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Assessing the relationship between ecosystem functions and services: Importance of local ecological conditions

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ABSTRACT

The development of standard procedures for mapping ecosystem services (ES) hotspots is an active research issue, mainly because it is very important to provide spatially reliable information to decision makers on land-use planning. When ES supply is estimated and mapped from sets of contributing ecosystem functions (EF), it is important to identify which of them contribute the most to a particular ES. Also, it is crucial to determine whether that contribution varies across different ecological contexts. In this work, we used an expert-knowledge-elicitation approach to build "integration matrices" that resume the relationships between EF and ES in four different ecoregions of southern South America (Valdivian Forests, Campos, Chaco and Pampas). To verify the utility of creating different matrices, we compared the results of the Pampas ecoregion with an average score matrix from the four selected ecoregions. Results showed that the contribution of EF to ES differed slightly using the Pampas and the general matrix. We also mapped hotspots of three ES in a real landscape from the Pampas, using both matrices and the ECOSER protocol for ES supply mapping. The location of ES supply hotspots differed between matrices, but the amount of discrepancies was not proportional to the differences in matrices scores. This suggests that the developed matrix that takes into account local ecological conditions provides a more reliable source of spatially explicit information on ES supply for decision makers than a general matrix. The integration matrices generated in this study are useful for different protocols of ES supply mapping.

1. Introduction

The mapping of ecosystem services (ES) supply areas is a useful tool for land-use planning (Daily and Matson, 2008; Maes et al., 2012). The spatial representation of ecosystem functions (EF) and ES is important for the identification of areas of high levels of ES supply (hotspots), which should be prioritized to ensure human wellbeing (Tallis and Polasky, 2009). For this reason, ES supply mapping tools have received much attention as a crucial step in implementing the ES framework (Naidoo et al., 2008; Maes et al., 2012; Pagella and Sinclair, 2014).

The ES cascade allows the connection between the biophysical structure and the ecosystem processes with the benefits provided to human beings, as well as an understanding of the drivers of this connection (Haines-Young and Potschin, 2010). Under this framework, the biophysical structure of ecosystems supports EF (or intermediate services sensu Fisher et al., 2009) that are integrated into final ES when they can be associated with a direct benefit to human beings. ES represent potential benefits that express themselves through the intervention of socioeconomic capital. EF can contribute to many ES and, in turn, each ES can be the result of many EF (de Groot et al., 2002).

Unfortunately, most of the ES assessments fail to consider multiple EF types contributing to the same ES type. In turn, the reduction of ES estimations to a single EF is usually not properly justified. Additionally, the different biophysical conditions of each ecological system suggest that the integration of EF in ES will differ across ecosystems. For example, for the "potential food production" ES, erosion control can be a relevant EF in a steep slope terrain or in sandy soils with low organic matter content. However, it is less important in a flat terrain or in clayey soils and high organic matter content (Montgomery, 2007). Similarly, pollination is an important EF for some crops (e.g. sunflower) but not for others (e.g. maize), thus the importance of pollination for food production differs according to the main crops cultivated in the region. Villarino et al. (2014) demonstrated that the dependence of some ES supply on soil organic carbon varies across different ecoregions. All of the above-mentioned variations difficult the production of ES supply maps based on EF.

Researchers have tried to overcome this problem by generating either general models (i.e. benefit transfer, Costanza et al. (1997)) or specific ad hoc models that are only applicable in specific contexts (e.g. Orúe et al., 2011). The latter are usually the result of a best guess made

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by the researchers involved in the particular ES assessment. None of these extremes fully solves the problem, and if the goal is the development of operative ES frameworks to deliver useful information for policy makers, there is still the need to find ways of producing robust models of ES supply.

Expert knowledge elicitation is a promising alternative to resume the available information and generate robust models (Haines-Young, 2011; Martin et al., 2012; Landuyt et al., 2013). Expert knowledge elicitation techniques can be used in neural networks (Liao, 2005), fuzzy systems (Ocampo-Melgar et al., 2016), Bayesian Belief Networks (Aguilera et al., 2011) and knowledge-based systems (Girard and Hubert, 1999) which have been applied in many case studies of environmental assessment and land-use planning (Witlox, 2005). Expert knowledge is frequently used as inputs to parameterize models with these methods.

The different techniques for expert knowledge elicitation are increasingly being applied in ES modeling. Burkhard et al. (2009) and Jacobs et al. (2015) used expert knowledge to parameterize models with a matrix structure and relate land use and ES supply. This matrix modeling approach is comparable to the benefit transfer models, with the advantage that it is simple to understand and it provides spatially explicit assessments of ES supply (when coupled with GIS tools) that are suitable for landscape analysis and planning.

In a recent review, Landuyt et al. (2013) summarized the application of Bayesian Belief Networks (BBN) and they found that this method was suitable for modeling ES supply in a cascade model, including stakeholders participation and incorporation of uncertainties. BBN can be used in ES modeling to assess the causal relationships between different steps in the cascade model. For instance, Rositano and Ferraro (2014) used this approach to uncover functional relationships between land management and ES supply in Pampean agroecosystems. They parameterized their conceptual model using expert knowledge and literature review. BBN are very useful in cases where the system is poorly known but they are not justified for well-documented ES, such as erosion prevention or carbon sequestration (Castelletti and Soncini-Sessa, 2007; Landuyt et al., 2013).

In this study, we resume existing expert knowledge in the South Cone of South America about the relative importance of EF on ES in different ecoregions. We aimed to reveal the importance of taking into account local ecological conditions and tested for potential discrepancies in the estimation of ES supply hotspots using a case study in the Argentine Pampas.

2. Methods

In order to summarize existing knowledge on EF and ES, we used an expert knowledge elicitation approach through an online survey. First, we identified contrasting ecoregions to build integration matrices. Second, we selected a set of EF potentially relevant for the supply of nine ES. Third, we identified the experts to consult and run the survey. Finally, we tested the effects of using different integration matrices on the estimation of ES supply hotspots in a case study of one of the selected ecoregions. These steps are explained in detail below.

2.1. Study areas

We selected four ecoregions as study areas: Pampas (Argentina), Chaco (Argentina and Paraguay), Valdivian Forests (Chile and Argentina) and Campos (Uruguay) (Fig. 1). These ecoregions differ in their socio-ecological contexts, mainly due to differences in the native vegetation, productivity, topography, climate and the social actors' characteristics (Morello et al., 2012) (Table 1).

2.2. Selection of EF and ES

We selected 11 EF and nine ES. The ES (n = 9) belong to the categories "provision" and "regulation and support" in the CICES framework (Haines-Young and Potschin, 2011). Given that there are still different frameworks for the definition of functions and services, we adopted specific operative definitions (Table 2).

