A DECISION-SUPPORT SYSTEM IN ICZM FOR PROTECTING THE ECOSYSTEMS: INTEGRATION WITH THE HABITAT DIRECTIVE

Leonardo Marotta[1], Luigi Ceccaroni[2], Gabriele Matteucci[3], Paolo Rossini[3], Stefano Guerzoni[4]

[1] Entropia Snc, via Corridoni 3, I-62019, Recanati, leonardo.marotta@entropia-env.it
(Corresponding author)

[2] Departament de Llenguatges i Sistemes Informàtics (LSI), Universitat Politècnica de Catalunya (UPC), Campus Nord, Edif. Omega, C. Jordi Girona, 1-3, 08034 Barcelona, Spain
[3] Istituto di Ricerca Gruppo CSA SpA, via Al Torrente 22, Rimini, Italy
[4] Stefano Guerzoni, CNR-ISMAR, Castello 1364/A, Venezia (Italy)

Abstract

This paper describes a decision-support system based on landscape ecology and focused on the study of ecosystems' health. System capabilities are illustrated with three cases of integrated coastal zone management (ICZM), in the Adriatic Sea (Italy): the lagoon of Venice and the Rimini and Ancona coastal areas. Indicators and indices are developed with a focus on sub-regional and local problems in coastal management, with a multi-scale approach based on landscape and seascape ecology. Land-use changes of the coastal areas were detected by analyzing two sets of satellite images. Indices combining satellite imagery, socio-economic and environmental indicators, and landscape and seascape maps were created, showing ecological changes, habitat loss and gaps in conservation policy. The approach used provides means for the identification of conflicts and for the assessment of sustainability. Results show that the lagoon of Venice plays an important role in mitigating and compensating the impacts of human activities, and needs to be protected and restored. The Rimini area shows high ecological footprint and development-intensity and low biocapacity. The Ancona area needs the protection of its natural coastal space from potential sources of anthropogenic impacts to maintain its sustainability. A model of environment changes is critical for formulating effective environmental policies and management strategies. The developed decision-support system provides a suitability map per each area analyzed, which can be used in order to maximize different policy objectives and reduce coastal conflicts.

Keywords ICZM, coastal ecosystem health, decision-support system, habitat and landscape loss, coastal change, urban sprawl

Introduction

In the frame of *integrated coastal zone management* (ICZM) and its related fields, the modeling of the ecological, social and economic systems is a key issue towards sustainable planning. In this sense, ICZM requires tools that cope with interdisciplinarity, multiple scales (e.g., spatial, temporal or organizational) and knowledge from various sources. Important initiatives exist, involving ICZM and the European Habitat Directive (92/43/EEC 1992), to study how components, ecosystems and geosystems interact with the multiple actors dealing with multilevel coastal governance (e.g., state, province, town) (COM(2000)547; 2000/60/EC 2000; 2002/413/EC 2002; COM(2005)504 final; COM(2005)505; COM(2007)0308 final). As outlined by Meiner (2009), the 2007 Integrated Maritime Policy for the European Union served as an important factor in stimulating consolidation of coastal and marine information to support policy implementation. This includes the development of coastal and marine *decision-support systems* (DSS) (Van Kouwen et al. 2008; Fabbri 2006), based on indicators, indices (aggregations of indicators into a single representation), *geographic information systems* (GIS), models, scenarios and *multicriteria assessment* (MCA) (Vallega 1999; Soncini Sessa 2004). Indices are used to describe the coastal system at a geo-ecological level, modeling earth processes, ecology, human society and economy, and coastal uses at multiple scales (Vallega 1999; Pearce 1993). MCA is a tool to support environmental and social decisions in sustainability science, ecological economics and strategic assessment (Munda 2003, 2004; Ceccaroni et al. 2004; Ortolano 1997).

The European ICZM expert group recognized the importance of indicators, created an working group on *indicators and data* (WG-ID), and proposed that member states and candidate countries employ two sets of indicators: (i) *progress indicators*; (ii) *indicators of sustainable development* (EEA 2006a; 2006b; 2006c; DEDUCE 2007). In this paper, these sets of indicators are taken into account and a complementary set is created, in order to integrate the Habitat Directive and to define a *sustainability state* for the coast.

A framework based on a landscape approach is used, which considers landscape as a cultural dimension of complexity of the coastal area, integrating the human ecosystem (Naveh and Lieberman 1994) with its cultural and historic construction (Farinelli 2003; Martínez Alier and Roca Jusmet 2001). Landscape is, at the same time, a system, a unit, a domain, a realized space, as well as a cognitive space (Farina 2006) and some authors (Brown and Vivas 2005) use landscape analysis as the core of sustainability management and preservation of ecosystems' health.

The paper aims at developing indicators which measure progress in achieving a sustainable development of the coast and which provide feedback to policymakers in the form of a suggestion of the need for further action in ICZM.

A specific analysis was carried out in three study areas (see Figure 1), in Italy:

(1) *Lagoon of Venice*, characterized by an extraordinary mix of activities: tourism, fishing, industry (petrochemical plants);
(2) *Rimini*, one of the most important mass-tourism areas in the Mediterranean Sea;
(3) *Conero* (Ancona), a mountain with a cliff coast, characterized by a *park* and a *marine protected area* with important ecosystems, and, in the northern part, by an important port (*Ancona*) and a petrochemical plant (at *Falconara*).

Materials and Methods

The method developed is based on a conceptual model (see Figure 2) and follows a framework with several steps:

1. *Definition of homogeneous environmental management units, and analysis of spatial and temporal structure, hierarchy and dynamics over multiple scales.* For this purpose a habitat map based on landscape ecology was produced following the work of Naveh and Lieberman (1994), Brenner et al. (2006) and Marotta (2006). A crucial first step here is to characterize seabed habitats accurately from geological and oceanographic data. The procedure adopted is based on the shelf classification applied in eastern Canada by Roff and Taylor (2000), who used physical properties (sediment type, physiography, bed roughness, wave and current regime) to define ecologically meaningful habitats.
2. *Analysis of land-use changes in the coastal system.* In this step, landscape features and changes are identified in a temporal framework (Marotta and Mulazzani 2006).
3. *Implementation of spatial indices.* The spatial approach is the basis for analysis and planning (Babcock et al. 2005; Brenner et al. 2006) and for the assessment of indices for each patch type and state. (A range of index's values is assigned to each type of patch.) This method links land and sea use with the value of some index (Marotta et al. 2007).
4. *Conservation-gaps analysis.* IDRISI™ (Andes version) (Eastman 2006) is used in order to assess changes of habitats (land and sea) over time (from 1972 to 2001), being the coastal habitats those defined by the Habitat Directive (as reported in Online Resource 1, Table A1). The analysis is oriented to the assessment of ecosystem health, cumulative impacts and habitat loss in coastal *ecotones* (Thrush et al. 2008). An urban and infrastructure index has been used as evaluation tool (Marotta 2004; Marotta et al. 2008).
5. *Assessment of coastal conflicts.* For this purpose, and following the work of Vallega (1999), a costal conflict index was used (Marotta 2004; 2006).
6. *MCA in order to minimize conflicts over a set of values and constraints.* The MCA, carried out with IDRISI, supports the representation of priorities distribution (*suitability maps*). These priorities are: i) industry and port development; ii) touristic development; iii) agriculture and/or aquiculture; iv) conservation of habitats and species.

A scenario for each area is modeled in order to define a sustainable state of the costal system.

Description of data

Landscape ecology investigates the effect of the spatial arrangement of patches, corridors and related processes in a geographic area (Forman and Godron 1986). The different coastal habitats and the definitions of *habitat* and *corridor* are presented in the Habitat Directive and in Eastman (2006). For the landscape analysis and identification, two Landsat satellite scenes are used for each study area (see Figure 3). The data are then integrated with mapping data base Corine Land Cover 2000 (CLC2000), based on work by Perdigão and Annoni (1997) and EEA (2002). Images are processed into landscape patch units; the classification is made by photo-interpretation and ground verification. Resulting data are used in order to calculate landscape metrics (fractal dimension and landscape diversity), and sustainability indicators and indices.

