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Assessing the impact of alternative land-use zoning policies on future ecosystem services

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ABSTRACT

Land use conversions rank among the most significant drivers of change in ecosystem services worldwide, affecting human wellbeing and threatening the survival of other species. Hence, predicting the effects of land use decisions on ecosystem services has emerged as a crucial need in spatial planning, and in the associated Strategic Environmental Assessment (SEA) practice. The paper presents a case-study research aimed at empirically exploring how the implementation of different land-use zoning policies affect the future provision of a set of ecosystem services (water purification, soil conservation, habitat for species, carbon sequestration and timber production). The study area is located in The Araucanía, one of Chile's Administrative Regions. The first part of the methods consisted in the construction of land-use scenarios associated to different policies. Subsequently, the effects of the land-use scenarios on the provision of the selected ecosystem services were assessed in a spatially explicit way, by using modeling tools. Finally, a set of metrics was developed to compare scenarios, and trade-offs in the provision of different ecosystem services were made explicit through trade-off curves. The results indicate that, for this case study, spatial configuration of land uses is as an important factor as their size. This suggests that the analysis of land-use patterns deserves attention, and that this information should be included in scenario exercises aimed to support spatial planning. The paper concludes by discussing the potential contribution of the approach to support SEA of spatial plans.

1. Introduction

Land-use conversions rank among the most significant drivers of change in ecosystem services worldwide, affecting human wellbeing and threatening the survival of other species (Foley et al., 2005; Metzger et al., 2006; Nelson et al., 2006). In many regions of the world, spatial plans are the principal policy instrument influencing the distribution of land uses within a jurisdiction (Willis and Keller, 2007). Spatial planning eventually results in actions that may affect the provision of a wide range of ecosystem services, and that are instrumental to their conservation and enhancement (TEEB, 2010). Hence, predicting effects on ecosystem services has emerged as a crucial need in spatial planning, and in the associated Strategic Environmental Assessment (SEA) practice (Geneletti, 2011). Despite the increasing body of literature, the use of ecosystem service concepts to support real-life decision-making processes is still limited, and there is a need to move "from conceptual framework and theory to practical integration of ecosystem services into decision-making, in a way that is credible, replicable, scalable and sustainable" (Daily and Matson, 2008).

A common feature in studies addressing the relationship between land use and ecosystem services is the use of scenario analysis to represent and compare possible futures. From the publication of the Millennium Ecosystem Assessment (MA, 2005) onwards, scenarios have been frequently employed in both conceptual frameworks (Balmford et al., 2008; Carpenter et al., 2006) and empirical applications (Birch et al., 2010; Nelson et al., 2009). In these exercises, future scenarios are constructed by making different assumptions on the underlying driving forces, and hence on the magnitude of land-use changes. For instance, Polasky et al. (2011) built different land-use scenarios by varying the rates of urban, agricultural and forestry expansion. Scenario analysis is also one of the fundamental tools of SEA, given the inherently high level of uncertainty associated to the future implementation of plans and policies. The exploration of future scenarios can be used to test the way in which different alternatives achieve a variety of goals, under different projections concerning the trend of key driving forces (Geneletti, 2012; Zhu et al., 2011).

Comparison of alternatives and justification of choices are crucial SEA elements, even though recent reviews of practices showed that they are often poorly considered in spatial planning (Fischer, 2010; Wende et al., 2012). In spite of the fact that alternative consideration has been constantly pointed out as one of the weaknesses of SEA, this issue does not appear to have progressed much over the last years. For example, the majority of SEA experts interviewed by Bragagnolo et al. (2012)

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perceived the exploration of alternatives in SEA as unsatisfactory, and the majority of the SEA reports of spatial plans reviewed by the same authors were not clear about how alternatives were defined and compared.

This paper addresses these issues by presenting a case-study research aimed at empirically exploring how the implementation of alternative land-use zoning policies will affect the future provision of ecosystem services. The term 'land-use zoning policy' is used here to indicate regulations concerning permitted, prohibited or preferred land uses. The design of such policies is often a core issue in spatial planning, and they represent one of the most tangible elements of a plan. The method is based on the generation of future land-use scenarios that simulate the implementation of alternative zoning policies. The effects of the land-use scenarios on selected ecosystem services are then modeled and compared through a set of metrics.

The study area is in The Araucanía region, southern Chile. This region is extremely rich in natural resources, but has a relatively low performance in development indicators. The application of the methodology to the case study addresses three more specific questions: What are the effects of different zoning policies on future land uses within the region? How do these effects affect the conservation of ecosystem services? What are the trade-offs among ecosystem services associated with the different policies? By answering these questions, the paper aims also at illustrating the potential contribution of the approach to support SEA of spatial planning.

2. Study area, selected ecosystem services and land-use zoning policies

The Araucanía, one of Chile's 15 Administrative Regions, covers an area of 31,842 km^2 and has a population of 890,000, about a third of which is distributed in rural areas (Fig. 1). It is considered among the regions with the highest natural capital of the Country, with 12 national parks and reserves (mainly distributed within the Andes Mountain Range), and almost 30% of the area covered by native forest (Gobierno de Chile, 2009). The Araucanía is also among Chile's poorest area, with a relatively low performance in development indicators and 27% of people living below the poverty line (Mideplan, 2009). In the last three decades, the region has experienced a rapid growth of monoculture conifer plantations (almost exclusively made of *Pinus Radiata* and *Eucalyptus* sp.), at the expense of native forest, marginal agricultural fields and grasslands. Remaining native forests are concentrated almost exclusively on the Coastal and Andes mountain ranges (CONAF et al., 1999; Gobierno de Chile, 2009). Another, and more recent, trend in land use is the development of market-oriented forms of agriculture, such as berry production (ODEPA and CIREN, 2006). These changes in land cover and land use brought about a number of environmental problems, including water scarcity, water pollution, soil erosion and biodiversity loss (Echeverria et al., 2006; Lara et al., 2009).