2.3. Selection of experts and survey

We made a list of experts on different ES from the four ecoregions, trying to balance their number among study areas and ES as much as possible. The experts (n = 139) were mainly academics (biologists, agronomists, foresters, environmental scientists), but we also included practitioners, policy makers and NGO members. All the consulted experts had experience in ES assessment or related areas (e.g. biodiversity conservation, agronomy, forestry, etc.). We conducted two rounds of surveys, the first for an initial parameterization of the matrices and the second to calibrate the results of the first round. We describe the process in detail below.

In the first round, the group of experts was contacted by e-mail and invited to fill in an online questionnaire in which they were informed about the objectives of the survey and the research project. They were also given definitions of all the basic concepts (EF, ES, ES cascade). The experts were allowed to select one or more of the four ecoregions according to their knowledge. Then they were asked to assign a level of relevance of each EF to each ES on a scale with the following values: (1) not relevant at all, (2) very low relevance, (3) low relevance, (4) moderately relevant, (5) fairly relevant, (6) highly relevant, (7) extremely relevant, and a DK/NA (don't know/not applicable) option. To obtain a preliminary integration matrix, the responses of all experts for each ES were averaged and rescaled in a 0–1 range.

In the second round, we calibrated the preliminary matrices by asking another set of experts (n = 29) to adjust the values of the results of the first round. They were given the averaged rescaled values with an explanation of the meaning of the range and they had the option to modify the scores (in which case they had to justify their answer) or leave them unmodified if they were considered appropriate. The final integration matrix was based on the averaged responses from the second survey.

In order to test the level of agreement among experts, we estimated the coefficients of variation (CV) of the assigned weighting factors of each EF to each ES for Pampas (CV_P) and the General matrix (CV_G) ecoregions as follows:

$$CV_{P_{ij}} = \frac{\overline{X}_{ij}}{SD_{ij}} \tag{1}$$

where i = EF, j = ES and P indicates that each combination was calculated using responses only for the Pampas ecoregion.

$$CV_{G_{ij}} = \frac{\overline{X}_{ij}}{SD_{ij}} \tag{2}$$

where i = EF, j = ES and G indicates each combination was calculated using all responses of the four ecoregions (General matrix).

$$R = \frac{N}{i*j} \tag{3}$$

where R represents the matrix robustness, N is the number of CV_P that are lower than CV_G and i * j is the total number of EF and ES combinations.

In order to measure the differences between the weighting factors of EF to ES in the Pampas and General matrices, we calculated the mean absolute difference as follows:

$$\mathrm{MAD}_j = \frac{|EF_P - EF_G|}{i} \tag{4}$$

where MADj is the mean absolute difference for ES = j, EF_p and ES_g are the weighting factors of EF of the Pampas and General matrices respectively, and i is the total number of EF (11).

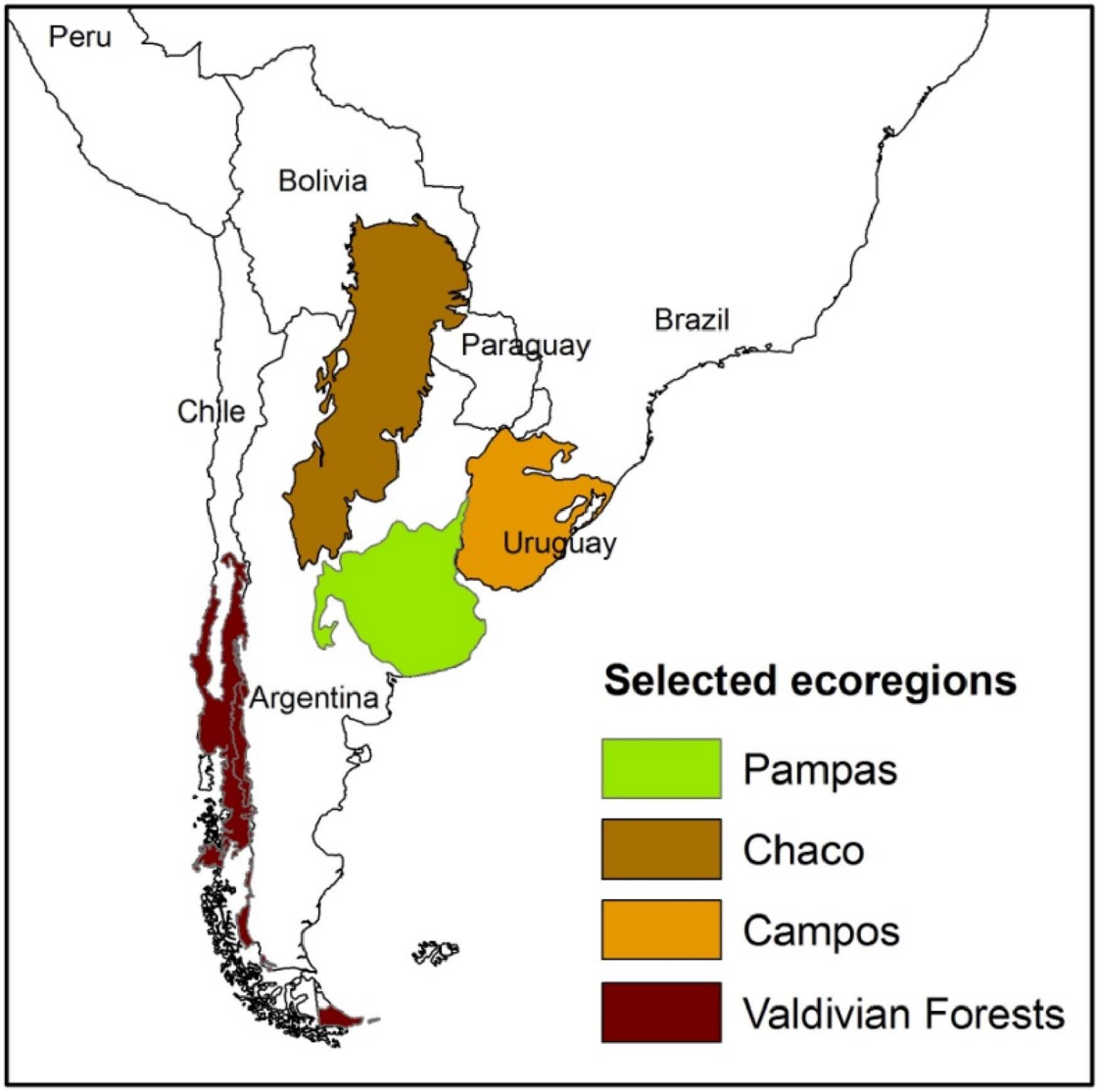

Fig. 1. Selected ecoregions in southern South America for the construction of integration matrices.

2.4. Application to a case study: Mar Chiquita Basin

In order to compare the application of different integration matrices for the estimation of ES supply hotspots we used the Mar Chiquita basin as a case study. Mar Chiquita basin is located in the southeast of the Buenos Aires Province, Argentina and has an area of 1.5 million ha composed of different agro-ecological systems (Fig. 2). These systems include a highland sector to the west and a lowland sector towards the

Table 1
Characterization of the four ecoregions evaluated in this study.

