The effects of CC scenarios (combination of RSLR, 15, 25 and 50 cm, and 1°C temperature increase) and CC_MOSE scenarios on the overall ES provision at the end of the 21st century are compared using the aggregated indicators ΔDir and ΔMed-T, and tourism variation (Figure 10). All these indicators are progressively reduced under more extreme CC scenarios. The functioning of MOSE does not change this overall trend, but produces different effects on the three indicators: (i) it does not offset the loss of direct ES, but rather tends to intensify the reduction of ΔDir in the more extreme CC scenarios; (ii) it has a positive effect on ΔMed-T with respect to CC_15 and CC_25 scenarios, but fails to produce an improvement with respect to CC_50; (iii) it has a positive impact on tourism in all cases, this effect becoming greater under more extreme scenarios. In any case, the MOSE system alone is not sufficient to prevent the effects of climate change on the multiple ES, and thus it requires to be combined with additional management options (the variation of ES

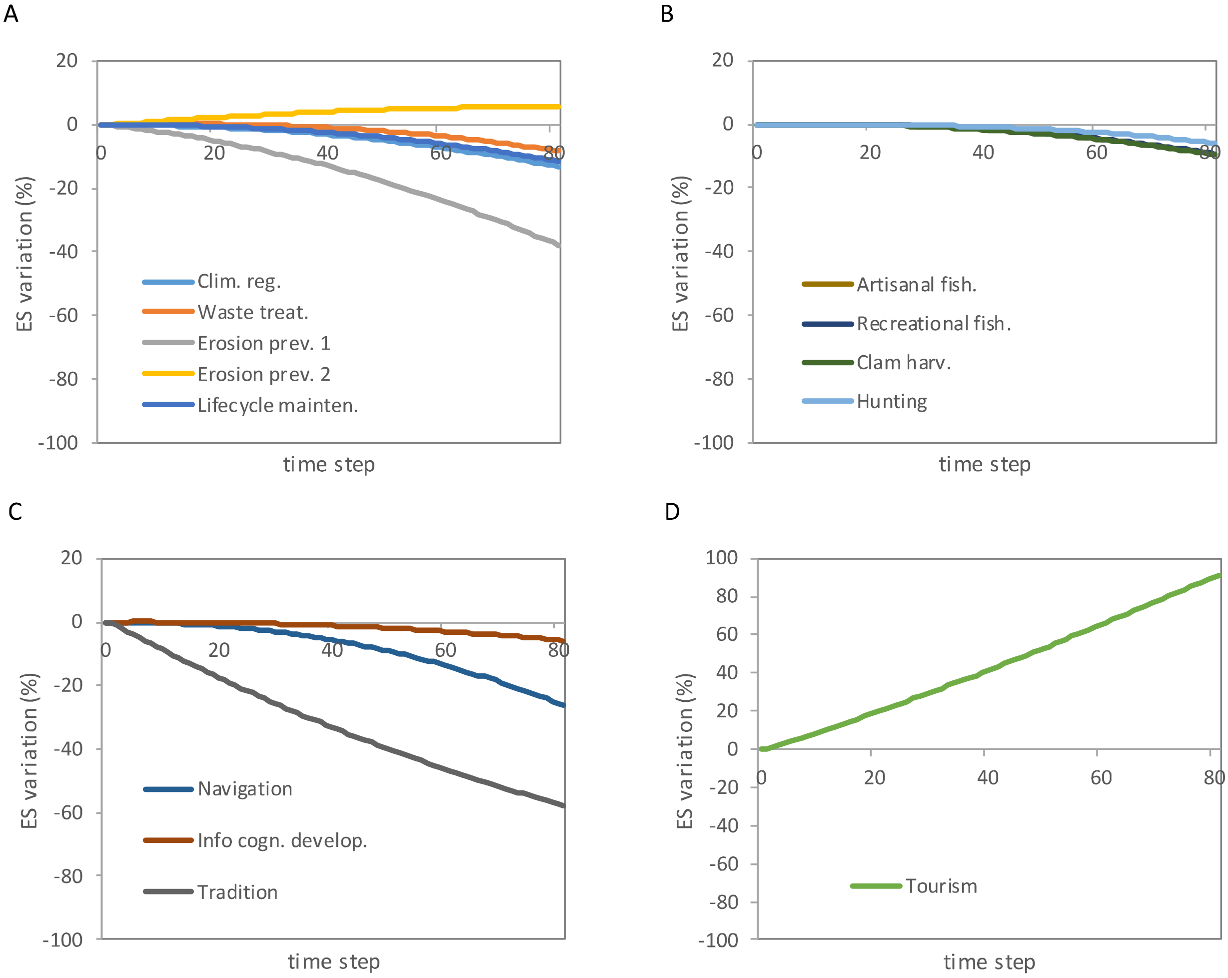

Figure 9. Ecosystem services (ES) variation (%) over time under Business-As-Usual (BAU) scenario. Regulating ES (A), provisioning ES (B), cultural ES except tourism (C), tourism (D)

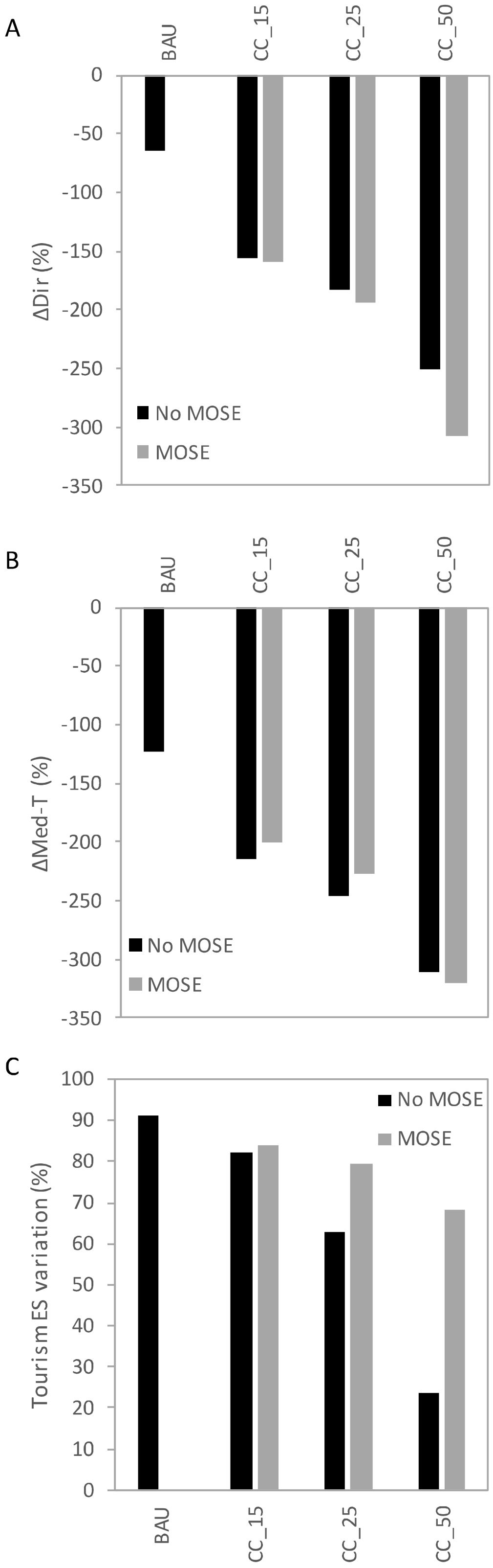

Figure 10. Values assumed by the two aggregated indicators ΔDir(A) and ΔMed-T (B), and variation of the Tourism ES (C), at the end of 21st century under the Businness-as-Usual (BAU) and climate change (CC) scenarios, with and without functioning of the MOSE system.

over time under CC_MOSE scenarios is shown in Figures C1, C2 and C3 of Appendix C).

3.3.2. Additional management options

Single additional management options have been tested under BAU and CC_MOSE scenarios, and their effectiveness has been evaluated with respect to the values assumed by the ΔDir and ΔMed-T indicators. The target for considering these interventions successful is the compensation of the reduction of these indicators with respect to the initial conditions. The two aggregated indicators have been given priority with respect to tourism's variation as long as the latter does not show a decrease with respect to the initial conditions

The single management options have been ranked based on their effectiveness with respect to each indicator (Table 9). The ranking is nearly the same in all scenarios. Maintenance of seagrasses produces the greatest effects in all cases, however, there is no case in which a single option can be effective in balancing both indicators. The lack of effectiveness of sectorial management points out the need to enforce management actions that operate at ecosystem level, combining different options together. To account for this, the following combinations of two, three and four management options have been tested in the model, designed based on the top three options of the rakings shown in Table 9.

Combinations of two:

- Seagrass maintenance & Salt marsh maintenance
- Seagrass maintenance & Tourism
- Seagrass maintenance & Benthic diatoms maintenance

Combinations of three:

- Seagrass maintenance & Salt marsh maintenance & Benthic diatoms maintenance
- Seagrass maintenance & Tourism & Benthic diatoms maintenance.

Table 9. Ranking of management options with respect to the two aggregated indicators ΔDir and ΔMed-T. The ranking is the same in the BAU and CC_MOSE scenarios, except for the groups of options marked with (*) and (**) (grey background), for which the relative ranking varies between scenarios.

	ΔDir		**ΔMed-T**
1	seagrass mainten.	1	seagrass mainten.
2	salt marsh mainten.	2	tourism
3	benthic diatoms mainten.	3	benthic diatoms mainten.
4	tourism	4	bare (intertidal) mainten.
5	navigation (*)	5	artisanal fishing(**)
5	bare (intertidal) mainten. (*)	5	salt marsh mainten. (**)
7	hunting	5	hunting (**)
8	artisanal fishing	5	macroalgae mainten. (**)
9	macroalgae mainten.	5	navigation (**)
10	recreational fishing	10	channels' dredging
11	clam harvesting	11	recreational fishing
12	channels' dredging	12	clam harvesting

- Seagrass maintenance & Tourism & Salt marsh maintenance

Combination of four:

- Seagrass maintenance & Tourism & Salt marsh maintenance & Benthic diatoms maintenance

Figure 11 summarizes the effects produced by these combinations under the four scenarios, with respect to the two aggregated indicators. In the case of combinations, the most effective solution(s) can be identified as that(those) meeting the target (counteracting the ES reduction with respect to initial conditions) with the fewest management options involved. Concerning ΔDir, combinations of two options are effective up to CC_MOSE_25, but fail to balance the loss of direct ES in CC_MOSE_50, for which a combination of three options is needed. Regarding ΔMed-T, the management options seem less effective than in case of direct ES. The combinations of two options are insufficient also in case of CC_MOSE_25, for which only seagrass maintenance + tourism is effective. For CC_MOSE_50, the combination of seagrasses maintenance + tourism + benthic diatoms maintenance is the only one that fully balances this indicator, and seagrasses maintenance + tourism + salt marshes maintenance is almost effective with a reduction of about -1%. Overall, the target can be met for both indicators under all scenarios only if combinations of three management options are enforced, which combine the maintenance of seagrass and either salt marshes or diatoms habitats with the reduction of tourism.

3.3.3. Effects of excluding the interactions among ecosystem services

If the interactions among ES are excluded from the model, we obtain a situation in which the multiple ES are isolated from each other. The consequences of this exclusion are visible by comparing the results obtained from the complete model with those obtained from the three configurations in which the ES interactions were removed partially or completely (Table 10).

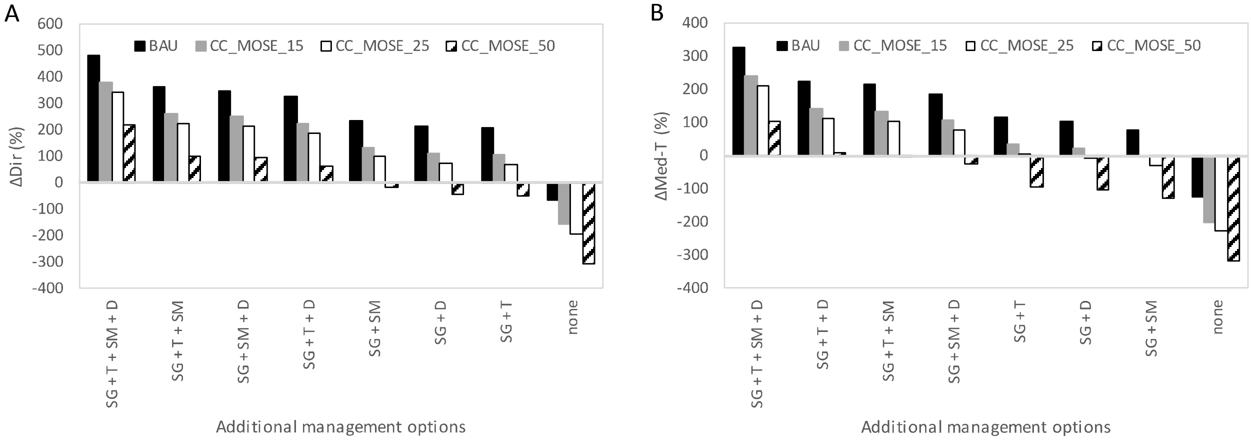

Figure 11. Effect of combined additional management options with respect to the two aggregated indicators ΔDir (A) and ΔMed-T (B) under the BAU and CC_MOSE scenarios. Abbreviations: SG, seagrasses maintenance; SM, salt marshes maintenance; D, benthic diatoms maintenance; T, tourism.

Table 10. Model results under the BAU and CC_MOSE scenarios (expressed as ecosystem services (ES) variation (%) at the end of the 21st century), obtained with the complete model and with the three additional configurations created to test the effects of neglecting the interactions among ES.

Scenario	Model configuration	Clim. reg.	Waste treat.	Erosion prev. 1	Erosion prev. 2	Lifecycle maint.	Tourism	Navigation	Info. cogn. dev.	Tradition	Artisanal fish.	Recreat. fish.	Clam harv.	Hunting	ΔDir	ΔMed-T
BAU	complete	-13	-8	-38	6	-11	91	-26	-6	-58	-9	-9	-10	-6	**-65**	**-124**
	NO_EcoFeedbacks	-13	-8	-37	6	-12	91	-27	-6	-58	0	0	0	0	**-64**	**-91**
	NO_ES_sideEffects	5	6	-19	18	4	110	0	2	-54	3	3	3	2	**15**	**-41**
	NO_ALL	5	6	-19	18	3	110	0	2	-54	0	0	0	0	**13**	**-52**
CC_MOSE_15	complete	-41	-23	-47	-21	-27	84	-32	-14	-61	-27	-27	-27	-14	**-158**	**-201**
	NO_EcoFeedbacks	-40	-22	-46	-20	-28	84	-35	-14	-61	-5	-5	-4	0	**-157**	**-124**
	NO_ES_sideEffects	-25	-10	-29	-10	-15	103	-2	-6	-58	-17	-17	-17	-7	**-89**	**-123**
	NO_ALL	-24	-9	-29	-9	-15	103	-2	-6	-58	-5	-5	-4	0	**-85**	**-79**
CC_MOSE_25	complete	-51	-29	-53	-28	-34	80	-35	-17	-63	-32	-32	-32	-18	**-194**	**-228**
	NO_EcoFeedbacks	-50	-28	-52	-27	-35	80	-38	-17	-63	-5	-5	-4	0	**-192**	**-131**
	NO_ES_sideEffects	-36	-16	-36	-18	-23	98	-3	-9	-59	-23	-23	-23	-11	**-129**	**-152**
	NO_ALL	-34	-15	-35	-17	-22	98	-3	-9	-59	-5	-5	-4	0	**-124**	**-85**
CC_MOSE_50	complete	-78	-51	-67	-53	-58	68	-42	-26	-67	-51	-51	-52	-32	**-307**	**-320**
	NO_EcoFeedbacks	-77	-50	-66	-53	-62	68	-48	-26	-67	-5	-5	-4	0	**-307**	**-155**
	NO_ES_sideEffects	-65	-41	-52	-45	-52	85	-12	-19	-64	-45	-45	-46	-27	**-256**	**-257**
	NO_ALL	-64	-39	-52	-43	-50	85	-12	-19	-64	-5	-5	-4	0	**-247**	**-109**

Looking at the BAU scenario, it appears that the lack of consideration of the ES interactions results in markedly different trends for most of the ES. In particular, the negative trends of many regulating ES are not captured if the ES side effects are not considered (NO_ES_sideEffects configuration). With this configuration, these ES even show an overall positive trend that is in net contrast with the negative one revealed by the complete model (ΔDir aggregated indicator). Additionally, both the configurations lacking either the ecological feedbacks or the ES side effects (NO_EcoFeedbacks and NO_ES_sideEffects) fail to capture the negative trend of the provisioning ES, that is related to the deterioration of the ecological conditions occurring under this scenario. By comparing the NO_EcoFeedbacks and NO_ES_sideEffects configurations, it appears that the second deviates from the complete model more than the first, suggesting that the consideration of social aspects (such as human activities and their side effects) is crucial to understand the system behavior. Overall, neglecting the interactions among ES (NO_ALL configuration) would lead to a radically different interpretation of the BAU scenario, which could be misleadingly thought to have relatively acceptable consequences for the multiple ES provided by the lagoon.

The effect of excluding the ES interactions is less pronounced under the CC_MOSE scenarios. This was expected, as these scenarios produce direct impacts on all the resource systems, and thus directly affect all the ES, whose resulting trends can be broadly detected also by a model that considers them separately. However, it should be noted that the exclusion of the ecological feedbacks (NO_EcoFeedbacks configuration) leads to quite different results for the provisioning ES: these ES are only very marginally reduced, and their negative trend does not increase with more severe scenarios, as instead indicated by the complete model. This suggests that failing to include the ecological feedbacks leads to a model that is not fully capable to capture the increasingly severe consequences of the drivers of change. Additionally, differently from what observed under the BAU scenario, in this case the model results seem to be more sensitive to the lack of ecological feedbacks, with respect to the lack of ES side effects.

Overall, the simulations under the four scenarios show that the results are remarkably different if the ES interactions are neglected, and in particular, that the interactions deriving from both social and ecological aspects are of crucial importance for understanding the potential effects of drivers of change (and management actions) on the system.

3.4. Discussion

3.4.1. Modeling approach

Within the vast panorama of ES models, the dynamic representation of ES has been identified as one of the crucial research frontiers in ES modeling research (Bennett et al., 2015; Rau et al., 2018; Rieb et al., 2017). To overcome these limitations, new tools are needed that are capable to simulate, in a dynamic way, the mechanisms that produce the relationships between ES (Bennett et al., 2015; Rieb et al., 2017), i.e. interactions among ES and effects of drivers on multiple ES (Bennett et al., 2009; Spake et al., 2017). This is the direction in which the innovative elements of our modeling approach are going.

First, the model includes the social and ecological elements involved in the provision of multiple ES, which are selected and organized based on the SES framework (McGinnis and Ostrom, 2014; Ostrom, 2009). The SES framework helps in the identification of variables and processes that are relevant for the analysis, which is the first and very challenging step as it requires simplifications and abstractions to be made (Schlüter et al., 2014). According to Bennett et al. (2009), an integrated social-ecological approach is the basis for a better understanding of ES relationships. On these regards, our results show that, from a modeling perspective, the inclusion of ES interactions deriving from both a social and ecological perspective is crucial for capturing the ES trends caused by different drivers of change. On the one hand, this underlines the limits of the modeling tools that consider the ES separately, such as the widely used InVEST (Sharp et al., 2014; Tallis and Polasky, 2009), that consists in a suite of models, each of which assesses a single ES. On the other hand, it highlights the need to further develop modeling tools that explicitly incorporate the interactions among ES. Adopting a social-ecological perspective from the very first steps of model development is crucial on these regards, as it facilitates the recognition of the interactions among ES, and subsequently, their implementation in the model. In our work, the social-ecological viewpoint proposed in Chapter 2, and in particular the distinction between direct and mediated ES, provided a useful baseline for the identification of the different ways in which ES interact, and their incorporation in the model.

Second, the model is structured as a single network of multiple ES, that emerge from the dynamic interactions (processes, functions, activities) occurring between the elements of the SES. The bipartite structure of Petri nets is well suited for this scope, as it alternates places (representing the different elements of the system) with transitions (representing the interactions between these elements). This network of ES behaves dynamically according to the rate functions that are associated to the transitions. The definition of rate functions is a very challenging step, as it requires a substantial simplification of complex processes and makes explicit the assumptions about the causal relationships between the variables involved (Schlüter et al., 2014). Finally, drivers of change, such as climate change and increasing tourism, act upon this model structure by producing changes in the SES resources and actors, which in turn generate the dynamic response of the whole set of interacting ES. In this way, the model captures both types of mechanisms that, according to Bennett et al. (2009), produce the relationships between ES, that is, interactions among ES and effects of drivers on multiple ES, and can thus represent the trends of multiple ES over time.

In addition, the dynamic features of the model allow to simulate the effects of management actions on the system. The evaluation of these actions requires the definition of objectives and performance measures (Martinez-Harms et al., 2015), which can be calculated based on the model outputs. These measures can be used to assess the improvements generated by different management options, and thus to prioritize the actions based on their effectiveness. Despite its potential usefulness for decision making, prioritization of management actions is still poorly addressed by ES studies (Martinez-Harms et al., 2015). In this work, the sum of the variations of direct and mediated ES (*sensu* Chapter 2) were used to evaluate the performance of the management options, the objective being the compensation of the negative effects of BAU and CC scenarios on these indicators. The distinction between direct and mediated ES is used here to keep track of the trends of ES that spontaneously arise from ecosystem functions and do not generate negative effects (direct ES), and of ES that could produce side effects due to the human inputs involved (mediated ES). The sum is indeed a very basic way of aggregating multiple ES, as all ES are considered to have the same importance within each indicator, but represents a first step of analysis.

A major limitation of the current model application is the related uncertainty. The uncertainty of our model mainly lies in the aggregation of variables and in the simplification of the represented processes. This is a consequence of the focus on multiple ES and their interactions, that increases the overall complexity of the model. This aspect was addressed by structuring the model in a way that all the processes are characterized by a similar degree of simplification and by repeatedly checking for an overall consistent model behavior during model development. Although the model is not calibrated, the sensitivity analysis shows overall ecologically sound results, with no illogical responses and a relatively low sensitivity to variations of input data. As a result, the model can be considered quite reliable in the representation of the broad trends produced by the drivers of change and management options, but should not be expected to provide quantitative ES predictions. Therefore, the model should be intended as an exploratory modelling tool, focused on understanding the general system’s behavior and trends under different “what-if” scenarios.

3.4.2. Case study application

The application to the Venice lagoon case study provides an example of the potential of this tool to investigate future trends of multiple ES, and to evaluate and prioritize potential management options. Four main take-home messages emerge from this application:

1) **The BAU scenario is unsustainable**. The increasing tourism pressure, combined with the decline of residents and the progressive salt marsh degradation result in a decreasing trend of most regulating, provisioning and cultural ES. Climate change then acts making these trends more severe, exacerbating a situation which is already compromised. Therefore, management strategies cannot focus only on climate change adaptation but need to address, at the same time, the negative trends that are occurring under the BAU conditions.
2) **The complex situation requires an integrated management approach**. The model outcomes call for a holistic management of environmental resources, or “ecosystem approach”, as defined in the UN Convention of Biological Diversity (see also Borja et al., 2016; Elliott, 2014, 2011), that is, a management approach that integrates management actions in diverse sectors for a common aim: maintaining the functioning of the system and the benefits it delivers to society. In fact, as the model shows, none of the management options tested, individually, is capable to counterbalance the negative trends observed in any of the scenarios. When multiple ES are modeled simultaneously, and combined to set management targets, the ineffectiveness of sectorial management is powerfully highlighted, and, in particular, the combination of multiple management actions emerges as the only way to balance the negative ES trends in the modeled system.