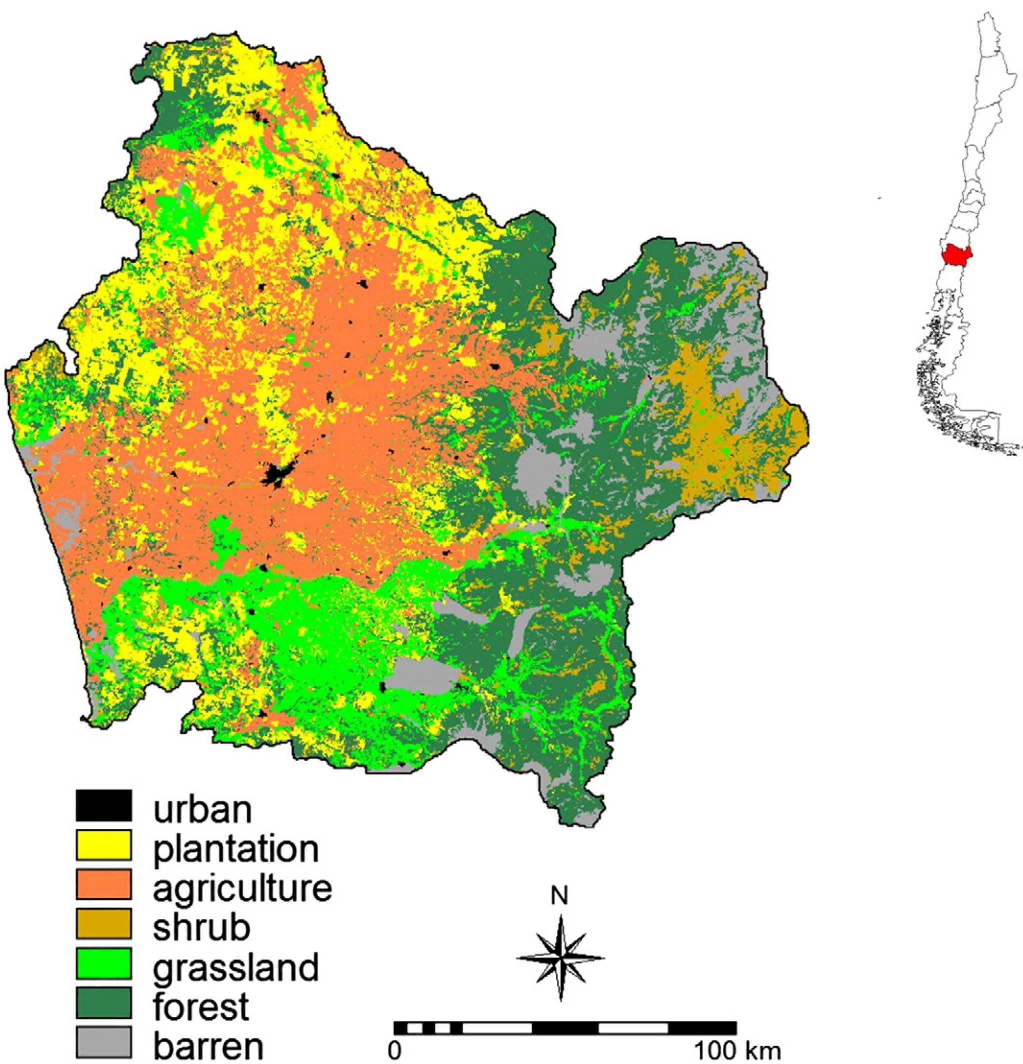

Fig. 1. Location of The Araucanía region in Chile (top right) and main land uses.

The characteristics of the study area suggested the selection of the ecosystem services considered in this study, which include water purification, soil retention, carbon sequestration, provision of habitat for species, and timber production. Water purification refers to the capacity of ecosystems to mitigate water pollution by retaining some non-point source pollutants. Soil retention refers to the capacity to keep soil in place, so avoiding erosion. Carbon sequestration is the capacity of plants and soil to store and accumulate carbon. The habitat service is the capacity of ecosystems to supply living space for species, hence supporting biodiversity. Besides being all extremely relevant to the land-use change processes that characterize the study area, these ecosystem services were selected also because they represent a mix among different categories of services, namely regulating (water purification, soil retention, carbon sequestration), supporting (habitat for species) and provisioning (timber production) services. This allows understanding a broad suite of ecosystem responses to land-use changes, and to assess the associated trade-offs (DeFries et al., 2004).

In Chile, SEA has been recently introduced, together with a new form of spatial plan at regional level, the *Plan Regional de Ordenamiento Territorial* (PROT). The PROT differs from existing plans because, among other things, it promotes the development of a land-use zoning policy that defines the preferred land uses for the whole territory, rather than for urban area only. This zoning policy aims at giving spatial representation to regional development strategies, by specifying where the strategies' objectives are to be achieved and through which uses of land (Subdere, 2010). By using existing information, mostly contained in available dataset and planning instruments (e.g., PRDUyT, 2005), a set of alternative land-use zoning policies were drafted for a study area within the region. This study area includes the central and western sectors of the region, leaving out the Andean range, which is largely covered by protected areas and native forest, hence less subject to land-use transformations (Fig. 2). The policies were designed by the author for the sole purpose of testing the proposed method, and do not represent the outcome of actual spatial planning exercises. The purpose was simply to simulate different zoning schemes for the regional context using existing information. The zoning policies subdivide the region into zones, and specify, within each zone, the land uses that are prohibited, disfavored, indifferent and preferred. The zones represent the boundaries within which land-use changes are envisaged by the different policies. Within these boundaries, the actual areas allocated to the different uses depend upon local suitability factors, as described in Section 3.1.

The first zoning policy (ZP0) represents the zero-alternative, or "laissez-faire", where no constraints or preferences on the distribution of future land uses are set. The second policy (ZP1) was inspired by the indications contained in the existing land-use plan on the preferred and prohibited uses of different land units. This policy favors the development of new conifer plantations in the northern and south-western sectors of the region and promotes new agricultural areas in the central part (Fig. 2). The third policy (ZP2) was designed by combining indications resulting from a survey on land suitability conducted at municipal scale (PRDUyT, 2005). This policy promotes conifer plantations in the eastern and western sectors, and new agricultural areas in larger tracts in the southern and central sectors of the region. Another important difference between ZP1 and ZP2 is in the "grain" of the zones, which are generally larger and more compact for ZP2, and smaller and scattered for ZP1.

3. Methods

The first part of the methods consisted of the construction of land-use scenarios associated to the three zoning policies previously described (Section 3.1). Subsequently, the effects of the land-use scenarios on the provision of the selected ecosystem services were assessed in a spatially explicit way, by using modeling tools (Section 3.2). Finally, a set of metrics was developed to compare scenarios and assess trade-offs (Section 3.3).