	Valdivian Forest	Campos	Chaco	Pampa
Climate	Cool temperate	Temperate	Subtropical dry	Temperate
Mean annual precipitation (mm)	1000 in the north and more than 6000 in the southern part of the ecoregion	1000 in the southern part, and 1300 in the northern part of the ecoregion	350–650	1000 in the northern part and 400 in the southeast part
Mean temperature (°C)	Maximum: 13–21 Minimum: 4–7	16–19	Minimum: 12 Maximum: 28	Minimum: 14 Maximum: 20
Relief	Mountain	Plain (hills in some sectors)	Plain	Plain (hills in south)
Original vegetation	Temperate broadleaf and mixed forests	Grassland	Xerophytic deciduous forest	Grassland
Productive potential	Forestry (plantations)	Agriculture and cattle	Forestry (extractive)	Agriculture and cattle
Anthropic pressure	Deforestation for conifer plantations	Soybean and Eucalyptus plantations expansion	Deforestation for agriculture, displacement of *criollos* and aborigines populations	Agricultural expansion, displacement of cattle raising
Presence of aboriginal populations	Yes	No	Yes	No[a]

[a] Although there are Mapuche populations in the province of Buenos Aires, social conflicts are not as pronounced as in the Chaco and Valdivian Forest regions.

Table 2
Definitions adopted for Ecosystem Functions (EF) and Ecosystem Services (ES).

Ecosystem functions	Definition
Carbon storage in biomass	Quantity of C in trees, shrubs and grassy vegetation and in litter
Carbon storage in soil	Quantity of C in soil organic matter
Erosion control	Reduction of soil sediments by protection of vegetation cover
Sediment and contaminant retention in wetlands	Represents the capacity of lentic water bodies to reduce the load of sediments and contaminants transported by water surface runoff
Sediment and contaminant retention in riparian vegetation strips	Represents the capacity of riparian vegetation strips to reduce the loads of sediments and contaminants transported by water surface runoff
Retention of precipitation excess by vegetation cover	Represents the proportion of precipitation that does not runoff. It depends mainly on the type of vegetation cover and its interaction with the soil properties
Aquifer protection by vegetation	Represents the capacity of the vegetation to retain contaminants and prevent lixiviation to aquifers
Retention of precipitation excess by wetlands	Capacity of wetlands to retain excess precipitation according to their area and position in the drainage network
Soil fertility	Capacity of the soil to provide plants the necessary nutrients in a balanced way and in the proper time for their growth and development
Pollination	Biotic fecundation of plants that are of interest for human beings
Pest and disease control	The action of fauna, bacteria and viruses to reduce crop pest species
Ecosystem Services	**Definition**
Climate regulation	Mitigation of global temperature rise, extreme climatic events and changes in precipitation regimes
Flood regulation	Reduction in the extent, length and frequency of floods resulting from excess precipitation and/or overflow of water bodies
Potential crop production	Potential production for most common crops in the region
Potential forage production	Potential forage production for cattle (cows, sheep and/or goats) according to common practices in the region
Potential wood production	Potential wood supply for firewood and building
Potential provision of non-timber forest products	Potential supply of biological resources other than wood, such as food, pharmaceutical, ornamental and aromatic products
Availability of clean groundwater	Clean groundwater availability for irrigation or as drinking water
Availability of clean surface water	Clean water availability for irrigation or as drinking water
Availability of water for hydroelectric power	Continuous water availability for hydroelectric power plants

East and North. The highland sector has a high erosion risk, whereas the lowland sector has poor drainage conditions that form numerous ponds and wetlands mostly destined for cattle production. The Mar Chiquita Lagoon is a key element of the basin because of its importance for biodiversity conservation and tourism, and it was declared Biosphere Reserve by UNESCO in 1996 (Iribarne, 2001). The area is under an agriculturalization process driven by the expansion of soybean crop, while cattle production is being displaced to marginal and less productive areas (Aizen et al., 2009; Modernel et al., 2016). This sets a scenario of trade-offs between different ES (Viglizzo and Frank, 2006; Laterra et al., 2012). Some initiatives of land-use planning are taking place in the area with the aim to solve environmental conflicts that arise as a consequence of these trade-offs (Maceira et al., 2011).

For this exercise, we chose three locally and/or globally important ES: availability of clean groundwater, flood regulation and climate regulation. The northern sector of Mar Chiquita basin is part of one of the six Pampa sub-ecoregions known as the Flooding Pampas because of frequent floods during the winter season (Viglizzo and Frank, 2006). For this reason, flood control is a very important ES in the area. The main source of clean water for human and cattle consumption in the study area is the aquifer. Due to the intensive agricultural land use, aquifers face the risk of contamination, thus making it relevant to manage the ES clean groundwater provision. Finally, climate change mitigation is a global concern and land use change is considered one of the main causes of this process (IPCC, 2013).

We mapped EF and ES supply following the ECOSER protocol. ECOSER is a collaborative tool under development. It is aimed to support land-use decision making for rural land-use planning, and it can be used for the design of sustainable development public policies (Laterra et al., 2012, 2016). Two steps or modules constitute ECOSER: 1) the evaluation of ES and benefits supply (used in this work) and 2) the socio-ecological vulnerability to ES and benefits loss analysis (http://www.eco-ser.com.ar). ECOSER builds upon the ES cascade model and, to date, nine EF have been modeled based on soil properties, topography, land use and land cover among others, allowing the generation of EF maps. These maps are then integrated through a weighted linear combination (hereafter, integration matrix) to generate ES supply maps (Fig. 3). This integration is a crucial step in ECOSER protocol and currently, it is left to the user's best knowledge to fill in the scores that represent the contribution of each EF to ES supply. Therefore, we aim to provide default integration matrices based on sound expert knowledge.

The EF can be calculated and mapped with an ArcGIS toolbox available in ECOSER (Barral, 2015). Once EF are mapped, the relative supply of the *i* ES (ESS_i) is obtained from the linear combination of *j* EF maps:

$$ESS_i = \sum_{i=1}^{n} b_{ij} * EF_j \tag{5}$$

where b_{ij} are the weighting factors obtained from the integration matrix. EF were normalized into a 0–100 scale before their combination because they differ in their measurement units (e.g. TnC/ha for soil organic carbon and mm of rain for retention of precipitation excess by vegetation). We used as references the maximum and minimum values of each EF within the study area. We calculated ES supply levels using a specific integration matrix for the pampas ecoregion (Pampas matrix) and an integration matrix of averaged responses for all the ecoregions (General matrix).

