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

Keywords:

Ecosystem services interactions; integrated management; social-ecological systems; Venice lagoon; climate change.

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.

# 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 by Rova and Pranovi (2017), turning it into an 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?

# 2. Materials and methods

## *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 by

Rova and Pranovi (2017), which has been translated into the general Petri Net structure shown in Figure 1 (please see below for a brief introduction to Petri nets). The model makes a distinction between ES with direct and mediated flow types (*sensu* Rova and Pranovi (2017)), 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 1A), whereas seafood is a mediated ES because it necessarily depends on fishing activities (Figure 1B). 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.

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 1).

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).

## *2.2. Application to the Venice lagoon.*

The application to the Venice lagoon, Italy (Figure 2) provides a representation of a set of 13 ES produced by the lagoon SES (Table 1), 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; Rova and Pranovi, 2017), and for which a scientific understanding is currently available .The main effort in the building of the model was put in obtaining a topology able to catch the multiple ES, their interactions and the cause-effect relationships with drivers of change, with no ambition of being quantitatively calibrated.

### *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 2). 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 3. The ES with similar characteristics have been grouped together, resulting in six ES “topological” groups, which share a similar net topology (Figure 3). 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 3). Each folded subnet is based on the general structure of Figure 1, 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 3 and more extensively described in Appendix A.

In general, regulating ES follow the general structure developed for the direct flow type ES (Figure 1A), whereas provisioning and cultural ES follow that of a mediated flow type ES (Figure 1B). Then, each subnet presents some variations that account for the specific characteristics of the ES "topological" group. Provisioning 1 ES' subnet (Figure 4B), which refers to low impact fishing and hunting activities, does not include places impacted through negative externalities. In the model, these activities were 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 4C) (cfr. Pranovi et al., 2004, 2003). Cultural 1 and 2 ES (Figure 4D-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 4F) 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 4, 5 and 6 (which are described in this section, section 2.2.2 and 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.

### *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 5A). 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 5B). 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 5C). 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 5D) 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 Rova and Pranovi (2017) for a more thorough discussion of these aspects).

### *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 6).

RSLR (Figure 6A) 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, 2018). 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 6A). 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.

The effects of temperature increase on habitats and fauna (Figure 6B) 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.

### *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.

### *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.

### *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.

### *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. Results

## *3.1. Business as usual, climate change and MOSE scenarios*

Figure 7 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 8) 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 8). 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 over time under CC_MOSE scenarios is shown in Figures C1, C2 and C3 of Appendix C).

### *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 4). 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 4.

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
- Seagrass maintenance & Tourism & Salt marsh maintenance

Combination of four:

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

Figure 9 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. 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 5).

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.

# 4. Discussion

## *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 by Rova and Pranovi (2017), 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* Rova and Pranovi, 2017) 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.

### *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.

# 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 by Rova and Pranovi (2017), 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 1 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.