Data about environment, emergy, ecological footprint and socioeconomics are based on the following reports and data sets:

- *Lagoon of Venice*: data from Tiezzi (2004), Bastianoni et al. (2005) and Assessorato all'Ambiente del Comune di Venezia (2005);

- *Rimini*: data from Tiezzi and Marotta (2006);
- *Conero* (Ancona): data from Tiezzi and Marchettini (2002).

Data about vegetation ecology are based on Pignatti (1994). Data about fauna are based on Casini and Gellini (2008), Bon et al. (2004) and Giacchini (2007). Data about social indices are derived by Cartocci (2007).

In Table 1, basic data for the study areas are summarized, together with their references. Table 2 shows the sustainability indices and constraints used for the case studies. Data are calculated in a 5-km coastal fringe (4 km landward and 1 km seaward).

Metrics, indicators, indices and threshold parameters

In this section a description is given for metrics, indicators, indices and parameters used in this paper.

Emergy is an index, introduced by Odum (1996), to take into account all the resources (natural and manufactured) sustaining a system. It is the quantity of solar energy needed to obtain a product or an energy flow in a given process. Units are *solar emjoules* (*sej*). Total emergy was subdivided into *renewable* and *non-renewable* emergy.

Empower is the emergy flow in time. Units are *sej* per time unit.

Empower density (ED) is the ratio between total empower and surface area of the system (expressed in hectares or m^2), a measure of the spatial concentration of emergy. The greater the ED, the more the area becomes a limiting factor for all future development.

Environmental loading ratio (ELR) is the ratio between non-renewable (local and imported) emergy and renewable environmental emergy.

Carbon dioxide equivalent production is used to identify and quantify anthropogenic sources and sinks of greenhouse gases (Eggleston et al. 2006). Units are tons of CO_2 eq / (person year)

Biocapacity, or *available biological capacity* (ABC), refers to the capacity of a given biologically productive area to generate an on-going supply of renewable resources and to absorb its spillover wastes. Unsustainability occurs if the area's ecological footprint exceeds its biocapacity.

Ecological footprint (EF), developed by Wackernagel and Rees (1996), is a measure of the consumption of renewable natural resources by the human population of a country, a region or the whole world (Wackernagel et al. 1999; 2004; 2006). A population's EF is the amount of productive area required to sustain that population. It is interesting to compare the EF with the more used *carrying capacity* (Chambers et al. 2000; Wackernagel et al. 2004). This latter quantity is defined as the population of a defined species that a region can support without irreversibly compromising the productivity of the region itself. The EF is a sustainability indicator, which provides a metric with a threshold (the biocapacity), that is a local carrying capacity.

Ecological balance (defined as ecological deficit if it is negative) is the difference between the EF of a population and the ABC in the space available for that population (Chambers et al. 2000; Wackernagel et al. 2004).

Landscape development intensity (LDI) is an index calculated from the non-renewable emergy per land use. Using land-use data and development-intensity measures (derived from energy use per area unit) LDI can be calculated for the coastal zones to estimate the potential impacts of human-dominated activities. LDI is used as an index of the human disturbance gradient (Brown and Vivas 2005).

Ecosystem value is based on ecosystem services (Costanza et al. 1997), i.e. the benefits arising from nature or the ecological services associated with a particular benefit. They include ecological contributions to both market and nonmarket goods and services.

Human value is based on land prices. Land prices vary extremely from city to city and are highest in urban cores. The values used are average values per land/sea type.

CO_2 absorption is calculated per each land use from the average vegetal biomass.

Biological capacity potential or *biological territorial capacity (BTC)* is a measure of ecosystem function (Ingegnoli and Pignatti 2007) based on resistance stability, vegetation type and metabolic data of vegetation. Important dynamic processes linked to the meta-stability of a landscape unit (at ecotope scale) can be expressed by the BTC. This synthetic function, referred to the main ecosystem, is able to compare landscape states by measuring the relative relation between respiration and gross production (R/GP) and between respiration and biomass (R/B):

$$BTC_i = 0.89\Omega - 0.0054\Omega^2$$

$$\Omega = (a_i + b_i), \quad a_i = \left(\frac{R}{GP}\right)_i \left(\frac{GP}{R}\right)_{\max} \quad b_i = \left(\frac{dS}{S}\right)_{\min} \left(\frac{S}{dS}\right)_i \qquad [1]$$

where i is the landscape patch and dS/S = R/B is the maintenance to structure ratio. BTC is expressed as Mcal/m^2/yr, which can be easily converted into Joule/ha/yr. A "healthier" state of an ecotope has a higher BTC value. It is possible to define the total BTC of a landscape as the sum of the values of all patches.

Exergy (Ex) of a system is the maximum work possible during a process that brings the system into equilibrium with a heat reservoir. When the surroundings are the reservoir, exergy is the potential of a system to cause a change as it achieves equilibrium with its environment. Exergy is then the energy that is available to be used. After system and surroundings reach equilibrium, the exergy is zero. *Eco-exergy* (or *ecosystem exergy*) is the chemical energy difference between the actual system and the thermodynamic equilibrium (Jørgensen 2006a). Exergy is calculated following Jørgensen (2006b) for the average biomass per land use. In this paper, the exergy index is calculated as the concentration of different groups (X_i) in the system multiplied by weighting factors (β_i), based on exergy detritus equivalents, according to Marques and Jørgensen (2002). Exergy links the chemical energy of the different species characterizing the ecosystem to the information embodied in DNA, as expressed by the following equation:

$$Ex = \sum_{i=1}^{n} \beta_i X_i \qquad [2]$$

Exergy detritus equivalents are expressed in g m^2, which can be converted to kJ m^2 using the approximate average energy content of 1 g of detritus, i.e. 18.7 kJ (Jørgensen 2000). A variation in the exergy value could be due to variations of biomass or to variations of the structural complexity of the biomass.

Percolation is based on the percolation theory, which, formulated to study the behavior of fluids spreading randomly through a medium, has found an interesting application in landscape ecology, and offers a method to describe and predict animal movement (Farina 2006). A *critical probability* (pc) = 0.593 marks the difference between when the fluid remains in finite regions (percolation < pc) and when the fluid crosses the lattice connecting every molecule of fluid with the others (percolation > pc). In the same way, when an animal moves in a habitat that has a percolation value higher than pc, the organism can cross the entire landscape. Therefore, percolation can be considered a connectivity measure.

Natural habitat loss, or habitat destruction, is the process in which an ecotope becomes functionally unable to support some of its species. In this process, the organisms which previously composed the ecotope are destroyed or move to another, more suitable landscape ecotope, reducing the biodiversity. Common habitat-destruction drivers are: human activity for the purpose of harvesting natural resources, urbanization, pollution and physical alteration.

Gross domestic product (GDP) is the total market value of all final goods and services produced in a country in a given year, equal to total consumer, investment and government spending, plus the value of exports, minus the value of imports.

Integrated indices

The conceptualization of a landscape described by patches of different land- and sea-use is made by the space transformation of indices in order to use them as a model.

A new *coastal, urban and infrastructural, sprawl index* (I_{sp}) was developed, based on previous work by Marotta et al. (2008), with the aim of understanding urban and infrastructural dynamics in coastal areas and of identifying problematic areas. Humans are components of ecosystems, and urban growth and sprawl, as well as coastal infrastructure growth, are the most important direct impacts on ecosystems and geosystems (Alberti 2008).The assessment of I_{sp} at a macro scale is a good proxy of all human pressures on the coastal zone. The I_{sp} index is defined as:

$$I_{sp} = 10 + \ln\left(\frac{1}{A\Delta t}\sum_{i=1}^{m} u_i\right) \qquad [3]$$

where u_i are the areas of non-urban/infrastructure transformed into urban/infrastructure, Δt is the time interval of the analysis in years, m is the number of patches that have changed, and A is the area. Using CLC2000 terminology, I_{sp} represents the sum of the *natural* and *agriculture* patches (codes 2.., 3.., 4.., 5..) changed into *urban and infrastructures* (codes 1..).

