Scenarios for land use and ecosystem services under global change

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Abstract

Scenarios provide a platform to explore the provision of ecosystem services under global change. Despite their relevance to land-use policy, there is a paucity of such assessments, particularly in developing countries. Central Chile provides a good example from the Latin American realm as the region has experienced rapid transformation from natural landscapes to urbanization and agricultural development. Local experts from Central Chile identified climate change, urbanization, and fire regimes as key drivers of change. Scenarios depicting plausible future trajectories of change were developed to assess the combined effects on carbon storage, wine production, and scenic beauty for the year 2050. Across the region, the action of the drivers reduced the total amount of carbon storage (by 85%) and wine production (by 52%) compared with a baseline scenario, with minor changes incurred for scenic beauty. The carbon storage and wine production had declined by 90% and scenic beauty by 28% when the reaction to changed fire regimes was also taken into account. The cumulative outcomes of climate change and urbanization are likely to place substantial pressures on ecosystem services in Central Chile by mid-century, revealing the need for stronger planning regulations to manage land-use change.

Keywords: carbon storage; scenic beauty; wine production; urbanization; climate change; fire.

1. Introduction

Global efforts to achieve the United Nations Sustainable Development Goals will require an understanding of how the provision of ecosystem services will be affected as a result of global environmental change (Schröter et al. 2005, Rockström et al. 2009, Nelson et al. 2010, González-Varo et al. 2013, Mace 2013). Drivers of environmental change are factors that influence ecosystem services directly (e.g. climate change, land use change, invasive species) or indirectly (policies, science and technology, cultural factors) shaping the direction, magnitude and rate of future global change (MEA 2005, Kosow and Gaßner 2008). The drivers of environmental change do not operate in isolation, necessitating that the combined consequences of multiple drivers be determined (Nelson et al. 2006, Carpenter et al. 2009, González-Varo et al. 2013).

Over the past three decades, scenario analyses have played a central role in assessments of the potential effects of global environmental change on land systems at a variety of scales (Nakicenovic et al. 2000, MEA 2005, O'Neill et al. 2008, Van Vliet et al. 2010, Bryan et al. 2016). Scenarios explicitly incorporate uncertainty by exploring the outcomes that could arise due to multiple plausible futures. Scenarios are derived from a coherent and internally consistent set of assumptions or storylines (Peterson et al. 2003, MEA 2005, Adams et al. 2016), which can be depicted as spatially and temporally-explicit projections of drivers such as land-use and land cover, and climate change (Rounsevell et al. 2006, Rounsevell and Metzger 2010). Such projections enhance the communication of ecosystem services assessments and thus inform the development of robust land-use policies (Dunford et al. 2014, Lamarque et al. 2014).

There has been a paucity of studies of ecosystem services assessments under global change [but see (Oteros-Rozas et al. 2015)], particularly in developing countries of Latin America (Seppelt et al. 2011, Runting et al. 2016). The exact nature of the effect of global change in these countries is largely unknown, and their adaptive capacity is expected to be low (Sinivasan 2010). In Latin America, the drivers assessed are climate change and deforestation, parameters that are just a limited subset of global change (Grau and Aide 2008, Martínez et al. 2009, Birch et al. 2010, Carreño et al. 2012, Mendoza-González et al. 2012, Nahuelhual et al. 2014). Measuring the aftermath of a more-extensive set of global changes on ecosystem services is an important policy-relevant task in Latin American countries (Schröter et al. 2005, González-Varo et al. 2013, Oliveira et al. 2013). Rapid assessments using expert judgment and existing empirical information can be used in initial policy cycle phases to help demonstrate potential possible futures involving the drivers of change and their likely effects. Such assessments are being called for to inform initiatives such as the Intergovernmental Science-Policy Platform on Biodiversity, and Ecosystem Services (IPBES) (Brooks et al. 2014, Kok et al. 2016).

In Chile, historical trends for the past 20 years and predictions covering the next century suggest major changes in climate with a decline in rainfall and higher temperatures (Fuenzalida et al. 2007, Falvey and Garreaud 2009). Such changes are expected to have an effect on the distribution of ecological communities (Marquet et al. 2010). Chile also has experienced a rapid process of economic development in the past 30 years, and this has resulted in the extensive urbanization of the Metropolitan Region (Cohen 2004, Banzhaf et al. 2013). In this region, the native Mediterranean vegetation is adapted to repeated cycles of forest fires associated with high temperatures (Castillo et al. 2012b). Forest fires have increased in the past decade resulting from human activity and land use change, and as a consequence, fires have been most prolific in proximity to urban centers and roads (Castillo et al. 2012b, Altamirano et al. 2013).

We demonstrate a rapid assessment of the effects of global change on key ecosystem services in the Central Chile region, where data is sparse. Our approach translated expert-derived qualitative scenario storylines into quantitative spatial predictions of the combined impacts of climate change, urbanization and fire on the future provision of carbon storage, wine production and scenic beauty for the year 2050. The three ecosystem services evaluated are critically important for the country's environmental sustainability, its economic activity, and societal well-being (Figueroa 2016). Central Chile provides an exemplary study case of the Latin American context as the region has experienced a long history of land conversion from forest to agriculture, rapid urbanization and a changing climate with consequent effects on fire regimes (Armesto et al. 2010, Schulz et al. 2010).

2. Methods

2.1 Study Area

The Metropolitan Region of Central Chile (33°26′ and 34°19′S, Fig. 1) encompasses approximately 15,402 km^2, with elevation ranging from 0 to 6500 m.a.s.l. Characterized by a Mediterranean climate (warm and dry summers; cool and rainy winters) with mean temperatures ranging from 20°C in summer to 8°C in winter and with an annual precipitation of approximately 350 mm in the central valley, increasing with altitude (Meza et al. 2014). Central Chile is the most densely populated area of the country with almost 7 million people inhabiting the region (or 40% of the country's population), with 97% of people living in urban areas (INE 2012) and producing, in 2014, 44% of Chile's total economic product (Central Bank of Chile 2015). Urban development has occurred mainly on alluvial floodplains, which are also the most fertile soils for agriculture (Puertas et al. 2014), especially for fruit and wine production (Romero and Ordenes 2004). Urbanization is also trending into higher elevation areas (Romero and Ordenes 2004, Romero et al. 2012). The study region has a high incidence of fire events that have caused considerable material and environmental losses (Castillo et al. 2012b), and their frequency has increased in the past 20 years with an average of 5,000 fire events per annum (Altamirano et al. 2013).

[Insert Figure 1 near here.]

2.2 Scenario Building Process

We developed and applied a framework for building scenarios that composed four main steps (Schwarz 1991, Metzger et al. 2010): (1) define the scope and the focal questions, (2) identify key drivers, (3) construct qualitative scenario storylines, and (4) quantify and map the provision of ecosystem services under baseline conditions and under projections of land-use and climate change.

[Insert Figure 2 near here.]

2.2.1 Scope of the scenarios

We defined the scope of the scenarios analysis as the exploration of the potential influence of key global change drivers on three ecosystem services: carbon storage, wine production, and scenic beauty, in Central Chile for the year 2050. Carbon storage in the native Mediterranean forest has been identified as an important mechanism for mitigating the burden of climate change (Gibbs et al. 2007, Caparros et al. 2011). Scenic beauty is defined as the aesthetic values derived from the appreciation of natural scenery and scenic views (Bourassa et al. 2004, Bagstad et al. 2014). The Mediterranean mountain landscapes in Central Chile are in demand for leisure activities due to scenic views (De la Fuente et al. 2006, Schirpke et al. 2013). The Mediterranean climate region is also an important region for wine production (Hannah et al. 2013), being the fifth largest exporter of wines in the world and the ninth largest producer (Lobos et al. 2014). Central Chile has a large area that is potentially suitable for irrigated high-quality wine production, particularly at the bottom of valleys (Montes et al. 2012).