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# FIGURES

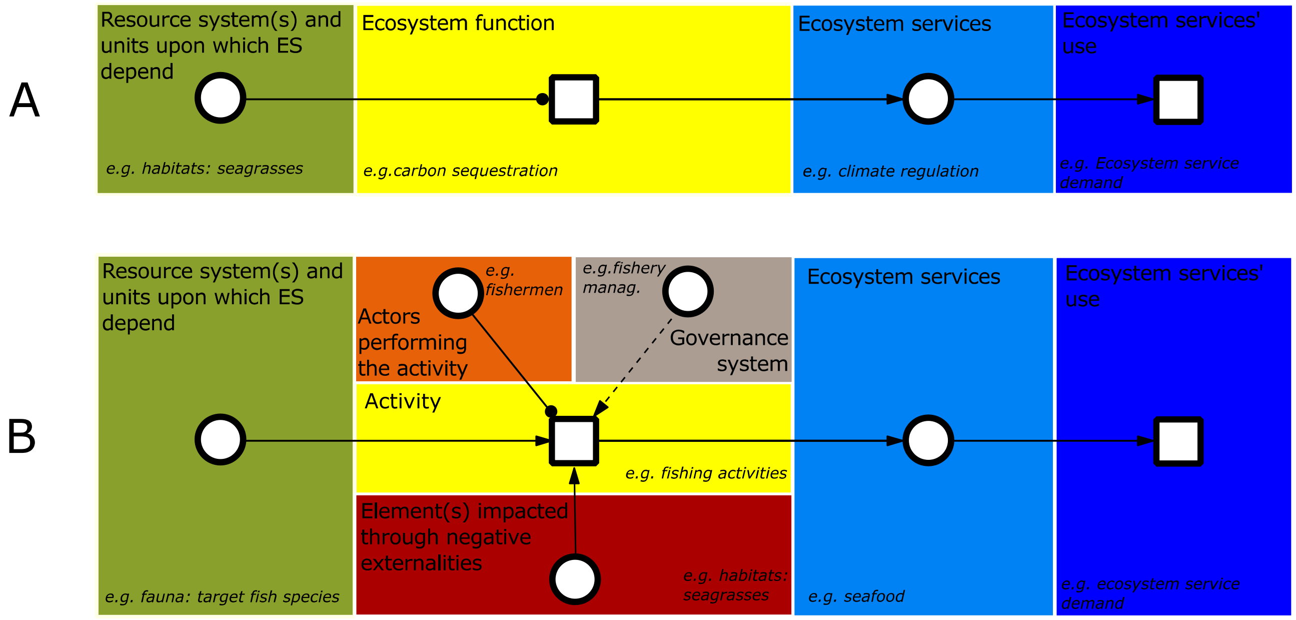

**Figure 1.** General Petri net structure developed for modeling ecosystem services (ES) with direct flow type (regulating ES, A) and with mediated flow type (provisioning and cultural ES, B). Circles = places (i.e. elements of the system); squares = transitions (ecosystem functions, activities, interactions); 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).