In order to identify the changes of EF factors that have the largest impact on ES supply levels, we conducted a local sensitivity analysis (Zi, 2011). The sensitivity index was calculated based on Lenhart et al. (2002), changing each model input variable (i.e. EF weighting factors) one at a time:

$$I_x = \frac{ES_0 - ES_1}{ES_0} \tag{6}$$

where I_x is the sensitivity index of the input variable x; ES_0 is the value of the dependent variable (ES supply level) using all input variables at its baseline value (Pampas integration matrix); and SE_1 is the value of the dependent variable when the input variable x takes the simulated or expected value according to the general matrix. All EF were set to 1 to evaluate the influence of variation in model parameters without considering variations in model inputs values (EF).

We tested the consequences of using different integration matrices in the estimation of ES supply hotspots. We divided the study area with

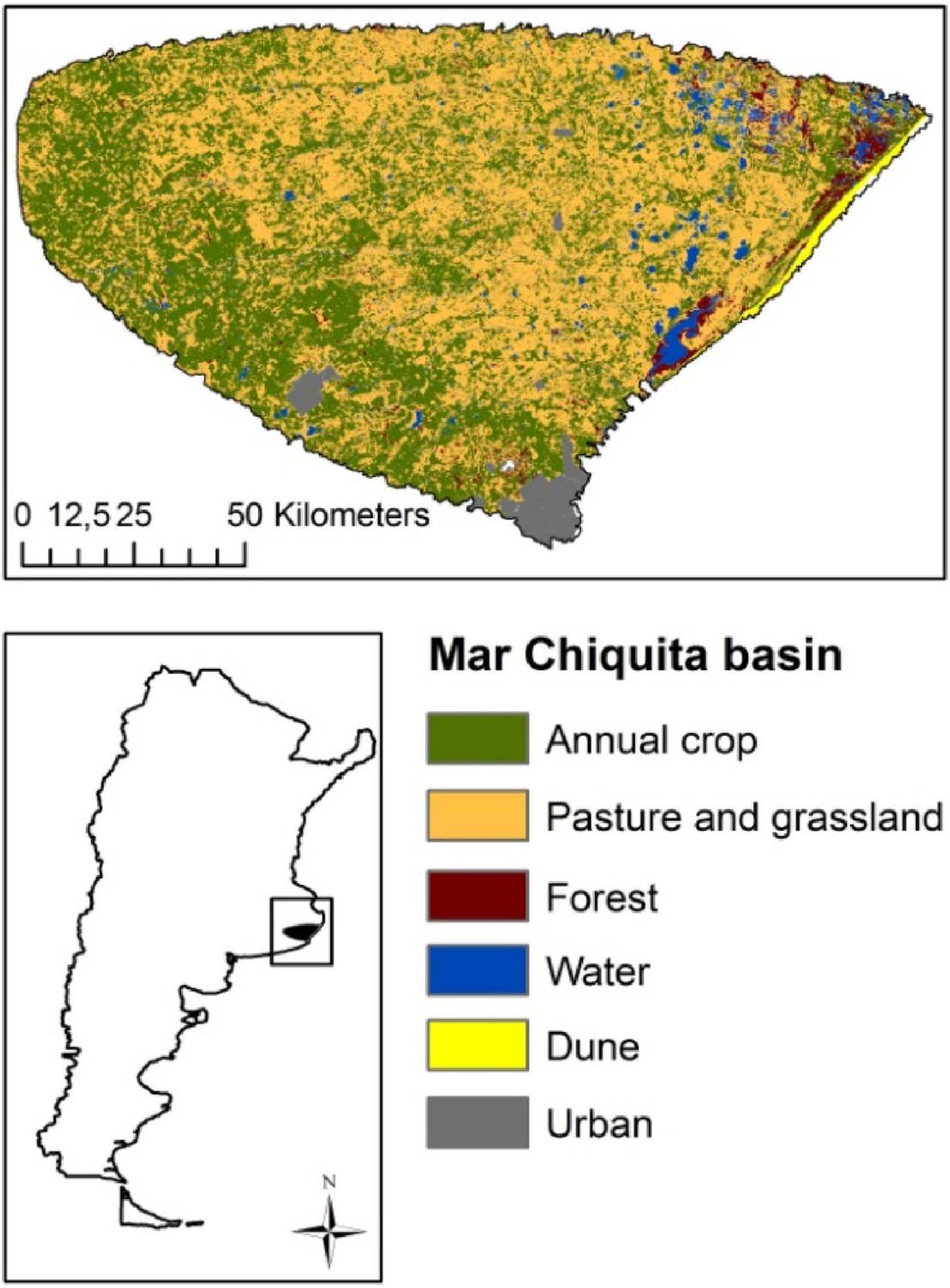

Fig. 2. Mar Chiquita Basin, case study area.

a 3 × 3 km cells grid and we calculated the supply levels for each of the three ES using the Pampas and General matrices. In this study, hotspots were defined as cells from the upper 20% percentile in ES supply level. Then we calculated the proportion of cells that were identified as hotspots using both integration matrices over the total number of cells identified as hotspots. If this proportion was 100%, all cells identified as hotspots using the Pampa matrix will coincide with the cells identified as hotspots using the General matrix and hence, both matrices are considered similarly useful.

3. Results

Fifty experts answered the survey in the first round (response rate = 36%) and 10 in the second round (response rate = 30%). Appendix A shows the summary of responses for each ES and ecoregion, both for the first and second round of the survey. The number of retrieved responses to assess the relation between an EF and an ES was considered sufficient for a first model parameterization, as also noted by other authors (Morgan, 2014). Complete integration matrices of the four ecoregions are summarized in Appendix B. Very few experts