2.2.2 Identification of key drivers of change

We developed a list of drivers of land-use and land-cover change via semi-structured interviews with local experts (Appendix A). We initially contacted 25 experts by email and completed 10 interviews. The experts were from different disciplines (demography, economics, urban development, climate change, water, ecology, conservation, and biodiversity) and possessed both local and regional-scale expertise of the study region. The list of potential drivers was presented to the experts, and they selected and ranked drivers they considered would have the greatest effect on the landscapes of the region for the year 2050 (Appendix A). We selected the two highest-ranked drivers for the development of the storylines: climate change (specifically increasing temperature and decreasing precipitation) and urbanization. Climate change is predicted to reduce the distribution of sclerophyllous and thorny Mediterranean forest and reduce the carbon storage capacity of the landscape (Marquet et al. 2010). Urbanization is being encouraged through regional urban plans (PRMS 2014), which seek to expand the peri-urban limits of cities, especially in the northern and southeastern sectors (Puertas et al. 2014). The ongoing expansion of urban areas is expected to lead to the loss of native vegetation and fertile soils for viticulture and could reduce the scenic beauty of the Andean foothills (Romero and Ordenes 2004, Banzhaf et al. 2013, Puertas et al. 2014).

2.2.3 The scenario storylines

To construct the storylines we developed a scenario matrix and defined assumptions about the possible trends associated with climate change and urbanization (Plieninger et al. 2013), reflecting ranges from low/weak to high/strong. The possible combination of drivers resulted in four scenario storylines (see Fig. 3 for the definition of scenarios A, B, C, and D).

To define the assumptions for climate change we considered the greenhouse gas trajectories (RCP: Representative Concentration Pathways) adopted in the Intergovernmental Panel on Climate Change (IPCC) fifth assessment report for the year 2050, describing possible climate futures (IPCC 2013). We focused on the lower and higher greenhouse gas-concentration level trajectories (RCP 2.6 and 8.5 respectively) to encompass the range of uncertainty. According to the climate change driver, scenarios A and B will follow trends defined in RCP 2.6 where predicted emissions are substantially reduced over time (Kay 2013). Under this pathway, the temperature will increase by no more than 2ºC and will result in a reduction in precipitation by no more than 10% by 2050 (Fuenzalida et al. 2007). Scenarios C and D will follow trends defined in RCP 8.5 representing the business-as-usual scenario characterized by increasing greenhouse gas emissions over time (Van Vuuren et al. 2011). "Business-as-usual" will result in an increase of temperature by 3.5ºC and a 15% reduction in precipitation by 2050, along with an increase in the frequency of long and severe dry seasons (Fuenzalida et al. 2007, IPCC 2013, Kay 2013).

For urbanization, we considered the Regulatory Plan of the Metropolitan Region of Santiago (PRMS 2014) and identified two opposing trajectories (see Fig. 3). Scenarios A and C maintain urbanization at the current urban limits. This translates to the maintenance of current urban areas and the locating of new dwellings on available land inside the urban radius (23,800 ha of land available for construction). Scenarios B and D follow the new urban limits defined in the regulatory plan PRMS 100 (PRMS 2014). This represents an expansion of the urban radius by approximately 100 km^2 in eight districts of Santiago and removing construction restrictions above an elevation of 1000 m.a.s.l.

Climate change and urbanization are not independent, and system feedbacks magnify the interaction of both drivers and their combined effects (Nelson and Bennett 2005). The projected consequences of climate change, along with the increasing human population density and associated expansion of the road network, are predicted to lead to an increase in the prevalence of fires in the study region. These interactions were included in the ecosystem service assessments (Castillo 2012a, Altamirano et al. 2013).

[Insert Figure 3 near here.]

2.2.4 Quantitative ecosystem service maps

To translate the storylines into quantitative scenario maps, we identified available spatial models and spatial criteria representing each of the assumptions behind the scenarios. We mapped and modeled ecosystem services under baseline conditions and then developed ecosystem services models representing likely changes in the provision of ecosystem services under projected conditions. Finally, we developed a new set of ecosystem service scenarios incorporating future shifts in the probability of fire, caused by the interaction between climate change and urbanization.

Ecosystem service maps under baseline conditions

Carbon storage

To define the level of carbon storage for our study, we considered the carbon present in the native forest where the tree cover density was greater than 10%, excluding exotic tree plantations and harvest areas. Although exotic tree plantations store carbon, we excluded them because in this region native forests have been heavily replaced with exotic plantations that have proved to be incompatible with biodiversity conservation and restoration (Miranda et al. 2017). Sixteen forest type categories (Appendix B, Table B2) were identified in the study region by intersecting four potential forest vegetation types (deciduous forest, sclerophyllous forest, sclerophyllous Andean forest and thorny forest) (Luebert and Pliscoff 2006) (Appendix B; Table B1) with the remnant native forest classes (closed >75%, semi-closed 50-75%, open 25-50% and very open 10-25% forest) from the land cover map (CONAF-CONAMA-BIRF 2014). The current carbon storage (total weight of carbon stored per hectare, Mg C ha^{-1}) of each forest type category was measured as the long-term confinement of aboveground (AGB) and belowground tree biomass (BGB). Aboveground carbon was quantified through a literature review of biomass and carbon estimates for the representative species (Muñoz et al. 2007) and BGB was estimated from ratios drawn from the literature (Aalde et al. 2006) (More details in Appendix B).

Wine production

Wine production was mapped based on the area cultivated with *Vitis vinifera* within the agricultural land cover class and the number of vines planted per area (Larrañaga 2011). The number of vines per hectare was converted to yield (tonnes ha^{-1} yr^{-1}) assuming that one vine produces 7 kg yr^{-1} of grapes for wine production (Muñoz et al. 2002). We obtained a map of current wine yield production that we classified in 4 yield categories: 3 to 5ton/ha, 6 to 8ton/ha, 9 to 10ton/ha and 11 to 16ton/ha.

Scenic Beauty

Scenic beauty was mapped through a viewshed analysis in ArcMap 10.3.1 (ESRI 2011). The viewshed analysis generated lines of sight between an observer site and the centroid of each 90 m resolution cell of a digital elevation model DEM (Jarvis et al. 2008, Nutsford et al. 2015). An average height of 22 m was then assigned to buildings in urban areas in the capital city and 5 m elsewhere (PRMS 2014). An average height of 5m was assigned to forest and 2 m to shrubs (CONAF-CONAMA-BIRF 2014). Viewpoints were selected for the viewshed analysis to represent each of the populated peripheral provinces in the region except provinces within the center of Santiago, excluded because of the high density of buildings taller than 20 m. We also included viewpoints in conservation areas that are known for recreational uses because of their scenery (see Appendix C for DEM and location of viewpoints).

We used one point per peripheral province (107 in the region) and one point per conservation areas (24 in the region). In Appendix H we present the geographic coordinates and characteristics of the 131 viewpoints. The viewpoint was set as the centroid of each commune and conservation area respectively. To calculate the centroid of the communes we used the Feature to Point (Data Management) tool in ArcMap 10.3.1 (ESRI 2011). This method calculates the geometric center of the province or conservation area as a polygon feature, computed using the weighted mean center of all the feature parts.