3) **Habitats' conservation and restoration is of primary importance for the provision of multiple ES in the lagoon SES**. Among the additional management options having, individually, the greater effects, it appears that those targeted to habitat maintenance are promising better outcomes than those aimed at limiting the environmental pressures insisting on the system, except for tourism control. This suggests that the ecological elements of the systems are crucial for maintenance of the ecological processes and functions, and for the delivery not only of regulating ES but also of provisioning and cultural ones.
4) **Multiple management options are needed that combine different types of intervention, to be enforced now.** If on the one hand the MOSE system plays a crucial role in maintaining cultural heritage and tourism in the face of climate change, and has a generally positive effect on the other mediated ES, on the other hand, it seems to exacerbate the decline of regulating ES, thus requiring to be combined with other interventions. The type of combination required depends on the scenario: the more severe the scenarios tested, the more complex the set of management options needed to offset the negative effects on ES. Considering the uncertainties on how climate change will evolve, the precautionary principle should be applied, and thus the management solutions that are effective in the worse scenario should be preferred. It should be noted that, although scenarios have a time span of decades, the implementation of management actions should start now, to gradually contribute to make the system more resilient, in the face of potential extreme scenarios. From the outcomes of the model, the most effective outcomes are obtained through conservation and restoration of crucial habitats (seagrasses and salt marshes or benthic diatoms), combined with a reduction of tourism. Tourism indeed plays a controversial role, being on the one hand the main economic engine of the area, and on the other, a major pressure on the other ES. If maintaining the provision of multiple ES

over time is taken as management priority, it appears necessary to enforce some control over tourism to balance the loss of other ES under CC scenarios.

An interesting field of application of the tool here proposed could be the implementation of the Ecosystem Approach to transitional water management. In particular, at present, a challenging issue is represented by the implementation of the Water Framework Directive 2000/60/EC (Voulvoulis et al., 2017). Indeed, it is not completely clear how to pass from the monitoring of the ecological status, based on biological quality elements, to the implementation of efficient management strategies to recovery from bad/scarce conditions. In this context, the management of multiple ES, which depend on the ecological status but also produce feedbacks on it, supported by a modeling tool capable to capture these feedbacks, could provide a new perspective for shifting from monitoring to implementation. This could be particularly helpful in highly co-evolved environments, as the Venice lagoon, allowing to produce simulations about possible effects of different management options.

3.5. Conclusions

This paper presents a new approach for the dynamic modelling of multiple ES provision, developed using the Petri net modeling framework. Three key characteristics of the model are of crucial importance for the representation of multiple ES' dynamics:

1) the model is structured as a single, complex network that provides a joint representation of the different ES provided by the system. The bipartite structure of Petri nets, that alternates places (elements of the system) and transitions (processes, functions, activities) proved to be well suited for this scope;
2) the SES perspective plays a crucial role for the model development, for the identification of the social and ecological elements and processes involved in the provision of the different ES, and for the identification of the different ways in which these ES interact. In this work, the SES viewpoint proposed in

Chapter 2, and in particular, distinction between direct and mediated ES, has provided a good foundation for the representation of interactions among ES. Failing to include the ES interactions in the model remarkably affects the results;

3) the model's structure can be customized to include the effects of drivers of change on ES. In the case study application, the core structure of the model, that represents the multiple ES, has been expanded to incorporate the potential effects produced by different drivers of change on the SES resources and actors, which are then reflected by changes in ES provision.

The first explorative application to the Venice lagoon case study suggests that most ES are declining under the BAU and CC scenarios, with a major trade-off between tourism and the other ES. The functioning of the MOSE system does not seem to be sufficient to compensate this decline, and requires to be combined with other interventions, among which those aimed at habitats' conservation and restoration seem to be the most effective. The major advantage of a model that jointly represents multiple ES is that it can be used to simulate the effects of very different management actions on the whole set of regulating, provisioning and cultural ES. Although being less accurate than discipline-specific models, it considers a wide range of direct and indirect implications that would not emerge from models focused on single ES, and can thus be a precious support for the definition of integrated management strategies.

This first version of the model leaves the floor open to several improvements and further steps. First, the "ES use" step of the general structure in Figure 3 could be used to model the ES demand by stakeholders, which is indeed another crucial frontier for ES models (Rieb et al., 2017). This would allow to investigate the ES synergies and trade-offs that are related to their use, e.g. concurring or conflicting use (Mouchet et al., 2014). Second, concerning the Venice lagoon case study, the application presented here could be upgraded to a numerically more realistic model, possibly moving towards a more operational tool. As data about several input variables and parameters are lacking, the model should be fed with a combination of available data and expert-based inputs. Third, the model could be used to prioritize management options with respect to more detailed management targets. More specific targets could imply a prioritization of some ES over others and/or the definition of specific thresholds of ES provision. This could be obtained from a deeper SES analysis that connects ES with specific dimensions of human well-being (Reyers et al., 2013), and/or from the collection of stakeholder preferences (Martinez-Harms et al., 2015). Overall, although still in its development phase, this modeling approach can hopefully contribute to generate new perspectives for the dynamic modeling of ES and can be the starting point for more advanced applications aimed at actively supporting the integrated management of social-ecological systems.

Chapter 4

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.

4.1. 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., 2012a). 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 (Chapter 2), 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), and the mapping and analysis of how multiple ES are co-produced within social-ecological systems (Bennett et al., 2015; Meacham et al., 2016b; Queiroz et al., 2015; Raudsepp-Hearne et al., 2010a). 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.

4.2. Material & Methods

4.2.1. 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 12), based on a combination of hydrological descriptors, existing pressures and chemical and ecological state. The water bodies

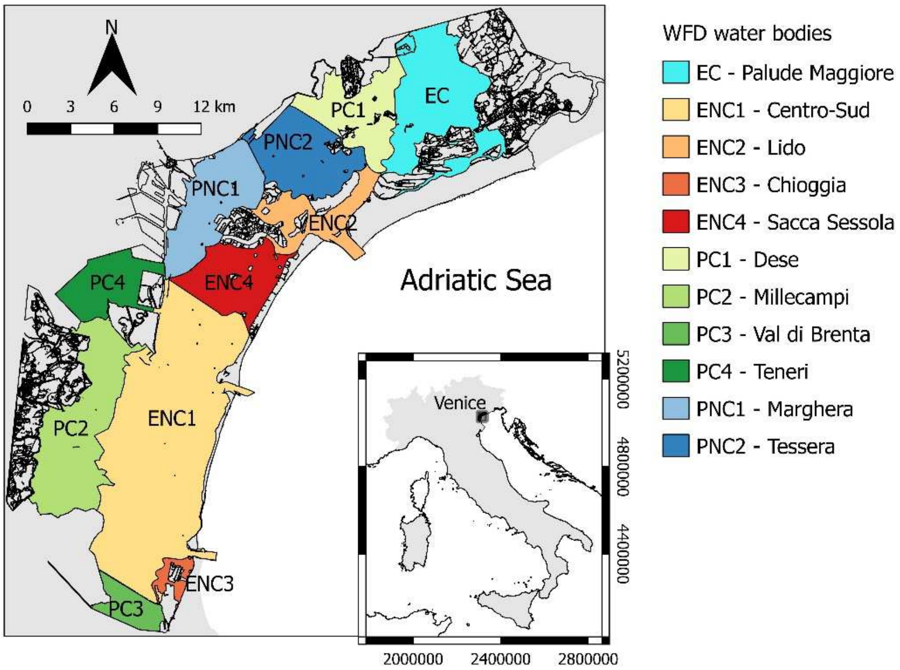

Figure 12. Venice lagoon (Italy) study area, subdivided into 11 water bodies defined in compliance with the Water Framework Directive. The heavily modified water bodies are not shown. Abbreviations: EC= euryhaline confined; ENC=euryhaline not-confined; PC=polyhaline confined; PNC=polyhaline not-confined.

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 12 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, 2018b). 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.

4.2.2. Ecosystem services mapping

A set of 13 ES has been mapped in the VL using quantitative biophysical indicators (Table 11. The ES have been selected based on Rova et al. (2015) and Chapter 2, 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 11. 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 12). 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).

Table 11. 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).
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).

Ecosystem service	Flow type	Indicator	Unit	Methods and data sources
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.

4.2.3. Ecosystem services modeling in water bodies

4.2.3.1. 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 in Chapter 3 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 (*sensu* Chapter 2): 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 11). 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.

4.2.3.2. 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 11), 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 11). 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).

4.2.4. 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* Chapter 2, Table 11), 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).

4.3. Results

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

The spatial distribution of ES in the VL water bodies is presented in Figure 13. 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 14) 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 15). 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 15) 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

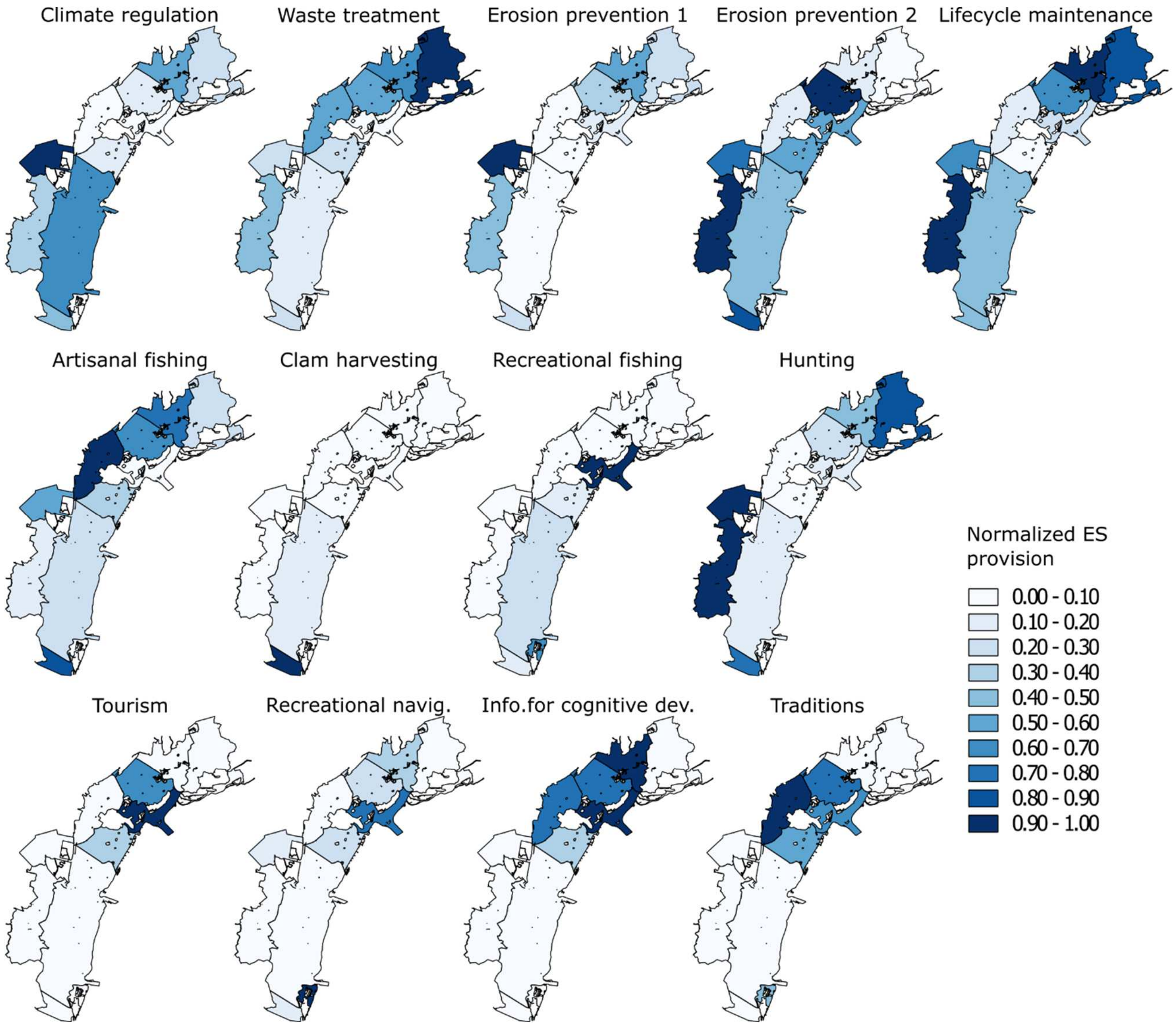

Figure 13. Maps representing the spatial distribution of each ES (top row: regulating ES; middle row: provisioning ES; bottom row: cultural ES). in the Venice lagoon water bodies. The level of ES provision has been normalized on a 0-1 scale.

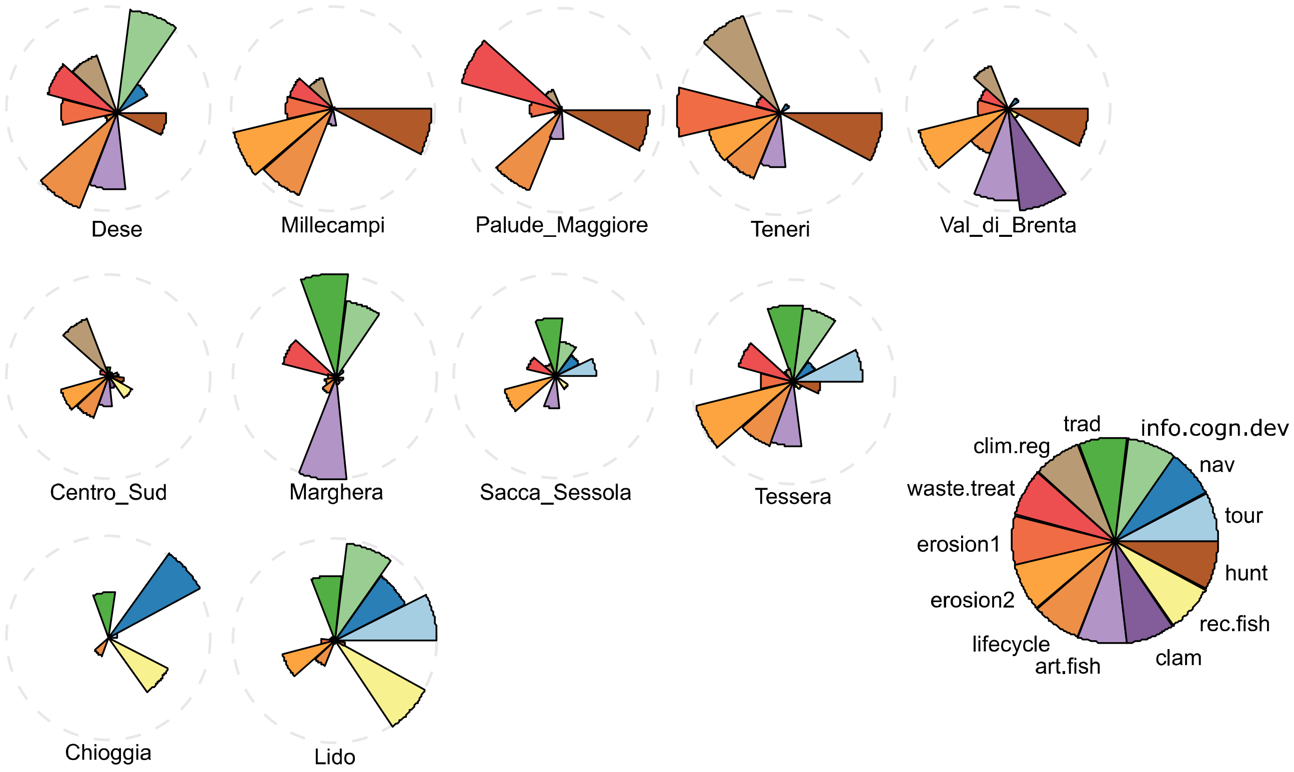

Figure 14. Star plots representing the pattern of multiple ecosystem services (ES) in each water body (top row: confined water bodies; middle and bottom rows: not-confined water bodies). The length of the sectors in each star represents the provision of the corresponding ES, according to the legend on 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.

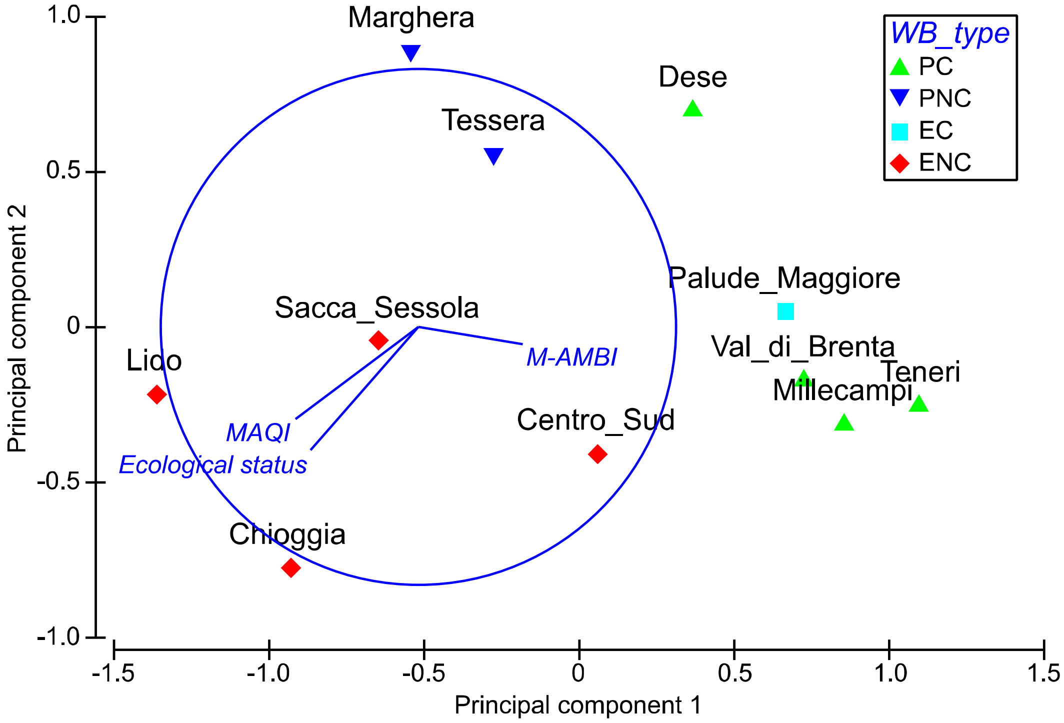

Figure 15. Plot of the Principal Component Analysis of the patterns of multiple ecosystem services in the Venice lagoon water bodies. The blue vectors represent the correlation (Spearman's rho) between the WFD biological quality elements (and overall ecological status) and the ordination axes, the blue 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).

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 14). 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 16. 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.

4.3.2. 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 17A. 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

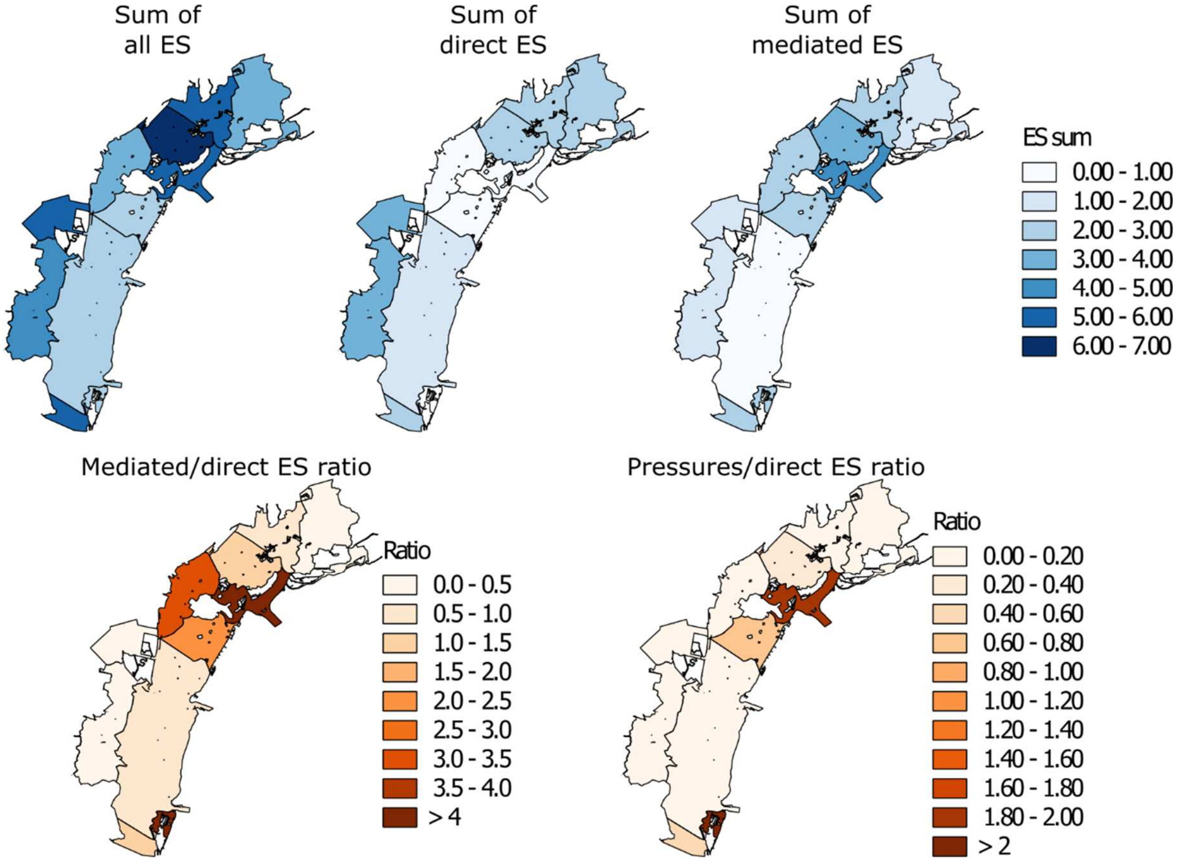

Figure 16. Spatial distribution of the aggregated ecosystem services (ES) indicators.