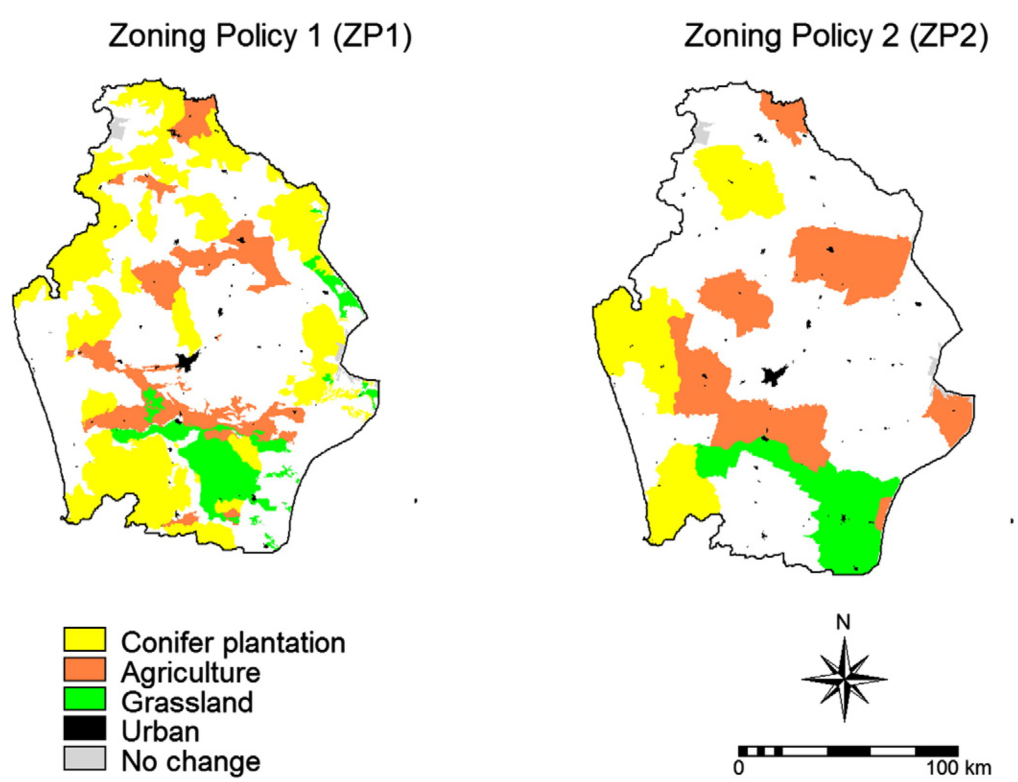

Fig. 2. Zoning policies 1 and 2 (for better visualization, only preferred land uses are represented). The zones represent the boundaries within which land-use changes are envisaged by the different policies. Within these boundaries, the actual areas allocated to the different uses depend upon local suitability factors, as described in the text.

3.1. Development of land use scenarios

Map representations of land-use scenarios were generated through spatial modeling in a GIS. The approach consisted of four main stages: land-use change analysis and modeling, projecting future land use quantities, setting incentives and constraints to future land-use transitions according to the different zoning policies, and finally projecting future land-use scenarios. All operations were carried out through the Land Change Modeler (LCM) tool implemented in the software package IDRISI Taiga (Eastman, 2009). Fig. 3 shows a flowchart of the analysis.

The input to the first stage was represented by two land-use maps of 1994 and 2007. Both maps have a spatial resolution of 30 m, and were obtained by classifying satellite images and field checks. After having harmonized their legend, the two maps were processed and compared to detect land-use changes. A transition matrix was built, showing the amount of land that was converted from each land use to any other use. Consistently with the objective of the study, the modeling of future land uses focused only on the main man-induced transitions, as opposite to transitions due to natural processes (e.g., from shrubs to forest). In particular, the following six transitions were considered: agriculture to urban, grassland to urban, forest to agriculture, and forest/grassland/agriculture to conifer plantation. For each transition, a mathematical sub-model was developed. Sub-models are based on the combination of user-selected explanatory variables, using the binomial logistic regression and the Maximum Likelihood method (more information on this procedure can be found in Aldrich and Nelson (1984) and Clark and Hosking (1986)). In short, each sub-model determines how the different variables explain a specific land-use transition that occurred in the period 1994–2007, and on the basis of this information is able to generate a map of "transition potential" for a given time in the future. The variables were selected from the existing regional database or generated from such database through GIS analysis (e.g., reclassification, distance calculation). For example, the sub-model for the agriculture-to-plantation transition included the following variables: elevation, slope, aspect, soil type, proximity to infrastructure and urban areas, and proximity to existing plantations. Prior to their use in the sub-models, the explanatory power of variables was tested using Cramer's V, in order to discard variables that showed low association with land uses (Eastman, 2009).

In the second stage, the rate of future land-use transitions was set. Two rates of change were considered in this study to illustrate the effects of the zoning policies in different conditions, hence expanding the scope of their comparison. The first one ("Rate 1") was derived from a Markov Chain prediction (Bell, 1974), which assumes that the type and rate of future land-use transitions will be equivalent to the ones that occurred in the past. Using the results of the land-use change analysis, the Markov Chain determines exactly how much land would be expected to transition from each land-use category to every other category in a given time in the future. The second rate ("Rate 2") was computed by increasing by 50% the Markovian rate of the considered land-use transitions. This was to simulate a condition characterized by a more rapid increase in conifer plantations, urban areas and agriculture. This condition was considered as a possible future trend in the area, in the light of the trends that occurred in recent years in the neighboring regions to the North and to the South.

In the third stage, maps of constraints/incentives were formulated to reflect the implementation of the different zoning policies, which, as described in Section 2, classify, within each zone, land-use types into four categories: prohibited, disfavored, indifferent and preferred land uses. Maps were generated by assigning to these categories respectively a value of 0, 0.5, 1 and 2. In the LCM, these maps are multiplied by the transition potentials maps developed in the first stage. As a result, a given the land-use transition cannot occur if it is prohibited by the zoning policy under consideration. Analogously, areas where the transition is disfavored or preferred by the zoning policy will get, respectively, lower and higher transition potential. Finally, land-use scenarios were generated for the three zoning policies, under the two assumptions concerning the future rate of land-use transitions. The final time horizon was set to 2050, even though scenarios were developed also for two intermediate times (2020 and 2035) in order to gain a better understanding of temporal trends. Hence, a total of 18 land-use scenarios were constructed (see Fig. 4). Operationally, scenarios are generated in LCM by an algorithm that first looks through all transitions and creates a list of host classes (classes that will lose some amount of land) and a list of claimant classes (classes that will acquire land) for each host (see Eastman, 2009 for more details). The land quantities for each class are determined as described in stage two. A multi-objective allocation process is then run to assign land for all claimants of a host class, using as a reference the maps of transition potential developed in stage two (and then adjusted according to the incentives/constraints maps, as per stage three). The results of the allocation of each host class are then overlaid to produce the final land-use map (full details on the allocation procedure can be found in Eastman et al., 1995). Therefore, at any

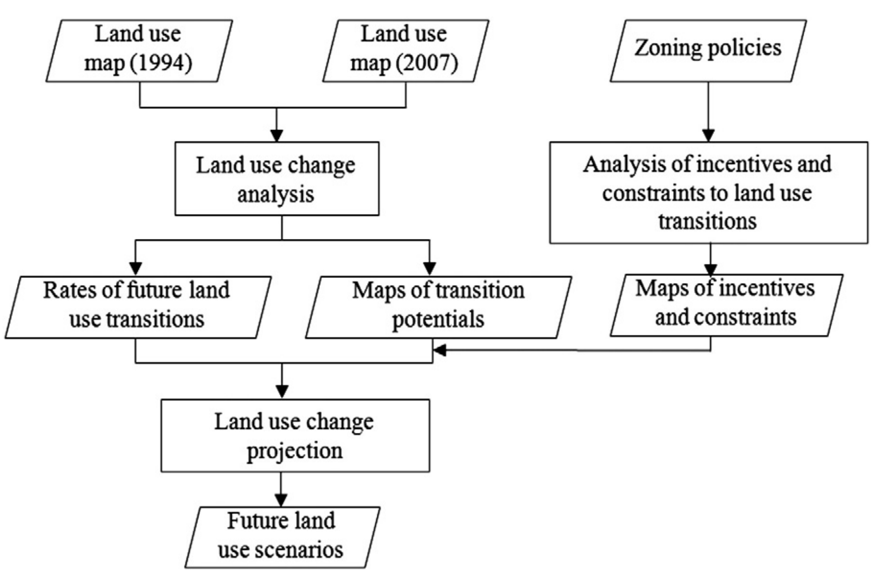

Fig. 3. Flow-chart of the analysis conducted to generate the land use scenarios (rectangles show operations, parallelograms show input/output).