The viewshed analysis produced a visibility raster recording the number of times each area was seen from the viewpoints' locations. We obtained a visibility raster map with values ranging from 1 to 65 (e.g. areas that can be seen up to 65 times from viewpoints). This map was classified in a qualitative scale map using the natural breaks categories of the visibility raster map ranging from: very low (1-12), low (13-25), medium (26-37), high (38-50) and very high (51-65). We also accounted for the contribution of scenic features providing high-quality views, based on features identified in local studies (De la Fuente et al. 2006, De La Fuente and Mühlhauser 2014). We extracted forest, water bodies and snow features from the land cover map and intersected them with the visible area from the visibility raster. We included water bodies and urban parks that were located in the visible area raster, which were obtained from the OpenStreetMap for Chile (OSM 2016). These features were assigned a high scenic value to represent people's preferences.

Ecosystem service maps under future conditions

To map the potential change in the distribution of the carbon and wine production under climate change we employed maximum entropy bioclimatic modeling techniques at a 100x100 m grid cell resolution using MaxEnt v3.3.3j (Phillips et al. 2004, Phillips et al. 2006). Each model was fitted using a split-sample approach (Guisan and Zimmermann 2000), using a random set of occurrence points and reserving 25% for testing the performance of the model. The minimum distance between the occurrence points for all dependent variables was restricted to a maximum of 1000 m to minimize spatial autocorrelation.

The models were trained by establishing a relationship with current climate and the selected environmental predictors at known occurrence points. The predictor variables used in the MaxEnt model for carbon were climate and topography, for wine: climate, soil, and hydrology (see Appendix D). The baseline scenario for carbon and wine production was the output of the application of the MaxEnt model on current observations. The relationship was then projected into the future climate under each of the RCP 2.6 and 8.5 scenarios by allocating each 100x100 m grid cell to the dependent variable with the highest likelihood of prediction. The climate predictor variables included a South American dataset available for baseline climate conditions (1950-2000) obtained from a total of 930 weather stations at 1 km resolution (Pliscoff et al. 2014). For future climate projections, the output of a global climate model (HadGEM2-AO (Fuenzalida et al. 2007, Falvey and Garreaud 2009) from the fifth phase of the Coupled Model Intercomparison Project (CMIP5) was employed (Pachauri et al. 2014). The remaining predictor variables used in each model are detailed in Appendix D.

The models were initially constructed using all predictor variables and then the variables were sequentially excluded based on their percentage contribution, permutation importance, the relative effect on model performance measured by the area under curve (AUC) scores (see Appendix E for details in the AUC scores and Appendix F for the marginal plots of the resultant models). To test how well the model predictions matched the reality we applied simple linear regression analysis using the t-test and F-test respectively and assessed the goodness-of-fit of the relationship between the current observation of carbon and wine production (predictor) and the predictions obtained from the baseline scenario (dependent variable). The result for current and future climate was a continuous value projection (0 to 1). The continuous probability maps were converted into binary presence/absence maps applying the maximum sensitivity plus specificity logistic threshold (Liu et al. 2005). To map the potential change in the distribution of scenic beauty under climate change, we considered the new potential distribution of forest cover under scenarios RCP 2.6 and RCP 8.5.

To map urbanization we employed the cartographic layer representing the new urban regulatory plan (PRMS 2014). For scenarios A and C we maintained the current boundaries of the city (no expansion), and for scenarios B and D we applied the new urban plan layer. We then used these layers to assess the effects of urbanization on the future provision of carbon, wine production, and scenic beauty. To combine both drivers in the final scenario maps the urbanization driver was first applied, and then the climate change driver was applied to the remaining area (see Fig. 4).

Ecosystem service maps under future conditions incorporating fire

To predict the future probability of fire occurrence, we applied bioclimatic suitability models based on historical fire data [datasets for the period 1986-2010 from the National Corporation of Forest (CONAF)] and environmental explanatory variables. We considered the dominant environmental factors that influence fire: climatic conditions that affect the length and severity of fire episodes; human activities that have increased the incidence of fires; and the presence of flammable vegetation (Moritz et al. 2012). Climatic conditions were included in the set of bioclimatic variables under scenarios RCP 2.6 and RCP 8.5 and the digital elevation model. Human variables were incorporated through the distance of observed fires to roads and cities considering the current urban plan and the new urban plan. Vegetation was included through land cover categories with vegetation (Appendix D). We developed a new set of scenarios A, B, C and D incorporating the effects of fire on the provision of the ecosystem services according to the climate change and urbanization assumptions in each scenario (see Fig. 4). To quantify the magnitude of change, we compared the percentage of change in the provision of each ecosystem service for the eight future scenarios, relative to the baseline conditions.

[Insert Figure 4 near here.]

3. Results

The simple regression model outputs testing the plausibility of the carbon and wine MaxEnt model predictions matched current observations and showed a robust significant and positive relationship for carbon ($R^2=0.55$, $p<0.0001$, F=7771, DF=6300) and wine ($R^2=0.35$, $p<0.0001$, F=136.2, DF=254).

The future scenarios revealed profound influence on the provision of ecosystem services relative to the baseline scenario. For carbon storage, the four scenarios predicted a substantial decline: close to 85% of baseline carbon stores and reaching up to 90% when the effects of fire were accounted for (see Fig. 5). For wine production, the four scenarios also predicted a decline, which ranged from 9 to 18% under scenarios A and B, with a pronounced decline of 48 to 52% under scenarios C and D. The decline was even more dramatic when changed fire regimes were accounted for, with total wine production declining by 90% (see Fig. 5). Scenic beauty did not change much under the four scenarios with a slight increase (7%) under scenario A and a slight decrease under scenarios considering urban expansion and a business-as-usual climate. Scenic beauty was projected to decrease by 18 to 28% (see Fig.5) when the outcomes of changes in the fire regimes were taken into account.

[Insert Figure 5 near here.]

3.1 Carbon storage

Carbon storage values ranged from 11 Mg ha^{-1} to 63 Mg ha^{-1} (see Fig. 6). The forest types with higher carbon values were the closed Mediterranean Andean sclerophyllous, sclerophyllous and deciduous forest types with lower values represented by the very open thorny and sclerophyllous forest (Appendix B, Table B2). Scenarios A and B predicted high carbon storage mainly concentrated on the southwest hills of the region in the coastal range. Under these scenarios, there was a slight increase in the carbon content in the western part of the region, specifically in the hills of the coastal range due to an expansion of closed sclerophyllous vegetation types (Appendix F). There were also important zones of carbon provision under these scenarios in the Andean foothills bordering the eastern part of the city (see Fig. 6a).

Scenarios C and D predicted lower values of carbon storage across the region (see Fig. 6b). The reduction was due to an expansion of open Mediterranean Andean sclerophyllous forest, which displaced sclerophyllous forest types. In the south-eastern part of the region, there was also a decrease in carbon storage caused by the displacement of the Mediterranean Andean sclerophyllous forest by very open deciduous forest bordering the city in the Andean range and central valley. Scenarios B and D predicted carbon losses in the north-eastern part of the city due to the expansion of the city limits converting sclerophyllous and Mediterranean Andean sclerophyllous forest to urban land (Appendix F). The expansion of the urban boundary did not have a strong influence on carbon storage, as this land-use change mainly affected agricultural lands bordering the city (which store less carbon). When the probability of fire was incorporated, carbon storage declined by up to 90% compared with the baseline, mainly affecting sclerophyllous forest types in the western coastal hills.