The use of the coast, the conflicts among uses and main changes in land-use can affect the coastal environment. Coastal, human structures are assessed according to coastal use. Therefore, monitoring changes in land-use and in loss of habitat function and diversity is fundamental, especially in areas facing rapid urbanization and urban sprawl (Brennan and Culverwell 2004; Alberti et al. 2007). Vallega (1999) defined *the coastal use interaction breakdown* as a square matrix where uses are indicated in the rows and columns in the same order. Grosskurth and Rotmans (2007) presented a qualitative index (QSSI) taking into account time, scale and domain. Their model is presented as a system of two matrixes: a cause-effect matrix and an inconsistence matrix. Identifying the *conflicts* in the use matrix, it is possible to build a quantitative sustainability index.

Gap analysis and multicriteria procedures

Gap analysis and MCA of geographic information are carried out using IDRISI's *geographic resources analysis support-system*. The gap analysis of biodiversity conservation at landscape and habitat scale over time is analyzed through IDRISI's *land change modeler for ecological sustainability*. Gap analysis of unprotected areas and corridors provided thresholds to identify areas that need protection for biodiversity sustainability as primary habitat, secondary habitat and corridors, as defined by Eastman (2006). IDRISI's *land change modeler* was also used in order to assess the gaps between protected areas and areas that need to be protected. The spatial assessment aspect of land-use/land-cover and coastal ecotope change required two maps derived from satellite images. The habitat analysis shows the dynamics and the gaps in conservation policy and planning. The processes analyzed with IDRISI's *land change modeler* are classified according to Forman (1995):

a. *Dissection*: the even subdivision of an area.
b. *Fragmentation*: the breaking of an area into pieces (that are often unevenly separated).
c. *Shrinkage*: the decrease in size of areas.
d. *Attrition*: the disappearance of areas.
e. *Perforation*: the creation of small patches acting like holes within the original habitat landscape.

The drivers of coastal space transformation, which increase habitat loss and isolation of species on the landscape, are also defined by Forman (1995). The change and the actual status of protection, and the significance of habitat losses are used to identify potential lack of protection, and are resumed in the gap analysis. Actual decision-support is based on a selection of land and sea allocation of activities, i.e. a suitability map, from a number of available choices. Each choice (industry and port development; touristic development; agriculture and/or aquiculture; conservation of habitats and species) represents a decision alternative. In the MCA, the selection is facilitated by evaluating each choice using the set of criteria of Table 3; the distribution of actual land use must be measured for every decision alternative. MCA outcomes, in the form of suitability maps (e.g., the conservation suitability map of Figure 4), provide the basis for comparison of choices and consequently facilitate the selection of one, optimal or sub-optimal choice. Table 4 lists the conservation constraints for ecological sustainability of the case studies.

Results and discussion

The differences between satellite images (in Figure 3) show how much coastal areas have changed in a period of about 30 years. Corresponding values of sustainability/ecosystem-health indices and indicators for the studied areas are reported in Tables 1 to 4. The assessment of the later state (see Table 2) shows that:

- Coastal landscapes have a very low level of eco-health state in Rimini, where BTC is very low, LDI is very high, percolation is 0.86 and the footprint is 12 times higher than the threshold (ABC=0.91; see Table 5).
- GDP per surface unit in Venice is lower than in other areas because also the surface of the lagoon where there are no habitants is considered.
- In the Conero area the highest net habitat loss is found, even though the state of landscapes eco-health (BTC, percolation) is good.
- The total fluxes of emergy in the Venice case show the importance of the lagoon in natural

fluxes: higher levels of emergy are in part due to the importance of estuarine-lagoon processes in the coastal area (see Table 1). This is consistent with the higher level of non-renewable emergy in the Venice lagoon with respect to the other areas (see Table 2).

- In Table 1, the lower level of empower density in the Conero area reflects the lower use of energy and a lower flux of materials in this area.
- The high environmental loading ratios in the Venice lagoon and Rimini, which are higher than the 60.32 Italy average, as shown in Sweeney et al. (2007), reflect the higher fluxes of non-renewable emergy per person (from both local and non-local energy and materials input).
- In Table 2, the loss of natural areas shows a higher trend of urbanization in the coast of Conero.
- The gap analysis (see Table 4) shows a strong need of protection (as primary habitat and primary corridors) in Venice
- The gap analysis (see Table 4) shows a need of management in the Conero area. Here, only a few areas of primary habitat and corridors need better conservation.
- In Rimini, the data of Table 4 highlight a need of policy focused to ecosystem recover and habitat reconstruction.

MCA and decision-support scenarios

The general principles used to derive scenarios of effective environmental policies and management strategies are based on an ecosystem approach, as described by Gaydos et al. (2009). The index developed takes into account these principles because: (1) the area is landscape shaped; (2) percolation is a connectivity measure; (3) gap reduction is a fragmentation minimization; (4) BTC is a measure of ecosystem integrity; (5) both economic and ecological values are taken into account.

The main objectives of the suitability maps used in the MCA are: minimizing conflicts and avoiding habitat conservation gaps. In each patch, different objectives can be maximized: industry and port development; touristic development; agriculture and/or aquaculture; conservation of habitats and species. For each objective, a suitability map is created, as the first step of the MCA, using the land-use and Table 3 data as criteria. Once the multicriteria suitability maps have been created for each objective, a multi-objective scenario is obtained for each area (assigning a weight to each objective).

The approach presented is oriented to *knowledge sharing* (Munda 2004; Van Kouwen et al. 2008; Wright et al. 1993) and facilitates stakeholders' participation process. Scenarios are characterized by the parameters presented in Table 5.

The conservation constraints (Table 4) derived by the gap analysis show a need of conservation measures in the Venice lagoon for primary and secondary habitats and corridors. In an area of 1699 ha (corresponding to the 1.17% of the total area) conservation measures are needed for a more efficient protection of key habitats. In the Conero area, conservation is needed in a relative high percentage (1.42%) of the total area, particularly in the secondary habitat, corresponding to 1.26% of the total.

Figure 4 presents, in the first row, the conflicts maps. Coastal-conservation suitability maps (i.e., maps of the distribution of the need of conservation of habitats and species) are presented in the middle row. The thresholds of biodiversity and habitat sustainability come from the gap analysis, and identify areas that need protection to achieve biodiversity sustainability (see Table 4). Each case-study area shown in Figure 4 is analyzed in more detail in the following paragraphs.

Final maps are reported in the third row of Figure 4, where the areas where conservation has to be implemented are shown in red and areas where the uses do not have to change are shown in black.

In the left column (Conero), in the area identified, urbanization and tourist beach-facilities have increased over time. Here, the highest level of conflict arises between tourist facilities and impacts on habitats and species. The involved landscapes are Mediterranean forests, scrubland in the rocky coast, and scrubland and wetland in sandy coast. In the seascapes, there are impacts of tourism on rocky coast assemblages.

In the middle column, the Rimini area is presented. The highest conflicts are found in the *Marecchia River* estuary and in the southern coastal area (*Gabicce*). The highlighted area includes the Marecchia River, expanding urban areas and important infrastructures (railroad and motorway).

The right column (lagoon of Venice) shows that tourism, industrial activities, shipping, fishing and coastal defenses are in conflict in both the northern and southern basins. The highlighted area is the one in which conflicts cause pollution and morphological changes, with impact on the *lagoonscapes* (on shallow water habitats, mud flats, and saltwater marshes).

In Table 5 scenarios are shown in which main conflicts are reduced or eliminated, and conservation areas are maximized; however the ecological footprint in the three areas is higher than the biocapacity. Therefore, in order for the scenarios to become really sustainable, an integrated policy is needed for material consumption and energy management.