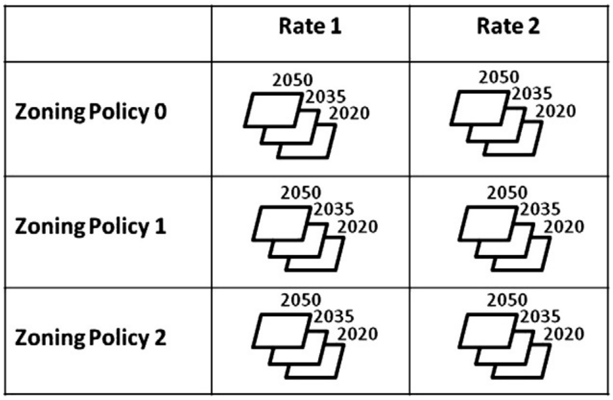

Fig. 4. Diagram of the set of land use scenarios resulting from the combination of the three zoning policies and the two rates of change, at three different time horizons.

time horizon, land-use scenarios associated to the three policies are characterized by constant quantities of each land-use type, but different spatial patterns.

3.2. Ecosystem service modeling

The provision of the selected ecosystem services was modeled across the 18 different land-use scenarios, and also for the 2007 land-use map, which was used as a baseline for comparison. Modeling of carbon sequestration, water purification and soil retention was performed through a recently developed set of GIS-based models, the Integrated Valuation of Ecosystem Services and Tradeoffs tool (InVEST) (Tallis and Polasky, 2009). Habitat provision was modeled using MaxEnt (Phillips et al., 2004). Finally, timber production was modeled by considering the land area covered by plantations. An overview of the models and of the input data that were used in this study follows. A full description of the models, including information on their assumptions and limitations, can be found in Tallis et al. (2011) and Phillips et al. (2004, 2006).

The carbon sequestration model aggregates the amount of carbon stored in four carbon pools: aboveground biomass (living plant material above the soil, such as trunks and branches), belowground biomass (root systems), soil organic matter and dead organic matter (litter and dead wood). The model allows also to include a fifth carbon pool, namely the harvested wood products (e.g., firewood or charcoal), which represents the biomass removed through harvest. However, this pool was not considered here because data concerning harvesting intensity and frequency across the study region were lacking. The basic assumption of the model is that each land-use type has a fixed storage level, so that changes over time are due to transition from one land-use type to another, disregarding other effects, such as natural succession of vegetation. This assumption is acceptable for the purpose of this work, which aims at assessing differences caused by land-use changes, rather than attempting to measure absolute values. Data on carbon stored in each of the four pools for each land-use type were taken from published reference data (IPCC, 2006), by using information on the climate domain of the study region and information on vegetation species. The outputs of this model are maps that represent the amount of carbon (in mg per grid cell) that will be stored under the different land-use scenarios.

The water purification service refers to the capacity of ecosystems to mitigate water pollution by retaining some non-point source pollutants through the action of vegetation and soil. The InVEST model uses data on runoff, land use, nutrient loading and filtration rate to determine the nutrient retention capacity of every grid cell in a given land-use scenario. Nitrogen was selected as target nutrient in this study. The model first calculates average runoff from each cell. Subsequently, it estimates how much nitrogen leaves each cell using appropriate export coefficients. Finally, it determines how much of this load is retained by the downstream cells, and eventually how much pollutant reaches waterways from each cell. The latter output (expressed in kg of N per cell) is the one used in this study to model the effect of the different land-use scenarios.

The soil conservation service refers to the capacity of vegetation to keep soil in place. For any given land parcel, the service is modeled by comparing the erosion rate on that parcel with the rate that would occur if no vegetation were present. Erosion rates are predicted by using the Universal Soil Loss Equation (USLE, Wischmeier and Smith, 1978), which accounts for land use, soil type, rainfall intensity and topography. The model also estimates how much of the sediment eroded is trapped by downstream vegetation. The final outputs are maps containing the total sediment retained by each cell (sediment retained on the cell itself + sediment removed from the loadings of the upstream cells), under the different scenarios.

The habitat provision service is the capacity of ecosystems to supply living spaces for species. In this study, it was modeled by selecting the kodkok *Oncifelis guigna* as a target species. *O. guigna*, one of the world's smallest and least known felids, has a very small geographical distribution, restricted to a narrow strip of temperate forests within southern Chile and Argentina (Sanderson et al., 2002). Its habitat includes forests and semi-open areas, and it is strongly associated with Araucaria native forests, which are endemic in the study region (Dunstone et al., 2002). *O. guigna* is considered endangered in Chile, its survival being threatened by forest loss and fragmentation (Acosta-Jamett et al., 2003). Presence data of *O. guigna* in the study region, collected over the last few years, were made available by the Fauna Australis Wildlife Laboratory of the *Pontificia Universidad Católica de Chile*. These data, in combination with GIS layers of environmental and land use variables thought to influence species distribution (vegetation type, elevation, slope, distance from water bodies, distance from roads, etc.), were used to model the habitat of *O. guigna*. Modeling was performed using MaxEnt, a species distribution model based on the ecological niche concept (Phillips et al., 2004). MaxEnt is a machine-learning model based on the maximum entropy concept that provides as a result maps showing the probability gradient for the potential distribution of a species in a 0–1 range. Further details on the tool and its algorithms can be found in Phillips et al. (2006, 2004). The selection of MaxEnt was suggested by recent studies that showed its good performance in comparison with other models (Gontier et al., 2010; Hernandez et al., 2006). Additionally, MaxEnt works with only species presence data, while other models require also absence data, which were not available for the study area. The model was run for the 2007 baseline, and for the 18 land-use scenarios.

Finally, commercial timber production was estimated by using the land area of plantations as a proxy. This index is commonly used to assess the productive capacity of forests (Haynes, 2003). The actual estimate of the volume of harvested timber would have required spatially-distributed data on harvest level and cycle, which were not available. The proposed proxy, even though highly simplified, was considered adequate to the purpose of this work, which aims at assessing changes from baseline conditions, as opposite to absolute biophysical or monetary quantification of services.

3.3. Metrics for policies comparison

The following metrics were developed to compare the effects of the zoning policies on the selected ecosystem services:

1. Percentage of change in service provision across the region with respect to the 2007 baseline;
2. Percentage of the landscape where the service is preserved. In any given cell, a service is considered preserved if its 2050 value is at least equivalent to 90% of its 2007 value;

3. Percentage of the landscape where the service is degraded. In any given cell, a service is considered degraded if its 2050 value is less than 50% of its 2007 value.

The combined used of these metrics aim at providing further understanding on the performance of the different policies. For example, they help discriminating policies with good overall performance but severe local degradation of services, from policies with relatively lower performance but more homogeneous effects across the landscape.