3.2 Wine production

The baseline scenario showed that western and southwestern sections of the region closer to the coast had the highest potential for wine production. Interestingly, scenarios A and B predicted some gains distributed along the central valley towards the coast (see Fig. 6a) while scenarios C and D predicted a stronger decline (see Fig. 6b). Areas that would remain with a high potential yield for wine production under these scenarios were located closer to the coast in the southwestern section of the region. The planned expansion of the city following scenarios B and D affected up to 9% of areas suitable for wine production, mainly on those north and southwestern areas bordering the city. The effects of fire were predicted to be severe for wine production because the modeled probability of fire-impacted areas were closer to cities and roads, which were the most suitable for wine production. When the probability of fire was incorporated, total wine production declined by 90% (see Fig. 5).

3.3 Scenic beauty

High values of scenic beauty for baseline and future conditions were found bordering the city in higher elevation zones at the foothills of the Andean range (see Fig. 6) particularly the eastern peripheral provinces from north to south (e.g. Colina, Huechuraba, Lo Barnechea, Vitacura, Las Condes, La Reina, Peñalolén, La Florida, Puente Alto and Pirque — see Fig. 1 for spatial reference). High values of scenic beauty were found in some western peripheral provinces bordering the city at the foothills of the coastal range (e.g. Lampa, Pudahuel, Isla de Maipo and Paine). Higher elevation areas of the coastal range in the southwest of the region in the Melipilla province presented a high potential for provision of scenic beauty.

Conservation areas located in higher elevation zones of the Andean (e.g. Natural Sanctuary “Yerba Loca” and “San Enrique”, National Reserve “Rio Clarillo”) and the Coastal range (e.g. “Cerro el Roble”, “Altos de Cantillana”, “Altos de Chicauma” — see

Fig. 1 for spatial reference) presented high scenic beauty values. This was because there are natural features providing high-quality views such as closed sclerophyllous and deciduous forest in the visible area (see Fig. 1 for pictures). Low-elevation areas of the central valley contained most of the zones with low values of scenic beauty.

Scenario A predicted an expansion of the sclerophyllous forest in the coastal hills, which increased the total scenic beauty value by 7%. The planned expansion of the city following scenarios B and D would not dramatically affect the provision of scenic beauty (See Fig. 6b). Nevertheless, there was a slight decline in scenic beauty (3%) concentrated in areas set aside for urban expansion in higher elevation zones at the periphery of the city. For example, some western peripheral (Lampa, Pudahuel, Quilicura and San Bernardo) and southern peripheral provinces (Paine and Pirque) of the region suffered a decline in the provision of scenic beauty. Taking the aftermath of fire into account, there was a greater decline, ranging from 18 to 28% of the total provision of scenic beauty, which was mainly due to the loss of coastal sclerophyllous forest (See Fig. 5).

[Insert Figure 6 near here.]

4. Discussion

Combining scenario analysis with ecosystem service assessments provided a powerful tool for exploring the effects of combined global change drivers on the provision of ecosystem services. Our application was significant because it evaluated the cumulative aftermaths of multiple global change drivers on ecosystem services in a developing country of Latin America, which had rarely been addressed in the literature (Runting et al. 2016).

The results demonstrated that global climate change, urbanization, and their interactions in the form of fire dynamics, were likely to place substantial pressures on the provision of carbon storage, wine production and scenic beauty in Central Chile by 2050. This was especially the case for carbon storage and wine production, which suffered major losses when the interactions between drivers were taken into account.

Climate change was predicted to have significantly different effects on ecosystem services, with a decline in most, but not all, scenarios. Scenic beauty under the scenario of moderate climate change and no urban expansion was the only service showing a minor increase, and this was due to a localized expansion of the sclerophyllous forest on the hills of the coastal range, which would provide higher quality views in these areas. Carbon storage and wine production were very sensitive to climate change showing a decline under all scenarios relative to baseline conditions. Carbon storage was the most severely affected service, with a pronounced decline of over 85% from the baseline in all scenarios. Wine production saw a small decline under moderate climate change scenarios (A and B), whereas the severe climate change scenarios (C and D) predicted a larger decline. This occurred because the mitigation scenarios (A and B) predicted localized gains at the center of the region from the central valley to the coast.

Altitudinal and latitudinal movement of forest types and viticulture responses to the new drier and hotter climate conditions explained the overall decline of carbon storage and wine production. Suitable areas for high-yield wine production were likely to shift towards the coast and southwards, where the temperature was likely to be lower and precipitation higher. This is consistent with previous studies of the strain imposed by climate change on plant communities and agricultural systems in the region (Marquet et al. 2010, Hannah et al. 2013). Mediterranean regions were notably vulnerable to climate change as the increase in temperature, and reduced precipitation is expected to extend the duration of severe drought (Schröter et al. 2005). Under these conditions water bodies would most likely be reduced in surface and volume and this could reduce the perception of quality aesthetic values (García-Llorente et al. 2012, Martínez Pastur et al. 2015) and potentially feedback to urban settlement patterns due to pressure on the water supply. We did not include these potential concerns in our analysis.

The urbanization driver did not dramatically affect the total provision of the ecosystem services we explored, but it may have localized effects. The expansion of the city was predicted to affect agricultural areas (including wine production) on the periphery of the city. Scenic beauty was also expected to be affected by this driver, mainly in the mountainous areas of the city periphery where expansion is planned to occur (Romero and Ordenes 2004, De la Fuente et al. 2006, Romero et al. 2012, Banzhaf et al. 2013, De La Fuente and Mühlhauser 2014, Puertas et al. 2014). Urban development at the foothills of the Andes and in the coastal range had been facilitated by a lack of regulations to protect natural areas and the ecosystem services they provided. The impact on ecosystem services was amplified when the results of fires were taken into consideration. This was decidedly evident for wine production because the occurrence of fire in this area was largely explained by human-induced variables, with a high probability of fire affecting areas close to the city and roads in locations that were suitable for wine production. These results were consistent with other studies modeling the occurrence of fire in Central Chile (Castillo 2012a, Altamirano et al. 2013) and highlighted the importance of fire as a major driver of change in the spatial patterns and overall provision of the selected ecosystem services.

Our research contributed to the literature on ecosystem services scenarios (Birch et al. 2010, Haines-Young et al. 2011, Swetnam et al. 2011, Goldstein et al. 2012, Lamarque et al. 2014, Lawler et al. 2014, Byrd et al. 2015) in that we rapidly and inexpensively estimated the impact of interacting global and regional drivers on the provision of ecosystem services. There were few scenario studies to date that had assessed future changes in ecosystem services under climate change (e.g. Bryan et al. 2010, Bryan et al. 2011, Bryan et al. 2014, Lamarque et al. 2014), fewer that had assessed the outcome of climate change and urban sprawl (e.g. Bohensky et al. 2011, Shaw et al. 2011, Hoyer and Chang 2014, Byrd et al. 2015), and even fewer that had taken into account the considered interactions between drivers (e.g. Oliveira et al. 2013). For example, Shaw et al. (2011) examined the impact of climate change on the production and value of ecosystem services in California. Byrd et al. (2015) developed climate and land-use change scenarios based on the IPCC narratives to understand the effect on ecosystem services and Hoyer and Chang (2014) mapped the provision of freshwater ecosystem services under urbanization and climate change scenarios.