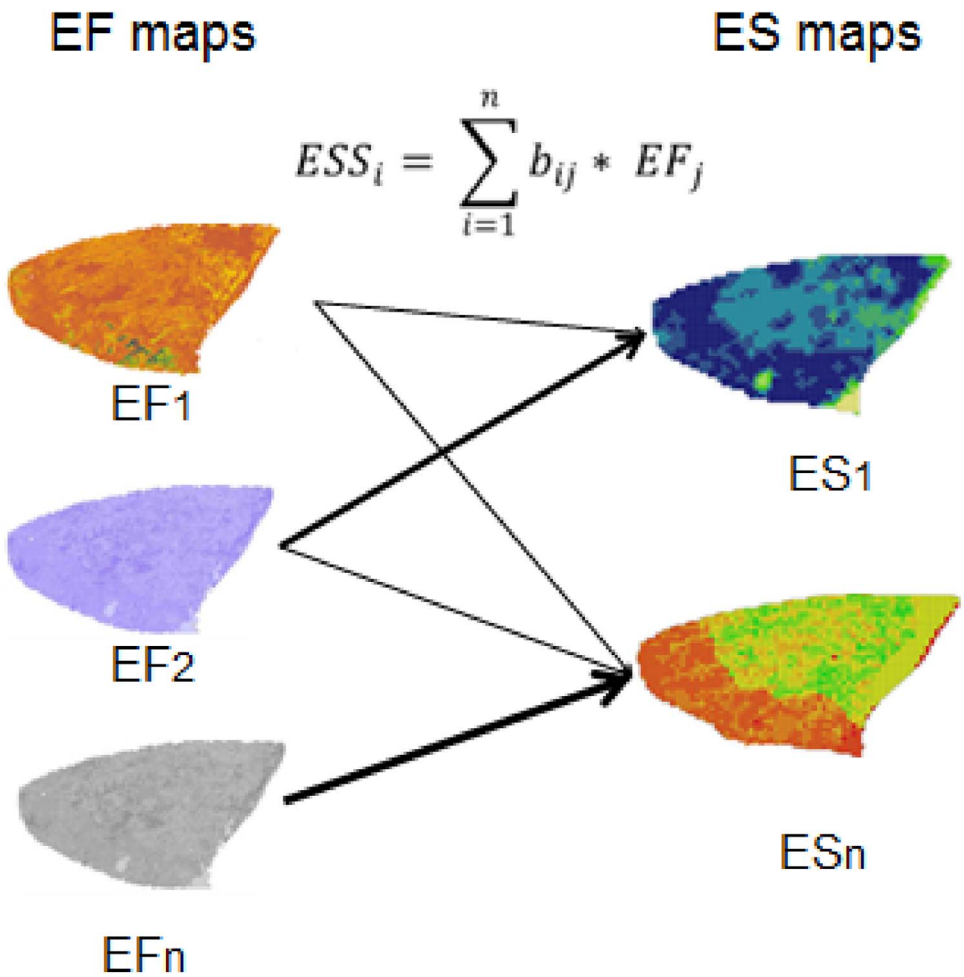

Fig. 3. Integration of EF maps into ES maps. Weighting factors of each EF to ES are collected from the expert survey and an integration matrix is constructed.

	Ecosystem services (ES)	
Ecosystem function (EF)	ES1	ES2
EF1	0,2	0,5
EF2	0,6	0,2
EFn	0	1

responded to the second round of the survey, therefore we were only able to calibrate the integration matrix for the Pampas ecoregion since it was the one with the highest number of responses (n = 7). The rest of the matrices show the results of the first round and should be taken as preliminary results.

When we compared the robustness of the matrices (R), results show that the proportion of CV that were lower within ecoregions than among ecoregions was 73% in Valdivian Forests, 69% in Campos, 34% in Pampas and 13% in Chaco. The higher values of Valdivian Forests and Campos matrices suggest that they are more robust than Pampas and Chaco in spite of being based on fewer responses.

Sensitivity indices allowed us to identify that the "availability of clean groundwater" ES and the EF "pest and disease control", "retention of precipitation excess by wetlands" and "sediments and contaminants retention in riparian vegetation strips" contributed less in the Pampas than in the General matrix (Fig. 4, Table 3). The mean absolute difference (MAD) between the EF of the Pampas and that of the General matrices (Eq. (4)) was 0.102. Experts concurred that there is little or no relationship of this ES with pest and diseases. On the other hand, the aquifer of the Pampas region contributes to water bodies. Therefore, the retention of contaminants and sediments by surface water and vegetation strips is less important than in other regions (Romanelli et al., 2014). Differences in the contribution of EF to "flood regulation" ES were due to lower influences of "carbon storage in biomass", "aquifer protection by vegetation" and "erosion control" in the Pampas than in the General matrix (Fig. 4, Table 3). The MAD for this ES was 0.079. Nonetheless, there were discrepancies among experts since some of them argued that erosion control may be important to favor water

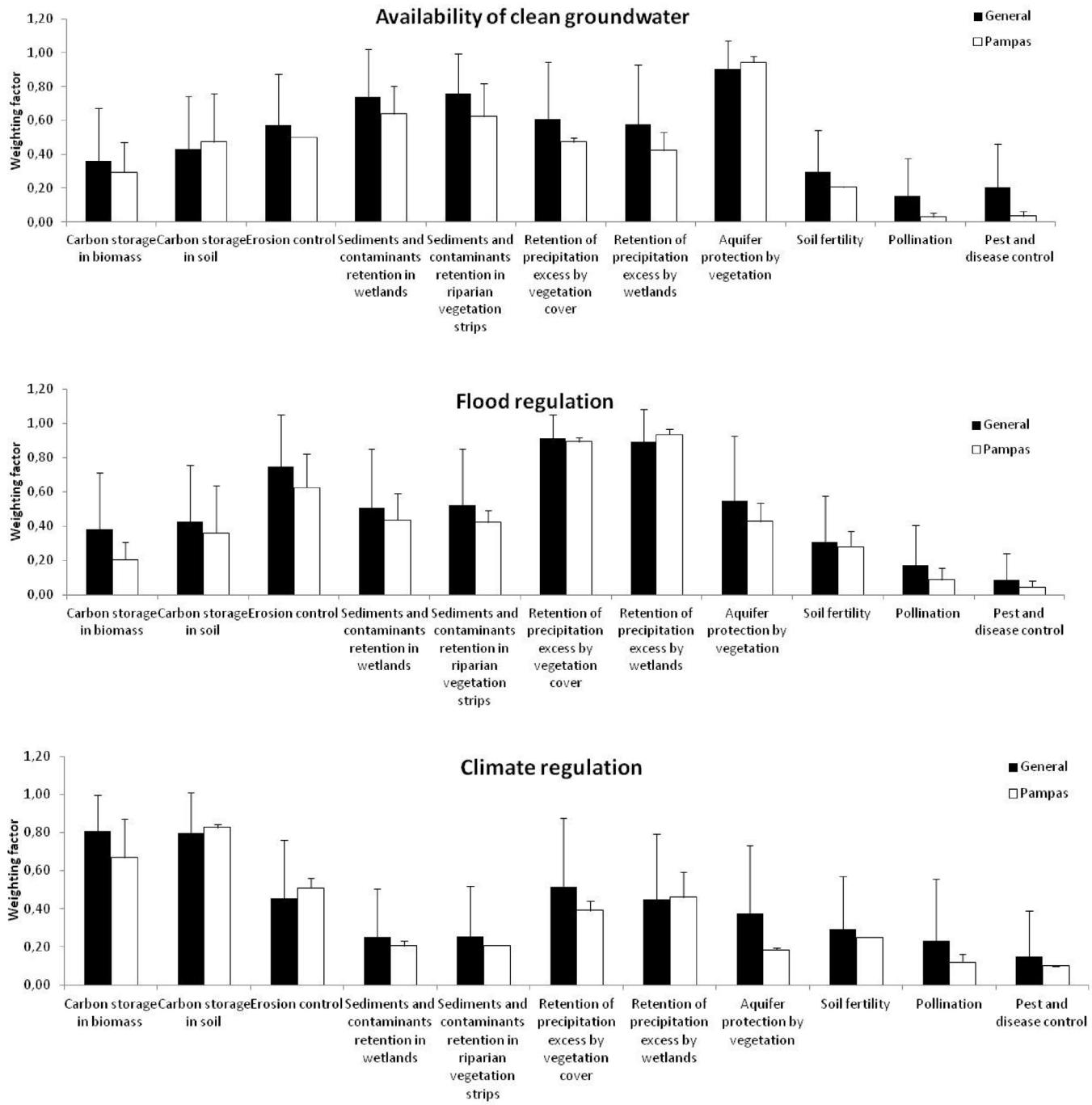

Fig. 4. Comparison of weighting factors of EF to ES in the General matrix and the Pampas region matrix.