4. Results

The transition matrix resulting from the analysis of the land-use change between 1994 and 2007 is presented in Table 1. A simplified legend is used to highlight transitions of interest for this study. Conifer plantations increased by about 32%, at the expenses of agricultural land, forest and grassland in that order. Urban areas increased by 24%, mainly as a result of the encroachment of agriculture and grasslands. Native forest experienced a total reduction of about 4%, due to conversion to agriculture and plantations. As anticipated in Section 3, these were the transitions addressed here. Other land-use changes are either minor, due to natural processes, or partly explained by classification errors affecting the land-use maps (e.g., plantation to forest and forest to grassland/shrub) (Gobierno de Chile, 2009). These results were used to compute the two rates of future land-use changes, which in turn were used to project the size of the different land uses in 2020, 2035, and 2050 (Fig. 5).

The land-use scenarios resulting from the modeling are presented in Fig. 6 (for conciseness only the 2050 scenarios are shown). A visual comparison of the scenarios shows the effects of the different zoning policies. ZP0 causes plantation to first grow in the northwestern sector, and then gradually expand to the South in a more scattered and patchy fashion. ZP1 produces an intrusion of plantations mainly in the central sector of the region, generating a more fragmented agricultural landscape. Under ZP2, plantations develop along a ring from the northern to the southwestern sectors of the region, leaving an agricultural core in the middle.

The results of the ecosystem services modeling are presented in the maps of Fig. 7 (for 2050 and Rate 1 only, spatial patterns being similar in the other scenarios), and in the graphs of Fig. 8. The latter figure shows the trends of the five ecosystem services through time under the three zoning policies, and for the two rates of change (metric 1, Section 3.3.). The values reported in the diagrams are obtained by summing-up the value of the service in each cell across the maps, and then normalizing by the 2007 values. The habitat provision service represents an exception in that the values were obtained by counting the cells with probability gradient above 0.5 (i.e., by looking at how many locations have a highly suitable habitat, rather than at the average habitat suitability). A sensitivity analysis was run by testing also different thresholds (0.75 and 0.85), but this did not change the relative performance of the policies. As expected, all policies produced the same general trend: a decline in water purification, soil retention and habitat provision (triggered by the progressive conversion to less natural land covers), and an increase in carbon sequestration and timber production (promoted by the expansion of conifer plantations). Timber production does not differ among policies because the adopted indicator measures the area of plantations. Carbon sequestration is also very similar because it is strongly related to the size of different land-use types. The spatial patterns of carbon sequestration and timber production are clearly associated to the land-use changes that occurred in the different scenarios (compare Figs. 6 and 7). However, the decline in water purification and soil retention is the result of watershed-scale phenomena, and affects also areas not directly involved in land-use changes (e.g., the central sector of the coastal strip and part of the pre-cordillera).

Table 1
Transition matrix showing land use changes (in thousands of hectares) occurred between 1994 and 2007 (the bold font indicates transitions addressed in this study).

2007 / 1994	Urban	Plantation	Agriculture	Grassland/ scrub	Forest	Other
Urban	10.48	0.04	0.00	0.00	0.00	0.03
Plantation	0.25	545.52	0.00	0.00	38.82	2.57
Agriculture	**1.74**	**107.69**	856.89	0.00	0.00	0.00
Grassland/scrub	**0.43**	**54.28**	0.00	394.68	0.00	2.36
Forest	0.12	**63.05**	**14.24**	13.97	820.71	0.00
Other	0.10	7.78	0.00	0.00	9.64	236.55

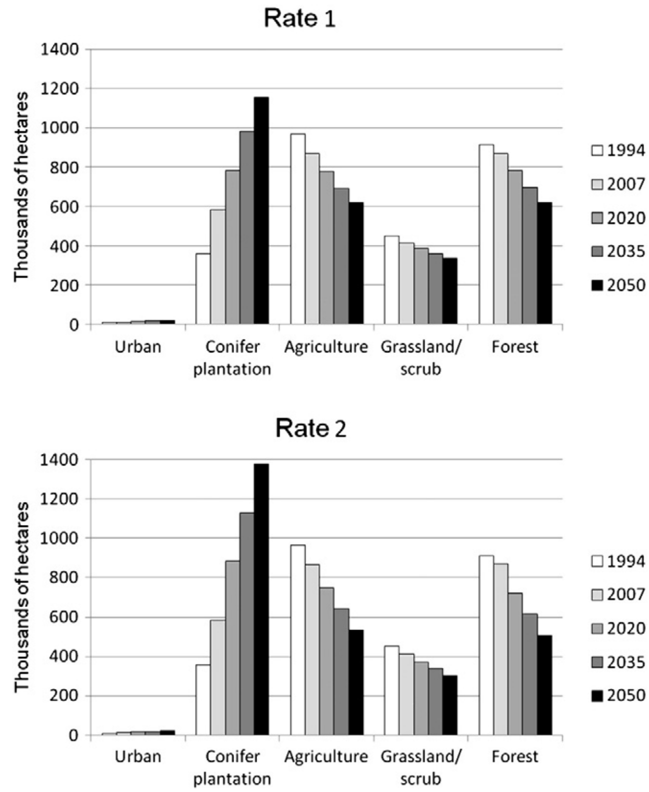

Fig. 5. Land use projections under the two rates of land use change.

The diagrams of Fig. 8 show that the gradient of the decline in water purification, soil retention and habitat provision depends upon the land-use zoning policy. The results indicate that ZP1 has the smallest impact in the conservation of the two regulating services of water filtration and soil retention, as well as the supporting service of habitat provision. Differences between the best and the worst performing policies are in the order of 5% for water and soil, and 10% for habitat. These differences are comparable in magnitude to the differences that characterize, for the same policy, the two rates of land-use changes (compare solid and dotted lines in Fig. 8). For example, the implementation of ZP0 assuming Rate 1 generates in 2050 the same decline in water filtration as the implementation of ZP1 assuming Rate 2 (hence increasing by 50% the rate of land conversion to urban areas and plantations). This is even more evident for soil retention and habitat: ZP1 assuming Rate 2 causes less reduction in these services than ZP2 assuming Rate 1.