Our study differed from previous studies in that we developed future scenarios highlighting that climate change and urbanization led to an overall decline in the provision of carbon, wine and scenic beauty, which was exacerbated by land-use interactions with climate. Considering the combined consequences was a significant advance over studies that focused on the trajectories of independent drivers (Bryan 2013, Bryan and Crossman 2013). Nonetheless, many challenges remained. There was a need to deepen our knowledge of the emergent properties, complexities, interconnections and synergistic interactions among multiple drivers of change and ecosystem services (Liu et al. 2015). While scenario analysis was an important tool for exploring alternative futures arising from uncertainties in the drivers of change, it did not encompass all the different sources of uncertainty in modeling future outcomes. For example, in this study, in the case of wine production, we did not consider all the possible socioeconomic drivers of vineyard distribution, or the possibility that under severe climate change conditions less favorable environmental conditions would arise for wine production (e.g. aspect, soil moisture, nutrient availability). The models developed could be improved with finer parametrization under future conditions as ecosystem services productivity was quite likely to change unevenly across space according to biophysical and socioeconomic parameters. Ideally, we would have incorporated these uncertainties and others, such as those arising from model parameters and model structure (Refsgaard et al. 2007), which would be likely to lead to further variation in the results presented here. More effective integration also required using more powerful tools than those presented in this study case (e.g. markov decision-making, supply chain analysis, multilevel modeling, agent-based modeling), to be able to predict the emergence of unexpected threats to ecosystem services (Liu et al. 2015).

The decision-making processes of governments typically ignore the consequences of global change on the long-term sustainability of ecosystem services (Liu et al. 2015). To address this critical situation, international and national policy needs to include strategies to protect and manage ecosystem services despite the substantial uncertainties in future conditions (Kok et al. 2016). Scenarios of ecosystem services are an important component of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), demonstrating their utility at multiple scales (Díaz et al. 2015). IPBES has identified the development of scenarios as a key tool for helping decision-makers identify potential impacts of different policy options on biodiversity and ecosystem services. The panel needs to engage with the great diversity of local contexts that are linked to global scale scenarios to improve the policy relevance of future IPBES scenarios (Kok et al. 2016). South America is a data sparse region in terms of ecosystem services knowledge (Boerema et al. 2016, Runting et al. 2016). The local scenarios developed in this study case have the potential to inform the IPBES Americas section by providing a rapid and inexpensive assessment of the possible effects of drivers on the productivity of ecosystem services that are key to local people.

5. Conclusion

Central Chile is a particularly sensitive area for climate change due to severe dry conditions predicted by business-as-usual scenarios. Scenarios depicting plausible future trajectories of change predicted that interactions between land-use and climate will give rise to favorable conditions for fire propagation, putting substantial pressure on the ecosystem services studied and especially on wine production, an important economic activity of the region. This information contributes to our growing understanding of the influence of global change on ecosystem services and highlights the urgent need for institutional responses better able to steer us towards a more desirable future.

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8. Figures

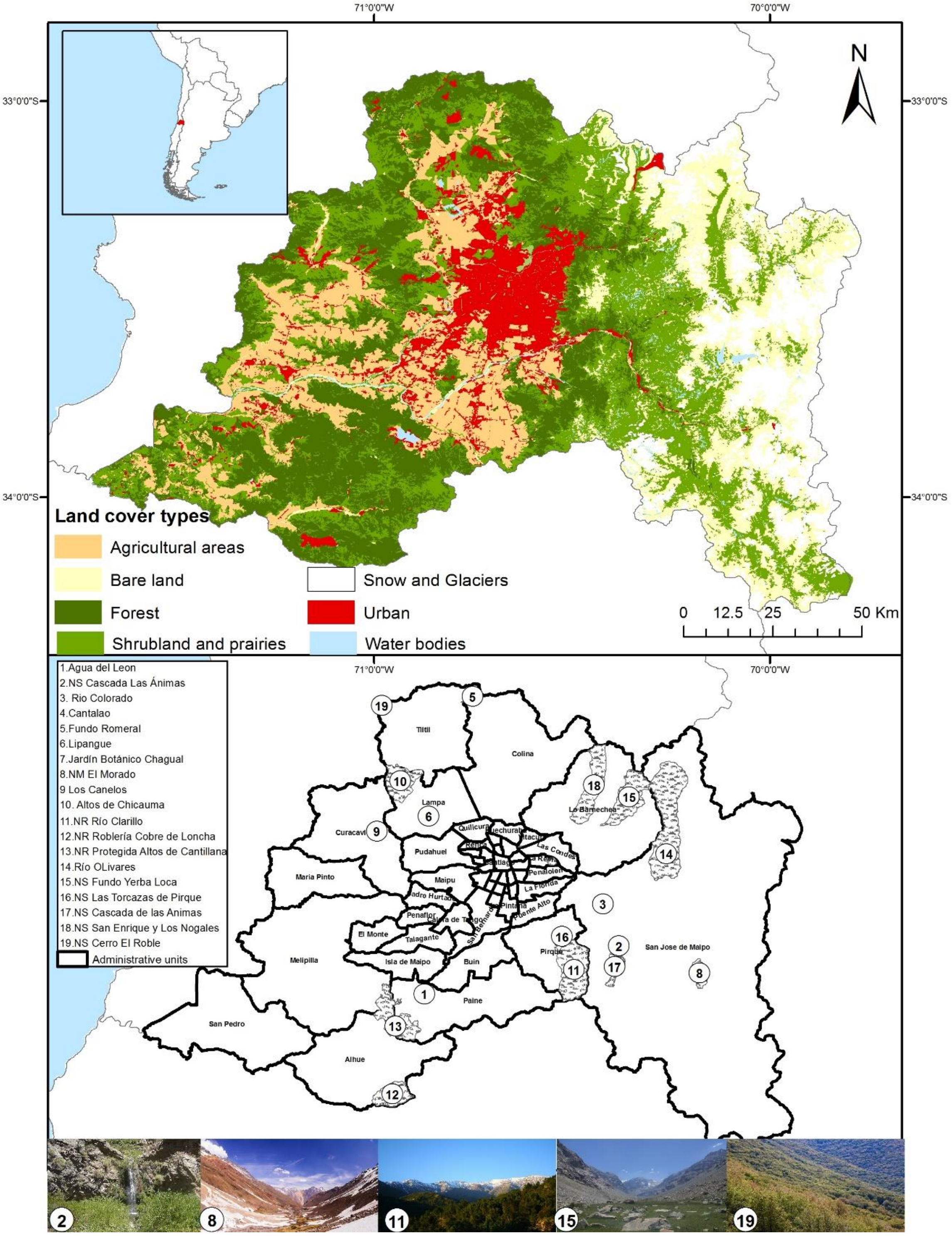


Figure 1. Study region in Central Chile depicting the main land cover types (above) administrative division of the provinces and the location of protected areas (below). All photos licensed by CC BY-NC-ND 2.0. Photos taken by: (2) Leonardo Needham, (8) Jose Letelier Hernandez, (11) Rodrigo Tejeda, (15) Hixaga and (19) Jorge Barahona.