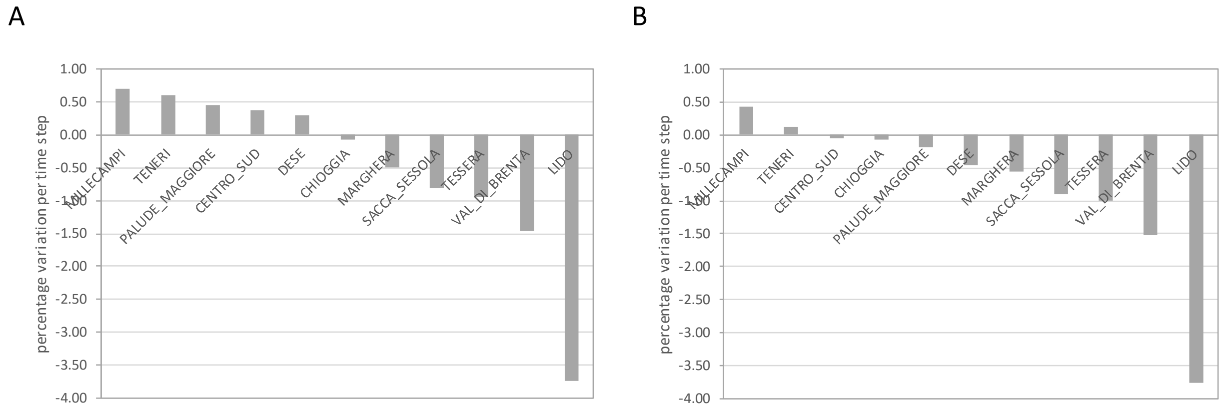

Figure 17. ES trends resulting from the models' simulations under the BAU and CC scenarios (A and B respectively). The results are expressed as average of all ES trends, expressed as percentage variation per time step, with respect to the initial conditions.

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 17B), 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.

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

Table 12 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

Table 12. 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	$0.54^{\dagger}$		-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	

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 15).

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.

4.4. Discussion

4.4.1. 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., 2016b; Queiroz et al., 2015; Raudsepp-Hearne et al., 2010a; 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., 2010a; 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 15). 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 (Chapter 3). 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.

4.4.2. 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 15), 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.

4.5. 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.

Chapter 5

Conclusions

This dissertation focuses on the integrated analysis, modeling and management of the multiple ecosystem services (ES) delivered by social-ecological systems, in a context of changing climate. Innovative contributions to this field are proposed through a path that starts from the conceptualization of a new social-ecological viewpoint for the analysis of multiple ES (Chapter 2), makes this viewpoint operational from a modeling perspective (Chapter 3) and finally shows how this approach can find application in the management environmental resources, within a context of climate change (Chapter 4). The main outcomes of the dissertation can be summarized by taking up the objectives outlined in section 1.2.

The **first objective** is the development of a theoretical approach for the analysis of multiple ES from a social-ecological perspective, considering both the ecological and social inputs involved in the delivery of ES and the way multiple ES interact. This objective has been tackled in Chapter 2, in which the social-ecological systems framework *(sensu* McGinnis and Ostrom, 2014; Ostrom, 2009) has been applied to the analysis of multiple ES through the development of a new conceptual viewpoint. The core of this viewpoint consists of two “ES production and use chains”, developed using the core variables of the social-ecological systems framework, that describe two possible ES flow types, “direct” and “mediated”. These two flow types differ by the involvement of actors’ activities as crucial factors of service delivery: in case of direct ES, the flow depends on ecological functions with no need of human interventions; in case of mediated ES, the flow necessarily occurs through human activities, that can produce negative feedbacks on the exploited resources and on other ES. This viewpoint allows to classify ES based on the involvement of social-ecological variables in their delivery, and thus based on the dominating flow type: in general, regulating ES are characterized by a direct flow type, whereas provisioning and cultural ones can be classified as mediated flow type ES. The application of this conceptual viewpoint to the Venice lagoon case study has led to the identification of the social-ecological variables (resource systems and units, actors, and governance system) that concur to the delivery of the set of multiple ES provided. This analysis allows to frame the contribution of social "actors" to the provision of ES, and facilitates a process-based understanding of the interactions between ES, through the representation of cause-effect relationships between and within social and ecological elements and processes of the system. As underlined by Costanza et al. (2017), the delivery of ES is the result of complex interactions and feedbacks between natural and human capital, which require a dynamic systems' perspective of analysis. The viewpoint and applications proposed in this dissertation provide a contribution in this direction, towards an analysis and modeling of multiple ES based on an integrated and systemic framework.

The **second objective**, that is, the development of a new approach for the dynamic modeling of multiple ES and their interactions under climate change scenarios, has been achieved by translating the conceptual viewpoint into a new dynamic ES model (Chapter 3). The modeling approach is based on the main idea that '*direct ES*' can be modeled as the output of ecological functions, whereas '*mediated ES*' as the outcome of human activities performed by actors, that exploit resources of the system; the last can produce negative externalities on other system elements and resources, and have to be regulated by the governance system. This relatively simple architecture, if applied to the whole set of 13 ES delivered by the Venice lagoon social-ecological system, results in a complex network of services. The integration of multiple ES in a single network makes this model different respect to other ES models available in literature, such as the widely used InVEST (Sharp et al., 2014; Tallis and Polasky, 2009), which consists in a suite of modeling tools, each addressing a single ES independently from the others. Differently from these types of models, which provide a static snapshot of single ES, the model here proposed allows the dynamic simulation of the evolution of multiple ES supply over time, that takes into account the interactions occurring among ES. Furthermore, ecological, social and climatic drivers of change act upon the ES network by producing changes in the SES resources and actors, which in turn generate the dynamic response of the whole set of interacting ES. This modeling approach, because of its integrated nature, implies that the processes are represented with a substantial degree of simplification. This means that it cannot be expected to provide the accurate ES predictions that can be obtained with more detailed sectoral models targeting single ES (Rieb et al., 2017). Further work could be done to improve the model performances, such as a deeper study of the interactions between services and of the underlying processes, through the assessment of historical ES changes (Renard et al., 2015; Tomscha et al., 2016), and the incorporation of expert-based inputs, which would allow to move towards a more quantitative calibration of the model. Nevertheless, the current model could be considered a significant step forward, in comparison with the state of the art, in terms of integration of multiple ES, and capacity to capture effects that different types of drivers (e.g. climate change and social dynamics) can produce on the overall set of ES and their delivery. A main take home message that emerges from the simulations presented in Chapter 3 is that if the various types of interactions among ES are excluded from the model, the resulting trends for the overall set of ES are remarkably different (e.g. overall positive rather than negative ES trends in the BAU scenario). This means that if we are seeking a realistic (though simplified) representation of the system' behavior, we have to account for the complex feedbacks occurring between the elements of the system.

The **third objective** is to analyze the spatial and temporal patterns of multiple ES from a sustainability perspective. This objective brings the focus on the analysis of the multiple ES provided by the Venice lagoon, and has been addressed in Chapter 4. This Chapter, building upon the conceptual viewpoint and the modeling approach proposed in the previous Chapters (2 and 3), contributes to advance towards more operational applications of the ES concept, by discriminating between sustainable and unsustainable ES patterns and by outlining possible management trajectories. The spatial analysis of multiple ES, which have been quantitatively mapped across the lagoon's water bodies, has been coupled with an application of the model that evaluates potential ES trends at the water body scale. The combined assessment and modeling of multiple ES has proved to be a promising way to identify the sustainable and unsustainable ES patterns, and the conceptual viewpoint of Chapter 2 provided an interesting key for the interpretation of these patterns. Under business-as-usual (BAU) conditions, the ES patterns of not-confined water bodies show negative temporal trends and are characterized by a dominance of mediated ES over direct ones; on the other hand, the ES patterns in confined water bodies show positive trends, associated to a general dominance of direct ES with respect to mediated ones. The MED/DIR ratio (ratio between mediated and direct ES) is proposed as an aggregated indicator that allows to compare the current ES patterns in terms of sustainability. In particular, a critical threshold has been found for the MED/DIR indicator under BAU conditions in the Venice lagoon, that discriminates between sustainable and unsustainable patterns in the VL: MED/DIR ratios higher than one correspond to patterns with negative trends, lower ratios correspond to sustainable patterns. What happens if the effects of climate change are considered? The results suggest that climate change undermines the capacity of the ecosystem to provide ES, turning unsustainable also those patterns that showed a sustainable trend under BAU conditions.

The **fourth objective** is the exploration of the role that multiple ES analysis, moving from a sustainability perspective, can play in the implementation of ecosystem-based management strategies (as the EU Water Framework Directive -WFD). As discussed in Chapter 4, the steps of the path traced in this dissertation lead to new insights on how ES can be used in concrete environmental management challenges. With respect to the WFD, the current standstill in the directive's implementation in the Venice lagoon is reflected by the rather contrasting relationships found between the ES patterns and the ecological status. A negative relationship was found between the overall ecological status classification and ES (and especially direct ES), and, if the metrics that concur to define it are considered separately, they show a remarkably different behavior: M-AMBI generally increases with more sustainable ES patterns whereas MAQI is higher in water bodies with unsustainable ES patterns. This suggests that the way the ecological status is currently defined in the VL might not be adequate, and that this inadequacy can be at the root of the current impasse in the WFD implementation. The normative judgement of ES patterns based on a sustainability perspective is aligned with the “systemic” meaning of ecological status, both pointing at uncompromised ecological functioning and reduced anthropogenic pressures. Therefore, the results of this dissertation suggest two possible contributions of the ES analysis in the context of the WFD implementation: (i) ES analysis can support the definition and choice of meaningful indicators of ecological status that positively resonate with sustainable ES patterns. Further advancements in the sustainability analysis of ES could lead to the definition of aggregated ES indicators to be directly used ecological status’ metrics; (ii) ES analysis can support the definition of management trajectories that point at obtaining a good ecological status through the management of unsustainable ES patterns. First indications concerning possible management trajectories emerge from the analysis carried out in Chapter 4. The water bodies of the Venice lagoon require management strategies that (i) “correct” the unsustainable ES patterns, and (ii) allow to preserve the ES delivery in the face of climate change. In order to make ES sustainable in the long-term, the provision of direct and mediated ES has to be balanced in favor of direct ES. This can be achieved by controlling/reducing the human activities that produce pressures on the system, balancing the provision of direct and mediated ES such that the latter are no longer dominating the ES patterns. These type of interventions, by preserving the functioning of the ecosystem, would contribute to the achievement of a good ecological status in the water bodies characterized by unsustainable ES patterns (not-confined areas). On the other hand, maintaining the ES delivery in a climate change context requires precautionary interventions aimed at preserving the ecological functioning. These interventions are needed also where the ES patterns per se do not produce unsustainable pressures, such as in the confined water bodies of the Venice lagoon. Therefore, from a climate change adaptation perspective, protection and restoration of most vulnerable habitats is necessary to increase the resilience of the system in the face of climate change, and to preserve its processes, functioning, and long-term delivery of ES.

To sum up, the following recommendations can be drawn:

- A consistent conceptualization of ES should be used throughout the assessment, modeling and analysis of ES. The social-ecological systems framework applied to the analysis of multiple ES (Chapter 2) provides a solid backbone from the conceptual analysis to the modeling to the definition of management strategies.
- Modeling tools such as that presented in this dissertation (Chapter 3), that incorporate the way ES interact, and the effects of drivers of change, are needed for a representation of the behavior of complex social-ecological systems and their ES provision.
- A normative interpretation of ES according to the goal of sustainability (Chapter 4) is a crucial step for the application of ES to management challenges also within a climate change context.

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Appendix A

Additional model description (Appendix to Chapter 3)

A.1. Ecosystem services subnets

A.1.1. Regulating ES

Climate regulation. The climate regulation ecosystem service (ES) depends on two types of habitat, salt marshes and seagrasses, characterized by capacity to sequester organic carbon in the medium-long term (Barbier et al., 2011). Each of these habitats generates a carbon sequestration function ("eco_function" transition in Table A1, with parameters k_0_0_eco_function for salt marshes and k_1_0_eco_function for seagrasses) which contributes to the total amount of carbon sequestered. Based on literature (Day, 1998; Roner et al., 2015; Sfriso et al., 2007, 2004; Sfriso and Facca, 2007; Sfriso and Ghetti, 1998) a higher sequestration capacity has been assigned to salt marshes, compared to seagrasses.

Waste treatment. The waste treatment ES depends on all types of submerged habitats, that is, seagrasses, bare (intertidal), benthic diatoms and macroalgae. Bottom habitats' direct denitrification rate (that is, denitrification supported by nitrate from the water column) depends on various factors, including water residence time (Seitzinger et al., 2006), nitrate concentration in the water column (Fennel et al., 2009; Svensson et al., 2000), oxygen penetration in sediments (Fennel et al., 2009; Svensson et al., 2000), and sediment bioturbation (Svensson et al., 2000). In the model, each of the submerged habitats is characterized by a denitrification function ("eco_function" transition in Table A1, with parameters k_1_1_eco_function, k_2_1_eco_function, k_3_1_eco_function and k_4_1_eco_function for seagrasses, bare (intertidal), benthic diatoms and macroalgae, respectively), each of which contributes to the total amount of nitrate that is denitrified by the lagoon ecosystem. Bare (intertidal) and benthic diatoms habitats have been assigned a higher denitrification rate than seagrasses and macroalgae habitats, following the findings reported by Svensson et al. (2000), which reflect the distribution of above mentioned factors among the lagoon's habitats.

Erosion prevention 1. The erosion prevention 1 ES consists in the wind fetch reduction by salt marshes, that reduces the wind-driven erosion. In fact, wind-produced bed shear stress increases with fetch length (Fagherazzi et al., 2006), and thus the presence of salt marshes reduces the open water surfaces over which the wind blows, contributing to the protection of bottom sediments from wind-driven erosion (Rova et al., 2015). This ES thus depends on a single type of habitat (salt marshes) and on a single function, wind fetch reduction ("eco_function" transition in Table A1, with k_0_2_eco_function parameter), which determines the area in which salt marshes provide a sheltering effect with respect to wind driven erosion.

Erosion prevention 2. The erosion prevention 2 ES depends on the vegetated submerged habitats, that is, seagrasses, benthic diatoms and macroalgae, that are characterized by the capacity to biostabilize the bottom sediments, making them less prone to erosion (Amos et al., 2004). Each of these habitats generate a biostabilization function ("eco_function" transition in Table A1, with parameters k_1_3_eco_function, k_3_3_eco_function and k_4_3_eco_function for seagrasses, benthic diatoms and macroalgae, respectively) that concur to determine the total erosion prevention capacity of the lagoon system. Based on Amos et al. (2004), the biostabilization capacity is higher for seagrasses, intermediate for benthic diatoms and lower for macroalgae.

Lifecycle maintenance. The lifecycle maintenance ES consists in the role of lagoon's habitats as nursery areas for different species of ichthyofauna and avifauna. It thus depends on all the types of habitats, each contributing with a specific nursery function ("eco_function" transition in Table A1, with parameters k_0_4_eco_function, k_1_4_eco_function, k_2_4_eco_function, k_3_4_eco_function and k_4_4_eco_function for salt marshes, seagrasses, bare (intertidal), benthic diatoms and macroalgae, respectively) to the overall nursery role of the lagoon. Based on Franco et al. (2006b, 2006a), a higher contribution has been assigned to salt marshes and benthic diatoms, followed by bare (intertidal) and seagrasses, and finally macroalgae.

A.1.2. Provisioning 1 ES

Artisanal fishing. The artisanal fishing ES refers to the fishing activities carried out with traditional gears, mainly gillnets and fish traps. This ES depends on target fish species, and the activity ("activity_prov1ES" transition in Table A1, with k0_effic parameter) is performed by artisanal fishermen under the control of the artisanal fishing management field.

Recreational fishing. The recreational fishing ES refers to the fishing activities carried out for recreational purposes. This ES depends on target fish species, and the activity ("activity_prov1ES" transition in Table A1, with k1_effic parameter) is performed by recreational fishermen under the control of the recreational fishing management field.

Artisanal and recreational fishing ES harvest the same resource unit, and thus are in direct competition. In relative terms, fish catches from recreational fishing ES have been set to be less than half of those from artisanal fishing (Table A2).

Hunting. The hunting ES refers to the harvest of birds through recreational hunting activities. This ES depends on birds, and the activity ("activity_prov1ES" transition in Table A1, with k2_effic parameter) is performed by hunters under the control of the hunting management field.

A.1.3. Provisioning 2 ES

Clam harvesting. The clam harvesting ES refers to the harvest of clams carried out with highly impacting mechanical gears. This ES depends on clams, and the activity ("activity_prov2ES" transition in Table A1, with k_clamH parameter) is performed by clam fishermen under the control of the clam harvesting management field. Due to the highly impacting fishing gears used, this activity produces different negative externalities on the system: it damages the seagrasses and benthic diatoms habitats, enhances channels' siltation and disturb the lagoon nursery function (lifecycle maintenance ES) (Pranovi et al., 2004, 2003). These negative externalities are modeled as a consumption of these elements, that occurs in parallel to the activity, and whose magnitude is expressed by the respective arc weights (see weights referred to the activity_prov2ES in Table A4).

A.1.4. Cultural 1 ES

Information for cognitive development. The information for cognitive development ES refers to the environmental education activities taking place in the lagoon. This ES depends on the natural attractiveness (represented by all types of habitats, whose relative contribution is defined by the w_Edu parameters), cultural attractiveness (represented by the density of cultural heritage) and accessibility (represented by channels). The relative importance of these three components is defined by the nat_attr_Edu, cult_attr_Edu and accessib_Edu parameters and it has been assumed to be higher for cultural attractiveness, intermediate for natural attractiveness and lower for accessibility. The activity ("activity_cult1ES" transition in Table A1) is carried out by the users of environmental education activities.

Traditions. The traditions ES refers to traditional rowing and sailing activities, whose practice is strongly linked with the traditional knowledge that originates from the tight relationship between man and lagoon in the past centuries. As the information for cognitive development, this ES depends on the natural attractiveness (represented by all types of habitats, whose relative contribution is defined by the w_Trad parameters), cultural attractiveness (represented by the traditional knowledge) and accessibility (represented by channels). The relative importance of these three components is defined by the nat_attr_trad, cult_attr_trad and accessib_trad parameters and it has been assumed to be higher for cultural attractiveness, intermediate for natural attractiveness and lower for accessibility. The activity ("activity_cult1ES" transition in Table A1) is carried out by residents.

A.1.5. Cultural 2 ES

Tourism. The tourism ES refers to the tourist activities carried out the lagoon. As cultural 1 ES, it depends on the natural attractiveness (represented by salt marshes habitats), cultural attractiveness (represented by the density of cultural heritage) and accessibility (represented by channels). The relative importance of these three components is defined by the nat_attr_Tour, cult_attr_Tour and accessib_Tour parameters and it has been assumed to be higher for cultural attractiveness, intermediate for natural attractiveness and lower for accessibility. The activity ("activity_cult2ES" transition in Table A1) is carried out by tourists under the control of tourism management field. The intensive navigation activities through which visiting occurs produce different negative externalities on the system: they damage salt marshes, seagrasses, bare (intertidal) and benthic diatoms habitats and enhances channels' siltation. These negative externalities are modeled as a consumption of these elements, that occurs in parallel to the activity, and whose magnitude is expressed by the respective arc weights (see weights referred to the activity_cult2ES in Table A4).

A.1.6. Cultural 3 ES

Navigation. The navigation ES refers to navigation in the lagoon using leisure boats. It mainly depends on channels, is carried out by boat owners and is controlled by the navigation management field. Like tourism, the navigation activities produce negative impacts on salt marshes, seagrasses, bare (intertidal), benthic diatoms and channels. These negative externalities are modeled as a consumption of these elements, that occurs in parallel to the activity, and whose magnitude is expressed by the respective arc weights (see weights referred to the activity_cult3ES in Table A4).

A.2. Underpinning ecological and social processes

A.2.1. Habitats

For each habitat type, an eco_process transition (Table A1) is defined, with a habitat-specific k_eco_process parameter (Table A3) which is modulated by the deviation of fauna (target fish species and birds) from the initial conditions. Habitat maintenance ("maintenance" transition in Table A1) is possible for all habitat types, but in steady-state conditions occurs for salt marshes only (see governance system's marking in table A2).

Salt marshes habitats are degraded in equal proportion by tourism and navigation ES. The arc weights representing this degradation are defined such that the total consumption under steady-state conditions is 0.8 percent/year. Under steady state, this consumption is balanced by a generation rate equally divided between the ecological process ("eco_process" transition in Table A1, with k0_eco_process parameter) and the salt marsh maintenance by the governance system. This reflects the real situation, in which, due to the lack of sufficient sediment inputs in the lagoon, the ecological processes alone are not sufficient to compensate the salt marshes degradation.

Seagrasses, bare (intertidal) and benthic diatoms habitats are degraded by tourism, navigation and clam ES (this latter ES does not affect bare (intertidal) habitat). The arc weights representing this degradation are defined such that the total consumption under steady-state conditions is between 0.8 and 0.9 percent/year for each of the three habitats. Under steady state, this consumption is balanced by the habitats' ecological process ("eco_process" transition in Table A1, with k1_eco_process, k2_eco_process and k3_eco_process parameters, for seagrasses, bare (intertidal) and benthic diatoms respectively), assuming that, in an ideal situation such as the steady state, they can potentially compensate the pressures acting upon these habitats.

Macroalgae are not consumed nor generated, assuming a constant state in all scenarios.

Environmental sensibilization ("sensibilization" transition in Table A1) accounts for a responsible behavior of the actors benefiting from the information for cognitive development and traditions ES. In the model, this is translated as an additional generation of habitats proportional to the deviation of these two ES from the initial conditions. It has a rate equal to zero in steady-state.

A.2.2. Channels

Channels' degradation, produced by clam, tourism and navigation ES, is set to 0.9 percent/year in total under steady-state scenario. Under steady-state, channels' self-regulation ("self_reg" transition in table A1 with k_self_reg parameter) is assumed not to be sufficient to compensate this degradation. The maintenance of channels ("dredging" transition in table A1) is necessary to balance the consumption under steady state. Channels' self-regulation is modulated by the deviation of erosion prevention 1 and 2 ES from the initial conditions.

A.2.3. Fauna

The growth of the three "populations" of fauna ("growth" transition in table A1) has been modeled as a logistic population growth. In steady-state, the populations have been set in equilibrium at a level lower than half of the carrying capacity, corresponding to overexploited populations. The effect of the lifecycle maintenance ES on the population growth has been modeled as a modulation of the carrying capacity proportional to the deviation of this ES from the initial conditions.

A.2.4. Actors

Actors growth is set to null under steady state (k_actor parameter). The “actors_growth” transition (Table A1) allows for the specification of increasing/decreasing rate functions for actors under the other modeled scenarios.

A.3. Effects of drivers of change

A.3.1. Drivers of the Business as usual scenario

In the BAU scenario, salt marshes consumption by tourism and navigation is increased by +25% in total (weights in Table A4). In this way, salt marshes’ consumption rate exceeds their generation rate, to reflect the current erosive trends of salt marshes. On the other hand, seagrasses growth rate has been increased by +30% (Table A3), unbalancing the initial rates in favor of generation, reflecting the expansion of seagrasses currently observed in the lagoon.

A decreasing growth function (“actor_growth” transition in table A1 with k0_actors parameter) has been set for residents, at a rate that proportionally reflects the current decline of residents in the historical center of Venice (Comune di Venezia, 2018).

An increasing growth function (“actor_growth” transition in table A1 with k6_actors parameter) has been set for tourists, which proportionally reflects the trend of incoming tourists in the Venice municipality (Comune di Venezia, 2018).

A.3.2. Relative sea level rise

The relative sea level rise (RSLR) scenarios are activated in the model through the RSLR_scenario place. Based on the scenario, the RSLR at each time step (RSLR place) is calculated following a linear increase (“RSLR_rate” transition in Table A1 with k0_RSLR, k1_RSLR and k2_RSLR parameters for the three scenarios respectively).