The trade-off diagrams represented in Fig. 9 offer a clear picture of the dominance of ZP1 over ZP0 and ZP2. The first set of diagrams (Fig. 9a–c) focuses on the trade-offs between provisioning (timber) and regulating and supporting services (soil retention, water purification, habitat provision). As expected, timber production is inversely related to the provision of all these three services. This is mainly due to the development of new plantations in areas previously covered by native vegetation, which decreases the capability to

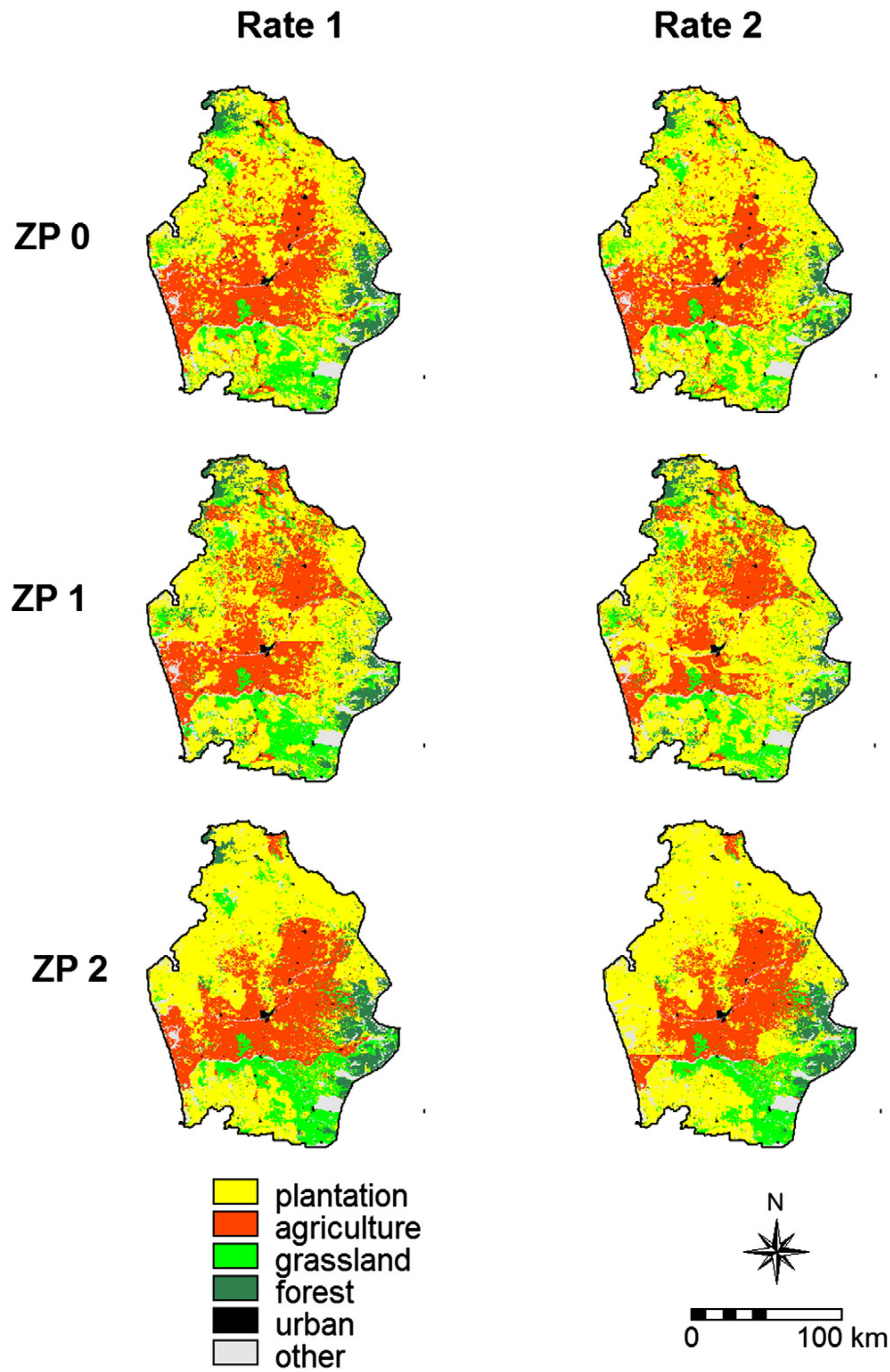

Fig. 6. The land use scenarios generated for the three zoning policies and the two rates of land use change (time horizon: 2050).

conserve soil, filtrates water and provides suitable habitat to species. The second set (Fig. 9d–f) illustrates trade-offs between regulating and supporting services that occur at different spatial scales: changes in soil retention, water purification and habitat provision (which can be considered regional-scale services) are compared with changes in carbon sequestration, a global-scale service. The diagrams show that carbon sequestration is inversely related the three other services. This is mainly explained by new conifer plantations that replaced ecosystems with higher retention and filtration capabilities, as well habitat suitability, such as shrublands and grasslands. Both sets of diagrams show that ZP1 is the most efficient policy: for the same levels of timber production or carbon sequestration, it preserves more habitat, soil and clean water.

Finally, Table 2 presents metrics 2 and 3, which were computed only for water, soil and habitat, as they are not relevant to the other two services. According to these metrics, the ranking of the policies is more fluctuating. However, SP1 is characterized by the best, or very close to the best, performance in terms of both minimizing areas where the three services are highly-degraded (metric 3), and maximizing areas where they are well preserved (metric 2). The only exception is represented by the preservation of habitat, for which SP2 has a much better performance.

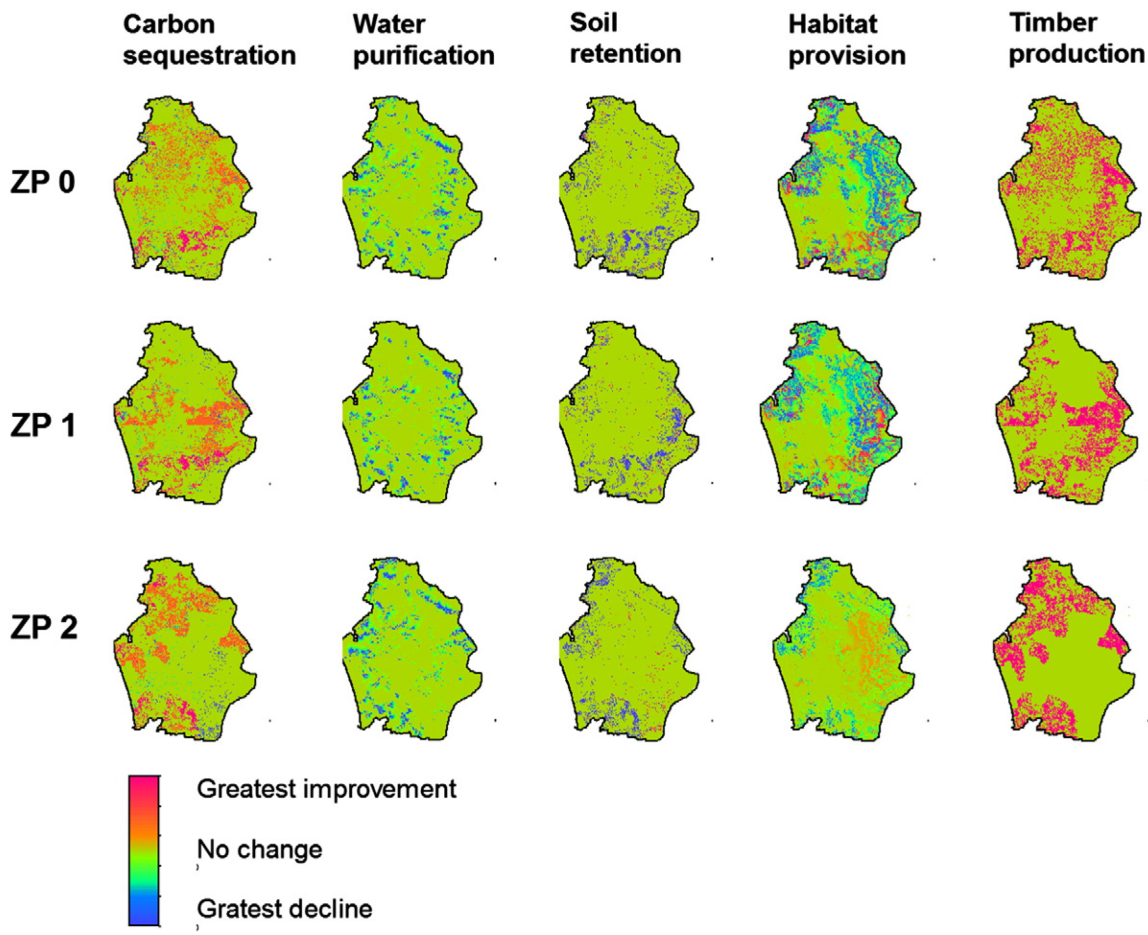

Fig. 7. Results of the ecosystem service modeling for Rate 1 (time horizon: 2050).