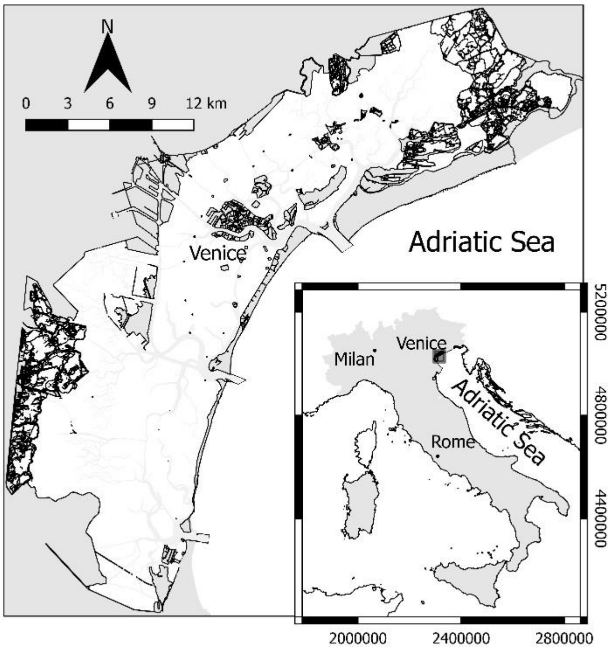

**Figure 2.** Case study area: the Venice lagoon (Italy).

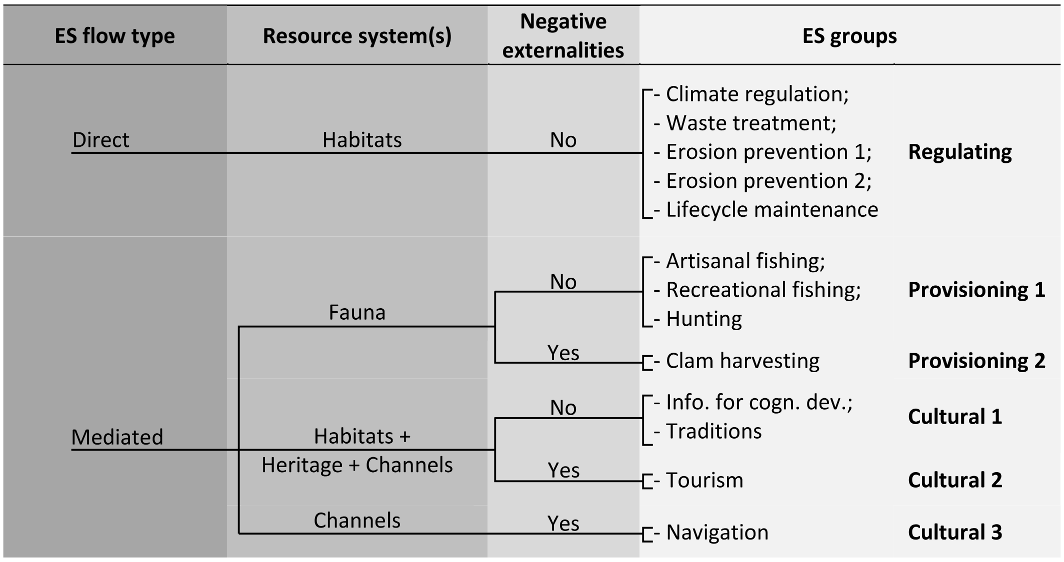

**Figure 3.** Logical flow diagram for the definition of the ecosystem services (ES) “topological” groups

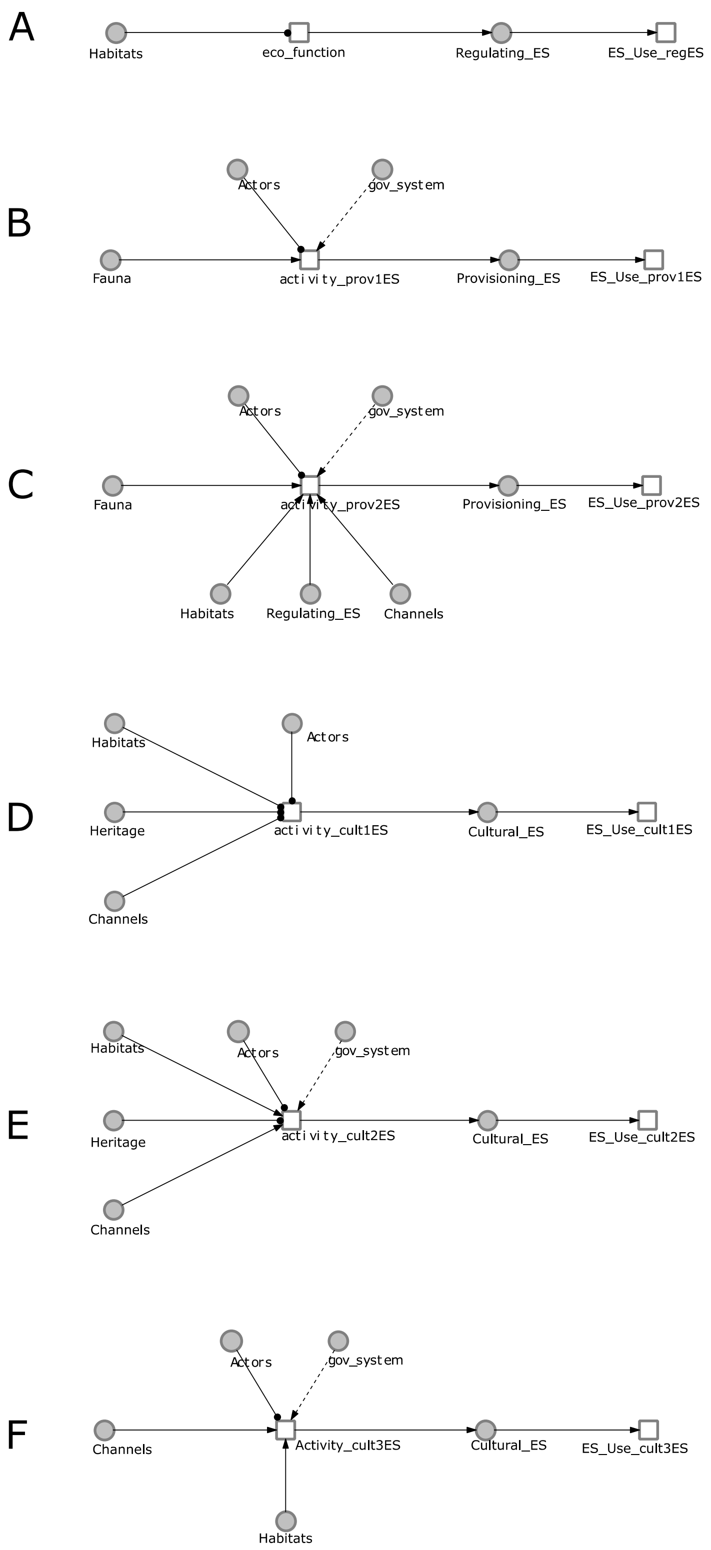

**Figure 4**. Graphical structure of the six ecosystem services (ES) subnets (regulating ES (A), provisioning 1 ES (B), provisioning 2 ES (C), cultural 1 ES (D), cultural 2 ES (E), cultural 3 ES (F)). Circles = places; squares = transitions; solid arrows = normal arcs; solid lines ending with a circle = read arcs; dashed arrows = modifier arcs.

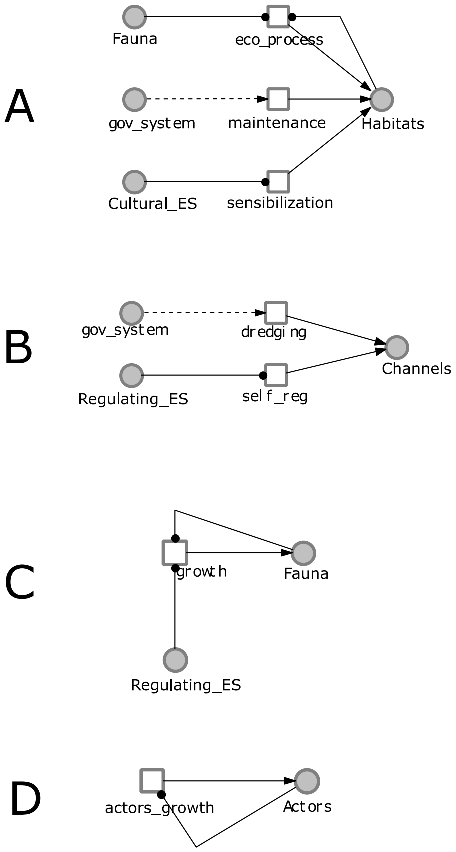

**Figure 5**. Graphical structure of the subnets representing the processes generating the resource units (habitats (A), channels (B) and fauna (C)), and actor’s growth (D). Circles = places; squares = transitions; solid arrows = normal arcs; solid lines ending with a circle = read arcs; dashed arrows = modifier arcs.