The effect of RSLR on habitats has been modeled as a transition (“RSLR_effect_HAB”) that consumes seagrasses and intertidal habitats (that is, bare (intertidal) and salt marshes). The rate of consumption increases with increasing RSLR, and is proportionally greater for seagrasses than for intertidal habitats. The negative effect on seagrasses reflects the reduced light availability (Saunders et al., 2013), which is especially relevant for species adapted to confined areas of the lagoon. The negative effects on intertidal habitats reflect the difficulty of these habitats to keep up with the increasing sea level in the context of low sediment availability (Marani et al., 2007), and the observed shift of marshes margins, occurring in agreement with RSLR rate (Rizzetto and Tosi, 2011).

The effect of RSLR on residents reflects the negative effects of increasing inundation rate of urban areas, which occurs during high tide events, which are expected to increase with RLSR (Carbognin et al., 2010). It has been modeled as an additional decrease of residents, proportional to the RSLR.

Moderate levels of RSLR have been assumed to increase the attractiveness of cultural heritage (modeled as an increase of heritage proportional to RSLR (“herit_PLUS” transition in table A1)). The threshold has been set at RSLR +10 cm, level above which every average spring tide would produce the flooding of portions of the historical center of Venice (considering a spring tide amplitude of ±50 cm (Umgiesser et al., 2004)). After this threshold, the effect has been assumed to become negative (“herit_MINUS” transition in table A1), reflecting the damages produced by the increasing flooding.

A.3.3. MOSE system

The activation of the MOSE system is under the control of the “lagoon-sea exchanges” governance system. Once activated, the “closures” transition (Table A1) calculates the yearly frequency of closures (days) as a function of RSLR, according to the trends estimated by Carbognin et al. (2010). A maximum number of closures has been set, equal to 300. Beyond this threshold the exchanges with the sea would be extremely reduced, shifting the system to a sort of coastal lake, whose characteristics can no longer be reproduced by this model.

The activation of the MOSE system by the governance system switches off the effects of RSLR on residents and cultural heritage (see the function for the “RSLR_effect_HAB”, “herit_PLUS” and “herit_MINUS” transitions in table A1), as it prevents the city from flooding.

Due to the reduced water renewal, which is proportional to the frequency of MOSE closures, submerged habitats are expected to be negatively impacted. This has been modeled as an additional loss of bare (intertidal), seagrasses, benthic diatoms and macroalgae (in order of decreasing magnitude of negative effects), proportional to the frequency of MOSE closures (“RSLR_effect_HAB” transition in table A1).

The reduced connectivity between the lagoon and the sea is expected to negatively affect the nursery role of the lagoon (lifecycle maintenance ES, affected by the “lag-sea_exchange” transition), and the reduced water exchanges and the related hydrodynamic changes are expected to affect the channels’ self-regulation capacity (“self_reg” transition in table A1), enhancing siltation processes.

A.3.4. Temperature increase

The temperature increase scenario is activated in the model through the T_scenario place. The temperature increase is calculated in the “T_increase” place for each time step, following a linear increase (“T_rate” transition in Table A1).

The effects of temperature increase have been modeled to be threshold dependent. The overall behavior follows evidences from literature (Bulthuis, 1987; Pranovi et al., 2013; Velez et al., 2017), whereas the thresholds were chosen arbitrarily by the authors, due to the lack of precise information on these regards.

In case of seagrasses, an initial positive effect is modeled as an additional growth of seagrasses proportional to the temperature increase (“T_effect_HAB_PLUS” transition in Table A1). Above a threshold of +0.3 °C, the effect becomes negative, assuming that a higher temperature increase, combined with a reduced light availability caused by RSLR, would become a stress factor for this type of habitat (Bulthuis, 1987). This is modeled as an additional consumption of seagrasses, proportional to the temperature increase (“T_effect_HAB_MINUS” transition in Table A1).

A similar behavior is modeled with respect to clams (“T_effect_FAU_PLUS” and “T_effect_FAU_MINUS” transitions in table A1, with k1_T_FAU_plus and k1_T_FAU_minus parameters respectively), as high values of temperature increase seem to become a stress factor for this species (Munari et al., 2011; Velez et al., 2017).

In case of target fish species, temperature increase has been assumed to have no effects until a threshold of 0.7 °C. This lack of effect reflects the substitution of the less tolerant native species with more thermophilic species, which instead seems to be no longer sufficient at higher values of temperature increase (Pranovi et al., 2013). Above this threshold, the negative effect of increasing temperature has been modeled as an additional consumption of this resource, proportional to the temperature increase (“T_effect_FAU_MINUS” transition in table A1, with k0_T_FAU_minus parameter).

A.4. Additional model configurations (without interactions)

A.4.1. No ecosystem services side effects

This configuration ("NO_ES_sideEffects”) does not include the positive and negative side effects produced by the ES. The modifications implemented to obtain this configuration are the following.

Elimination of the negative effects produced by tourism, navigation and clam ES:

Tourism: the arcs connecting habitats and channels to the “activity_cult2ES” transition were substituted with read arcs.

Navigation: the arc connecting channels to the “activity_cult3ES” transition was substituted with a read arc; the arc connecting habitats to the “activity_cult3ES” transition was removed.

Clam harvesting: the arcs connecting habitats, regulating ES and channels to the "activity_prov2ES" transition were removed.

Elimination of the positive effects produced by information for cognitive development, tradition and erosion prevention 1 and 2 ES:

Information for cognitive development and tradition: the “sensibilization” transition was removed.

Erosion prevention 1 and 2: in the rate function of the “self_reg” transition, the modulation by the erosion prevention 1 and 2 ES was removed; the arc connecting regulating ES to the “self_reg” transition was removed.

With these modifications, the model is no longer in steady state, because the generation of habitats, channels and regulating ES is no longer balanced by consumption. To bring the model to steady state and reproduce the same conditions of the complete model, three new transitions were introduced that consume habitats, channels and regulating ES, respectively, at the same rate as in the complete model.

Similarly, in order to reproduce exactly the same conditions of the complete model under the BAU scenario, the consumption of salt marshes has been increased by +25% when running the simulations.

A.4.2. No ecological feedbacks

This configuration ("NO_EcoFeedbacks") does not include the ecological feedbacks (i.e. fauna influencing the habitats' processes, and lifecycle maintenance ES influencing the growth of fauna). To obtain this configuration, the following modifications were implemented:

In the rate function of the "eco_process" transition, the modulation by fauna was removed; the arc connecting fauna to the "eco_process" transition was removed.

In the rate function of the "growth" transition, the modulation by the lifecycle maintenance ES was removed; the arc connecting regulating ES to the "growth" transition was removed.

A.4.3. No all interactions

To obtain this configuration ("NO_ALL"), the modifications made for the "NO_ES_sideEffects" and NO_EcoFeedbacks configurations were merged.

Table A1. Transitions' rate functions. Abbreviations: HAB, Habitats; FAU, Fauna; CNL, Channels; HER, Heritage; ESR, Regulating ES; ESC, Cultural ES; GS, governance system; A, Actors; T, temperature.

Transition name	Purpose	Rate	Description
eco_function	functions generating regulating ES	$k_{eco\_function} * HAB$	ES-specific and habitat-specific ES generation rate per unit of habitat (k_eco_function)
activity_prov1ES	activity generating artisanal fishing, recreational fishing, hunting	$k_{effic} * A * FAU * GS$	The rate is the product of the exploited fauna by the actors (a simplified proxy of the harvesting effort) by the ES-specific harvesting efficiency (k_effic). The rate is modulated by the governance system.
activity_prov2ES	activity generating clam harvesting ES	$k_{clamH} * A * FAU * GS$	Same rate function as activity_prov1ES. The arc weights (Table A4) express the consumption of the input places associated with the firing of this transition (externalities).
activity_cult1ES	activity generating info for cognitive development and traditions ES	$A * \Big[nat\_attr * \left(1 + \frac{\sum_{i=0}^{4} w_i * (HAB_i - HAB_{t0i})}{\sum_{i=0}^{4} w_i * HAB_{t0i}}\right)$ $+ \ cult\_attr * \left(1 + \frac{HER - HER_{t0}}{HER_{t0}}\right)$ $+ accessib * \left(1 + \frac{CNL - CNL_{t0}}{CNL_{t0}}\right)\Big]$	The rate is directly dependent on actors and it is modulated by changes in the input places that contribute to natural attractiveness (HAB), cultural attractiveness (HER) and accessibility (CNL), respect to their initial conditions (HABt0, HERt0 and CNLt0, respectively), with ES-specific weights for the contribution of each component. All habitats contribute to the natural attractiveness, and this is represented as a weighted sum with ES-specific weights for each habitat (i: colors of HAB, w_i: w_edu or w_trad for each HAB).
activity_cult2ES	activity generating tourism ES	$A * \Big[nat\_attr\_Tour * \left(1 + \frac{HAB - HAB_{t0}}{HAB_{t0}}\right)$ $+ \ cult\_attr\_Tour * \left(1 + \frac{HER - HER_{t0}}{HER_{t0}}\right)$ $+ accessib\_Tour * \left(1 + \frac{CNL - CNL_{t0}}{CNL_{t0}}\right)\Big] * GS$	Same structure as activity_cultu1ES, with a modulation by governance system. The arc weights (Table A4) express the consumption of the input places associated with the firing of this transition (externalities).

Transition name	Purpose	Rate	Description
activity_cult3ES	activity generating navigation ES	$A * \left(1 + \frac{CNL - CNL_{t0}}{CNL_{t0}}\right) * GS$	The rate is directly dependent on actors and is modulated by the governance system and by the change of channels (CNL) respect to their initial condition (CNLt0). The arc weights (Table A4) express the consumption of the respective places associated with the firing of this transition (externalities).
eco_process	ecological processes generating each habitat	$k_{eco\_process} * HAB * \left[1 + k_{FAU\_feedback} * \left(\frac{FAU0 - FAU0_{t0}}{FAU0_{t0}}\right) + k_{FAU\_feedback} * \left(\frac{FAU2 - FAU2_{t0}}{FAU2_{t0}}\right)\right]$	Exponential growth function. The growth is modulated by the extent to which target fish spp (FAU0) and birds (FAU2) move away from the initial condition (FAU0t0 and FAU2t0, respectively). The k_FAU_feedback coefficient expresses the strength of this modulation (change in rate per unit of FAU change)
maintenance	maintenance of habitats	$GS * HAB_{t0}$	Habitats' yearly maintenance rate. The governance system value for the habitat maintenance colors indicates the yearly maintenance rate expressed as proportion of the habitats' initial condition.
sensibilization	effect of env. sensibilization (or lack of)	$k_{sensib} * \left[\frac{ESC2 - ESC2_{t0}}{ESC2_{t0}} + \frac{ESC3 - ESC3_{t0}}{ESC3_{t0}}\right]$	Rate equal to zero in steady state conditions. The effect of environmental sensibilization (or lack of) is modeled as an additional growth (loss) of habitats proportional to the increase (decrease) of information of cognitive development ES (ESC2) and traditions ES (ESC3) respect their initial conditions (ESC2to and ESC3t0, respectively). The k_sensib coefficient expresses the strength of this modulation (change in rate per unit of ES change).
growth	growth of fauna	$k_{growth} * FAU * \left[1 - \frac{FAU}{k_{carryingCap} * \left(1 + k_{ESR4\_feedback} * \frac{ESR - ESR_{t0}}{ESR_{t0}}\right)}\right]$	Logistic growth function. The carrying capacity (k_carryingCap), that is, the maximum number of individuals that can be supported by the lagoon system, is modulated by the change in lifecycle maintenance ES (ESR) respect to its initial condition (ESRt0). The k_ESR4_feedback coefficient expresses the strength of this modulation (change in carrying capacity per unit of ES change).
dredging	maintenance of channels	$GS * CNL_{t0}$	Channels' yearly dredging rate. The governance system value for channel dredging indicates the yearly maintenance rate expressed as proportion of the channels' initial condition.

Transition name	Purpose	Rate	Description
self_reg	channels' self-regulation capacity	$k_{self\_reg} * \left(1 + \frac{ESR2 - ESR2_{t0}}{ESR2_{t0}} + \frac{ESR3 - ESR3_{t0}}{ESR3_{t0}}\right) * \left(\frac{365 - MOSE}{365}\right)$	Constant rate (k_self_reg) representing the yearly self-regulation capacity, modulated by the change in the erosion prevention 1 and 2 ES (ESR2 and ESR3) respect to their initial condition (ESR2t0 and ESR3t0) and by the proportion of days of the year in which the MOSE closes.
actors_growth	Actors' population growth function	$k_{actors} * A + k_{RSLR\_A} * RSLR * A * (1 - GS)$	Growth function for residents and tourists. The second element of the function expresses the effect of RSLR on residents, which is compensated by MOSE activation (when GS lagoon_sea_exchanges=1). Growth function set to null in SS scenario.
ES_Use	yearly contribution of the corresponding ES to the well-being of society	ES	The rate is equal to the amount of the corresponding ES generated in each time step.
RSLR_rate	RSLR rate	k_{RSLR}	Constant rate depending on RSLR scenario
closures	number of MOSE closures per year	$k_{MOSE\_t0} * e^{k_{MOSE\_RSLR} * RSLR}$	Exponential function to compute the number of MOSE closures per year as a function of RLSR (estimated from Carbognin et al., 2010). The maximum n. of closures/yr is set to 300 (through the weight of the inhibitor arc, Table A4)
MOSE_out		$MOSE$	Removes tokens from MOSE place, so that the state of this place is equal to the number of closures per year.
T_rate	Rate of T increase	k_T	Constant rate of T increase under 1°C T increase scenario

Transition name	**Purpose**	**Rate**	**Description**
herit_PLUS	Initial positive effect of RSLR on cultural heritage	$k_{RSLR\_HER\_plus} * RLSR * (1 - GS)$	The “increase” of cultural heritage is the way the model reflects the positive effect of low levels of RSLR on cultural heritage’s attractiveness. It is compensated by MOSE activation (when GS lagoon_sea_exchanges=1). This function is assumed to be switched off at 10 cm RSLR (through the weight of the inhibitor arc, Table A4)
herit_MINUS	Negative effect of higher RSLR on cultural heritage	$k_{RSLR\_HER\_minus} * RLSR * (1 - GS)$	Loss of cultural heritage caused by RSLR > 10 cm (threshold set through arc weight, Table A4) It is compensated by MOSE activation (when GS lagoon_sea_exchanges=1).
RSLR_effect_HAB	Loss of habitats due to RSLR and MOSE	$k_{RSLR\_HAB} * RSLR + k_{MOSE\_HAB} * MOSE$	Rate of habitat loss due to RSLR and MOSE activation
lag_sea_exchange	contribution of lagoon-sea exchange to lifecycle maintenance ES	$k_{lag\_sea\_ex} * \left(\frac{365 - MOSE}{365}\right)$	Constant rate (k_lag_sea_ex) representing the yearly contribution of the exchanges between the lagoon and the sea to the lifecycle maintenance ES, modulated by the proportion of days of the year in which the MOSE closes.
T_effect_HAB_PLUS	Initial positive effect of T increase on seagrasses	$k_{T\_HAB\_plus} * T$	Seagrasses additional growth rate related to low levels of T increase. This function is assumed to be switched off at 0.3°C T increase (through the weight of the inhibitor arc, Table A4)
T_effect_HAB_MINUS	Loss of seagrasses due to further T increase	$k_{T\_HAB\_minus} * T$	Loss of seagrasses caused by T increase > 0.3 °C (threshold set through arc weight, Table A4).
T_effect_FAU_PLUS	Initial positive effect of T increase on fauna	$k_{T\_FAU\_plus} * T$	Additional clams’ growth rate related to low levels of T increase. This function is assumed to be switched off at 0.3°C T increase (through the weight of the inhibitor arc).

Transition name	**Purpose**	**Rate**	**Description**
T_effect_FAU_MINUS	Loss of fauna due to further T increase	$k_{T\_FAU\_minus} * T$	Loss of target fish species and clams due to T increase > 0.7 °C ad 0.3 °C respectively.

Table A2. Initial conditions of the social-ecological system's (SES) elements involved in the model

Colorset	**Color**	**Indicator**	**Marking at t0**
Habitats	Salt marshes	surface	100
	Seagrasses	surface	100
	Bare (intertidal)	surface	100
	Benthic diatoms	surface	100
	Macroalgae	surface	100
Fauna	Target fish species	biomass	6000
	Clam	biomass	6000
	Birds	abundance	6000
Channels	Channels	surface	50
Heritage	Density of cultural heritage	density with respect to surface	100
	Traditional knowledge	qualitative scale	100
Regulating_ ES	Climate regulation	amount of carbon sequestered	1000
	Waste treatment	amount of nitrogen removed through denitrification	100
	Erosion prevention 1	areas in which salt marshes provide a sheltering effect with respect to wind driven erosion	500
	Erosion prevention 2	sum of habitats' biostabilization capacity	500
	Lifecycle maintenance	sum of habitats' nursery role	1000
Cultural_ES	Tourism	n. of visitors to the lagoon (historical center of Venice excluded)	100000
	Navigation	n. of recreational boats' passages	50000
	Info for cognitive development	n. of visitors through environmental education activities	2000
	Traditions	n. of people practicing traditional activities	1000
Provisioning ES	Artisanal fishing	yield	1050
	Recreational fishing	yield	450
	Clam harvesting	yield	1875
	Hunting	yield	375
gov_system	Tourism	effect of gov. system on the respective ES activity	1
	Navigation	effect of gov. system on the respective ES activity	1
	Artisanal fishing	effect of gov. system on the respective ES activity	1
	Recreational fishing	effect of gov. system on the respective ES activity	1
	Clam harvesting	effect of gov. system on the respective ES activity	1
	Hunting	effect of gov. system on the respective ES activity	1
	salt marsh mainten.	habitat maintenance rate expressed as fraction of the habitat's surface at t0	0.004
	Seagrass mainten.	habitat maintenance rate expressed as fraction of the habitat's surface at t0	0
	Bare (intertidal) mainten.	habitat maintenance rate expressed as fraction of the habitat's surface at t0	0
	Benthic diatoms mainten.	habitat maintenance rate expressed as fraction of the habitat's surface at t0	0
	Macroalgae mainten.	habitat maintenance rate expressed as fraction of the habitat's surface at t0	0
	Channel dredging	channel dredging rate expressed as fraction of the channels' surface at t0	0.006

Colorset	Color	Indicator	Marking at t0
	lag. sea exchanges	MOSE activation (0-1)	0
Actors	Residents	n. of people	1000
	Art. fishermen	n. of people	100
	Recr. fishermen	n. of people	1000
	Clam fishermen	n. of people	500
	Hunters	n. of people	1000
	Users of Env. edu. activities	n. of people	2000
	Tourists	n. of people	100000
	Boat owners	n. of boats	50000

Table A3. Values of the model's parameters

Parameter	Description	Value
k0_eco_process	salt marshes' growth rate	0.004
k1_eco_process	seagrasses' growth rate	SS: 0.009; BAU: 0.012
k2_eco_process	bare (intertidal)'s growth rate	0.008
k3_eco_process	benthic diatoms' growth rate	0.009
k_0_0_eco_function	carbon sequestration rate per unit of salt marsh surface	6
k_1_0_eco_function	carbon sequestration rate per unit of seagrasse surface	4
k_1_1_eco_function	denitrification rate per unit of seagrass surface	0.15
k_2_1_eco_function	denitrification rate per unit of bare (intertidal) surface	0.35
k_3_1_eco_function	denitrification rate per unit of benthic diatoms' surface	0.35
k_4_1_eco_function	denitrification rate per unit of macroalgae's surface	0.15
k_0_2_eco_function	area of fetch reduction per unit of salt marsh surface	5
k_1_3_eco_function	biostabilization per unit of seagrasses surface	2.25
k_3_3_eco_function	biostabilization per unit of b. diatoms surface	1.5
k_4_3_eco_function	biostabilization per unit of macroalgae surface	1.25
k_0_4_eco_function	contribution of salt marshes to lifecycle maintenance ESS	2.5
k_1_4_eco_function	contribution of seagrasses to lifecycle maintenance ESS	2
k_2_4_eco_function	contribution of bare (intertidal) to lifecycle maintenance ESS	2
k_3_4_eco_function	contribution of benthic diatoms to lifecycle maintenance ESS	2.5
k_4_4_eco_function	contribution of macroalgae to lifecycle maintenance ESS	1
nat_attr_Tour	% contribution of natural attractiveness to visiting rate in Tourism ES	0.3
cult_attr_Tour	% contribution of cultural attractiveness to visiting rate in Tourism ES	0.6
accessib_Tour	% contribution of accessibility to visiting rate in Tourism ES	0.1
nat_attr_Edu	% contribution of natural attractiveness to visiting rate in Info for Cognitive dev. ES	0.3
cult_attr_Edu	% contribution of cultural attractiveness to visiting rate in Info for Cognitive dev. ES	0.6
accessib_Edu	% contribution of accessibility to visiting rate in Info for Cognitive dev. ES	0.1
nat_attr_trad	% contribution of natural attractiveness to visiting rate in Tradition ES	0.3
cult_attr_trad	% contribution of cultural attractiveness to visiting rate in Tradition ES	0.6
accessib_trad	% contribution of accessibility to visiting rate in Tradition ES	0.1

Parameter	Description	Value
w0_Edu	salt marshes' weight in natural attractiveness for Info for Cognitive dev. ES	0.3
w1_Edu	seagrasses' weight in natural attractiveness for Info for Cognitive dev. ES	0.3
w2_Edu	bare (intertidal)'s weight in natural attractiveness for Info for Cognitive dev. ES	0.3
w3_Edu	benthic diatoms' weight in natural attractiveness for Info for Cognitive dev. ES	0.05
w4_Edu	macroalgae's weight in natural attractiveness for Info for Cognitive dev. ES	0.05
w0_trad	salt marshes' weight in natural attractiveness for Traditions ES	0.3
w1_trad	seagrasses' weight in natural attractiveness for Traditions ES	0.3
w2_trad	bare (intertidal)'s weight in natural attractiveness for Traditions ES	0.3
w3_trad	benthic diatoms' weight in natural attractiveness for Traditions ES	0.05
w4_trad	macroalgae's weight in natural attractiveness for Traditions ES	0.05
k0_growth	growth rate of target fish spp	0.4
k1_growth	growth rate of clams	0.5
k2_growth	growth rate of birds	0.1
k0_carryingCap	carrying capacity for target fish spp	16000
k1_carryingCap	carrying capacity for clams	16000
k2_carryingCap	carrying capacity for birds	16000
k0_effic	fishing efficiency for artisanal fishing	0.00175
k1_effic	fishing efficiency for recreational fishing	0.000075
k3_effic	hunting efficiency	0.0000625
k_clamH	efficiency of clam harvesting	0.000625
k_ESR4_feedback	strenght of the feedback of lifecycle maintenance ES on fauna growth	1
k_UEF_feedback	strenght of the feedback of fauna on the growth of habitats	0.25
k_self_reg	self -regulation capacity per unity of channels	0.6
k_lag_sea_ex	contribution of lagoon-sea exchanges to lifecycle maintenance ES	90
k_sensib	habitats "growth" rate for 100% increase of environmental sensibilization	0.1
k0_actors	residents' growth rate	SS: 0; BAU: -0.01
k6_actors	tourists' growth rate	SS: 0 ; BAU: 0.01
k0_RSLR_A	additional growth rate for residents, expressed as % increase per cm of RSLR	-0.001
k0_RSLR	annual RSLR increase under scneario +15 cm	0.183
k1_RSLR	annual RSLR increase under scneario +25 cm	0.305

Parameter	Description	Value
k2_RSLR	annual RSLR increase under scneario +50 cm	0.61
k_MOSE_t0	n. of MOSE closures per year at RSLR=0	4
k_MOSE_RSLR	coefficient relating RSLR to n. of MOSE closures/yr	0.08
k_T	rate of temperature increase under 1°C temperature increase scenario	0.012
k_RSLR_HER_plus	rate of cultural heritage attractiveness' increase at to low levels of RSLR	0.02
k_RSLR_HER_minus	rate of cultural heritage loss due to RSLR	0.02
k0_RSLR_HAB	rate of salt marshes loss due to RSLR	0.015
k1_RSLR_HAB	rate of seagrasses loss due to RSLR	0.025
k2_RSLR_HAB	rate of bare (intertidal) loss due to RSLR	0.015
k1_MOSE_HAB	rate of seagrasses loss due to MOSE closures	0.004
k2_MOSE_HAB	rate of bare (intertidal) loss due to MOSE closures	0.005
k3_MOSE_HAB	rate of benthic diatoms loss due to MOSE closures	0.003
k4_MOSE_HAB	rate of macroalgae loss due to MOSE closures	0.002
k1_T_HAB_plus	rate of seagrasses' increase at to low levels of temperature increase	1
k1_T_HAB_minus	rate of seagrasses loss due to temperature increase	0.9
k1_T_FAU_plus	rate of clams' increase at to low levels of temperature increase	50
k0_T_FAU_minus	rate of target fish spp loss due to temperature increase	50
k1_T_FAU_minus	rate of clams loss due to temperature increase	50

Table A4. Model's arc weights. Arcs are identified through the input place and the transition they connect. Where needed, the unfolding specifies the color of the input place's colorset, or of the transitions' output place's colorset. Arcs not specified here have weight = 1. Abbreviations: SS, steady state scenario; BAU, business-as-usual scenario.