5. Discussion and conclusions

5.1. Scenario analysis and ecosystem services modeling

This paper applied spatially-explicit models to generate land-use scenarios associated to different zoning policies, and to predict their effect on a set of ecosystem services. The research contributes to the growing literature on the interactions between land-use changes and the provision of multiple ecosystem services (Nelson et al., 2010; Polasky et al., 2011). Consistently with an emerging consensus in this literature (Birch et al., 2010), the approach compared the effects of alternative policy actions, rather than performing a static analysis of current service provision. In line with the literature on SEA and scenario analysis, scenarios have been used in this study to describe what could happen, rather than to predict what will happen, or even what is likely to happen. In particular, the use of empirical modeling allowed building land-use scenarios that are based on the analysis of the factors that have driven past land-use transitions (e.g., slope, soil, proximity to roads). In this way, scenarios allowed to represent the possible effects "on the ground" of the different zoning policies. This is particularly relevant at the regional level, where land-use zoning aims to provide indications on the general allocation of land uses, rather than specifying the future use of each land parcel (Bragagnolo and Geneletti, in press; Geneletti et al., 2007).

The use of two different rates of future land-use transitions allowed to compare the magnitude of the effects on the ecosystem services attributable to changes in the size of land uses, with the one attributable to changes in their pattern. The results indicate that, for this case study, spatial configuration of land uses is as an important factor as their size. This suggests that the analysis of land-use patterns, hence the design of the zoning scheme, need to be included in scenario exercises aimed to support SEA of spatial planning. In reality, land-use transitions and zoning policies are not likely to be independent from each other because the policies themselves drive, at least to some extent, the intensity of future changes (especially if the zoning schemes are particularly restrictive). However, keeping them independent was instrumental to the purpose of better understanding the effects of alternative decisions in spatial planning.

The research made use of InVEST, a GIS-based tool to model the future provision of multiple ecosystem services. The use of InVEST has been demonstrated in several scientific papers over the last 2 years (Nelson et al., 2009, 2010; Polasky et al., 2011), and this tool currently offers the most complete suite of models for the spatial representation of services. Although a discussion on the models' performance and limitations goes beyond the objectives of this paper, an obvious strategy to improve the reliability of the results would be to improve the input data, which in this research were limited to those data that are typically available in a regional planning setting. To test the feasibility of the approach in actual SEA and planning settings, only existing data generated by local authorities and research institutions were used, complemented by available global-scale information (e.g., on carbon storage in different climate domains). Fieldwork can be performed to calibrate and refine such data. Additionally, sensitivity analysis can be run to test the robustness of the ranking of the policies, and to determine the most critical input variables for the different ecosystem service models.

5.2. Use of multiple metrics and representation of trade-offs

This research presented an approach to include information of ecosystem services in a specific stage of SEA of spatial planning,

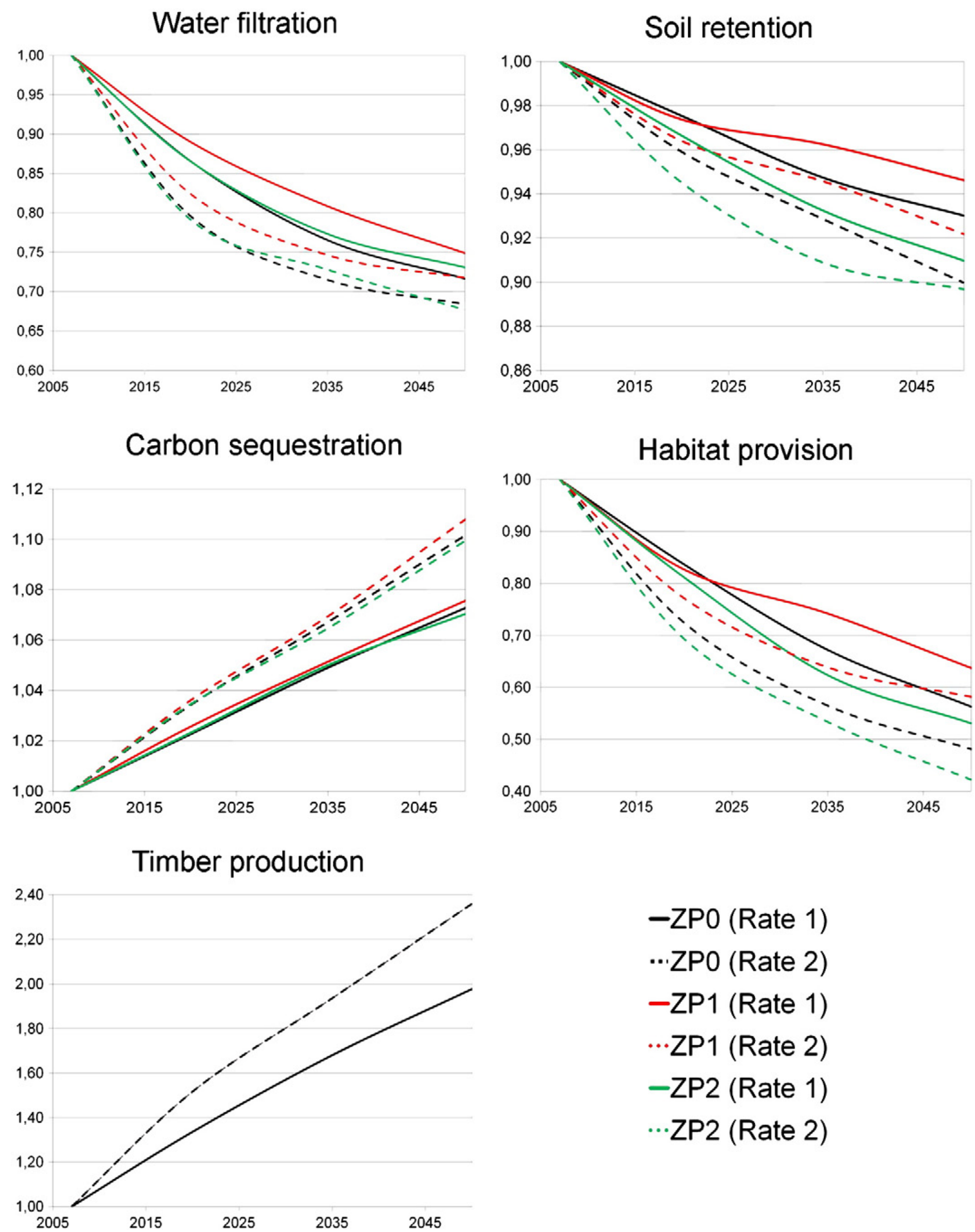

Fig. 8. Trends of the five ecosystem services through time under the three zoning policies.