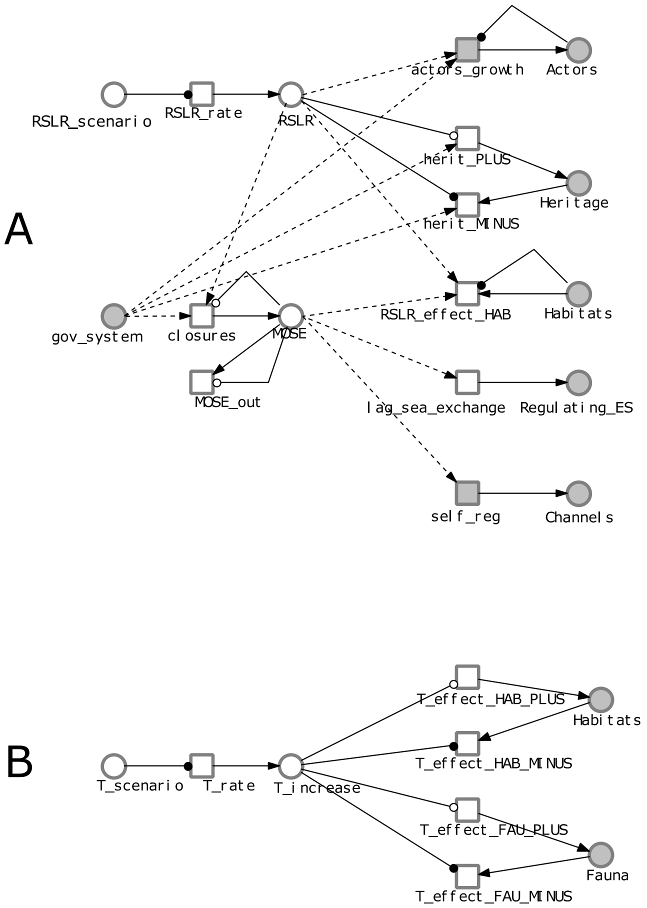

**Figure 6**. Graphical structure of the subnets modeling the effects of relative sea level rise (RSLR) and MOSE system (A) and of temperature (T) increase (B). The following additional model variables were added to model these effects: RSLR_scenario: specifies the RSLR scenario (none, +15 cm, +25 cm 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.