Arc	Unfolding	Description	Weight
Habitats → activity_prov2ES	seagrasses	seagrasses' consumption per clam harvested	0.00016
	benthic diatoms	benthic diatoms' consumption per clam harvested	0.00016
Regulating_ES → activity_prov2ES	lifecycle maintenance	lifecycle maintenance's consumption per clam harvested	0.048
Channels → activity_prov2ES		channels' consumption per clam harvested	0.00016
Habitats → activity_cult2ES	salt marshes	salt marshes' consumption per visitor (tourism)	SS: 0.000004; BAU: 0.000005
	seagrasses	seagrasses' consumption per visitor (tourism)	0.000003
	bare (intertidal)	bare (intertidal)'s consumption per visitor (tourism)	0.000004
	benthic diatoms	diatoms' consumption per visitor (tourism)	0.000003
Channels → activity_cult2ES		channels' consumption per visitor (tourism)	0.000003
Habitats → activity_cult3ES	salt marshes	salt marshes' consumption per boat passage (navigation)	SS: 0.000008; BAU: 0.00001
	seagrasses	seagrasses' consumption per boat passage (navigation)	0.000006
	bare (intertidal)	bare (intertidal)'s consumption per boat passage (navigation)	0.000008
	benthic diatoms	diatoms' consumption per boat passage (navigation)	0.000006
Channels → activity_cult3ES		channels' consumption per boat passage (navigation)	0.000006
RSLR → herit_PLUS	density of cultural heritage	RSLR threshold above which it no longer produces positive effects on cultural heritage	10
RSLR → herit_MINUS	density of cultural heritage	RSLR threshold above which it produces negative effects on cultural heritage	10

MOSE → closures		Maximum n. of MOSE closures per year	300
MOSE → MOSE_out		Maximum n. of MOSE closures per year	300
T_increase → T_effect_HAB_PLUS	seagrasses	T increase threshold above which it no longer produces positive effects on seagrasses	0.3
T_increase → T_effect_HAB_MINUS	seagrasses	T increase threshold above which it produces negative effects on seagrasses	0.3
T_increase → T_effect_FAU_PLUS	target fish species	T increase threshold above which its effect on target fish species is no longer compensated by species substitution	0.7
	clam	T increase threshold above which it no longer produces positive effects on clams	0.3
T_increase → T_effect_FAU_MINUS	target fish species	T increase threshold above which it produces negative effects on target fish species	0.7
	clam	T increase threshold above which it produces negative effects on clams	0.3

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Appendix B

Sensitivity analysis (Appendix to Chapter 3)

Table B1. Model results obtained by varying the model's initial conditions, one at a time, by ±10% and ±25%, departing from steady-state conditions. Results are expressed as % variation, at the end of the 21st century, with respect to the steady-state conditions.

			Regulating ES					Cultural ES				Provisioning ES				Habitats					Fauna			Heritage		Channels	Actors							
colorset	place	variation	Clim. reg.	Waste treat.	Erosion prev. 1	Erosion prev. 2	Lifecycle maint	Tourism	Navigation	Info. cogn. dev.	Tradition	Artisanal fish.	Recreat. fish.	Clam harv.	Hunting	Salt marshes	Seagrasses	Bare (intertidal	Benthic diatom	Macroalgae	Target fish spp.	Clam	Birds	Density cult. H	Tradit. Knowle	Channels	Residents	Art. fishermen	Recr. fisherme	Clam fisherme	Hunters	Users of Env. e	Tourists	Boat owners
Habitat	Salt marshes	-25%	-15.90	3.70	-29.41	3.15	-4.13	-10.27	-14.50	-3.24	-3.24	-4.49	-4.49	-4.44	-4.74	-29.44	4.46	4.65	4.46	-0.47	-4.44	-4.39	-4.72	0.00	0.00	-14.64	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	-6.38	1.49	-11.81	1.27	-1.65	-4.13	-5.81	-1.30	-1.30	-1.80	-1.80	-1.78	-1.89	-11.83	1.80	1.88	1.80	-0.19	-1.78	-1.76	-1.88	0.00	0.00	-5.87	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	6.42	-1.51	11.88	-1.29	1.66	4.15	5.83	1.30	1.30	1.80	1.80	1.78	1.89	11.89	-1.82	-1.89	-1.82	0.19	1.78	1.76	1.88	0.00	0.00	5.88	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	16.10	-3.80	29.82	-3.24	4.15	10.40	14.59	3.26	3.26	4.51	4.51	4.46	4.73	29.86	-4.58	-4.77	-4.58	0.47	4.47	4.41	4.71	0.00	0.00	14.73	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Seagrasses	-25%	-19.89	-7.79	0.25	-22.60	-9.31	-0.93	-10.03	-5.57	-5.57	-8.78	-8.78	-8.87	-7.42	0.27	-50.53	-0.84	0.33	-0.61	-8.85	-8.94	-7.49	0.00	0.00	-10.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	-8.05	-3.15	0.10	-9.14	-3.76	-0.37	-4.03	-2.25	-2.25	-3.54	-3.54	-3.58	-2.98	0.11	-20.44	-0.34	0.14	-0.24	-3.57	-3.61	-3.01	0.00	0.00	-4.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	8.16	3.19	-0.10	9.27	3.82	0.38	4.06	2.28	2.28	3.58	3.58	3.62	2.99	-0.11	20.75	0.34	-0.14	0.24	3.62	3.65	3.02	0.00	0.00	4.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	20.63	8.06	-0.26	23.44	9.65	0.94	10.21	5.75	5.75	9.04	9.04	9.15	7.51	-0.28	52.45	0.84	-0.36	0.61	9.12	9.22	7.58	0.00	0.00	10.37	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Bare (Intertidal)	-25%	-1.64	-18.19	-1.79	-1.18	-10.22	-0.37	1.64	-4.63	-4.63	-9.48	-9.48	-9.60	-7.83	-1.83	-1.44	-50.18	-1.44	-0.52	-9.57	-9.69	-7.92	0.00	0.00	1.66	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	-0.66	-7.35	-0.72	-0.47	-4.12	-0.15	0.66	-1.87	-1.87	-3.82	-3.82	-3.87	-3.14	-0.74	-0.58	-20.27	-0.58	-0.21	-3.86	-3.91	-3.17	0.00	0.00	0.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	0.66	7.44	0.72	0.47	4.18	0.15	-0.67	1.89	1.89	3.86	3.86	3.91	3.15	0.74	0.58	20.54	0.58	0.21	3.90	3.95	3.18	0.00	0.00	-0.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	1.65	18.77	1.81	1.19	10.53	0.38	-1.67	4.78	4.78	9.72	9.72	9.85	7.88	1.85	1.45	51.88	1.45	0.53	9.82	9.96	7.97	0.00	0.00	-1.69	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Benthic diatoms	-25%	-0.14	-18.12	-0.30	-15.01	-11.91	-0.62	-5.35	-1.46	-1.46	-11.16	-11.16	-11.28	-9.38	-0.30	0.11	-1.72	-50.51	-0.14	-11.26	-11.38	-9.47	0.00	0.00	-5.43	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	-0.05	-7.35	-0.12	-6.08	-4.83	-0.25	-2.15	-0.59	-0.59	-4.51	-4.51	-4.56	-3.77	-0.12	0.05	-0.69	-20.49	-0.06	-4.55	-4.61	-3.80	0.00	0.00	-2.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	0.05	7.48	0.12	6.19	4.91	0.25	2.17	0.60	0.60	4.58	4.58	4.63	3.79	0.12	-0.06	0.69	20.87	0.06	4.62	4.68	3.83	0.00	0.00	2.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	0.11	18.94	0.29	15.69	12.44	0.63	5.47	1.50	1.50	11.58	11.58	11.72	9.50	0.29	-0.16	1.74	52.90	0.14	11.69	11.83	9.60	0.00	0.00	5.55	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Macroalgae	-25%	0.37	-3.57	0.36	-5.98	-2.05	-0.26	-3.70	-0.67	-0.67	-2.11	-2.11	-2.10	-2.08	0.38	0.40	0.02	0.40	-25.09	-2.10	-2.09	-2.08	0.00	0.00	-3.73	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	0.15	-1.43	0.15	-2.39	-0.82	-0.10	-1.48	-0.27	-0.27	-0.84	-0.84	-0.84	-0.83	0.15	0.16	0.01	0.16	-10.04	-0.84	-0.84	-0.83	0.00	0.00	-1.49	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	-0.15	1.43	-0.15	2.39	0.82	0.10	1.48	0.27	0.27	0.84	0.84	0.84	0.83	-0.15	-0.16	-0.01	-0.16	10.04	0.84	0.84	0.83	0.00	0.00	1.49	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	-0.38	3.56	-0.37	5.98	2.05	0.26	3.70	0.67	0.67	2.10	2.10	2.10	2.06	-0.38	-0.40	-0.02	-0.40	25.09	2.10	2.09	2.06	0.00	0.00	3.73	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fauna	Target fish spp.	-25%	-0.48	-0.67	-0.25	-0.61	-0.53	-0.11	-0.32	-0.21	-0.21	-0.50	-0.50	-0.51	-0.42	-0.25	-0.82	-0.74	-0.82	-0.02	-0.50	-0.51	-0.42	0.00	0.00	-0.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	-0.17	-0.25	-0.09	-0.23	-0.20	-0.04	-0.12	-0.08	-0.08	-0.19	-0.19	-0.19	-0.15	-0.09	-0.30	-0.27	-0.30	-0.01	-0.19	-0.19	-0.16	0.00	0.00	-0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	0.16	0.22	0.08	0.21	0.18	0.04	0.11	0.07	0.07	0.17	0.17	0.17	0.14	0.08	0.27	0.25	0.27	0.01	0.17	0.17	0.14	0.00	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	0.37	0.52	0.20	0.48	0.42	0.08	0.25	0.16	0.16	0.39	0.39	0.40	0.33	0.20	0.65	0.58	0.65	0.02	0.39	0.40	0.33	0.00	0.00	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Clam	-25%	0.16	0.30	-0.21	0.54	0.21	0.01	0.70	0.11	0.11	0.21	0.21	0.21	0.22	-0.21	0.71	-0.18	0.71	0.02	0.21	0.21	0.22	0.00	0.00	0.69	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	0.06	0.11	-0.08	0.20	0.08	0.00	0.25	0.04	0.04	0.08	0.08	0.08	0.08	-0.08	0.26	-0.06	0.26	0.01	0.08	0.08	0.08	0.00	0.00	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	-0.05	-0.10	0.07	-0.18	-0.07	0.00	-0.23	-0.04	-0.04	-0.07	-0.07	-0.07	-0.07	0.07	-0.23	0.06	-0.23	-0.01	-0.07	-0.07	-0.07	0.00	0.00	-0.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	-0.12	-0.23	0.16	-0.41	-0.16	0.00	-0.53	-0.08	-0.08	-0.16	-0.16	-0.16	-0.17	0.16	-0.54	0.14	-0.54	-0.01	-0.16	-0.16	-0.17	0.00	0.00	-0.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Birds	-25%	-1.59	-2.17	-0.89	-2.00	-1.75	-0.36	-0.91	-0.67	-0.67	-1.62	-1.62	-1.65	-2.89	-0.89	-2.67	-2.41	-2.67	-0.06	-1.64	-1.66	-2.85	0.00	0.00	-0.93	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	-0.60	-0.81	-0.33	-0.75	-0.66	-0.13	-0.34	-0.25	-0.25	-0.61	-0.61	-0.62	-1.02	-0.33	-1.00	-0.90	-1.00	-0.02	-0.61	-0.62	-1.01	0.00	0.00	-0.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	0.55	0.75	0.30	0.70	0.61	0.12	0.32	0.23	0.23	0.56	0.56	0.57	0.90	0.31	0.93	0.84	0.93	0.02	0.57	0.58	0.89	0.00	0.00	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	1.31	1.79	0.72	1.65	1.44	0.29	0.76	0.55	0.55	1.34	1.34	1.36	2.09	0.72	2.21	1.99	2.21	0.05	1.35	1.37	2.07	0.00	0.00	0.78	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Channels	Channels	-25%	7.29	6.79	7.52	5.19	6.38	1.13	-11.26	1.14	1.14	5.72	5.72	5.83	4.19	7.60	7.05	9.67	7.05	-0.11	5.81	5.92	4.27	0.00	0.00	-11.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	2.91	2.71	3.00	2.07	2.54	0.45	-4.51	0.45	0.45	2.28	2.28	2.33	1.68	3.04	2.81	3.86	2.81	-0.05	2.32	2.36	1.71	0.00	0.00	-4.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	-2.90	-2.70	-3.00	-2.06	-2.53	-0.45	4.51	-0.45	-0.45	-2.28	-2.28	-2.32	-1.68	-3.03	-2.80	-3.84	-2.80	0.05	-2.31	-2.36	-1.72	0.00	0.00	4.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	-7.24	-6.72	-7.48	-5.13	-6.32	-1.12	11.28	-1.11	-1.11	-5.68	-5.68	-5.79	-4.23	-7.56	-6.97	-9.57	-6.97	0.12	-5.77	-5.87	-4.30	0.00	0.00	11.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Heritage	Density cult. Heritage	-25%	2.76	2.38	2.99	1.55	2.30	-13.42	6.87	-13.46	1.54	2.08	2.08	2.12	1.55	3.02	2.45	3.86	2.45	-1.08	2.11	2.15	1.58	-25.00	0.00	6.95	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	1.10	0.95	1.20	0.62	0.92	-5.37	2.75	-5.39	0.61	0.83	0.83	0.85	0.62	1.21	0.98	1.54	0.98	-0.43	0.84	0.86	0.63	-10.00	0.00	2.78	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	-1.10	-0.95	-1.20	-0.62	-0.92	5.37	-2.75	5.39	-0.61	-0.83	-0.83	-0.85	-0.62	-1.21	-0.98	-1.54	-0.98	0.43	-0.84	-0.86	-0.63	10.00	0.00	-2.78	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	-2.76	-2.37	-2.99	-1.54	-2.29	13.42	-6.86	13.47	-1.53	-2.08	-2.08	-2.11	-1.56	-3.02	-2.44	-3.84	-2.44	1.08	-2.11	-2.14	-1.58	25.00	0.00	-6.94	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Tradit. Knowledge	-25%	-1.47	-1.60	-1.34	-1.55	-1.42	-0.48	-0.76	-0.54	-15.54	-1.26	-1.26	-1.29	-0.90	-1.36	-1.69	-1.71	-1.69	-1.24	-1.28	-1.31	-0.92	0.00	-25.00	-0.78	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	-0.59	-0.64	-0.54	-0.62	-0.57	-0.19	-0.31	-0.22	-6.22	-0.50	-0.50	-0.51	-0.36	-0.55	-0.68	-0.68	-0.68	-0.50	-0.51	-0.52	-0.37	0.00	-10.00	-0.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	0.59	0.64	0.54	0.62	0.57	0.19	0.31	0.22	6.22	0.50	0.50	0.52	0.36	0.55	0.68	0.68	0.68	0.50	0.51	0.52	0.37	0.00	10.00	0.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	1.47	1.61	1.34	1.55	1.43	0.48	0.76	0.54	15.54	1.26	1.26	1.29	0.90	1.36	1.69	1.71	1.69	1.24	1.28	1.31	0.92	0.00	25.00	0.78	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Regulating ES	Clim. reg.	-25%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Waste treat.	-25%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Erosion prev. 1	-25%	0.09	0.08	0.09	0.06	0.08	0.01	-0.14	0.01	0.01	0.07	0.07	0.07	0.05	0.09	0.08	0.11	0.08	0.00	0.07	0.07	0.05	0.00	0.00	-0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	0.03	0.03	0.04	0.02	0.03	0.01	-0.05	0.01	0.01	0.03	0.03	0.03	0.02	0.04	0.03	0.05	0.03	0.00	0.03	0.03	0.02	0.00	0.00	-0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	-0.03	-0.03	-0.04	-0.02	-0.03	-0.01	0.05	-0.01	-0.01	-0.03	-0.03	-0.03	-0.02	-0.04	-0.03	-0.05	-0.03	0.00	-0.03	-0.03	-0.02	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	-0.09	-0.08	-0.09	-0.06	-0.08	-0.01	0.14	-0.01	-0.01	-0.07	-0.07	-0.07	-0.05	-0.09	-0.08	-0.11	-0.08	0.00	-0.07	-0.07	-0.05	0.00	0.00	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Erosion prev. 2	-25%	0.09	0.08	0.09	0.06	0.08	0.01	-0.14	0.01	0.01	0.07	0.07	0.07	0.05	0.09	0.08	0.11	0.08	0.00	0.07	0.07	0.05	0.00	0.00	-0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	0.03	0.03	0.04	0.02	0.03	0.01	-0.05	0.01	0.01	0.03	0.03	0.03	0.02	0.04	0.03	0.05	0.03	0.00	0.03	0.03	0.02	0.00	0.00	-0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	-0.03	-0.03	-0.04	-0.02	-0.03	-0.01	0.05	-0.01	-0.01	-0.03	-0.03	-0.03	-0.02	-0.04	-0.03	-0.05	-0.03	0.00	-0.03	-0.03	-0.02	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	-0.09	-0.08	-0.09	-0.06	-0.08	-0.01	0.14	-0.01	-0.01	-0.07	-0.07	-0.07	-0.05	-0.09	-0.08	-0.11	-0.08	0.00	-0.07	-0.07	-0.05	0.00	0.00	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Lifecycle maint.	-25%	-0.10	-0.13	-0.11	-0.07	-0.11	-0.03	0.04	-0.04	-0.04	-0.10	-0.10	-0.10	-0.13	-0.11	-0.09	-0.23	-0.09	0.00	-0.10	-0.10	-0.13	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	-0.04	-0.05	-0.04	-0.03	-0.04	-0.01	0.02	-0.01	-0.01	-0.04	-0.04	-0.04	-0.05	-0.04	-0.03	-0.09	-0.03	0.00	-0.04	-0.04	-0.04	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	0.03	0.04	0.04	0.02	0.04	0.01	-0.02	0.01	0.01	0.03	0.03	0.03	0.04	0.04	0.03	0.08	0.03	0.00	0.03	0.03	0.04	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	0.08	0.10	0.09	0.05	0.08	0.02	-0.04	0.03	0.03	0.08	0.08	0.08	0.10	0.09	0.07	0.19	0.07	0.00	0.08	0.08	0.10	0.00	0.00	-0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cultural ES	Tourism	-25%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Navigation	-25%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Info. cogn. dev.	-25%	-0.04	-0.04	-0.03	-0.04	-0.04	-0.01	-0.03	-0.02	-0.02	-0.04	-0.04	-0.04	-0.03	-0.03	-0.05	-0.05	-0.05	-0.03	-0.04	-0.04	-0.03	0.00	0.00	-0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	-0.02	-0.02	-0.01	-0.02	-0.02	0.00	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.02	-0.02	-0.02	-0.01	-0.01	-0.01	-0.01	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	0.02	0.02	0.01	0.02	0.02	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	0.04	0.04	0.03	0.04	0.04	0.01	0.03	0.02	0.02	0.04	0.04	0.04	0.03	0.03	0.05	0.05	0.05	0.03	0.04	0.04	0.03	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Tradition	-25%	-0.04	-0.04	-0.03	-0.04	-0.04	-0.01	-0.03	-0.02	-0.02	-0.04	-0.04	-0.04	-0.03	-0.03	-0.05	-0.05	-0.05	-0.03	-0.04	-0.04	-0.03	0.00	0.00	-0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	-0.02	-0.02	-0.01	-0.02	-0.02	0.00	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.02	-0.02	-0.02	-0.01	-0.01	-0.01	-0.01	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	0.02	0.02	0.01	0.02	0.02	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	0.04	0.04	0.03	0.04	0.04	0.01	0.03	0.02	0.02	0.04	0.04	0.04	0.03	0.03	0.05	0.05	0.05	0.03	0.04	0.04	0.03	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Provisioning ES	Artisanal fish.	-25%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

