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# Ecosystem services and biodiversity values in grasslands and shrublands in Santa Cruz province (Argentina)

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## Research Article

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### Abstract

Effective land use planning must consider both instrumental (monetary) and intrinsic (non-monetary) values derived from nature to ensure that the significance of natural assets is adequately integrated into our perspectives, planning processes and resource management strategies. As an initial step toward this broader objective, we characterize ecosystem services (cultural, supporting, regulating and provisioning) and potential biodiversity (indicator species of plants, insects, lizards, birds and mammals) within the predominant vegetation types (wetlands, shrublands and grasslands) located in Santa Cruz province, Argentina. Our findings reveal that vegetation types support distinct potential biodiversity and offer unique bundles of ecosystem services. The findings of this study provide valuable insights for land use planning in Santa Cruz (Argentina), integrating considerations of ecosystem services and biodiversity values. For cultural ecosystem services, wetlands exhibited the highest aesthetic and recreational values, while dwarf-shrublands scored highest for existence values. Wetlands were also important for regulating ecosystem services, whereas steppe grasslands ranked the lowest in this regard. Although steppe grasslands possess the highest potential biodiversity values, these values are not distributed homogeneously, with hotspots located: (i) on the southern border of Santa Cruz (4 million ha), (ii) 2.75 million ha in the north, and (iii) one smaller area of 1.25-million ha in the central-east.

### Impact statement

Rangeland ecosystems deliver vital ecosystem services (ESs), including instrumental benefits such as food and fiber from livestock. Additionally, rangelands may contribute to human well-being through intrinsic or non-monetary ES values. Rangelands also support a distinct potential biodiversity that plays a crucial role in regulating climate and hydrological cycles, which underpin numerous cultural ESs. The concept of ESs has been fundamental in various high-level policy frameworks, such as the Convention on Biological Diversity, the Intergovernmental Platform on Biodiversity and Ecosystem Services, the World Bank's Global Partnership for Wealth Accounting, the Valuation of Ecosystem Services, and the EU Biodiversity Strategy. However, the application of the ES framework at the regional scale within Latin America has been limited, with the notable exception of the Natural Capital Trust in Costa Rica (Hernández-Blanco et al., 2025). In this context, mapping potential biodiversity values and ES at the landscape level in Southern Patagonia represents an important step toward a better understanding of potential trade-offs and synergies between management and conservation strategies. The mapping and analyses presented here fill some of these gaps and aim to enhance current land use planning efforts.



## Introduction

The concept of ecosystem services (ESs) seeks to elucidate the diverse benefits that humans obtain from nature. This includes provisioning ES, which are related to tangible products directly consumed by humans that possess identifiable market values, such as wool, food and clean water. Additionally, ES encompasses more intangible benefits, including aesthetic appreciation, recreation, ecotourism, artistic inspiration and a sense of place (MEA, 2005; Martínez Pastur et al., 2016a). Biodiversity is central to the provision of ES due to the ecological functions and processes that the different species sustain (Daily, 1997), however, the links between biodiversity and ES will also be determined by the interplay between demand and supply (Yahdjian et al., 2015). Thus, while previous research was concentrated on how much ES are produced (supply), sustainable management requires addressing the gap between this supply and what society needs (demand). The provision of ES from rangeland ecosystems in the Global South has received comparatively limited research attention (Eldridge et al., 2024). Moreover, the interconnections between ES and biodiversity within rangeland ecosystems have rarely been explored (Duarte-Guardia et al., 2024).

Vegetation types in Southern Patagonia (Santa Cruz province, Argentina) have been classified and mapped in detail (Peri et al., 2024). Steppe grasslands cover the largest extension (58% of the province), with shrubland, dwarf shrubland, Mata Negra Matorral thickets and deciduous *Nothofagus* forests covering lesser extensions (Peri et al., 2021a, 2024). The human footprint (e.g. roads, infrastructure, livestock grazing, desertification) is variable but has a profound effect on local biodiversity (Rosas et al., 2021a, 2021b). Extensive sheep grazing is the main land use. Livestock production is heavily dependent on the environment and management (Trier Bjerring et al., 2025). Heavy and unsustainable stocking rates threaten the future of livestock productivity and the long-term viability of the local economy. Broadening the appreciation of the values that rangeland generates to include also potential biodiversity, regulating, supporting and cultural ES could result in more rational management proposals of the natural capital in Southern Patagonia (Peri et al., 2013; Oñatibia, 2021). In this context, the objective was to characterize the generation of ES (cultural, supporting, regulating and provisioning) and potential biodiversity values of different vegetation types in rangeland ecosystems of Santa Cruz province, Argentina and discuss potential synergies and trade-offs among them. We hypothesized that the provision of the different ES is not independent, where interaction occurred among them according to the species assemblage (vegetation types), biophysical characteristics of the ecosystems and human pressures on natural ecosystems due to economic activities generating synergies and trade-offs between ES and biodiversity.