In the Conero scenario, a policy of 70% reduction in nonrenewable energy consumption, 80% increase in waste recycling, and 70% shift from private transport to public transport (trains and electric buses) is needed to reach an ecological footprint of 2.1 ha per person per year, considering an increase of population around 1% per year (as per current trends).

In the Rimini scenario, a policy of 80% reduction in nonrenewable energy consumption, 90% increase in waste recycling, and 90% shift from private transport to public transport (trains and electric buses) is needed to reach an ecological footprint of 1.0 ha per person per year, considering an increase of population around 2% per year (as per current trends). In this case, a policy for an increase of biocapacity is needed, too.

In the Venice scenario, a policy of 60% reduction in nonrenewable energy consumption, 78% increase in waste recycling, and 70% shift from private transport to public transport (trains, boats and electric buses) is needed to reach an ecological footprint of 1.8 ha per person per year, considering no increase of population (as per current trends).

Additional data are given in Online Resource 1.

Conclusion

Limited progress has been made by the scientific community to adapt the existing frameworks for integrated environmental assessment based on a systemic approach to the evolving procedures in planning and management of coastal areas. In this paper an index and a methodology for integrated coastal zone management have been presented. A decision-support system using this methodology integrates indices and agents' preferences, takes into account growth limits of coastal zones, and is suitable to support general policies in an evolving management setting.

Sustainability of Rimini and Venice coastal zone is a difficult goal in the short term. The lagoon of Venice mitigates the impacts of the inland area and of the port, fishing and tourism activities, and for this reason needs to be protected and restored. The Rimini area presents high ecological footprint, high landscape development intensity and low biocapacity, together with a critical value of percolation (connectivity among habitats). The Conero area can reach a sustainability level through the protection of natural coastal space from potential sources of anthropogenic impacts.

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Table 1 Basic data used for the study areas. [a] Tiezzi (2004);[b] Bastianoni et al. (2005);[c] Assessorato all'Ambiente del Comune di Venezia (2005); [d] Tiezzi and Marotta (2006); [e] Tiezzi and Marchettini (2002)

	Venice lagoon (2004)[a,b,c]	**Rimini Province (2005)[d]**	**Conero area (2002)[e]**
Emergy, Total Flux sej/yr	6.9E+22	1.3E+22	0.5E+22
Emergy per person sej/(person yr)	8.5E+13	3.8E+13	3.2E+13
Empower Density (ED) sej/m^2	2.8E+13	2.0E+13	0.7E+13
Environmental loading ratio (ELR)	72	73	57
Carbon dioxide production t CO_2 eq/(person yr)	14.4	7.2	7.9
Ecological Footprint ha eq per person	4.68	7.38	6.11
Biocapacity ha eq per person	1.45	0.44	2.07
Ecological balance ha eq per person	-3.23	-6.94	-4.04

Table 2 Coastal sustainability indices and constraints for the case studies. Data are calculated in the 5 km of coastal fringe (4km landward and 1km seaward, for Venice lagoon is calculated whit the entire Lagoon and 4 km Landward and 1 km seaward). [1]LDI, Coastal Urban and Infrastructure in total area Sprawl Index (1970-2001*) and Coastal use conflicts have not unit of measures. * First year of analysis for Venice is 1972, for Rimini is 1975, for the Conero area is 1976

	Venice lagoon	**Rimini province**	**Conero area**	**Error**
Non renewable Emergy (sej/yr) per ha	9.3E+16	5.5E+16	7.3E+16	20%
Renewable Emergy (sej/yr) per ha	26E+10	1.0E+10	1.0E+10	20%
LDI[1]	4.86*	7.12*	3.95*	30%
Ecosystem value (euro) per ha	3.4E+03	0.9E+03	1.9E+03	10%
Human Value (euro) per ha	5.0E+05	7.9E+05	6.6E+05	30%
CO_2 absorption (tonn) per ha	3.8E+03	1.3E+03	3.6E+03	20%
BTC (J/yr) per ha	3.8E+10	0.9E+10	3.6E+10	15%
Exergy (J) per ha	5.8E+09	1.9E+09	6.0E+09	20%
Percolation (in total area)	0.93	0.86	0.91	5%
Percolation in coastal area (5km)	0.71	0.41	0.89	5%
Percolation in coastal area (1km)	0.68	0.35	0.68	5%
Natural habitat Loss in total area (1970-2001*)	2.29E+3	4.11E+3	18.7E+3	5%
GDP (total per year, 2004), euro/ha	0.9E+5	1.8E+5	7.2E+5	10%
Coastal Urban and Infrastructure in total area Sprawl Index (1970-2001*)[1]	7.8	7.5	7.6	10%
Coastal use conflicts[1]	0.85	0.41	0.53	5%

Table 3 Indices used for landscape and seascape (land/sea uses and patches). In the first column is presented the CORINE LAND COVER code