infiltration. Finally, differences in the ES "climate regulation" were due to lower influences of "aquifer protection by vegetation", "carbon storage in biomass" and "retention of precipitation excess by vegetation" (Fig. 4, Table 3). The MAD for this ES was 0.077. The consulted experts considered that the Pampas ecosystem carbon stock is currently low (decreased by agricultural use) when compared to other ecosystems. Overall, results showed a tendency of the general matrix to overestimate the contribution of EF to ES compared to the Pampas matrix (Fig. 4, Table 3).

The spatial congruence of ES supply hotspots in both integration matrices was similar for "availability of clean groundwater" (proportion of coincident hotspot cells = 77.1%) and "flood regulation" (82.1%) (Fig. 5). On the other hand, "climate regulation" had the lowest level of coincidence between hotspot cells (54.4%) (Fig. 5).

4. Discussion

In the last years, it has been argued that the focus of ES research should move from ES supply assessments to ES in real-world decision making (Daily et al., 2009) given the urgent need to manage ecosystems sustainably to ensure the wellbeing of vulnerable populations (Biggs et al., 2012; Fisher et al., 2013). Although this argument is valid, results

Table 3
Sensitivity indices (*I*) of the comparison of weighting factors of the general and Pampas matrices.

	Ecosystem services		
	Availability of clean groundwater *I*	Flood regulation *I*	Climate regulation *I*
Carbon storage in biomass	−0.013	−0.038	−0.033
Carbon storage in soil	0.009	−0.015	0.008
Erosion control	−0.015	−0.025	0.015
Sediments and contaminants retention in wetlands	−0.022	−0.017	−0.010
Sediments and contaminants retention in riparian vegetation strips	−0.028	−0.021	−0.013
Retention of precipitation excess by vegetation cover	−0.028	−0.004	−0.031
Retention of precipitation excess by wetlands	−0.032	0.008	0.003
Aquifer protection by vegetation	0.009	−0.025	−0.048
Soil fertility	−0.017	−0.006	−0.010
Pollination	−0.026	−0.017	−0.028
Pest and disease control	−0.037	−0.008	−0.013

from our study suggest that there are still many gaps in knowledge regarding ES assessments in order to provide decision makers with reliable and useful information.

Our study shows that the influences of EF on ES tend to vary among ecoregions, as expressed in the integration matrices. The case study application to a real landscape demonstrated that these differences, although less markedly than we expected, yielded a variation in the estimation of hotspots of ES supply. What is more interesting is that the spatial coincidence of hotspots was not always lower the higher the differences in the integration matrices weighting factors, as we would expect, revealing a very complex relationship between the different steps in the ES cascade that cannot be easily anticipated. This alerts that recommendations to policy makers based on general models, even when differences with specific models seem not as pronounced, could be misleading. For example, policies for payments of ES are usually based on the identification of hotspots of ES. If these are not correctly identified, incentives could be incorrectly assigned (Wünscher and Engel, 2012).

Our results constitute a contribution respect to classical models in which usually one EF is related to one ES (Eigenbrod et al., 2010) and thus fail to capture the complex relationships between them. On the contrary, in our study the surveyed experts revealed the importance of considering the influence of more than one EF on each ES. Other authors who have used the same matrix approach, related land use and ES supply (Burkhard et al., 2009; Jacobs et al., 2015). However, it is more difficult from these examples to draw interpretations about complex mechanistic relationships.

Further steps for increasing the realism of integration matrices should revise the implicit assumptions of the linear EF to ES relationships. As noted by Maynard et al. (2010), models can also be improved by considering the possible interactions and non-linear effects of the influence of the spatial configuration in the supply of ES. While empirical tests of alternative models relating multiple EF to ES are difficult to envisage, linear models could be improved on the basis of theoretical considerations. Most of the contributions of EF to ES can only be considered as meaningful within certain ranks with minimum threshold and asymptotic or critical values. For example, crop production may describe logarithmic responses to bee abundance (e.g. Rogers et al., 2014) to pest disease control (e.g. Johnson, 1994). Non-linear relationships may be incorporated using methods such as fuzzy logic,