			Regulating ES					Cultural ES				Provisioning ES				Habitats					Fauna			Heritage		Channels	Actors							
colorset	place	variation	Clim. reg.	Waste treat.	Erosion prev. 1	Erosion prev. 2	Lifecycle maint	Tourism	Navigation	Info. cogn. dev	Tradition	Artisanal fish.	Recreat. fish.	Clam harv.	Hunting	Salt marshes	Seagrasses	Bare (intertidal	Benthic diatom	Macroalgae	Target fish spp.	Clam	Birds	Density cult. H	Tradit. Knowle	Channels	Residents	Art. fishermen	Recr. fishermer	Clam fishermer	Hunters	Users of Env. e	Tourists	Boat owners
		+10%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Recreat. fish.	-25%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Clam harv.	-25%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Hunting	-25%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Governance syste	Tourism	-25%	7.20	6.78	7.38	5.27	6.34	-22.37	12.94	3.53	3.53	5.67	5.67	5.79	4.13	7.46	7.04	9.47	7.04	0.27	5.76	5.87	4.21	0.00	0.00	13.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	2.84	2.67	2.91	2.08	2.50	-8.75	5.12	1.40	1.40	2.24	2.24	2.29	1.65	2.95	2.78	3.74	2.78	0.11	2.28	2.32	1.68	0.00	0.00	5.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	-2.80	-2.63	-2.87	-2.04	-2.46	8.50	-5.05	-1.37	-1.37	-2.21	-2.21	-2.25	-1.63	-2.90	-2.73	-3.67	-2.73	-0.11	-2.24	-2.28	-1.66	0.00	0.00	-5.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	-6.90	-6.49	-7.08	-5.04	-6.07	20.78	-12.49	-3.39	-3.39	-5.46	-5.46	-5.57	-4.06	-7.16	-6.73	-9.06	-6.73	-0.27	-5.54	-5.65	-4.13	0.00	0.00	-12.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Navigation	-25%	7.54	7.08	7.73	5.51	6.63	3.67	-14.85	3.69	3.69	5.91	5.91	6.03	4.28	7.83	7.36	9.89	7.36	0.28	6.00	6.12	4.36	0.00	0.00	13.72	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	2.90	2.72	2.97	2.12	2.55	1.41	-5.31	1.42	1.42	2.28	2.28	2.32	1.67	3.00	2.83	3.80	2.83	0.11	2.31	2.36	1.70	0.00	0.00	5.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	-2.75	-2.58	-2.81	-2.01	-2.42	-1.34	4.54	-1.35	-1.35	-2.17	-2.17	-2.22	-1.61	-2.84	-2.68	-3.61	-2.68	-0.11	-2.21	-2.25	-1.64	0.00	0.00	-5.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	-6.60	-6.22	-6.76	-4.84	-5.81	-3.22	10.05	-3.25	-3.25	-5.25	-5.25	-5.35	-3.92	-6.83	-6.45	-8.69	-6.45	-0.26	-5.32	-5.42	-3.99	0.00	0.00	-12.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Artisanal fishing	-25%	4.45	5.88	2.61	5.43	4.81	0.97	1.87	1.76	1.76	1.03	34.70	4.27	2.87	2.65	7.35	6.57	7.35	0.11	34.81	4.35	2.94	0.00	0.00	1.93	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	1.72	2.27	1.01	2.09	1.86	0.38	0.73	0.68	0.68	2.14	13.49	1.65	1.12	1.03	2.83	2.53	2.83	0.04	13.52	1.68	1.14	0.00	0.00	0.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	-1.64	-2.16	-0.98	-1.99	-1.77	-0.36	-0.70	-0.65	-0.65	-4.31	-13.01	-1.58	-1.08	-0.99	-2.69	-2.41	-2.69	-0.04	-13.03	-1.61	-1.10	0.00	0.00	-0.72	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	-3.96	-5.18	-2.37	-4.78	-4.26	-0.88	-1.69	-1.56	-1.56	-14.58	-31.67	-3.80	-2.61	-2.41	-6.45	-5.81	-6.45	-0.10	-31.72	-3.87	-2.67	0.00	0.00	-1.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Recreational fishing	-25%	1.85	2.43	1.09	2.25	1.99	0.40	0.78	0.73	0.73	14.47	-14.15	1.77	1.20	1.11	3.04	2.72	3.04	0.05	14.51	1.81	1.23	0.00	0.00	0.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	0.73	0.96	0.43	0.88	0.78	0.16	0.31	0.29	0.29	5.72	-4.85	0.70	0.47	0.44	1.19	1.07	1.19	0.02	5.74	0.71	0.49	0.00	0.00	0.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	-0.71	-0.94	-0.42	-0.87	-0.77	-0.16	-0.30	-0.28	-0.28	-5.63	3.80	-0.69	-0.47	-0.43	-1.17	-1.05	-1.17	-0.02	-5.64	-0.70	-0.48	0.00	0.00	-0.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	-1.76	-2.31	-1.05	-2.13	-1.89	-0.39	-0.75	-0.69	-0.69	-13.91	7.61	-1.69	-1.15	-1.06	-2.87	-2.58	-2.87	-0.05	-13.94	-1.72	-1.18	0.00	0.00	-0.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Clam harvesting	-25%	-0.39	-0.57	0.15	-0.90	-0.96	-0.14	-1.83	-0.29	-0.29	-0.90	-0.90	5.27	-0.71	0.16	-1.23	0.10	-1.23	-0.02	-0.91	40.35	-0.72	0.00	0.00	-1.86	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	-0.35	-0.53	0.18	-0.86	-0.82	-0.11	-1.64	-0.26	-0.26	-0.77	-0.77	4.18	-0.63	0.18	-1.16	0.13	-1.16	-0.02	-0.78	15.74	-0.63	0.00	0.00	-1.66	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	0.61	0.93	-0.32	1.52	1.42	0.19	2.85	0.45	0.45	1.34	1.34	-7.10	1.09	-0.33	2.06	-0.24	2.06	0.03	1.35	-15.54	1.10	0.00	0.00	2.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	2.04	3.10	-1.08	5.06	4.76	0.62	9.45	1.48	1.48	4.46	4.46	-23.90	3.59	-1.11	6.84	-0.80	6.84	0.10	4.50	-39.10	3.63	0.00	0.00	9.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Hunting	-25%	4.79	6.27	2.86	5.80	5.16	1.04	1.80	1.87	1.87	4.35	4.35	4.48	9.11	2.91	7.87	7.02	7.87	0.11	4.46	4.59	45.66	0.00	0.00	1.86	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	1.80	2.35	1.08	2.17	1.93	0.39	0.68	0.70	0.70	1.64	1.64	1.69	5.68	1.10	2.94	2.63	2.94	0.04	1.67	1.72	17.48	0.00	0.00	0.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	-1.65	-2.14	-1.00	-1.98	-1.77	-0.36	-0.63	-0.64	-0.64	-1.50	-1.50	-1.54	-7.92	-1.02	-2.68	-2.40	-2.68	-0.04	-1.53	-1.58	-16.35	0.00	0.00	-0.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	-3.84	-4.97	-2.34	-4.59	-4.10	-0.85	-1.47	-1.49	-1.49	-3.49	-3.49	-3.59	-22.86	-2.38	-6.22	-5.59	-6.22	-0.09	-3.57	-3.67	-38.43	0.00	0.00	-1.52	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	salt marsh mainten.	-25%	-5.08	0.45	-8.83	0.39	-1.72	-2.90	-2.48	-0.94	-0.94	-1.58	-1.58	-1.61	-1.20	-8.94	0.56	0.56	0.56	-0.07	-1.60	-1.63	-1.22	0.00	0.00	-2.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	-2.03	0.18	-3.53	0.15	-0.69	-1.16	-0.99	-0.38	-0.38	-0.63	-0.63	-0.64	-0.48	-3.58	0.22	0.22	0.22	-0.03	-0.64	-0.65	-0.49	0.00	0.00	-1.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	2.03	-0.18	3.53	-0.15	0.69	1.16	0.99	0.38	0.38	0.63	0.63	0.64	0.48	3.58	-0.22	-0.22	-0.22	0.03	0.64	0.65	0.49	0.00	0.00	1.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	5.09	-0.45	8.84	-0.39	1.72	2.90	2.48	0.94	0.94	1.58	1.58	1.61	1.20	8.96	-0.56	-0.56	-0.56	0.07	1.60	1.63	1.22	0.00	0.00	2.54	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Channel dredging	-25%	1.76	1.55	1.87	1.18	1.50	-0.31	-8.74	-0.34	-0.34	1.23	1.23	1.27	0.78	1.92	1.63	2.23	1.63	-0.05	1.27	1.31	0.81	0.00	0.00	-8.81	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	0.70	0.62	0.75	0.47	0.60	-0.13	-3.49	-0.14	-0.14	0.49	0.49	0.51	0.32	0.77	0.65	0.89	0.65	-0.02	0.51	0.52	0.33	0.00	0.00	-3.52	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	-0.70	-0.62	-0.75	-0.47	-0.60	0.13	3.50	0.14	0.14	-0.49	-0.49	-0.51	-0.32	-0.77	-0.65	-0.89	-0.65	0.02	-0.51	-0.52	-0.33	0.00	0.00	3.52	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	-1.76	-1.55	-1.87	-1.18	-1.50	0.31	8.74	0.34	0.34	-1.23	-1.23	-1.27	-0.79	-1.92	-1.63	-2.22	-1.63	0.05	-1.27	-1.31	-0.81	0.00	0.00	8.81	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Actors	Residents	-25%	-2.44	-2.66	-2.23	-2.57	-2.36	-0.80	-1.27	-0.90	-25.67	-2.09	-2.09	-2.13	-1.50	-2.26	-2.80	-2.84	-2.80	-2.05	-2.12	-2.17	-1.54	0.00	0.00	-1.30	-25.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	-0.98	-1.07	-0.89	-1.03	-0.95	-0.32	-0.51	-0.36	-10.32	-0.84	-0.84	-0.86	-0.60	-0.91	-1.13	-1.14	-1.13	-0.82	-0.85	-0.87	-0.61	0.00	0.00	-0.52	-10.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	0.98	1.07	0.90	1.04	0.95	0.32	0.51	0.36	10.40	0.84	0.84	0.86	0.60	0.91	1.13	1.14	1.13	0.83	0.86	0.87	0.61	0.00	0.00	0.52	10.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	2.46	2.69	2.25	2.60	2.39	0.80	1.28	0.91	26.13	2.11	2.11	2.16	1.50	2.28	2.83	2.87	2.83	2.07	2.14	2.19	1.54	0.00	0.00	1.31	25.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Artisanal fishermen	-25%	4.45	5.88	2.61	5.43	4.81	0.97	1.87	1.76	1.76	1.03	34.70	4.27	2.87	2.65	7.35	6.57	7.35	0.11	34.81	4.35	2.94	0.00	0.00	1.93	0.00	-25.00	0.00	0.00	0.00	0.00	0.00	0.00
		-10%	1.72	2.27	1.01	2.09	1.86	0.38	0.73	0.68	0.68	2.14	13.49	1.65	1.12	1.03	2.83	2.53	2.83	0.04	13.52	1.68	1.14	0.00	0.00	0.75	0.00	-10.00	0.00	0.00	0.00	0.00	0.00	0.00
		+10%	-1.64	-2.16	-0.98	-1.99	-1.77	-0.36	-0.70	-0.65	-0.65	-4.31	-13.01	-1.58	-1.08	-0.99	-2.69	-2.41	-2.69	-0.04	-13.03	-1.61	-1.10	0.00	0.00	-0.72	0.00	10.00	0.00	0.00	0.00	0.00	0.00	0.00
		+25%	-3.96	-5.18	-2.37	-4.78	-4.26	-0.88	-1.69	-1.56	-1.56	-14.58	-31.67	-3.80	-2.61	-2.41	-6.45	-5.81	-6.45	-0.10	-31.72	-3.87	-2.67	0.00	0.00	-1.74	0.00	25.00	0.00	0.00	0.00	0.00	0.00	0.00
	Recreational fishermer	-25%	1.85	2.43	1.09	2.25	1.99	0.40	0.78	0.73	0.73	14.47	-14.15	1.77	1.20	1.11	3.04	2.72	3.04	0.05	14.51	1.81	1.23	0.00	0.00	0.80	0.00	0.00	-25.00	0.00	0.00	0.00	0.00	0.00
		-10%	0.73	0.96	0.43	0.88	0.78	0.16	0.31	0.29	0.29	5.72	-4.85	0.70	0.47	0.44	1.19	1.07	1.19	0.02	5.74	0.71	0.49	0.00	0.00	0.32	0.00	0.00	-10.00	0.00	0.00	0.00	0.00	0.00
		+10%	-0.71	-0.94	-0.42	-0.87	-0.77	-0.16	-0.30	-0.28	-0.28	-5.63	3.80	-0.69	-0.47	-0.43	-1.17	-1.05	-1.17	-0.02	-5.64	-0.70	-0.48	0.00	0.00	-0.31	0.00	0.00	10.00	0.00	0.00	0.00	0.00	0.00
		+25%	-1.76	-2.31	-1.05	-2.13	-1.89	-0.39	-0.75	-0.69	-0.69	-13.91	7.61	-1.69	-1.15	-1.06	-2.87	-2.58	-2.87	-0.05	-13.94	-1.72	-1.18	0.00	0.00	-0.77	0.00	0.00	25.00	0.00	0.00	0.00	0.00	0.00
	Clam fishermen	-25%	-0.39	-0.57	0.15	-0.90	-0.96	-0.14	-1.83	-0.29	-0.29	-0.90	-0.90	5.27	-0.71	0.16	-1.23	0.10	-1.23	-0.02	-0.91	40.35	-0.72	0.00	0.00	-1.86	0.00	0.00	0.00	-25.00	0.00	0.00	0.00	0.00
		-10%	-0.35	-0.53	0.18	-0.86	-0.82	-0.11	-1.64	-0.26	-0.26	-0.77	-0.77	4.18	-0.63	0.18	-1.16	0.13	-1.16	-0.02	-0.78	15.74	-0.63	0.00	0.00	-1.66	0.00	0.00	0.00	-10.00	0.00	0.00	0.00	0.00
		+10%	0.61	0.93	-0.32	1.52	1.42	0.19	2.85	0.45	0.45	1.34	1.34	-7.10	1.09	-0.33	2.06	-0.24	2.06	0.03	1.35	-15.54	1.10	0.00	0.00	2.89	0.00	0.00	0.00	10.00	0.00	0.00	0.00	0.00
		+25%	2.04	3.10	-1.08	5.06	4.76	0.62	9.45	1.48	1.48	4.46	4.46	-23.90	3.59	-1.11	6.84	-0.80	6.84	0.10	4.50	-39.10	3.63	0.00	0.00	9.58	0.00	0.00	0.00	25.00	0.00	0.00	0.00	0.00
	Hunting	-25%	4.79	6.27	2.86	5.80	5.16	1.04	1.80	1.87	1.87	4.35	4.35	4.48	9.11	2.91	7.87	7.02	7.87	0.11	4.46	4.59	45.66	0.00	0.00	1.86	0.00	0.00	0.00	0.00	-25.00	0.00	0.00	0.00
		-10%	1.80	2.35	1.08	2.17	1.93	0.39	0.68	0.70	0.70	1.64	1.64	1.69	5.68	1.10	2.94	2.63	2.94	0.04	1.67	1.72	17.48	0.00	0.00	0.70	0.00	0.00	0.00	0.00	-10.00	0.00	0.00	0.00
		+10%	-1.65	-2.14	-1.00	-1.98	-1.77	-0.36	-0.63	-0.64	-0.64	-1.50	-1.50	-1.54	-7.92	-1.02	-2.68	-2.40	-2.68	-0.04	-1.53	-1.58	-16.35	0.00	0.00	-0.65	0.00	0.00	0.00	0.00	10.00	0.00	0.00	0.00
		+25%	-3.84	-4.97	-2.34	-4.59	-4.10	-0.85	-1.47	-1.49	-1.49	-3.49	-3.49	-3.59	-22.86	-2.38	-6.22	-5.59	-6.22	-0.09	-3.57	-3.67	-38.43	0.00	0.00	-1.52	0.00	0.00	0.00	0.00	25.00	0.00	0.00	0.00
	Users of Env. edu. activ	-25%	-2.44	-2.66	-2.23	-2.57	-2.36	-0.80	-1.27	-25.67	-0.90	-2.09	-2.09	-2.13	-1.50	-2.26	-2.80	-2.84	-2.80	-2.05	-2.12	-2.17	-1.54	0.00	0.00	-1.30	0.00	0.00	0.00	0.00	0.00	-25.00	0.00	0.00
		-10%	-0.98	-1.07	-0.89	-1.03	-0.95	-0.32	-0.51	-10.32	-0.36	-0.84	-0.84	-0.86	-0.60	-0.91	-1.13	-1.14	-1.13	-0.82	-0.85	-0.87	-0.61	0.00	0.00	-0.52	0.00	0.00	0.00	0.00	0.00	-10.00	0.00	0.00
		+10%	0.98	1.07	0.90	1.04	0.95	0.32	0.51	10.40	0.36	0.84	0.84	0.86	0.60	0.91	1.13	1.14	1.13	0.83	0.86	0.87	0.61	0.00	0.00	0.52	0.00	0.00	0.00	0.00	0.00	10.00	0.00	0.00
		+25%	2.46	2.69	2.25	2.60	2.39	0.80	1.28	26.13	0.91	2.11	2.11	2.16	1.50	2.28	2.83	2.87	2.83	2.07	2.14	2.19	1.54	0.00	0.00	1.31	0.00	0.00	0.00	0.00	0.00	25.00	0.00	0.00
	Tourists	-25%	7.20	6.78	7.38	5.27	6.34	-22.37	12.94	3.53	3.53	5.67	5.67	5.79	4.13	7.46	7.04	9.47	7.04	0.27	5.76	5.87	4.21	0.00	0.00	13.11	0.00	0.00	0.00	0.00	0.00	0.00	-25.00	0.00
		-10%	2.84	2.67	2.91	2.08	2.50	-8.75	5.12	1.40	1.40	2.24	2.24	2.29	1.65	2.95	2.78	3.74	2.78	0.11	2.28	2.32	1.68	0.00	0.00	5.19	0.00	0.00	0.00	0.00	0.00	0.00	-10.00	0.00
		+10%	-2.80	-2.63	-2.87	-2.04	-2.46	8.50	-5.05	-1.37	-1.37	-2.21	-2.21	-2.25	-1.63	-2.90	-2.73	-3.67	-2.73	-0.11	-2.24	-2.28	-1.66	0.00	0.00	-5.11	0.00	0.00	0.00	0.00	0.00	0.00	10.00	0.00
		+25%	-6.90	-6.49	-7.08	-5.04	-6.07	20.78	-12.49	-3.39	-3.39	-5.46	-5.46	-5.57	-4.06	-7.16	-6.73	-9.06	-6.73	-0.27	-5.54	-5.65	-4.13	0.00	0.00	-12.65	0.00	0.00	0.00	0.00	0.00	0.00	25.00	0.00
	Navigation	-25%	7.54	7.08	7.73	5.51	6.63	3.67	-14.85	3.69	3.69	5.91	5.91	6.03	4.28	7.83	7.36	9.89	7.36	0.28	6.00	6.12	4.36	0.00	0.00	13.72	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-25.00
		-10%	2.90	2.72	2.97	2.12	2.55	1.41	-5.31	1.42	1.42	2.28	2.28	2.32	1.67	3.00	2.83	3.80	2.83	0.11	2.31	2.36	1.70	0.00	0.00	5.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-10.00
		+10%	-2.75	-2.58	-2.81	-2.01	-2.42	-1.34	4.54	-1.35	-1.35	-2.17	-2.17	-2.22	-1.61	-2.84	-2.68	-3.61	-2.68	-0.11	-2.21	-2.25	-1.64	0.00	0.00	-5.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.00
		+25%	-6.60	-6.22	-6.76	-4.84	-5.81	-3.22	10.05	-3.25	-3.25	-5.25	-5.25	-5.35	-3.92	-6.83	-6.45	-8.69	-6.45	-0.26	-5.32	-5.42	-3.99	0.00	0.00	-12.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	25.00

Table B2. Model results obtained by varying the model's parameters, one at a time, by ±10% and ±25%, departing from steady-state conditions. Results are expressed as % variation, at the end of the 21st century, with respect to the steady-state conditions. For the parameters' description please refer to Appendix A.