CLC	Description	Non renow_Emergy E14 sej/[ha*yr]	Renow Emergy E14 sej/[ha*yr]	Ecos_value €/[ha*yr]	Human_value €/[ha*yr]	LDI	CO_2 Absorption tonn/[ha*yr]	Btc MJ/[ha*yr]	Eco-exergy J/[ha*yr]	Percolation
111	Continuous urban fabric	12825.00	1.47E-04	0.00	30000000.00	9.46	1133.00	4186.80	7.30	NOT
112	Discontinuous urban fabric	7391.50	1.47E-04	0.00	17000000.00	8.91	1888.00	25120.80	7.30	NOT
121	Industrial or commercial units	8935.80	1.47E-04	0.00	10000000.00	9.10	755.00	8373.60	7.30	NOT
122	Road and rail networks and associated land	3080.00	1.47E-04	0.00	5000000.00	8.03	189.00	4186.80	7.30	NOT
123	Port Areas	5210.60	4.68E-05	0.00	8000000.00	8.56	3775.00	8373.60	7.30	NOT
124	Airports	5020.00	1.47E-04	0.00	20000000.00	8.52	3775.00	8373.60	7.30	NOT
131	Mineral extraction sites	4333.47	1.47E-04	0.00	3000000.00	8.37	1189.00	8373.60	0.00	NOT
132	Dump sites	3835.30	1.47E-04	0.00	3000000.00	8.25	189.00	75362.40	0.00	NOT
133	Construction sites	2175.00	1.47E-04	0.00	10000000.00	7.69	1189.00	8373.60	7.30	NOT
141	Green urban areas	6.55	1.47E-04	91.08	1000000.00	2.23	1888.00	41868.00	100.00	YES
142	Sport and leisure facilities	1230.00	1.47E-04	91.08	2000000.00	7.12	1888.00	41868.00	100.00	YES
211	Non-irrigated arable land	107.13	1.47E-04	91.08	50000.00	4.70	5285.00	33494.40	100.00	YES
221	Vineyards	44.00	1.47E-04	91.08	100000.00	3.84	1888.00	83736.00	100.00	YES
222	Fruit trees and berry plantations	44.00	1.47E-04	229.68	100000.00	3.84	1888.00	50241.60	100.00	YES
231	Pastures	8.00	1.47E-04	91.08	30000.00	2.37	2642.50	62802.00	94.00	YES
242	Complex cultivation patterns	1349.20	1.47E-04	91.08	70000.00	7.21	5285.00	50241.60	127.00	YES
243	Agricultural lands with natural vegetation	32.03	1.47E-04	150.00	50000.00	3.55	4908.00	62802.00	127.00	YES
311	Broad-leaved forest	0.00	1.47E-04	240.00	30000.00	1.00	4908.00	355878.00	260.00	YES
312	Coniferous forest	0.00	1.47E-04	298.98	40000.00	1.00	8305.00	267955.20	260.00	YES
313	Mixed forest	0.00	1.47E-04	298.98	30000.00	1.00	5285.00	343317.60	260.00	YES
321	Natural grassland	0.00	1.47E-04	91.08	30000.00	2.37	2642.50	62802.00	260.00	YES
322	Moors and heathland	0.00	1.47E-04	298.98	10000.00	1.00	3775.00	133977.60	127.00	YES
324	Transitional woodland-scrub	0.00	1.47E-04	260.00	20000.00	1.00	9438.00	146538.00	7.30	YES
331	Beaches, dunes, sands	6.55	1.47E-04	86.67	500000.00	2.23	113.00	4186.80	7.30	YES
332	Bare rocks	0.00	1.47E-04	26.00	5000.00	1.00	189.00	4186.80	94.00	YES
411	Inland marshes	0.00	1.50E-04	8413.02	20000.00	1.00	9438.00	83736.00	94.00	YES
421	Salt marshes	0.01	1.33E-02	8413.02	20000.00	1.00	9438.00	83736.00	69.80	YES
421	Fishfarming areas	33.31	1.33E-02	8413.02	100000.00	3.58	1888.00	83736.00	4.90	NOT
422	Salines	33.31	1.33E-02	4011.48	50000.00	3.58	2642.50	41868.00	5.00	NOT
423	Mud flats	0.01	1.50E-04	14341.45	5000.00	1.00	3775.00	37681.20	1.57	YES
511	Water courses	0.01	1.47E-04	8413.02	5000.00	1.00	1510.00	25120.80	1.57	NOT
512	Water bodies	0.01	1.47E-04	8413.02	5000.00	1.00	1510.00	62802.00	2.44	NOT
5211	Open Lagoon and channels	0.01	1.33E-02	8413.02	5000.00	1.00	1510.00	62802.00	4.88	NOT
5212	Subtidal bottoms	0.01	1.33E-02	4011.48	5000.00	1.00	3500.00	29307.60	4.88	NOT
523	Coastal waters (estuarine)	0.01	4.68E-05	20548.80	5000.00	1.00	4000.00	40934.00	4.50	NOT
523	Coastal waters (silty sand offshore)	0.01	4.68E-05	4011.48	5000.00	1.00	2300.00	20934.00	4.50	NOT
523	Coastal waters (silty clay offshore)	0.01	4.68E-05	4011.48	5000.00	1.00	2300.00	20934.00	4.50	NOT
523	Coastal waters (silty sand near offshore)	0.01	4.68E-05	4011.48	5000.00	1.00	2300.00	20934.00	4.50	NOT
523	Coastal waters (silty clay near offshore)	0.01	4.68E-05	4011.48	5000.00	1.00	2300.00	20934.00	4.50	NOT
523	Coastal waters (silty sand near shore)	0.01	4.68E-05	4011.48	5000.00	1.00	2300.00	20934.00	4.50	NOT
523	Coastal waters (silt, loam)	0.01	4.68E-05	4011.48	5000.00	1.00	2300.00	20934.00	4.50	NOT
523	Coastal waters (sandy beach)	0.01	4.68E-05	4011.48	10000.00	1.00	2300.00	20934.00	4.90	NOT
523	Rocky coast nearshore	0.02	4.68E-05	4011.48	12000.00	1.00	3000.00	30934.00	0.75	NOT
523	Coastal waters (continental shelf Z<-20m)	0.01	4.68E-05	4011.48	5000.00	1.00	2300.00	20934.00	0.75	NOT
523	Coastal waters (continental shelf relict deposit)	0.01	4.68E-05	4011.48	7500.00	1.00	2300.00	20934.00	0.75	NOT

Table 4 Table of the conservation constraints for ecological sustainability of the case studies

Gap, unprotected areas	**Venice Lagoon** ha	**Rimini province** ha	**Conero area** ha	**Error**
Primary potential corridor	490	67	22	10%
Secondary potential corridor	122	98	35	10%
Primary habitat	73	0	12	10%
Secondary habitat	1014	680	520	10%
Total area of the coastal landscapes	145000	84800	41400	0.1%

Table 5 Table of results for final decision scenario

Scenario at 2015	Venice Lagoon	Rimini province	Conero area	Error
Ecological footprint at the actual level of consumption (ha)	7.2	7.9	6.6	>20%
ABC (ha)	1.8	0.91	2.1	>20%
Gap, unprotected areas (ha)	0	0	0	5%
Coastal Urban and Infrastructure Sprawl Index	3.2	3.1	3.1	>20%
Coastal use conflicts	0.10	0.10	0.10	5%

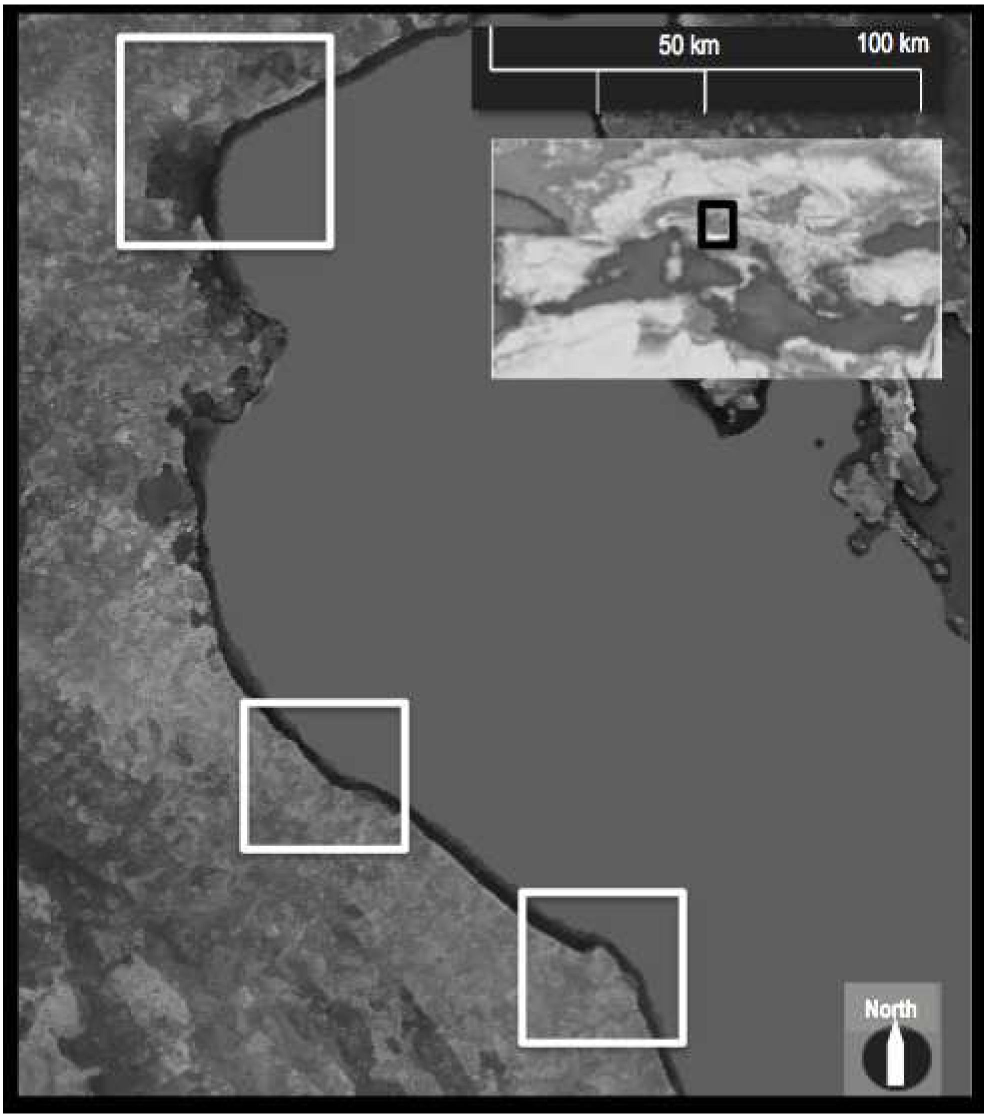


Figure 1 The geographic location of the three study areas (central and northern Adriatic Sea) in the Mediterranean Sea