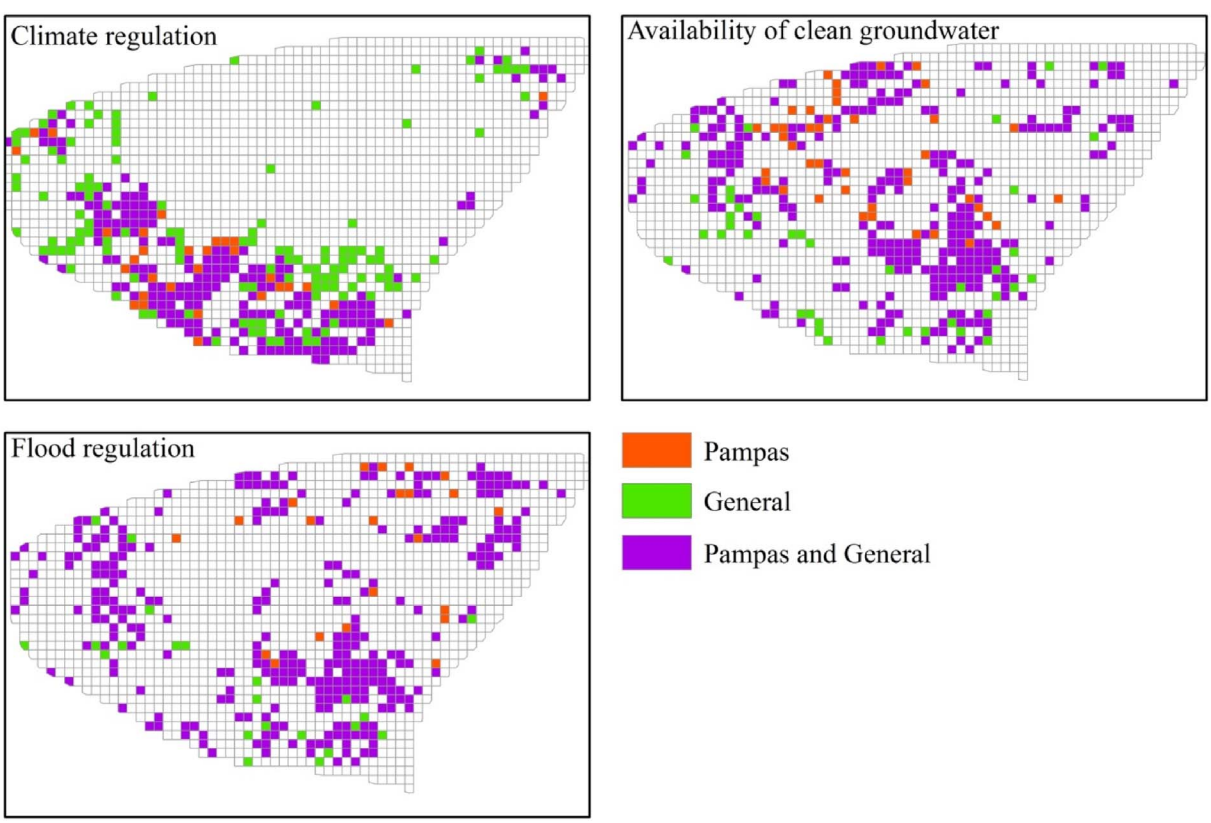

Fig. 5. ES supply hotspots maps using the General and Pampas matrices in the case study area (Mar Chiquita basin). Cells in purple where identified as hotspots by both matrices.

which allow to consider complex relations between input variables and to parameterize them with expert knowledge (Center and Verma, 1998).

The resulting integration matrices could be used as inputs in future ES assessments using the ECOSER protocol or similar tools (e.g. Landuyt et al., 2015). The utility of the developed matrices goes beyond the specific ecoregions evaluated in this study. The user can choose them as a template for an evaluation of a region with similar ecological conditions making adjustments wherever necessary to his/her best knowledge. The application of the integration matrices in more case studies will also allow their calibration and increase their usefulness.

It is also worthwhile to explore the utility of expert knowledge elicitation methods in the assessment of cultural ES, which were not undertaken in our work and have not been incorporated in the protocol ECOSER. In the case of provision and regulation ES, the relationship with ecosystem properties and processes is relatively straightforward, as they rely mainly on biophysical mechanisms. Instead, the supply of cultural ES is a more complicated process that takes into account the stakeholders' valuation and idiosyncratic issues (Milcu et al., 2013). Therefore, the use of expert knowledge would be an essential tool for their assessment. Moreover, in the case of cultural ES, the so-called "experts" are the beneficiaries of ES supply and are not necessarily academics. Therefore, it implies a transdisciplinary approach (Hadorn et al., 2006; Mobjörk, 2010).

A highly relevant aspect in ES assessments is the uncertainty inherent to supply maps (Egoh et al., 2012). ES researchers work in a context where decision-makers demand information to satisfy both local needs and international agreements on socio-environmental issues (Balvanera et al., 2012; Mastrangelo et al., 2015). However, ES research is still conducted in a context of high uncertainty regarding the knowledge of the relations between the different steps in the ES cascade. These uncertainties lead to internal tensions and contradictory policy recommendations, resulting in a low applicability of the ES concept. What is of more concern is that uncertainties are usually not acknowledged when maps or other products are reported (Pagella and Sinclair, 2014). In a review, Seppelt et al. (2011) revealed that only one-third of ES assessments account for uncertainties in a quantitative way. If uncertainties are disregarded, the decision makers are provided with very unreliable information. For instance, in our case study "climate regulation" ES hotspots differ when using the different integration matrices. As a result, conservation policies, such as payments for ES and land-use planning in different socio-ecological contexts, might be poorly (and probably erroneously) informed when using a common integration matrix.

The uncertainties identified in our study arise not only from the local biophysical conditions but also from the method used to build the integration matrices. We used an expert survey approach, which has proved its usefulness to resume available information in environmental sciences (Haines-Young, 2011; Grêt-Regamey et al., 2013; Rositano and Ferraro, 2014). However, it is necessary to acknowledge the possible shortcomings of this approach. Even when we provided experts with precise and operative definitions of all the used concepts in this study, the multiplicity of conceptual frameworks in ES research (Nahlik et al., 2012) made it difficult to evaluate the relationship between EF and ES. For example, some researchers had difficulties in the assignment of an ecosystem process as an EF or an ES. On the other hand, the online survey approach made it difficult to interpret results when the causal relationship between functions and services was not evident. For example, we did not repeat the questions when answers were not fully understood. As a consequence, the quest to include a large number of experts in the survey limited the quality control of the response.

While some studies show that online questionnaires are as reliable as personal interviews (Fleming and Bowden, 2009), others point out that online survey questions can be understood differently by experts (e.g. Knol et al., 2010). Morgan (2014) also agrees that when using a qualitative scale for valuation, such as words (e.g., low, high, etc.), they may have different meanings for different experts. This may explain why in some ecoregions (e.g. Validivan Forests) the contribution of EF to ES seems to be consistently higher than in others. It also may be the cause of the low robustness of some matrices expressed in high CV of responses.

A way to overcome the above-mentioned issues is by performing personal interviews, which give the possibility to reformulate questions if they are not understood. A well-established approach is the use of Delphi method, which allows adjusting the expert's estimates through the interaction in several rounds (Martin et al., 2011; Rositano and Ferraro, 2014). Another possible approach is the one used by Maynard et al. (2011) in the development of an ES framework in South East Queensland. They worked with small groups of experts in thematic expert panels to revise data, modify scores of previous ES valuations and fine-tune the term definitions used in the study. However, we were not able to adopt this approach because we were not able to organize workshops due to logistic difficulties.

Our work has revealed the need to continue the effort of adjusting methodological issues in ES assessments, in spite of the equally important need to apply the framework. Continued tests in real landscapes using all the available knowledge with proper techniques will be necessary in order to attain those objectives.

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Appendix A. Summary of responses of the expert knowledge elicitation survey.

a. Number of experts who responded in the first and second round of the survey for each ES

Round	Ecoregion	Flood regulation	Availability of water for hydroelectric power	Availability of clean surface water	Potential crop production	Potential forage production	Potential provision of non-timber forest products	Potential wood production	Climate regulation
1	Campos	8	6	8	7	9	6	7	7
	Chaco	6	5	7	9	8	9	9	8
	Pampas	13	8	13	15	11	3	9	12
	Valdivian Forest	7	5	8	6	6	6	6	7
	Total	**34**	**24**	**36**	**37**	**34**	**24**	**31**	**34**

2	Campos	1	1	1	1	1	1	1	1
	Chaco	0	0	0	1	1	0	0	0
	Pampas	2	3	3	3	3	2	2	5
	Valdivian Forest	1	1	1	0	0	1	1	1
	Total	**3**	**4**	**4**	**4**	**4**	**3**	**3**	**6**

b. Total number of experts that responded in the first and second round of the survey

Ecoregion	First round	Second round
Campos	10	1
Chaco	15	3
Pampas	19	7
Valdivian Forest	8	1
Total[a]	**52**	**12**

[a]Fifty experts responded the first round of the survey, but two of them responded for more than one ecoregion.