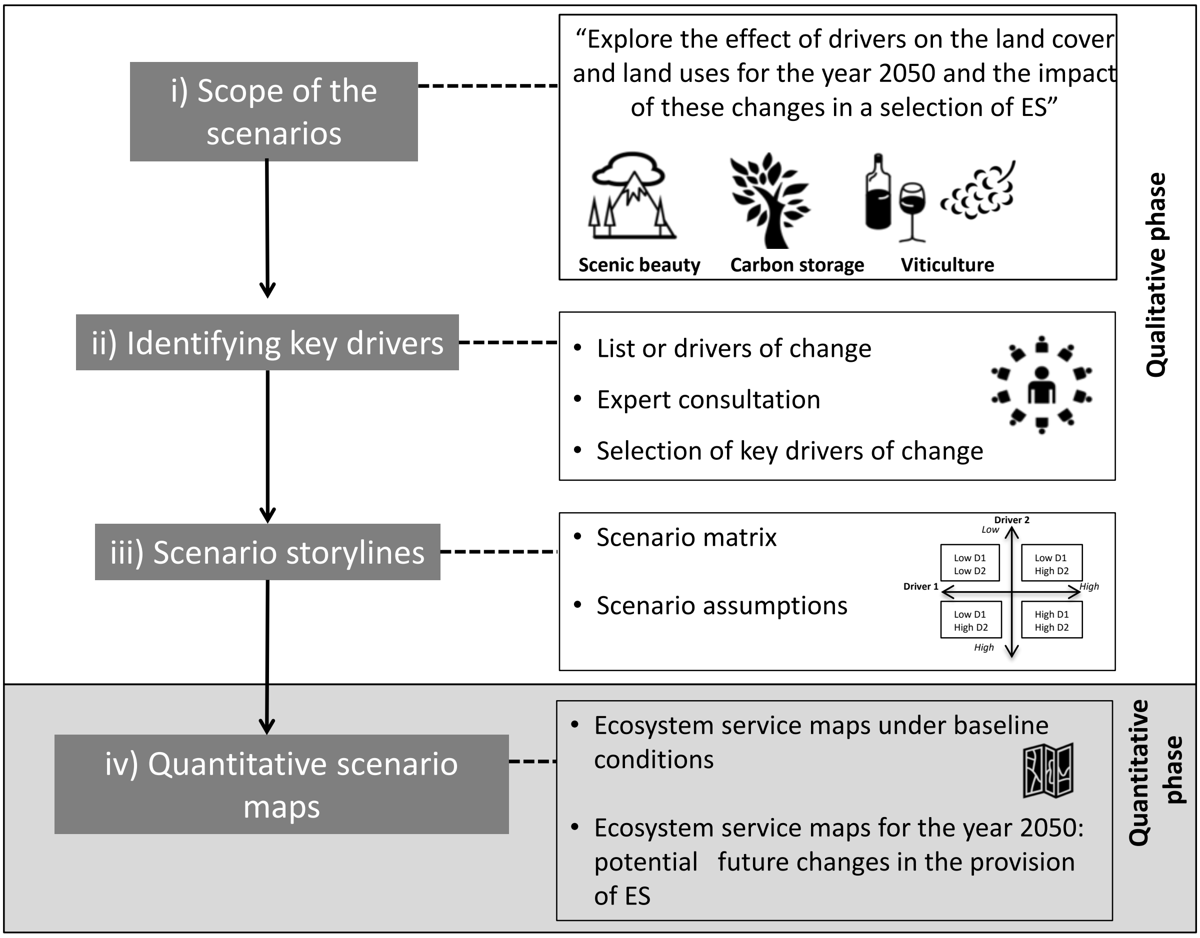
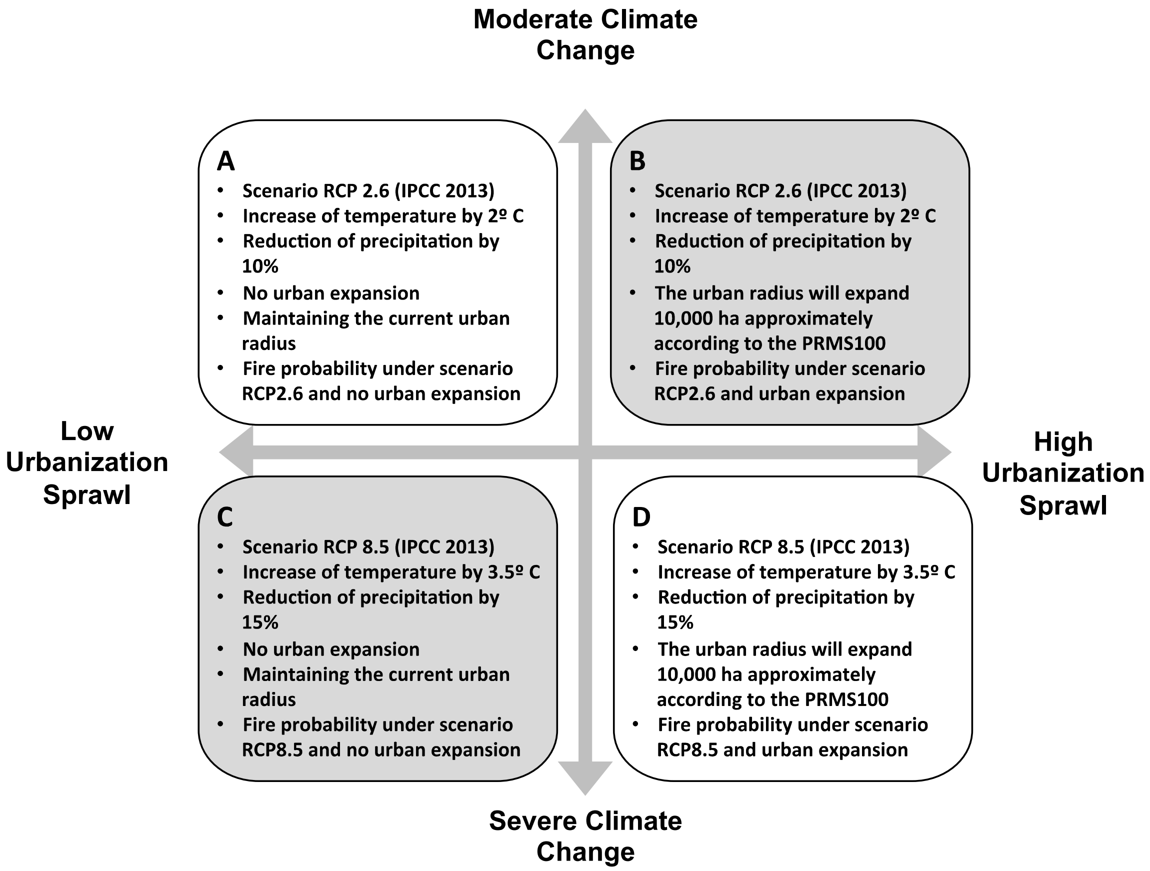


Figure 2. Methodological framework of the scenario building process.



A

- Scenario RCP 2.6 (IPCC 2013)
- Increase of temperature by 2º C
- Reduction of precipitation by 10%
- No urban expansion
- Maintaining the current urban radius
- Fire probability under scenario RCP2.6 and no urban expansion

B

- Scenario RCP 2.6 (IPCC 2013)
- Increase of temperature by 2º C
- Reduction of precipitation by 10%
- The urban radius will expand 10,000 ha approximately according to the PRMS100
- Fire probability under scenario RCP2.6 and urban expansion

C

- Scenario RCP 8.5 (IPCC 2013)
- Increase of temperature by 3.5º C
- Reduction of precipitation by 15%
- No urban expansion
- Maintaining the current urban radius
- Fire probability under scenario RCP8.5 and no urban expansion

D

- Scenario RCP 8.5 (IPCC 2013)
- Increase of temperature by 3.5º C
- Reduction of precipitation by 15%
- The urban radius will expand 10,000 ha approximately according to the PRMS100
- Fire probability under scenario RCP8.5 and urban expansion

Figure 3. Scenario storylines according to climate change and urbanization drivers. All scenarios were implemented with and without fire probability.