		Regulating ES					Cultural ES				Provisioning ES				Habitats					Fauna			Heritage		Channels	Actors								
parameter	variation	Clim. reg.	Waste treat.	Erosion prev. 1	Erosion prev. 2	Lifecycle maint	Tourism	Navigation	Info. cogn. dev	Tradition	Artisanal fish.	Recreat. fish.	Clam harv.	Hunting	Salt marshes	Seagrasses	Bare (intertida	Benthic diaton	Macroalgae	Target fish spp	Clam	Birds	Density cult. H	Tradit. Knowle	Channels	Residents	Art. fishermen	Recr. fisherme	Clam fisherme	Hunters	Users of Env. e	Tourists	Boat owners
k0_eco_process	-25%	-4.86	0.44	-8.44	0.38	-1.64	-2.77	-2.40	-0.90	-0.90	-1.52	-1.52	-1.54	-1.16	-8.55	0.54	0.54	0.54	-0.07	-1.53	-1.55	-1.18	0.00	0.00	-2.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	-2.00	0.18	-3.47	0.15	-0.67	-1.14	-0.98	-0.37	-0.37	-0.62	-0.62	-0.63	-0.47	-3.51	0.22	0.22	0.22	-0.03	-0.63	-0.64	-0.48	0.00	0.00	-1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	2.07	-0.18	3.60	-0.16	0.70	1.18	1.00	0.38	0.38	0.64	0.64	0.65	0.49	3.65	-0.23	-0.23	-0.23	0.03	0.65	0.66	0.49	0.00	0.00	1.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	5.33	-0.46	9.25	-0.40	1.81	3.03	2.56	0.98	0.98	1.65	1.65	1.68	1.24	9.38	-0.57	-0.58	-0.57	0.07	1.67	1.70	1.26	0.00	0.00	2.62	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k1_eco_process	-25%	-9.46	-3.66	-0.02	-10.66	-4.43	-0.33	-3.19	-2.48	-2.48	-3.92	-3.92	-4.01	-2.84	-0.02	-24.00	-0.30	0.04	-0.17	-3.99	-4.08	-2.90	0.00	0.00	-3.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	-4.04	-1.56	-0.01	-4.55	-1.89	-0.14	-1.34	-1.05	-1.05	-1.66	-1.66	-1.70	-1.19	-0.01	-10.25	-0.12	0.02	-0.07	-1.69	-1.73	-1.21	0.00	0.00	-1.37	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	4.41	1.70	0.01	4.97	2.07	0.15	1.42	1.15	1.15	1.80	1.80	1.85	1.27	0.01	11.21	0.13	-0.02	0.08	1.84	1.88	1.30	0.00	0.00	1.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	11.82	4.56	0.03	13.31	5.54	0.38	3.72	3.06	3.06	4.79	4.79	4.91	3.33	0.03	30.07	0.35	-0.04	0.20	4.89	5.01	3.41	0.00	0.00	3.82	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k2_eco_process	-25%	-0.37	-7.53	-0.41	-0.25	-4.12	-0.07	0.50	-1.91	-1.91	-3.62	-3.62	-3.70	-2.59	-0.43	-0.30	-21.38	-0.30	-0.14	-3.68	-3.77	-2.64	0.00	0.00	0.52	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	-0.15	-3.19	-0.17	-0.10	-1.74	-0.03	0.21	-0.81	-0.81	-1.52	-1.52	-1.56	-1.08	-0.18	-0.12	-9.06	-0.12	-0.06	-1.55	-1.59	-1.10	0.00	0.00	0.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	0.16	3.44	0.18	0.11	1.88	0.03	-0.22	0.87	0.87	1.63	1.63	1.67	1.14	0.19	0.13	9.81	0.13	0.06	1.66	1.70	1.17	0.00	0.00	-0.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	0.41	9.14	0.46	0.28	4.99	0.08	-0.57	2.32	2.32	4.30	4.30	4.41	2.97	0.48	0.33	26.06	0.33	0.16	4.39	4.50	3.04	0.00	0.00	-0.59	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k3_eco_process	-25%	-0.05	-8.41	-0.11	-7.07	-5.56	-0.21	-1.72	-0.57	-0.57	-4.91	-4.91	-5.01	-3.54	-0.11	0.03	-0.47	-23.95	-0.04	-4.99	-5.10	-3.62	0.00	0.00	-1.76	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	-0.02	-3.59	-0.05	-3.02	-2.37	-0.09	-0.72	-0.24	-0.24	-2.08	-2.08	-2.13	-1.48	-0.05	0.01	-0.19	-10.24	-0.02	-2.12	-2.17	-1.52	0.00	0.00	-0.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	0.02	3.93	0.05	3.30	2.60	0.09	0.77	0.26	0.26	2.26	2.26	2.31	1.58	0.05	-0.02	0.20	11.23	0.02	2.30	2.36	1.62	0.00	0.00	0.79	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	0.06	10.53	0.13	8.87	6.97	0.24	2.02	0.70	0.70	6.01	6.01	6.16	4.16	0.13	-0.05	0.53	30.15	0.04	6.13	6.29	4.25	0.00	0.00	2.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k_0_0_eco_function	-25%	-15.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	-6.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	6.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	15.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k_1_0_eco_function	-25%	-10.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	-4.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	4.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	10.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k_1_1_eco_function	-25%	0.00	-3.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	0.00	-1.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	0.00	1.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	0.00	3.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k_2_1_eco_function	-25%	0.00	-8.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	0.00	-3.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	0.00	3.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	0.00	8.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k_3_1_eco_function	-25%	0.00	-8.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	0.00	-8.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	0.00	-8.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	0.00	-8.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k_4_1_eco_function	-25%	0.00	-8.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	0.00	-8.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	0.00	-8.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	0.00	-8.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k_0_2_eco_function	-25%	3.46	3.04	-22.24	2.32	2.94	-0.65	-17.59	-0.72	-0.72	2.41	2.41	2.49	1.52	3.77	3.20	4.37	3.20	-0.10	2.48	2.56	1.57	0.00	0.00	-17.73	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	1.38	1.21	-8.68	0.92	1.17	-0.26	-6.97	-0.28	-0.28	0.96	0.96	1.00	0.61	1.50	1.28	1.74	1.28	-0.04	0.99	1.02	0.63	0.00	0.00	-7.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	-1.37	-1.20	8.40	-0.92	-1.17	0.25	6.90	0.28	0.28	-0.96	-0.96	-0.99	-0.61	-1.49	-1.27	-1.73	-1.27	0.04	-0.98	-1.02	-0.63	0.00	0.00	6.95	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	-3.41	-2.99	20.46	-2.28	-2.90	0.62	17.10	0.68	0.68	-2.38	-2.38	-2.46	-1.52	-3.72	-3.16	-4.31	-3.16	0.10	-2.45	-2.53	-1.57	0.00	0.00	17.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k_1_3_eco_function	-25%	1.55	1.36	1.65	-10.37	1.32	-0.29	-7.84	-0.32	-0.32	1.08	1.08	1.12	0.69	1.69	1.44	1.96	1.44	-0.04	1.11	1.15	0.71	0.00	0.00	-7.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	0.62	0.54	0.66	-4.11	0.53	-0.12	-3.13	-0.13	-0.13	0.43	0.43	0.45	0.27	0.67	0.57	0.78	0.57	-0.02	0.44	0.46	0.28	0.00	0.00	-3.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	-0.62	-0.54	-0.66	4.06	-0.52	0.11	3.11	0.13	0.13	-0.43	-0.43	-0.45	-0.27	-0.67	-0.57	-0.78	-0.57	0.02	-0.44	-0.46	-0.28	0.00	0.00	3.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	-1.54	-1.35	-1.64	10.06	-1.31	0.28	7.76	0.31	0.31	-1.08	-1.08	-1.11	-0.69	-1.68	-1.43	-1.95	-1.43	0.04	-1.11	-1.14	-0.71	0.00	0.00	7.82	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k_3_3_eco_function	-25%	1.03	0.91	1.10	-6.88	0.88	-0.19	-5.22	-0.21	-0.21	0.72	0.72	0.74	0.46	1.12	0.96	1.30	0.96	-0.03	0.74	0.77	0.47	0.00	0.00	-5.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	0.41	0.36	0.44	-2.73	0.35	-0.08	-2.08	-0.08	-0.08	0.29	0.29	0.30	0.18	0.45	0.38	0.52	0.38	-0.01	0.30	0.31	0.19	0.00	0.00	-2.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	-0.41	-0.36	-0.44	2.71	-0.35	0.08	2.08	0.08	0.08	-0.29	-0.29	-0.30	-0.18	-0.45	-0.38	-0.52	-0.38	0.01	-0.30	-0.31	-0.19	0.00	0.00	2.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	-0.41	-0.36	-0.44	2.71	-0.35	0.08	2.08	0.08	0.08	-0.29	-0.29	-0.30	-0.18	-0.45	-0.38	-0.52	-0.38	0.01	-0.30	-0.31	-0.19	0.00	0.00	2.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k_4_3_eco_function	-25%	0.86	0.75	0.91	-5.67	0.73	-0.16	-4.33	-0.18	-0.18	0.60	0.60	0.62	0.38	0.94	0.80	1.08	0.80	-0.02	0.62	0.64	0.39	0.00	0.00	-4.37	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	0.34	0.30	0.37	-2.27	0.29	-0.06	-1.73	-0.07	-0.07	0.24	0.24	0.25	0.15	0.37	0.32	0.43	0.32	-0.01	0.25	0.25	0.16	0.00	0.00	-1.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	-0.34	-0.30	-0.37	2.27	-0.29	0.06	1.73	0.07	0.07	-0.24	-0.24	-0.25	-0.15	-0.37	-0.32	-0.43	-0.32	0.01	-0.25	-0.25	-0.16	0.00	0.00	1.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	-0.86	-0.75	-0.91	5.68	-0.73	0.16	4.34	0.18	0.18	-0.60	-0.60	-0.62	-0.38	-0.94	-0.79	-1.08	-0.79	0.02	-0.62	-0.64	-0.39	0.00	0.00	4.37	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k_0_4_eco_function	-25%	-1.03	-1.22	-1.20	-0.57	-6.70	-0.19	1.68	-0.24	-0.24	-6.55	-6.55	-6.58	-6.00	-1.23	-0.78	-2.44	-0.78	-0.01	-6.57	-6.60	-6.03	0.00	0.00	1.69	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	-0.41	-0.49	-0.48	-0.23	-2.70	-0.08	0.67	-0.09	-0.09	-2.63	-2.63	-2.64	-2.40	-0.49	-0.31	-0.98	-0.31	0.00	-2.64	-2.65	-2.42	0.00	0.00	0.68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	0.41	0.49	0.48	0.23	2.72	0.08	-0.68	0.09	0.09	2.65	2.65	2.66	2.41	0.49	0.31	0.98	0.31	0.00	2.66	2.67	2.42	0.00	0.00	-0.68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	1.02	1.22	1.20	0.56	6.84	0.19	-1.70	0.23	0.23	6.66	6.66	6.69	6.03	1.23	0.77	2.46	0.77	0.01	6.69	6.72	6.06	0.00	0.00	-1.71	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k_1_4_eco_function	-25%	-0.82	-0.98	-0.96	-0.46	-5.39	-0.15	1.35	-0.19	-0.19	-5.27	-5.27	-5.29	-4.82	-0.98	-0.62	-1.95	-0.62	-0.01	-5.28	-5.30	-4.84	0.00	0.00	1.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	-0.33	-0.39	-0.39	-0.18	-2.16	-0.06	0.54	-0.08	-0.08	-2.11	-2.11	-2.12	-1.93	-0.39	-0.25	-0.78	-0.25	0.00	-2.12	-2.13	-1.93	0.00	0.00	0.54	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	0.33	0.39	0.38	0.18	2.17	0.06	-0.54	0.07	0.07	2.12	2.12	2.13	1.93	0.39	0.25	0.78	0.25	0.00	2.13	2.13	1.93	0.00	0.00	-0.54	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	0.82	0.97	0.96	0.45	5.44	0.15	-1.35	0.19	0.19	5.31	5.31	5.33	4.81	0.98	0.61	1.96	0.61	0.01	5.32	5.35	4.84	0.00	0.00	-1.36	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k_2_4_eco_function	-25%	-0.82	-0.97	-0.96	-0.46	-5.33	-0.15	1.34	-0.19	-0.19	-5.21	-5.21	-5.23	-4.78	-0.98	-0.62	-1.95	-0.62	-0.01	-5.23	-5.25	-4.80	0.00	0.00	1.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	-0.33	-0.39	-0.38	-0.18	-2.15	-0.06	0.54	-0.08	-0.08	-2.10	-2.10	-2.11	-1.92	-0.39	-0.25	-0.78	-0.25	0.00	-2.11	-2.12	-1.93	0.00	0.00	0.54	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	0.33	0.39	0.39	0.18	2.18	0.06	-0.54	0.07	0.07	2.13	2.13	2.14	1.93	0.39	0.25	0.79	0.25	0.00	2.13	2.14	1.94	0.00	0.00	-0.55	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	0.82	0.98	0.97	0.45	5.51	0.15	-1.36	0.19	0.19	5.36	5.36	5.38	4.85	0.98	0.62	1.97	0.62	0.01	5.38	5.40	4.87	0.00	0.00	-1.37	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k_3_4_eco_function	-25%	-1.03	-1.22	-1.20	-0.57	-6.73	-0.19	1.68	-0.24	-0.24	-6.58	-6.58	-6.60	-6.02	-1.23	-0.78	-2.44	-0.78	-0.01	-6.60	-6.62	-6.05	0.00	0.00	1.69	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	-0.41	-0.49	-0.48	-0.23	-2.70	-0.08	0.67	-0.09	-0.09	-2.64	-2.64	-2.65	-2.41	-0.49	-0.31	-0.98	-0.31	0.00	-2.65	-2.66	-2.42	0.00	0.00	0.68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	0.41	0.49	0.48	0.23	2.72	0.08	-0.68	0.09	0.09	2.65	2.65	2.66	2.41	0.49	0.31	0.98	0.31	0.00	2.66	2.67	2.42	0.00	0.00	-0.68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	1.02	1.21	1.20	0.56	6.81	0.19	-1.69	0.23	0.23	6.64	6.64	6.67	6.01	1.23	0.77	2.45	0.77	0.01	6.66	6.69	6.04	0.00	0.00	-1.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k_4_4_eco_function	-25%	-0.41	-0.49	-0.48	-0.23	-2.71	-0.08	0.67	-0.09	-0.09	-2.64	-2.64	-2.65	-2.41	-0.49	-0.31	-0.98	-0.31	0.00	-2.65	-2.66	-2.42	0.00	0.00	0.68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	-0.16	-0.19	-0.19	-0.09	-1.08	-0.03	0.27	-0.04	-0.04	-1.06	-1.06	-1.06	-0.96	-0.20	-0.12	-0.39	-0.12	0.00	-1.06	-1.06	-0.97	0.00	0.00	0.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	0.16	0.19	0.19	0.09	1.08	0.03	-0.27	0.04	0.04	1.06	1.06	1.06	0.96	0.20	0.12	0.39	0.12	0.00	1.06	1.06	0.96	0.00	0.00	-0.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	0.41	0.49	0.48	0.23	2.71	0.08	-0.68	0.09	0.09	2.64	2.64	2.65	2.40	0.49	0.31	0.98	0.31	0.00	2.65	2.66	2.41	0.00	0.00	-0.68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k0_growth	-25%	-6.75	-8.78	-4.09	-8.10	-7.23	-1.51	-2.83	-2.65	-2.65	-57.34	-57.34	-6.45	-4.41	-4.16	-10.93	-9.86	-10.93	-0.17	-57.41	-6.57	-4.51	0.00	0.00	-2.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	-2.53	-3.32	-1.51	-3.06	-2.73	-0.56	-1.07	-1.00	-1.00	-20.36	-20.36	-2.43	-1.66	-1.54	-4.14	-3.72	-4.14	-0.06	-20.40	-2.48	-1.70	0.00	0.00	-1.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

		Regulating ES					Cultural ES				Provisioning ES				Habitats					Fauna			Heritage		Channels	Actors							
parameter	variation	Clim. reg.	Waste treat.	Erosion prev. 1	Erosion prev. 2	Lifecycle maint	Tourism	Navigation	Info. cogn. dev	Tradition	Artisanal fish.	Recreat. fish.	Clam harv.	Hunting	Salt marshes	Seagrasses	Bare (intertida	Benthic diaton	Macroalgae	Target fish spp	Clam	Birds	Density cult. H	Tradit. Knowle	Channels	Residents	Art. fishermen	Recr. fisherme	Clam fisherme	Hunters	Users of Env. e	Tourists	Boat owners
	+10%	2.27	3.00	1.34	2.77	2.45	0.50	0.97	0.90	0.90	17.67	17.67	2.18	1.48	1.36	3.74	3.35	3.74	0.06	17.72	2.23	1.51	0.00	0.00	0.99	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	5.24	6.94	3.06	6.41	5.67	1.14	2.23	2.08	2.08	40.22	40.22	5.04	3.40	3.11	8.67	7.75	8.67	0.13	40.35	5.14	3.48	0.00	0.00	2.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k1_growth	-25%	4.54	6.98	-2.55	11.45	10.47	1.32	20.85	3.29	3.29	9.79	9.79	-51.39	7.86	-2.63	15.47	-1.93	15.47	0.24	9.87	-51.36	7.96	0.00	0.00	21.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	1.51	2.34	-0.89	3.85	3.39	0.43	6.96	1.09	1.09	3.18	3.18	-15.93	2.61	-0.91	5.19	-0.67	5.19	0.08	3.21	-15.91	2.64	0.00	0.00	7.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	-1.20	-1.87	0.74	-3.09	-2.66	-0.34	-5.58	-0.87	-0.87	-2.51	-2.51	12.21	-2.09	0.76	-4.17	0.56	-4.17	-0.07	-2.53	12.18	-2.11	0.00	0.00	-5.64	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	-2.59	-4.06	1.62	-6.72	-5.71	-0.72	-12.09	-1.89	-1.89	-5.40	-5.40	25.94	-4.53	1.66	-9.05	1.23	-9.05	-0.15	-5.44	25.89	-4.57	0.00	0.00	-12.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k2_growth	-25%	-4.30	-5.55	-2.63	-5.12	-4.59	-0.95	-1.62	-1.66	-1.66	-3.89	-3.89	-4.00	-45.05	-2.68	-6.95	-6.25	-6.95	-0.10	-3.98	-4.09	-45.25	0.00	0.00	-1.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	-1.74	-2.26	-1.05	-2.08	-1.86	-0.38	-0.66	-0.67	-0.67	-1.58	-1.58	-1.62	-17.57	-1.08	-2.82	-2.53	-2.82	-0.04	-1.61	-1.66	-17.64	0.00	0.00	-0.68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	1.70	2.21	1.02	2.05	1.82	0.37	0.65	0.66	0.66	1.55	1.55	1.59	16.06	1.04	2.77	2.48	2.77	0.04	1.58	1.63	16.11	0.00	0.00	0.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	4.09	5.36	2.44	4.96	4.41	0.89	1.57	1.60	1.60	3.74	3.74	3.85	37.12	2.48	6.72	6.00	6.72	0.09	3.83	3.94	37.24	0.00	0.00	1.62	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k0_carryingCap	-25%	-3.54	-4.64	-2.11	-4.28	-3.81	-0.79	-1.53	-1.40	-1.40	-27.50	-27.50	-3.41	-2.35	-2.14	-5.78	-5.20	-5.78	-0.09	-27.54	-3.47	-2.40	0.00	0.00	-1.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	-1.43	-1.88	-0.85	-1.73	-1.54	-0.32	-0.61	-0.57	-0.57	-11.21	-11.21	-1.38	-0.94	-0.86	-2.34	-2.10	-2.34	-0.04	-11.23	-1.40	-0.96	0.00	0.00	-0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	1.45	1.91	0.86	1.77	1.57	0.32	0.61	0.57	0.57	11.50	11.50	1.39	0.94	0.87	2.39	2.14	2.39	0.04	11.53	1.42	0.96	0.00	0.00	0.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	3.67	4.85	2.16	4.48	3.97	0.80	1.53	1.45	1.45	29.28	29.28	3.52	2.36	2.20	6.06	5.42	6.06	0.09	29.37	3.59	2.42	0.00	0.00	1.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k1_carryingCap	-25%	2.10	3.26	-1.27	5.39	4.68	0.59	9.67	1.52	1.52	4.39	4.39	-21.67	3.62	-1.30	7.27	-0.96	7.27	0.12	4.43	-21.64	3.66	0.00	0.00	9.79	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	0.82	1.27	-0.49	2.10	1.82	0.23	3.78	0.59	0.59	1.71	1.71	-8.44	1.42	-0.51	2.83	-0.37	2.83	0.05	1.73	-8.43	1.43	0.00	0.00	3.82	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	-0.79	-1.23	0.48	-2.03	-1.76	-0.22	-3.67	-0.58	-0.58	-1.66	-1.66	8.16	-1.38	0.49	-2.73	0.36	-2.73	-0.04	-1.67	8.14	-1.39	0.00	0.00	-3.71	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	-1.92	-3.00	1.16	-4.94	-4.29	-0.55	-8.97	-1.41	-1.41	-4.05	-4.05	19.89	-3.37	1.19	-6.66	0.88	-6.66	-0.11	-4.08	19.85	-3.40	0.00	0.00	-9.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k2_carryingCap	-25%	-2.71	-3.52	-1.64	-3.25	-2.90	-0.60	-1.06	-1.05	-1.05	-2.48	-2.48	-2.55	-25.35	-1.67	-4.40	-3.95	-4.40	-0.06	-2.53	-2.60	-25.41	0.00	0.00	-1.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	-1.05	-1.37	-0.64	-1.26	-1.13	-0.23	-0.40	-0.41	-0.41	-0.96	-0.96	-0.99	-10.13	-0.65	-1.71	-1.54	-1.71	-0.02	-0.98	-1.01	-10.16	0.00	0.00	-0.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	1.02	1.33	0.61	1.23	1.09	0.22	0.38	0.40	0.40	0.92	0.92	0.95	10.11	0.63	1.66	1.49	1.66	0.02	0.94	0.97	10.15	0.00	0.00	0.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	2.49	3.24	1.50	3.00	2.67	0.54	0.92	0.97	0.97	2.25	2.25	2.32	25.25	1.53	4.07	3.64	4.07	0.05	2.30	2.37	25.36	0.00	0.00	0.95	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k0_effic	-25%	4.45	5.88	2.61	5.43	4.81	0.97	1.87	1.76	1.76	1.03	34.70	4.27	2.87	2.65	7.35	6.57	7.35	0.11	34.81	4.35	2.94	0.00	0.00	1.93	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	1.72	2.27	1.01	2.09	1.86	0.38	0.73	0.68	0.68	2.14	13.49	1.65	1.12	1.03	2.83	2.53	2.83	0.04	13.52	1.68	1.14	0.00	0.00	0.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	-1.64	-2.16	-0.98	-1.99	-1.77	-0.36	-0.70	-0.65	-0.65	-4.31	-13.01	-1.58	-1.08	-0.99	-2.69	-2.41	-2.69	-0.04	-13.03	-1.61	-1.10	0.00	0.00	-0.72	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	-3.96	-5.18	-2.37	-4.78	-4.26	-0.88	-1.69	-1.56	-1.56	-14.58	-31.67	-3.80	-2.61	-2.41	-6.45	-5.81	-6.45	-0.10	-31.72	-3.87	-2.67	0.00	0.00	-1.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k1_effic	-25%	1.85	2.43	1.09	2.25	1.99	0.40	0.78	0.73	0.73	14.47	-14.15	1.77	1.20	1.11	3.04	2.72	3.04	0.05	14.51	1.81	1.23	0.00	0.00	0.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	0.73	0.96	0.43	0.88	0.78	0.16	0.31	0.29	0.29	5.72	-4.85	0.70	0.47	0.44	1.19	1.07	1.19	0.02	5.74	0.71	0.49	0.00	0.00	0.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	-0.71	-0.94	-0.42	-0.87	-0.77	-0.16	-0.30	-0.28	-0.28	-5.63	3.80	-0.69	-0.47	-0.43	-1.17	-1.05	-1.17	-0.02	-5.64	-0.70	-0.48	0.00	0.00	-0.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	-1.76	-2.31	-1.05	-2.13	-1.89	-0.39	-0.75	-0.69	-0.69	-13.91	7.61	-1.69	-1.15	-1.06	-2.87	-2.58	-2.87	-0.05	-13.94	-1.72	-1.18	0.00	0.00	-0.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k2_effic	-25%	4.79	6.27	2.86	5.80	5.16	1.04	1.80	1.87	1.87	4.35	4.35	4.48	9.11	2.91	7.87	7.02	7.87	0.11	4.46	4.59	45.66	0.00	0.00	1.86	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	1.80	2.35	1.08	2.17	1.93	0.39	0.68	0.70	0.70	1.64	1.64	1.69	5.68	1.10	2.94	2.63	2.94	0.04	1.67	1.72	17.48	0.00	0.00	0.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	-1.65	-2.14	-1.00	-1.98	-1.77	-0.36	-0.63	-0.64	-0.64	-1.50	-1.50	-1.54	-7.92	-1.02	-2.68	-2.40	-2.68	-0.04	-1.53	-1.58	-16.35	0.00	0.00	-0.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	-3.84	-4.97	-2.34	-4.59	-4.10	-0.85	-1.47	-1.49	-1.49	-3.49	-3.49	-3.59	-22.86	-2.38	-6.22	-5.59	-6.22	-0.09	-3.57	-3.67	-38.43	0.00	0.00	-1.52	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k_clamH	-25%	-0.39	-0.57	0.15	-0.90	-0.96	-0.14	-1.83	-0.29	-0.29	-0.90	-0.90	5.27	-0.71	0.16	-1.23	0.10	-1.23	-0.02	-0.91	40.35	-0.72	0.00	0.00	-1.86	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	-0.35	-0.53	0.18	-0.86	-0.82	-0.11	-1.64	-0.26	-0.26	-0.77	-0.77	4.18	-0.63	0.18	-1.16	0.13	-1.16	-0.02	-0.78	15.74	-0.63	0.00	0.00	-1.66	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	0.61	0.93	-0.32	1.52	1.42	0.19	2.85	0.45	0.45	1.34	1.34	-7.10	1.09	-0.33	2.06	-0.24	2.06	0.03	1.35	-15.54	1.10	0.00	0.00	2.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	2.04	3.10	-1.08	5.06	4.76	0.62	9.45	1.48	1.48	4.46	4.46	-23.90	3.59	-1.11	6.84	-0.80	6.84	0.10	4.50	-39.10	3.63	0.00	0.00	9.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k_self_reg	-25%	3.56	3.13	3.78	2.39	3.03	-0.65	-17.89	-0.72	-0.72	2.48	2.48	2.57	1.58	3.88	3.30	4.50	3.30	-0.10	2.55	2.64	1.63	0.00	0.00	-18.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	1.41	1.24	1.50	0.95	1.20	-0.25	-7.06	-0.28	-0.28	0.99	0.99	1.02	0.63	1.54	1.31	1.79	1.31	-0.04	1.02	1.05	0.65	0.00	0.00	-7.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	-1.40	-1.23	-1.49	-0.94	-1.19	0.25	6.93	0.27	0.27	-0.98	-0.98	-1.02	-0.63	-1.53	-1.30	-1.77	-1.30	0.04	-1.01	-1.04	-0.65	0.00	0.00	6.98	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	-3.48	-3.06	-3.70	-2.33	-2.96	0.60	17.07	0.66	0.66	-2.44	-2.44	-2.52	-1.57	-3.79	-3.23	-4.40	-3.23	0.10	-2.51	-2.59	-1.62	0.00	0.00	17.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
k_lag_sea_ex	-25%	-3.48	-3.06	-3.70	-2.33	-2.96	0.60	17.07	0.66	0.66	-2.44	-2.44	-2.52	-1.57	-3.79	-3.23	-4.40	-3.23	0.10	-2.51	-2.59	-1.62	0.00	0.00	17.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	-10%	-0.15	-0.18	-0.17	-0.08	-0.98	-0.03	0.24	-0.03	-0.03	-0.95	-0.95	-0.96	-0.87	-0.18	-0.11	-0.35	-0.11	0.00	-0.95	-0.96	-0.87	0.00	0.00	0.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+10%	0.15	0.18	0.17	0.08	0.98	0.03	-0.24	0.03	0.03	0.95	0.95	0.96	0.86	0.18	0.11	0.35	0.11	0.00	0.95	0.96	0.87	0.00	0.00	-0.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	+25%	0.15	0.18	0.17	0.08	0.98	0.03	-0.24	0.03	0.03	0.95	0.95	0.96	0.86	0.18	0.11	0.35	0.11	0.00	0.95	0.96	0.87	0.00	0.00	-0.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Appendix C

Additional model results (Appendix to Chapter 3)

Figure C1. ES variation (%) over time under CC_MOSE_15 scenario. Regulating ES (A), provisioning ES (B), cultural ES except tourism (C), tourism (D).