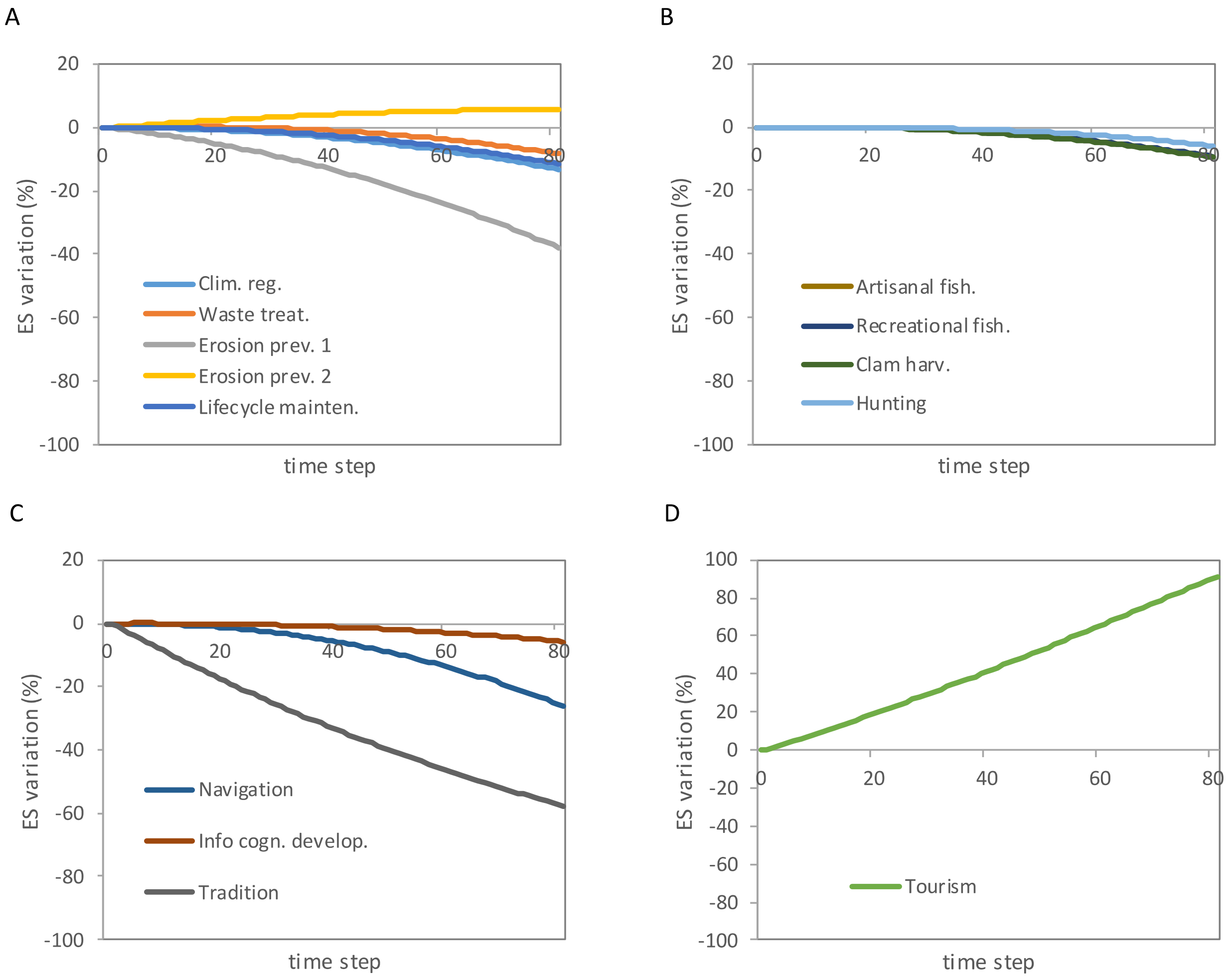

**Figure 7**. Ecosystem services (ES) variation (%) over time under Businness-As-Usual (BAU) scenario. Regulating ES (A), provisioning ES (B), cultural ES except tourism (C), tourism (D).

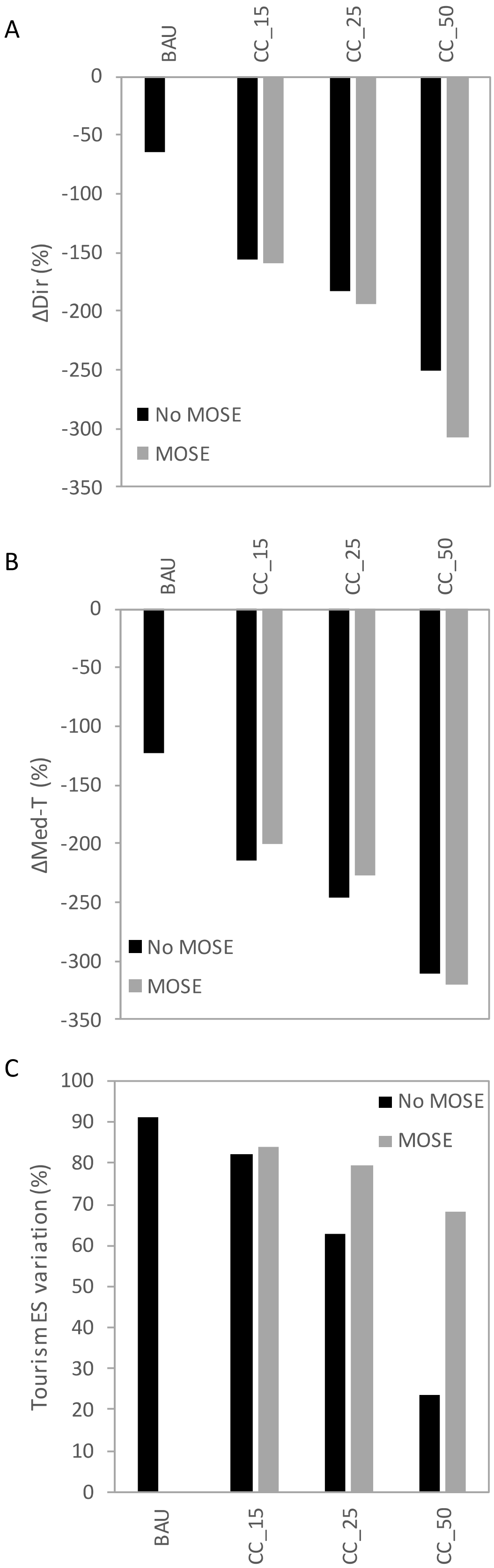

**Figure 8**. Values assumed by the two aggregated indicators ΔDir(A) and ΔMed-T (B), and variation of the Tourism ES (C), at the end of 21st century under the Businness-as-Usual (BAU) and climate change (CC) scenarios, with and without functioning of the MOSE system.