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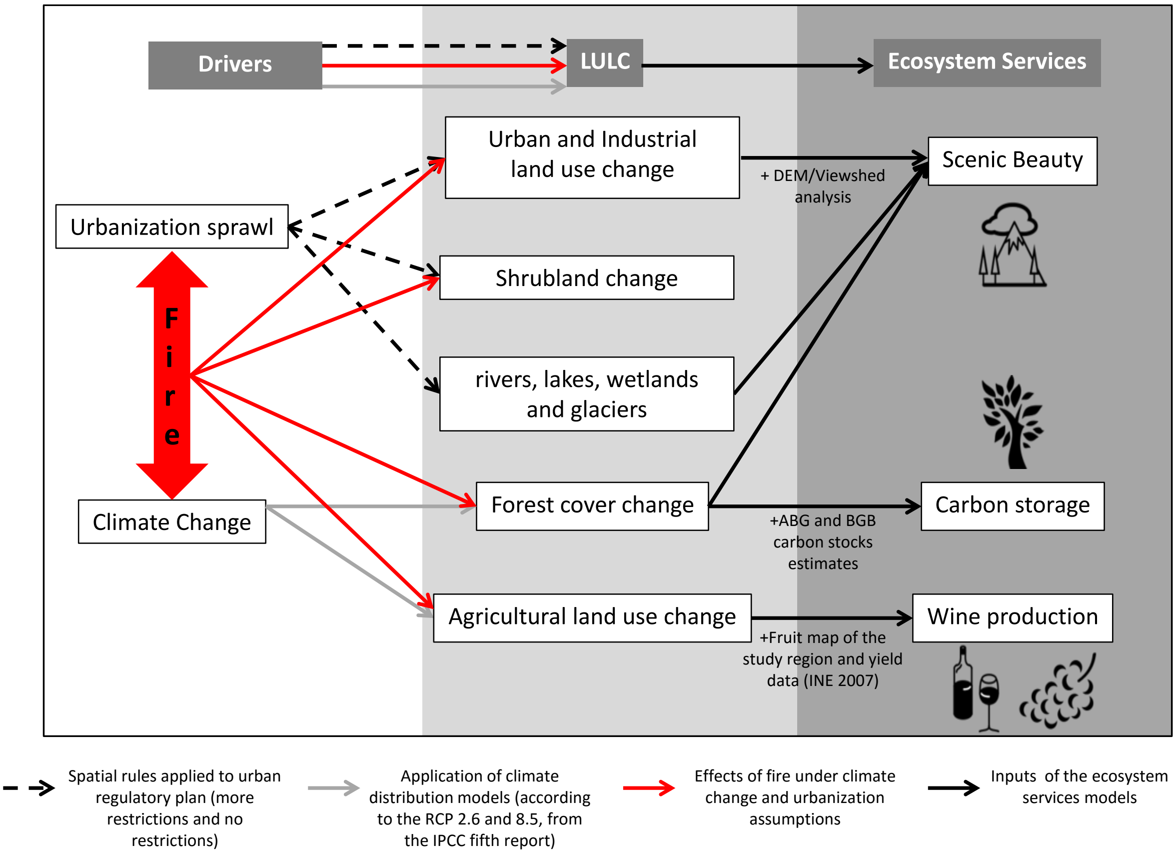

Figure 4. Translation of the trajectories of the drivers defined in the storylines into ecosystem service scenario maps.

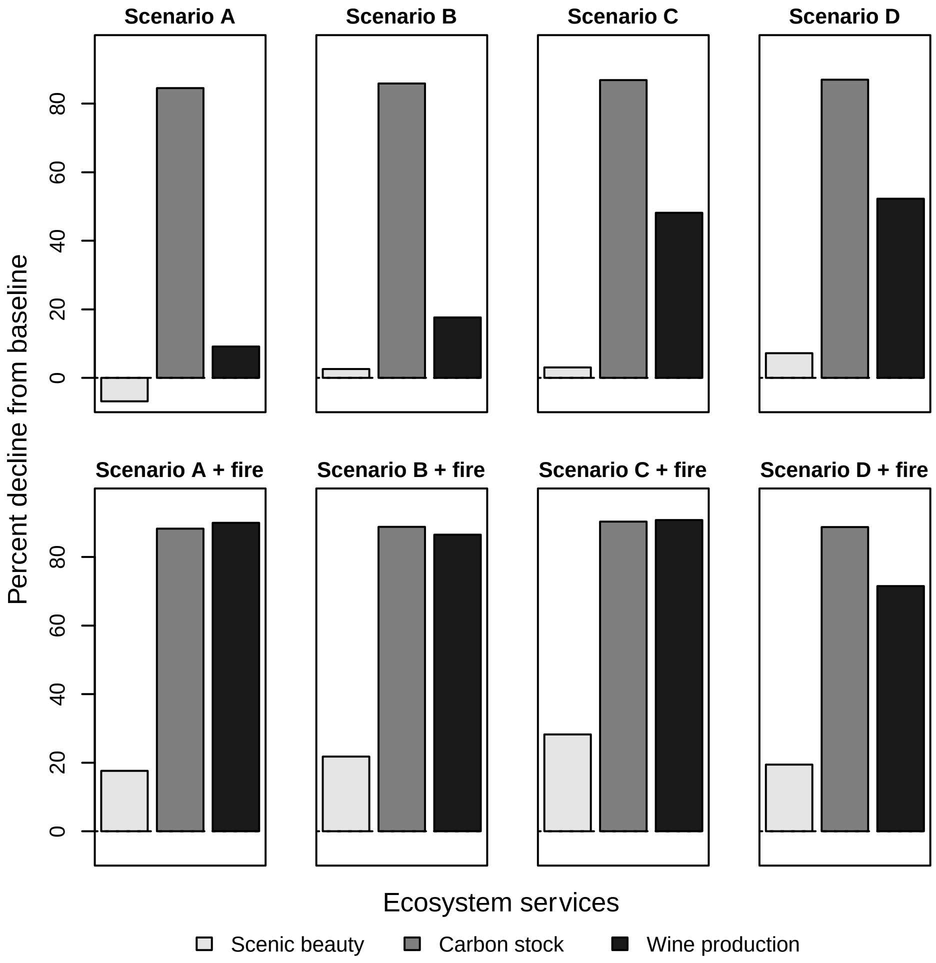

Figure 5. Percentage decline in the total provision of carbon storage, wine production and scenic beauty for all scenarios considering climate, urbanization and fire pressures compared with baseline conditions.