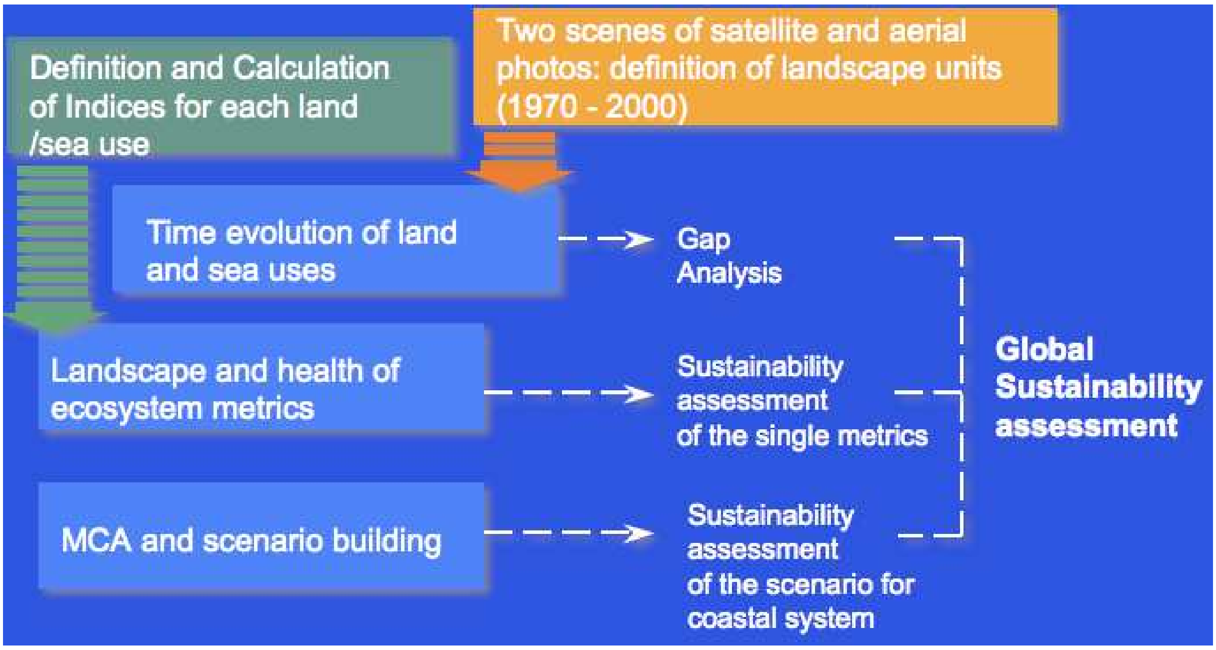
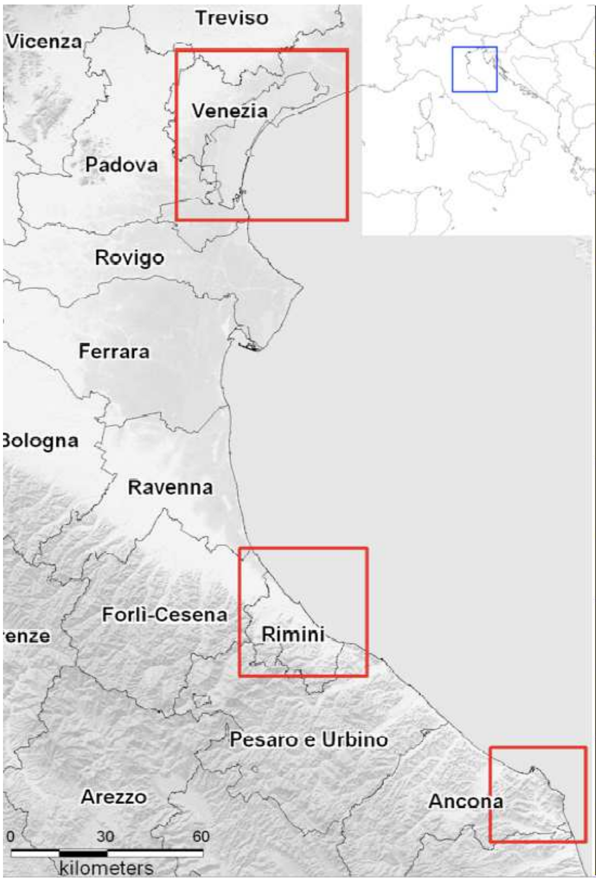


Figure 2 The general framework developed as a method. The upper boxes precede the lower ones in the methodological path



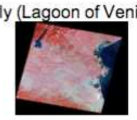
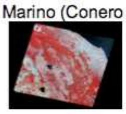
[WRS: P/R]	[Acq. Date]	Dataset	Location (Study Area)
1: 207/029	12-08-1972	MSS	Italy (Lagoon of Venice) 
2: 192/028	26-08-2001	ETM+	Austria, Italy (Lagoon of Venice) 
1: 206/029	28-04-1975	MSS	Croatia,Italy, San Marino (Rimini Province) 
2: 191/029	16-08-2000	ETM+	Croatia, Italy, San Marino (Rimini Province) 
1: 205/030	3-04-1976	MSS	Italy (Conero Mountain) 
2: 191/030	3-08-2001	ETM+	Italy, San Marino (Conero Mountain) 

Figure 3 Study areas and data used (Landsat satellite images). Two scenes are used in the temporal analysis to evaluate land-use changes in coastal areas