namely the comparison of alternative land-use zoning policies. This comparison was characterized by two elements: the use of multiple metrics to express the effects on ecosystem services, and the representation of the trade-offs among services. The literature has emphasized that studies in ecosystem services should not focus only on the average level of services, because local "bottlenecks" may be very important in constraining service supply and use (see for instance van Jaarsveld et al., 2005). By building on this concept, additional metrics were computed in this study to describe effects such as the degradation and preservation of services across the landscape. The inclusion of these metrics offers a broader picture of the consequences of the different policies. However, the proposed metrics are meant to be exemplary only, and further or different metrics can be developed, ideally to answer case-specific questions. Analogously, in this study the thresholds that define the preservation and degradation conditions were arbitrarily set. These thresholds can be revised and adapted in the light of available scientific evidence and/or by considering policy objectives. For example, the importance of maintaining portions of the landscape where a given service is well-preserved can be suggested by the state of conservation and/or the strategic relevance of the service at different scales (e.g., at national level). Finally, as shown in this research, the computation of similar metrics requires spatially-explicit representation of service provision. We consider the availability of this information to be a key element to mainstream ecosystem services in decision-making.

Spatial planning is about resolving conflicts on competing demand for limited resources, and uneven distribution of costs and benefits. Hence, the analysis of trade-offs associated to planning choices represents a pivotal issue in SEA. By driving future land-use changes, spatial planning decisions affect the relative mix of ecosystem services within a region, determining trade-offs among them. Such trade-offs can be an explicit choice, but can also arise without awareness (Rodríguez et al., 2006). Typically, trade-offs involving regulating services and trade-offs across space (e.g., when benefits accrue locally, but the cost

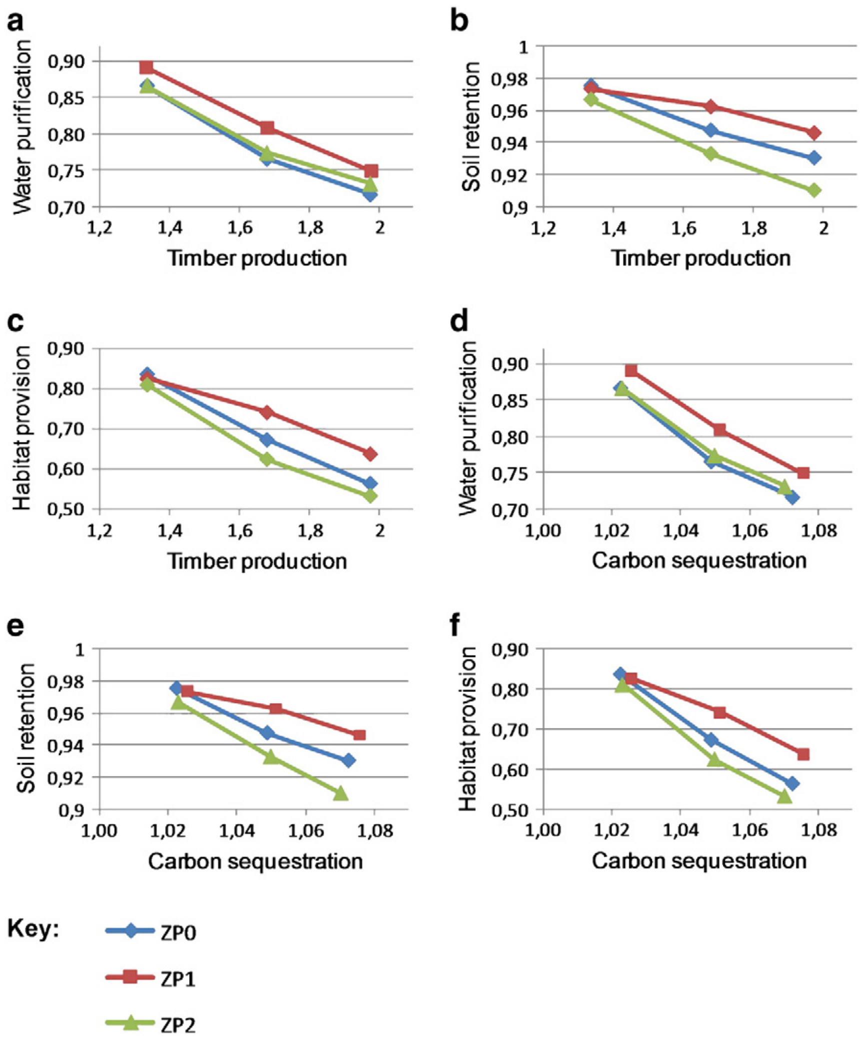

Fig. 9. Diagrams of the trade-offs between pairs of ecosystem services. a–c represent trade-offs between provisioning and regulating/supporting services. d–f represent trade-offs between regulating services that occur at regional and global scale.

are borne elsewhere) are less visible, hence less likely to be properly addressed. This study generated a representation of the trade-offs between provisioning and regulating services, and between regulating services that occur at different spatial scales. The resulting trade-off curves are useful to identify inefficient alternatives, but also to highlight conditions such as "small loss–big gain" (when a small reduction in one service has major benefit for another service), or vice-versa (DeFries et al., 2004). This information provides valuable support to planning, by narrowing the scope of potential decisions.

One last note addresses a potential further improvement of this research, currently under development: the analysis of how different policies affect the fruition of services by beneficiaries. Policies may differ not only in terms of changing the flow of services across the landscape, but also in being more or less effective in providing the services where they are most needed and used. A conceptual framework needs to be built to link changes in services with expected effects on the well-being of beneficiaries (for instance in terms of material assets, sufficient food, safety, health, etc.). This can be achieved by combining the output of this study with spatially-resolved socio-economic variables (e.g., population density, livelihood systems, poverty indicators) that estimate the appropriation of services by people. In this way, the scope of the policy comparison can be expanded to include the analysis of trade-offs among different groups of beneficiaries, characterized by different needs and levels of dependency from the selected services.

Table 2
Results obtained by applying metric 2 (percent age of the landscape where the service is preserved) and metric 3 (percentage of the landscape where the service is degraded).

	Water filtration [% of area]		Soil conservation [% of area]		Habitat provision [% of area]	
	Preserved	Degraded	Preserved	Degraded	Preserved	Degraded
ZP0	29.92	19.59	76.12	4.58	24.73	14.98
ZP1	43.78	15.12	82.96	4.75	26.93	10.39
ZP2	44.09	16.93	72.85	10.44	43.37	28.93

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