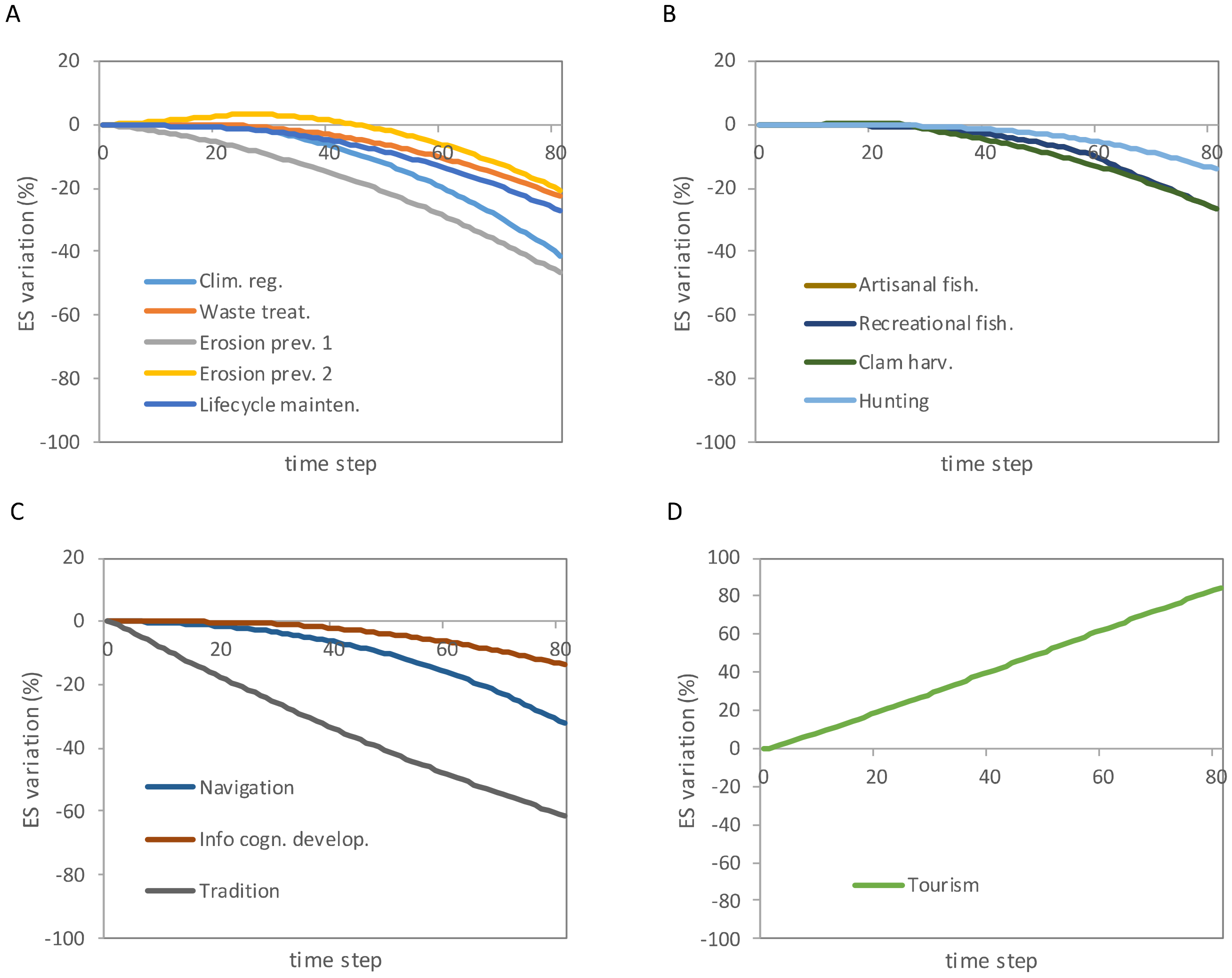


Figure C2. ES variation (%) over time under CC_MOSE_25 scenario. Regulating ES (A), provisioning ES (B), cultural ES except tourism (C), tourism (D).

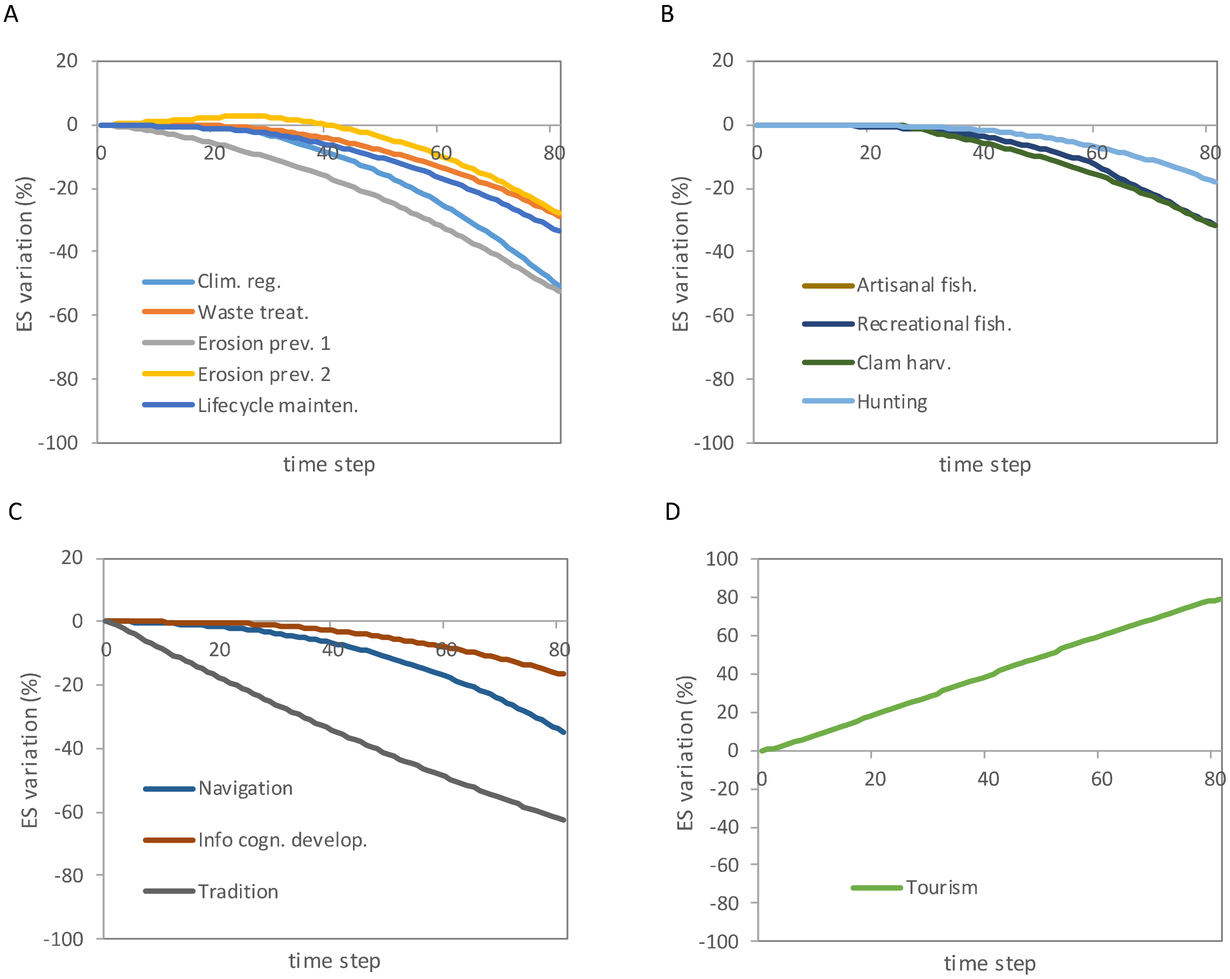
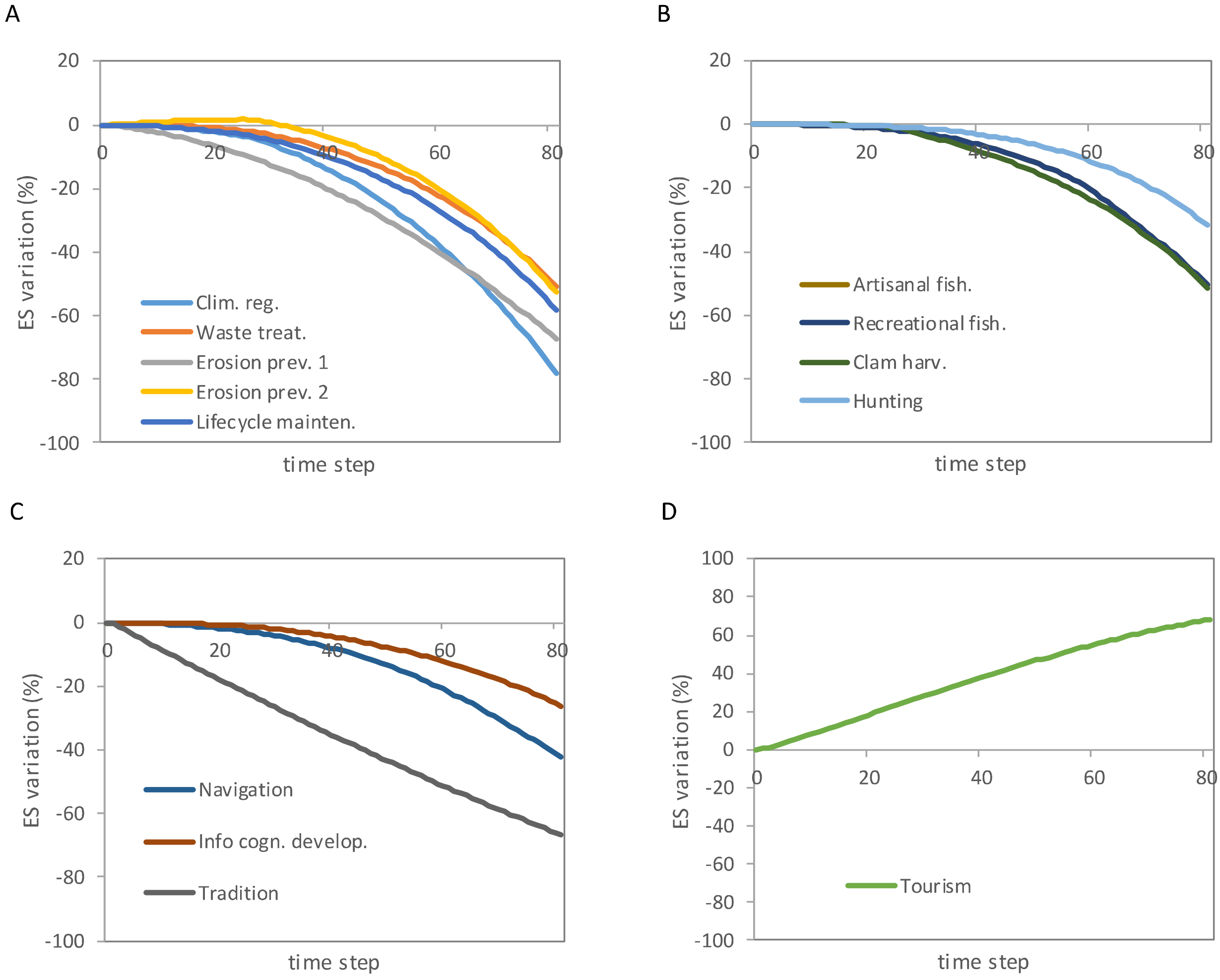


Figure C3. ES variation (%) over time under CC_MOSE_50 scenario. Regulating ES (A), provisioning ES (B), cultural ES except tourism (C), tourism (D).



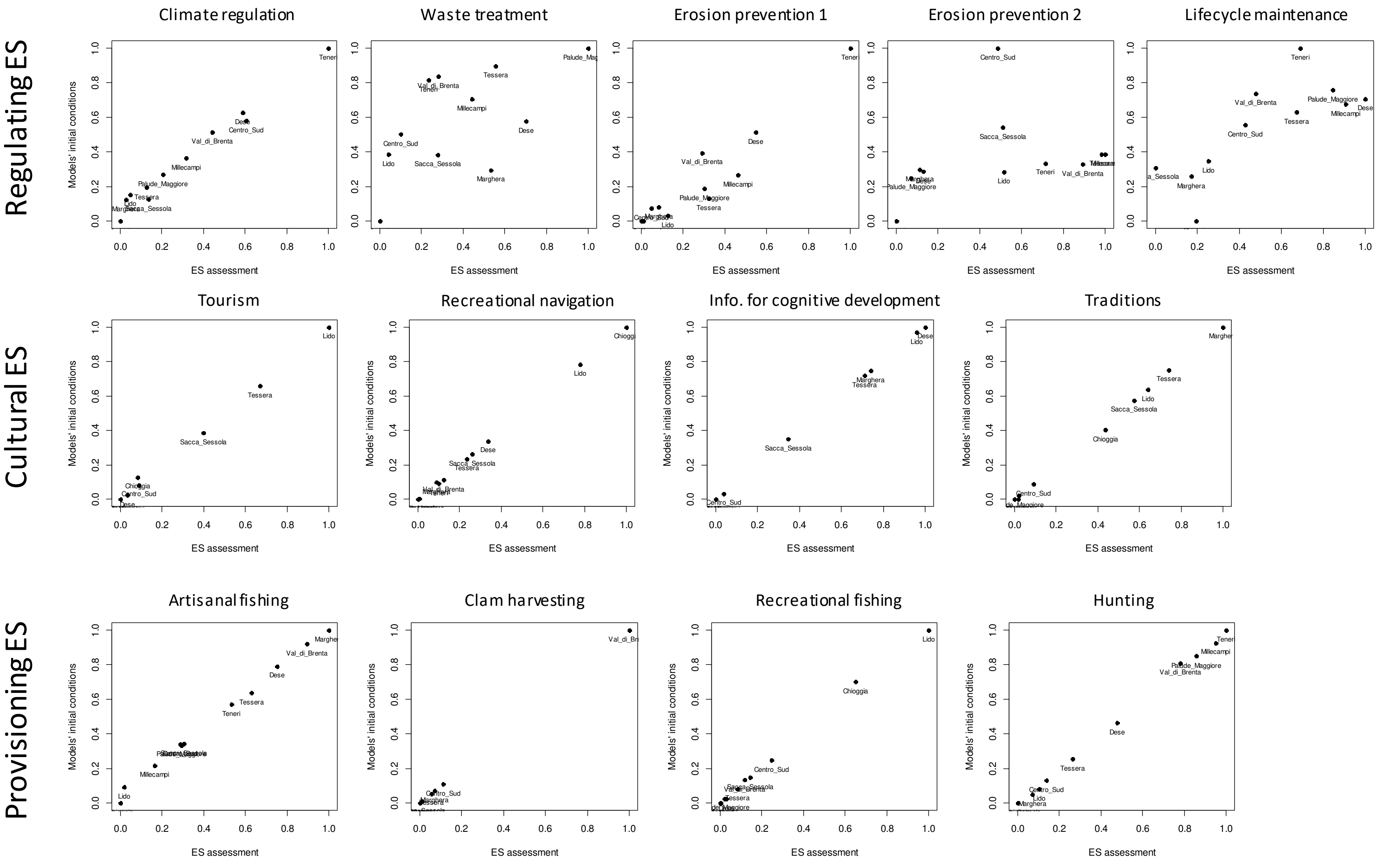
Appendix D

Model setup in the 11 water bodies of the Venice lagoon, and comparison between assessed and modeled ES (Appendix to Chapter 4)

Table D1. Values assigned to the input variables of the models relative to the 11 water bodies of the Venice lagoon (the model parameters and functions, not shown here, remain unchanged with respect to the overall model presented in Chapter 3.

Resources/ Actors	**Variable**	**Indicator**	**Centro-Sud**	**Chioggia**	**Dese**	**Lido**	**Marghera**	**Millecampi**	**Palude Maggiore**	**Sacca Sessola**	**Teneri**	**Tessera**	**Val di Brenta**
Habitats	Salt marshes	surface	15	0	17	1	4	18	13	0	22	6	5
	Seagrasses	surface	92	0	0	3	0	0	0	5	0	0	0
	Bare (intertidal)	surface	10	0	8	3	2	12	40	0	7	15	4
	Benthic diatoms	surface	22	0	4	6	5	24	6	8	6	15	4
	Macroalgae	surface	32	1	9	0	15	6	19	9	3	4	1
Fauna	Target fish species	biomass	1950	90	522	582	756	252	414	318	294	534	246
	Clam	biomass	3060	0	0	0	480	0	0	60	0	360	2040
	Birds	abundance	660	0	480	60	60	1740	1560	0	840	300	300
Channels	Channels	surface	18.5	2	2.5	9	3	3	4	2.5	2	2.5	1
Heritage	Density of cultural heritage	density with respect to surface	32	1	7	6	8	12	12	7	5	8	2
	Traditional knowledge	qualitative scale	32	1	7	6	8	12	12	7	5	8	2
Actors	Residents	n. of people	120	20	0	130	330	0	10	160	0	230	0
	Art. fishermen	n. of people	50	50	50	50	50	50	50	50	50	50	50
	Recr. fishermen	n. of people	500	500	500	500	500	500	500	500	500	500	500
	Clam fishermen	n. of people	400	400	100	100	100	400	100	400	400	100	400
	Hunters	n. of people	500	500	500	500	500	500	500	500	500	500	500
	Users of Env. edu. activities	n. of people	80	0	480	420	420	0	0	180	0	420	0
	Tourists	n. of people	16000	1000	1000	35000	0	0	0	16000	0	31000	0
	Boat owners	n. of boats	4000	4000	6500	13000	3500	1500	1500	6500	1500	6500	1000

Figure D1. Comparison between the ecosystem services (ES) resulting from the models' initial conditions and the results of the current ES assessment, for each ES across the WFD water bodies in the Venice lagoon (values normalized between 0 and 1).



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nata a VENEZIA (prov. VE) il 07/12/1987
residente a VENEZIA in CASTELLO n. 2169/A
Matricola (se posseduta) 956158 Autore della tesi di dottorato dal titolo:

Analysis and management of multiple ecosystem services in social-ecological systems under a changing climate

Dottorato di ricerca in Scienza e Gestione dei Cambiamenti Climatici

Ciclo 30°

Anno di conseguimento del titolo 2019

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Estratto per riassunto della tesi di dottorato

Studente: SILVIA ROVA matricola: 956158

Dottorato: Scienza e Gestione dei Cambiamenti Climatici

Ciclo: 30°

Titolo della tesi: Analysis and management of multiple ecosystem services in social-ecological systems under a changing climate

Abstract (lingua inglese):

This thesis aims to develop new methods for the analysis and management of multiple ecosystem services (ES) in the context of climate change. Taking the Venice lagoon (Italy) as case study, it focuses on two major research challenges in the ES field of study, that are, understanding how multiple ES are co-produced and interact, and how they can be managed sustainably. These challenges are addressed first through a conceptual viewpoint based on the social-ecological systems framework, which distinguishes between ES with “direct” and “mediated” flow type: the first occur directly through some ecological functions, whereas the second require the involvement of human activities, which can generate feedbacks on the same and/or other ES. This viewpoint is then translated into a dynamic ES model, which represents multiple ES together as a single network, accounting for their interactions and for the effects of drivers of change. This represents a significant step forward with respect to current ES models, which provide static snapshots of single ES. The modeling results highlight the importance of including the ES interactions, the absence of which remarkably affects the results. Finally, the modeling application is merged with a quantitative mapping of the multiple ES delivered by the Venice lagoon, aiming at analyzing the sustainability of the ES patterns. This analysis allows to delineate management trajectories for correcting the unsustainable ES patterns and preserving the ES delivery in the face of climate change. The joint analysis of multiple ES and their interactions, along with a sustainability-driven interpretation, seems crucial for the application of ES to management challenges in the context of climate change.

Abstract (lingua italiana):

Questa tesi mira a sviluppare nuove metodologie per l’analisi e la gestione dei servizi ecosistemici (ES) multipli nel contesto dei cambiamenti climatici. Prendendo la laguna di Venezia come caso studio, il lavoro si concentra su due grandi sfide nel campo dei ES: la comprensione di come ES multipli siano coprodotti e interagiscano tra loro, e di come si possa gestirli in modo sostenibile. Viene proposta un’analisi concettuale basata sulla framework per i sistemi socio-ecologici, che distingue tra ES con flusso “diretto” e “mediato”: i primi sono forniti direttamente attraverso funzioni ecologiche, i secondi invece richiedono l’intervento di attività umane, che possono generare feedback sugli stessi o altri ES. Questa analisi viene poi tradotta in un modello dinamico che rappresenta i ES multipli come un’unica rete, che tiene conto delle loro interazioni e degli effetti di drivers esterni. Ciò rappresenta un importante passo avanti rispetto agli attuali modelli di ES, che forniscono un’immagine statica di singoli ES. I risultati del modello evidenziano l’importanza di includere le interazioni tra ES, l’assenza delle quali influenza marcatamente i risultati. Infine, l’applicazione modellistica è unita alla mappatura quantitativa dei ES multipli forniti dalla laguna di Venezia, mirata a valutare la sostenibilità dei pattern di ES. Questa analisi permette di delineare delle traiettorie gestionali per correggere i pattern non sostenibili e per preservare la fornitura di ES in vista dei cambiamenti climatici. L’analisi congiunta di ES multipli e delle loro interazioni, e l’interpretazione in chiave di sostenibilità, appaiono dunque cruciali per l’applicazione dei ES a sfide gestionali, nel contesto dei cambiamenti climatici.

Firma dello studente