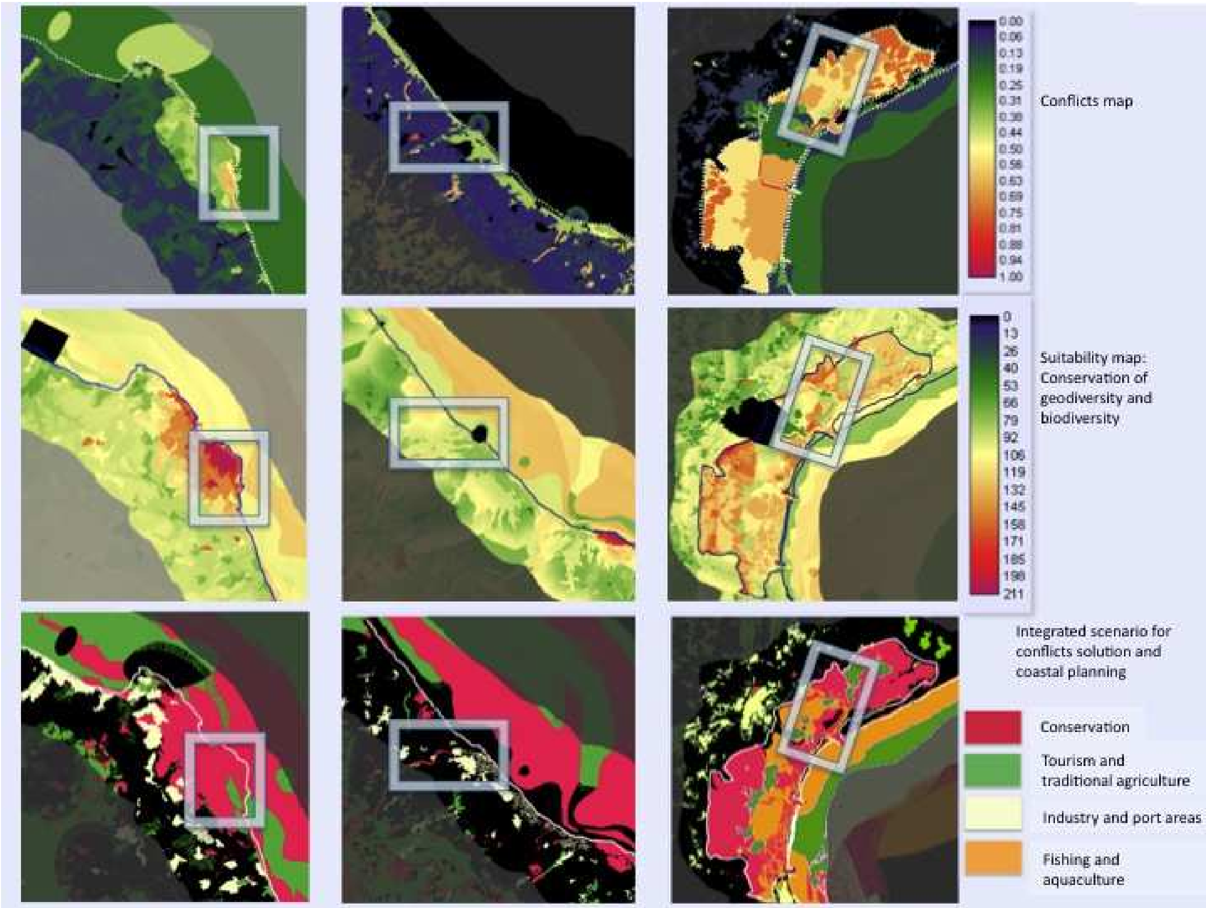


Figure 4 Decision-support results. The squares outline the critical areas. Each column shows three maps of the same area (from left to right: Conero, Rimini, Venice) and each row shows maps related to the same subject (from top to bottom: conflict, suitability, multiobjective). In conflict maps (top of the legend) conflicts increase from zero (black) to one (violet); in suitability maps the value for conservation grows with the index (from black to violet); in scenario maps (bottom) the colors indicate the most suitable use, taking into account minimization of conflicts and conservation gaps.

Online Resource 1 - Annexes

In table A1 the habitat type (following the Habitat Directive), the state of the habitats and their description as landscape units (linking habitat with microchores) are described.
In Figure A1 and A2 the landscape dynamics and the conservation gaps are mapped, respectively.

Table A1 Habitat, landscape units (mainly microchores), habitat conservation status, landscape dynamic, and principal impacts (the impact presence is described by 1). The code corresponds to the NATURA 2000 code. * Priority habitat types. [(a)] The entire lagoon is a mesochore. (To be continued)

	Habitat code and description	Microchore	State	Landscape dynamics	Impacts: Tourist activities and facilities	Impacts: Urban Sprawl	Impacts: Industry and ports (including navigation)	Impacts: Fishing and agricolture
Venice Lagoon	1110 Sandbanks which are slightly covered by sea water all the time	Open Lagoon	Habitat conservation gap	Dissection and Fragmentation	0	0	1	1
Venice Lagoon	1140 Mudflats and sandflats not covered by seawater at low tide	Open Lagoon	Habitat conservation gap	Dissection and Fragmentation	0	0	1	1
Venice Lagoon	1150 *Coastal lagoons	(a)	Habitat conservation gap	Dissection and Fragmentation	0	0	1	1
Venice Lagoon	1310 *Salicornia* and other annuals colonizing mud and sand	Salt Marshes	Habitat conservation gap	Perforation	0	0	1	1
Venice Lagoon	1320 *Spartina* swards (*Spartinion maritimae*)	Salt Marshes	Habitat conservation gap	Perforation	0	0	1	1
Venice Lagoon	1330 Atlantic salt meadows (*Glauco-Puccinellietalia maritimae*)	Salt Marshes	Habitat conservation gap	Perforation	0	0	1	1
Venice Lagoon	1410 Mediterranean salt meadows (*Juncetalia maritimi*)	Salt Marshes	Habitat conservation gap	Perforation	0	0	1	1
Venice Lagoon	1420 Mediterranean and thermo-Atlantic halophilous scrubs (*Sarcocornetea fruticosi*)	Salt Marshes	Habitat conservation gap	Perforation	0	0	1	1
Venice Lagoon	1510 * Mediterranean salt steppes (*Limonietalia*)	Salt Marshes	Habitat conservation gap	Perforation	0	0	1	0
Venice Barrier island	1210 Annual vegetation of drift lines	Beach	Habitat conservation gap	Perforation/ Shrinkage	1	0	1	0
Venice Barrier island	2120 Shifting dunes along the shoreline with *Ammophila arenaria* ('white dunes')	Beach	Habitat conservation gap	Perforation/ Shrinkage	1	0	1	0
Venice Barrier island	2130 * Fixed coastal dunes with herbaceous vegetation ('grey dunes')	Beach	Habitat conservation gap	Perforation/ Shrinkage	1	1	1	0
Venice Barrier island	2230 *Malcolmietalia* dune grasslands	Beach	Habitat conservation gap	Perforation/ Shrinkage	1	1	1	0
Venice Barrier island	2250 * Coastal dunes with *Juniperus* spp.	Beach	Habitat conservation gap	Perforation/ Shrinkage	1	1	1	0
Venice Barrier island	2270 * Wooded dunes with *Pinus pinea* and/or *Pinus pinaster*	Beach	Habitat conservation gap	Perforation/ Shrinkage	1	1	1	0
Venice coastal landscape	Traditional agricolture area	Coastal agroecosystem with natural vegetation and channels	Cultural landscape conservation gap	Shrinkage	1	1	0	0

Table A1 (Follows) Habitat, landscape units (mainly microchores), habitat conservation status, landscape dynamic, and principal impacts (the impact presence is described by 1). The code corresponds to the NATURA 2000 code.

	Habitat code and description	Microchore	State	Landscape dynamics	Impacts: Tourist activities and facilities	Urban Sprawl	Industry and ports (including navigation)	Fishing and agricolture
Rimini Province	1210 Annual vegetation of drift lines	Beach	Habitat conservation gap	Dissection and Fragmentation	1	1	0	0
Rimini Province	2120 Shifting dunes along the shoreline with *Ammophila arenaria* ('white dunes')	Beach	Habitat conservation gap	Dissection and Fragmentation	1	1	0	0
Rimini Province	Traditional agricolture area	Coastal agroecosystem with natural vegetation	Cultural landscape conservation gap	Dissection and Fragmentation	0	0	0	0

Table A1 (Follows) Habitat, landscape units (mainly microchores), habitat conservation status, landscape dynamic, and principal impacts (the impact presence is described by 1). The code corresponds to the NATURA 2000 code.

	Habitat code and description	Microchore	State	Landscape dynamics	Impacts: Tourist activities and facilities	Urban Sprawl	Industry and ports (including navigation)	Fishing and agricolture
Conero area	1240 Vegetated sea cliffs of the Mediterranean coasts with endemic Limonium spp.	Sea cliff and Beach	Habitat conservation gap	Perforation/attrition	1	0	0	0
Conero area	1160 Large shallow inlets and bays	Sea cliff and Beach	Habitat conservation gap	Perforation/ Shrinkage	0	0	0	1
Conero area	1170 Reefs	Sea cliff and Beach	Habitat conservation gap	Perforation/ Shrinkage	1	0	0	1
Conero area	1240 Vegetated sea cliffs of the Mediterranean coasts with endemic *Limonium* spp.	Sea cliff and Beach	Habitat conservation gap	Perforation/ Shrinkage	1	0	0	0
Conero area	1210 Annual vegetation of drift lines	Beach	Habitat conservation gap	Perforation/ Shrinkage	1	0	0	0
Conero area	1310 *Salicornia* and other annuals colonizing mud and sand	Beach	Habitat conservation gap	Perforation/ attrition	1	0	0	0
Conero area	5210 Arborescent matorral with *Juniperus* spp.	Sea Mountain	Habitat conservation gap	Perforation/ attrition	0	1	0	0
Conero area	9340 *Quercus ilex* and *Quercus rotundifolia* forests	Sea Mountain	Habitat conservation gap	Perforation/ attrition	1	1	0	0
Conero area	Traditional agricolture area	Coastal agroecosystem with natural vegetation	Cultural landscape conservation gap	Shrinkage/ attrition	1	1	1	0