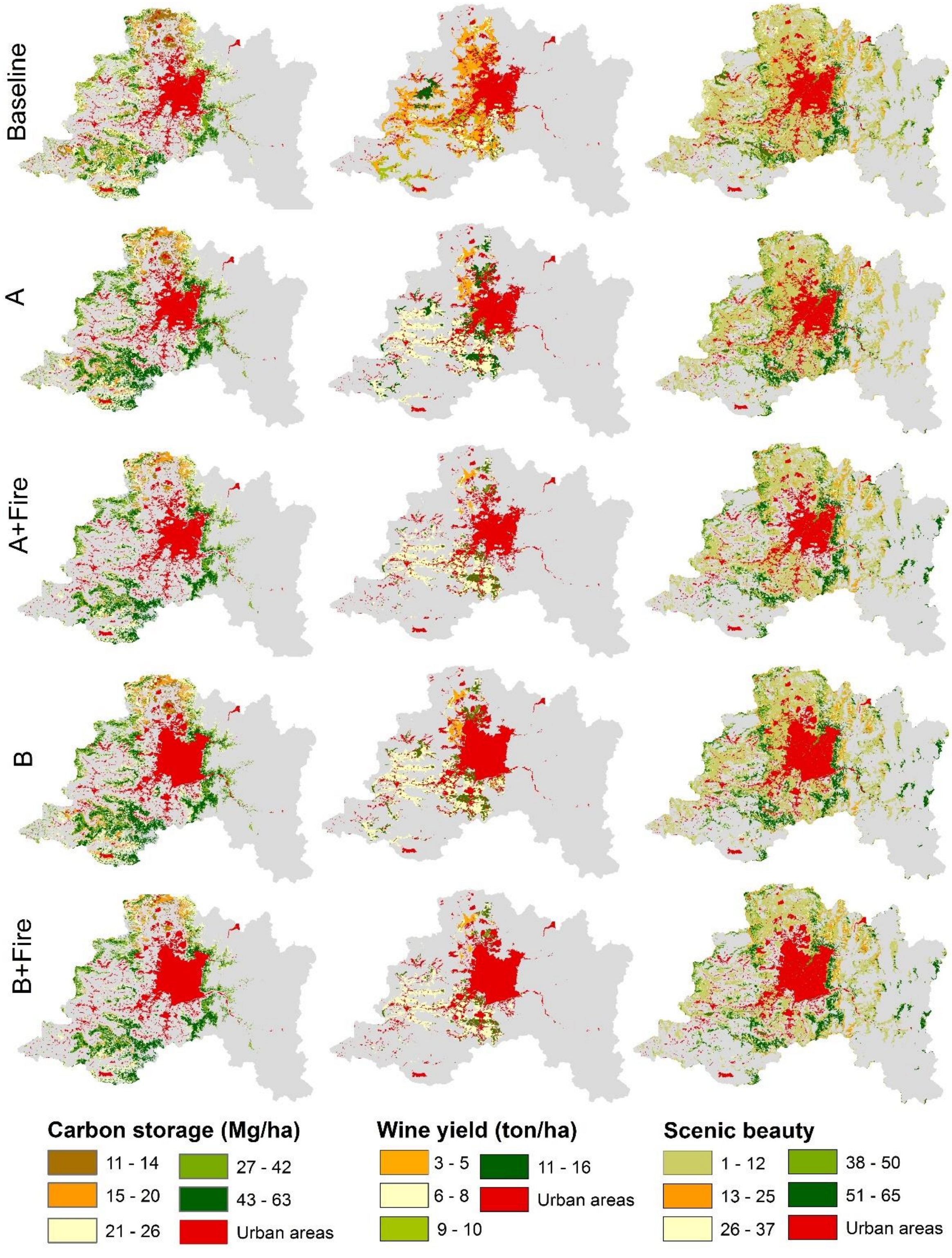

Figure 6a. Maps representing the ecosystem services scenarios part 1.

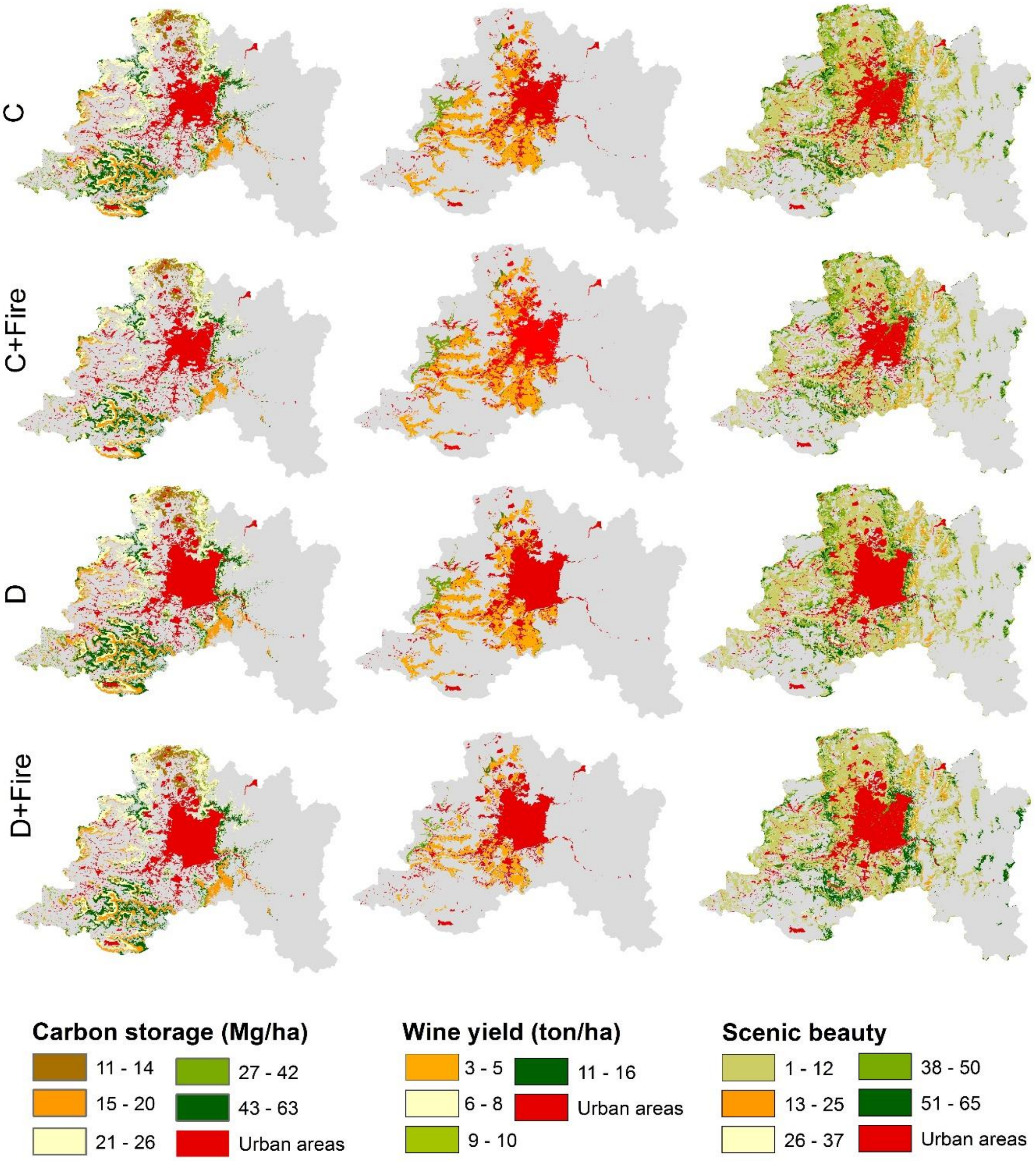

Figure 6b. Maps representing the ecosystem services scenarios part 2.