Appendix B. Integration matrices with weighting factors of EF to ES.

a. Valdivian Forests

	Ecosystem Services								
Ecosystem Functions	Climate regulation	Flood regulation	Potential crop production	Potential forage production	Potential wood production	Potential provision of non-timber forest products	Availability of clean groundwater	Availability of clean surface water	Availability of water for hydroelectric power
Carbon storage in biomass	0.79	0.37	0.73	0.73	1	1	0.33	0.39	0.56
Carbon storage in soil	0.76	0.47	0.83	0.8	0.93	0.96	0.42	0.37	0.67
Erosion control	0.36	0.88	0.92	0.92	0.75	0.64	0.58	0.9	0.87
Sediments and contaminants retention in wetlands	0.31	0.61	0.44	0.53	0.33	0.42	0.81	0.79	0.5
Sediments and contaminants retention in riparian vegetation strips	0.31	0.52	0.64	0.58	0.33	0.44	0.9	0.83	0.71
Retention of precipitation excess by vegetation cover	0.71	0.98	0.53	0.56	0.69	0.61	0.73	0.9	0.6
Retention of precipitation excess by wetlands	0.57	0.98	0.53	0.56	0.28	0.53	0.63	0.67	0.53
Aquifer protection by vegetation	0.64	0.83	0.6	0.61	0.61	0.58	0.94	0.88	0.79
Soil fertility	0.33	0.28	1	0.97	0.83	0.86	0.33	0.36	0.27
Pollination	0.5	0.25	0.94	0.8	0.87	0.94	0.25	0.23	0.21
Pest and disease control	0.22	0.11	0.97	0.94	0.72	0.89	0.23	0.37	0.2

b. Campos

Ecosystem Functions	Ecosystem Services								
	Climate regulation	Flood regulation	Potential crop production	Potential forage production	Potential wood production	Potential provision of non-timber forest products	Availability of clean groundwater	Availability of clean surface water	Availability of water for hydroelectric power
Carbon storage in biomass	0.67	0.54	0.69	0.93	0.92	0.67	0.67	0.65	0.67
Carbon storage in soil	0.79	0.61	0.9	0.93	0.83	0.73	0.71	0.71	0.67
Erosion control	0.45	0.89	0.95	0.83	0.78	0.73	0.79	0.92	0.87
Sediments and contaminants retention in wetlands	0.37	0.56	0.44	0.48	0.3	0.54	0.83	0.96	0.71
Sediments and contaminants retention in riparian vegetation strips	0.46	0.69	0.43	0.4	0.5	0.54	0.79	0.94	0.71
Retention of precipitation excess by vegetation cover	0.47	0.94	0.76	0.63	0.61	0.54	0.79	0.83	0.8
Retention of precipitation excess by wetlands	0.47	0.91	0.58	0.38	0.33	0.5	0.77	0.83	0.8
Aquifer protection by vegetation	0.4	0.81	0.44	0.38	0.47	0.5	0.94	0.83	0.75
Soil fertility	0.33	0.38	0.98	0.94	0.86	0.77	0.37	0.33	0.27
Pollination	0.24	0.12	0.89	0.67	0.47	0.9	0.25	0.35	0.2
Pest and disease control	0.17	0.1	0.95	0.8	0.83	0.87	0.37	0.6	0.27

c. Chaco

Ecosystem Functions	Ecosystem Services								
	Climate regulation	Flood regulation	Potential crop production	Potential forage production	Potential wood production	Potential provision of non-timber forest products	Availability of clean groundwater	Availability of clean surface water	Availability of water for hydroelectric power
Carbon storage in biomass	0.87	0.42	0.42	0.65	0.92	0.73	0.44	0.6	0.33
Carbon storage in soil	0.74	0.44	0.73	0.62	0.7	0.73	0.43	0.56	0.37
Erosion control	0.43	0.71	0.73	0.67	0.62	0.65	0.57	0.92	0.63
Sediments and contaminants retention in wetlands	0.26	0.6	0.44	0.36	0.27	0.6	0.62	0.79	0.33
Sediments and contaminants retention in riparian vegetation strips	0.21	0.58	0.3	0.38	0.28	0.6	0.69	0.9	0.53
Retention of precipitation excess by vegetation cover	0.56	0.83	0.48	0.59	0.48	0.6	0.73	0.94	0.63

Retention of precipitation excess by wetlands	0.46	0.73	0.35	0.31	0.26	0.56	0.62	0.77	0.53
Aquifer protection by vegetation	0.45	0.38	0.43	0.44	0.43	0.56	0.76	0.6	0.43
Soil fertility	0.26	0.19	0.95	0.83	0.73	0.64	0.4	0.46	0.3
Pollination	0.19	0.15	0.62	0.64	0.69	0.79	0.23	0.29	0.17
Pest and disease control	0.17	0.1	0.74	0.81	0.55	0.56	0.27	0.38	0.22

d. Pampas

	Ecosystem Services								
Ecosystem Functions	Climate regulation	Flood regulation	Potential crop production	Potential forage production	Potential wood production	Potential provision of non-timber forest products	Availability of clean groundwater	Availability of clean surface water	Availability of water for hydroelectric power
Carbon storage in biomass	0.67	0.2	0.51	0.59	0.8	0.31	0.29	0.32	0.05
Carbon storage in soil	0.83	0.36	0.8	0.77	0.63	0.22	0.47	0.33	0.03
Erosion control	0.51	0.63	0.76	0.72	0.5	0.17	0.5	0.81	0.03
Sediments and contaminants retention in wetlands	0.21	0.44	0.22	0.27	0.13	0.06	0.64	0.9	0.03
Sediments and contaminants retention in riparian vegetation strips	0.21	0.42	0.21	0.24	0.21	0.06	0.62	0.93	0.03
Retention of precipitation excess by vegetation cover	0.39	0.89	0.62	0.6	0.39	0.06	0.47	0.69	0.03
Retention of precipitation excess by wetlands	0.46	0.94	0.6	0.62	0.15	0.06	0.42	0.72	0.03
Aquifer protection by vegetation	0.19	0.43	0.42	0.24	0.17	0	0.94	0.51	0.03
Soil fertility	0.25	0.28	0.9	0.84	0.63	0.13	0.21	0.26	0.03
Pollination	0.12	0.09	0.72	0.5	0.37	0.25	0.03	0.06	0.03
Pest and disease control	0.1	0.04	0.85	0.62	0.48	0.17	0.04	0.06	0.03

Appendix C. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2017.05.062.

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