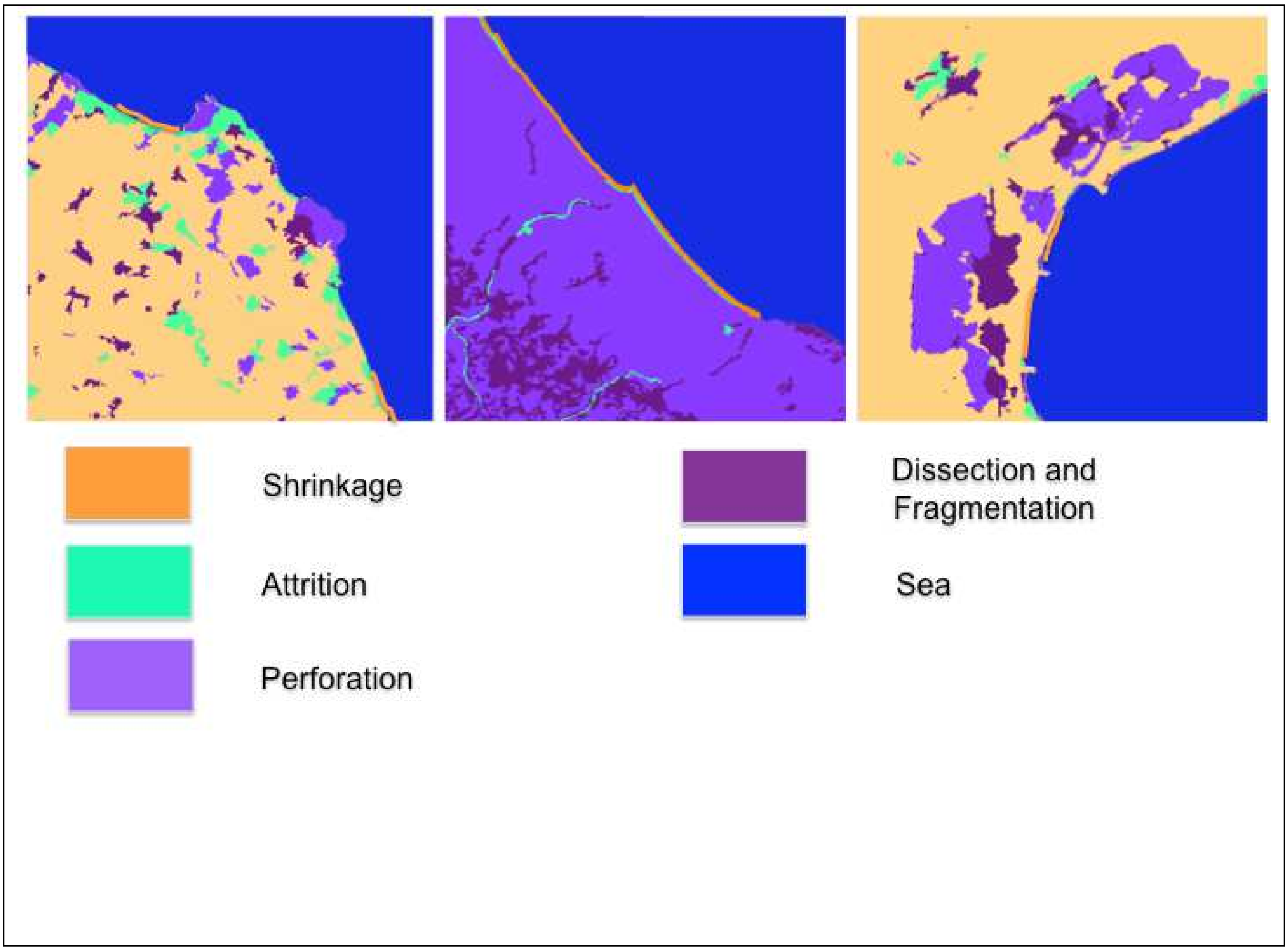


Figure A1 Landscape dynamics and transformation during 30 years

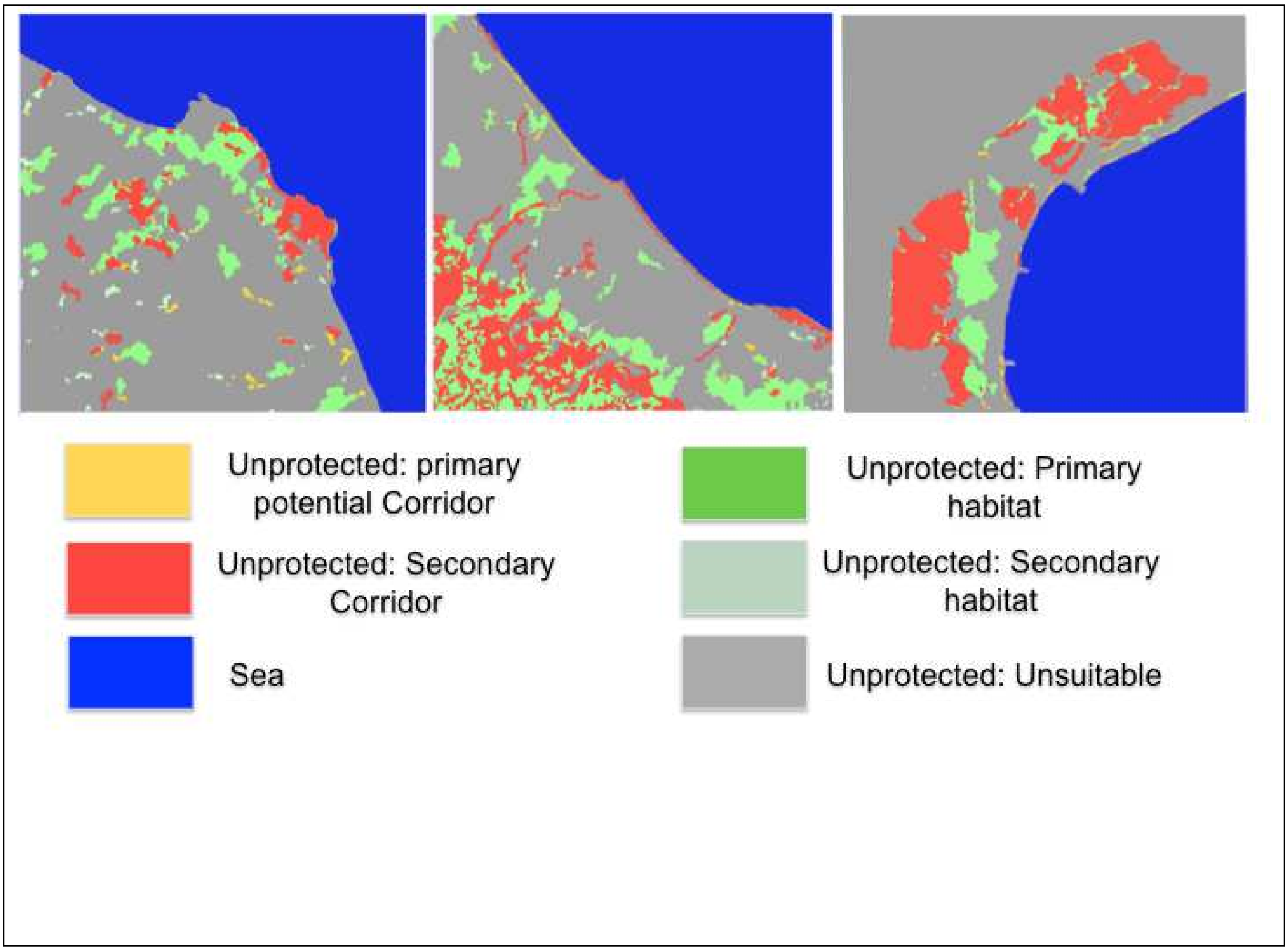


Figure A2 Conservation gaps