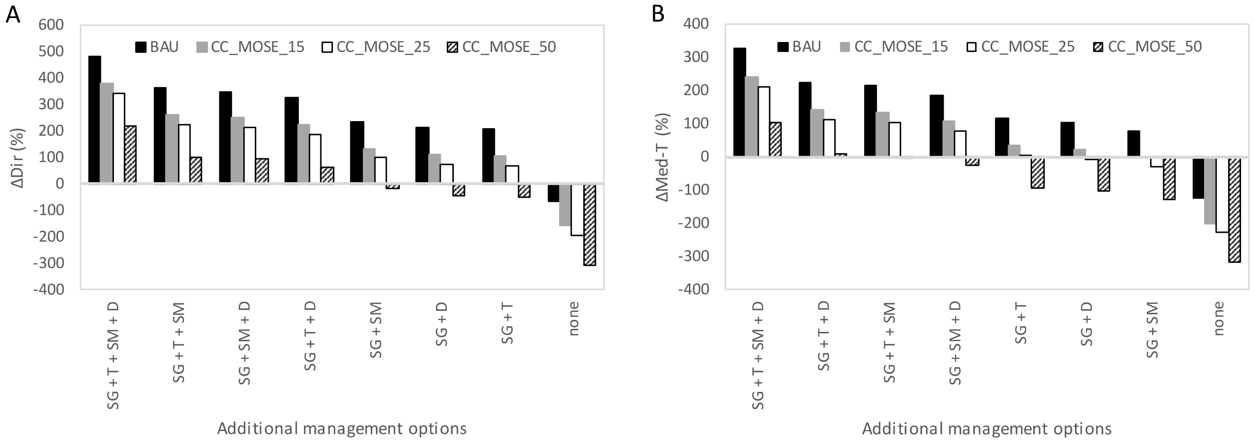

**Figure 9**. Effect of combined additional management options with respect to the two aggregated indicators ΔDir (A) and ΔMed-T (B) under the BAU and CC_MOSE scenarios. Abbreviations: SG, seagrasses maintenance; SM, salt marshes maintenance; D, benthic diatoms maintenance; T, tourism.

# TABLES

**Table 1**. 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 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 |

**Table 2**. 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 | - 0 Target fish species | - 0 Channels | - 0 Density of cultural heritage |
| - 1 Seagrasses | - 1 Clams | | - 1 Traditional knowledge |
| - 2 Bare (intertidal) | - 2 Birds | | |
| - 3 Benthic diatoms | | | |
| - 4 Macroalgae | | | |

**ES categories (colorsets) and ES (colors within the colorsets)**

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

**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.

**Table 3**. 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. 2A) | Climate regulation | Salt marshes<br>Seagrasses | | | | | | |
| **R** (Fig. 2A) | Waste treatment | Seagrasses<br>Benthic diatoms<br>Bare (intertidal)<br>Macroalgae | | | | | | |
| **R** (Fig. 2A) | Erosion prevention 1 | Salt marshes | | | | | | |
| **R** (Fig. 2A) | Erosion prevention 2 | Seagrasses<br>Benthic diatoms<br>Macroalgae | | | | | | |
| **R** (Fig. 2A) | Lifecycle maintenance | ALL | | | | | | |
| **P1** (Fig. 2B) | Artisanal fishing | | Target fish species | | | Artisanal fishermen | Artisanal fishing | |
| **P1** (Fig. 2B) | Recreational fishing | | Target fish species | | | Recreational fishermen | Recreational fishing | |
| **P1** (Fig. 2B) | Hunting | | Birds | | | Hunters | Hunting | |
| **P2** (Fig. 2C) | Clam harvesting | Seagrasses (*)<br>Benthic diatoms (*) | Clams | Channels (*) | | Clam fishermen | Clam harvesting | Lifecycle maintenance (*) |
| **C1** (Fig. 2D) | Info. for cognitive development | ALL | | Channels | Density of cultural heritage | Users of environmental education activities | | |
| **C1** (Fig. 2D) | Traditions | ALL | | Channels | Traditional knowledge | Residents | | |
| **C2** (Fig. 2E) | Tourism | Salt marshes(*)<br>Seagrasses(*)<br>Bare (intertidal)(*)<br>Benthic diatoms(*) | | Channels (*) | Density of cultural heritage | Tourists | Tourism | |
| **C3** (Fig. 2F) | Navigation | Salt marshes(*)<br>Seagrasses(*)<br>Bare (intertidal)(*)<br>Benthic diatoms(*) | | Channels (*) | | Boat owners | Navigation | |

(*) places impacted through negative externalities

**Table 4**. 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 |

**Table 5**. 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** |