## Methods

### *Study area*

The present work is focused on the grasslands and shrublands ecosystems of the Patagonian steppe in Santa Cruz province (243,943 km$^2$) between latitudes 46°00′ and 52°30’ S (Southern Patagonia, Argentina) (Figure 1). We used the vegetation types proposed by Peri et al. (2024), which include: (i) Steppe grasslands characterized by the presence of tussock grasses (*Festuca* spp., *Pappostipa* spp.), short grasses (*Poa* spp.), graminoids (*Carex* sp.) and shrubs. These species are the main feed resource for sheep farming (Peri et al., 2021b). The steppe grassland type (Figure 2A) is subdivided into two subcategories: (a) Grass steppe dominated by grasses and sedges (*Bromus* sp., *Carex* sp., *Festuca* spp., *Hordeum* sp., *Pappostipa* sp., *Poa* sp., *Rytidosperma* sp. and *Trisetum* sp.) with dwarf shrubs and herbs such as *Nardophyllum* sp., *Perezia* sp., *Azorella* sp. and *Nassauvia* sp. at lower densities; and (b) grass-shrub steppe dominated by the grasses *Pappostipa* sp., *Agrostis* sp., *Festuca* spp., *Hordeum* sp., and *Trisetum* sp. and shrubs (*Berberis* sp., *Adesmia* sp., *Chuquiraga* sp., *Azorella prolifera*, *Mulguraea* sp., *Schinus* sp. and *Senecio* sp.) with shrubs present at higher densities. (ii) The wetland vegetation type (Figure 2B) dominated by Cyperaceae, Juncaceae and Gramineae species, in areas where water naturally accumulates. Wetlands are the most important vegetation type for livestock production, mainly located on floodplains, glacial plains and on hydro-eolian basins. (iii) Shrublands are dominated by woody plants (>40%) generally less than 3 m in height. Here, we recognize three distinct types: (a) The Mata Negra Matorral thicket (Figure 2C), dominated by the evergreen shrub *Mulguraea tridens*, which is sclerophyllous and grows in association with xeric steppe vegetation, creating spatial heterogeneity in the landscape because

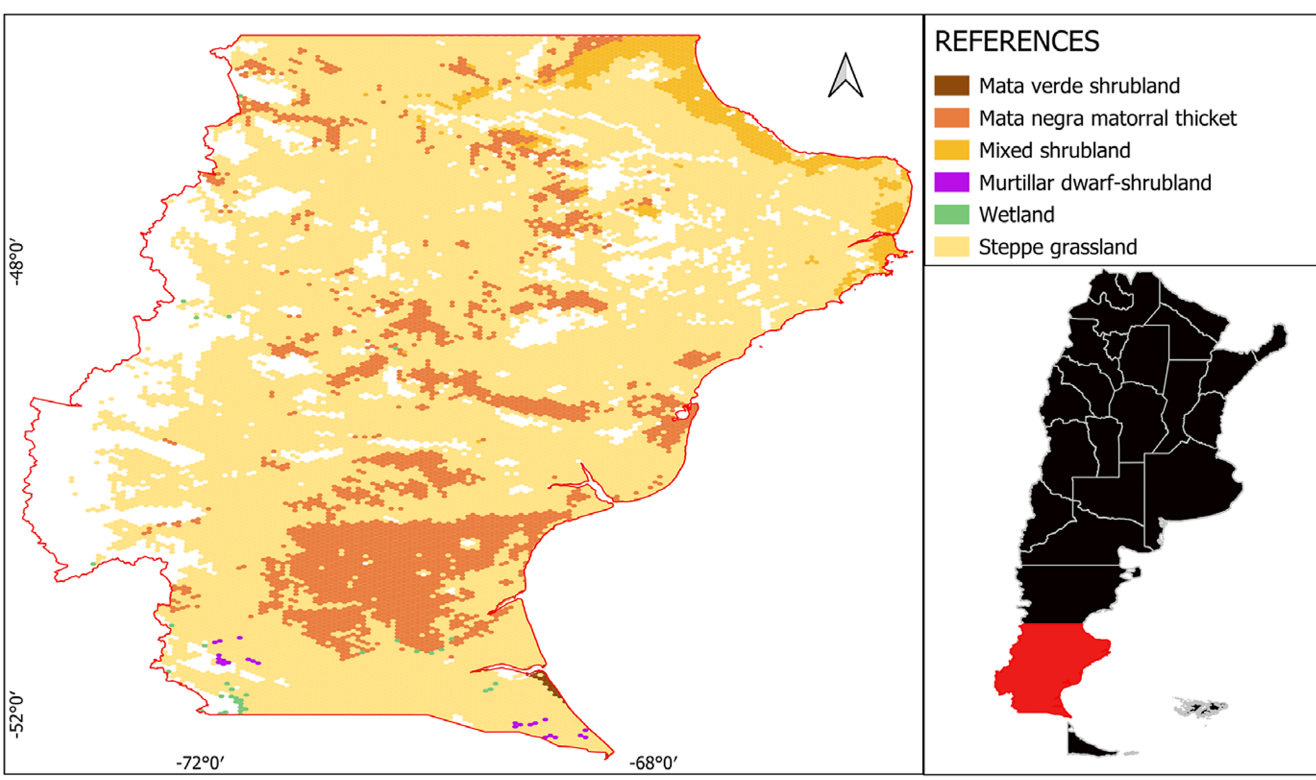


**Figure 1.** Characterization of the study area: Location of Santa Cruz province (red) and main vegetation types. White areas are bare soil, mountains, forests, water bodies, icefields and snow cover (Peri et al., 2024).


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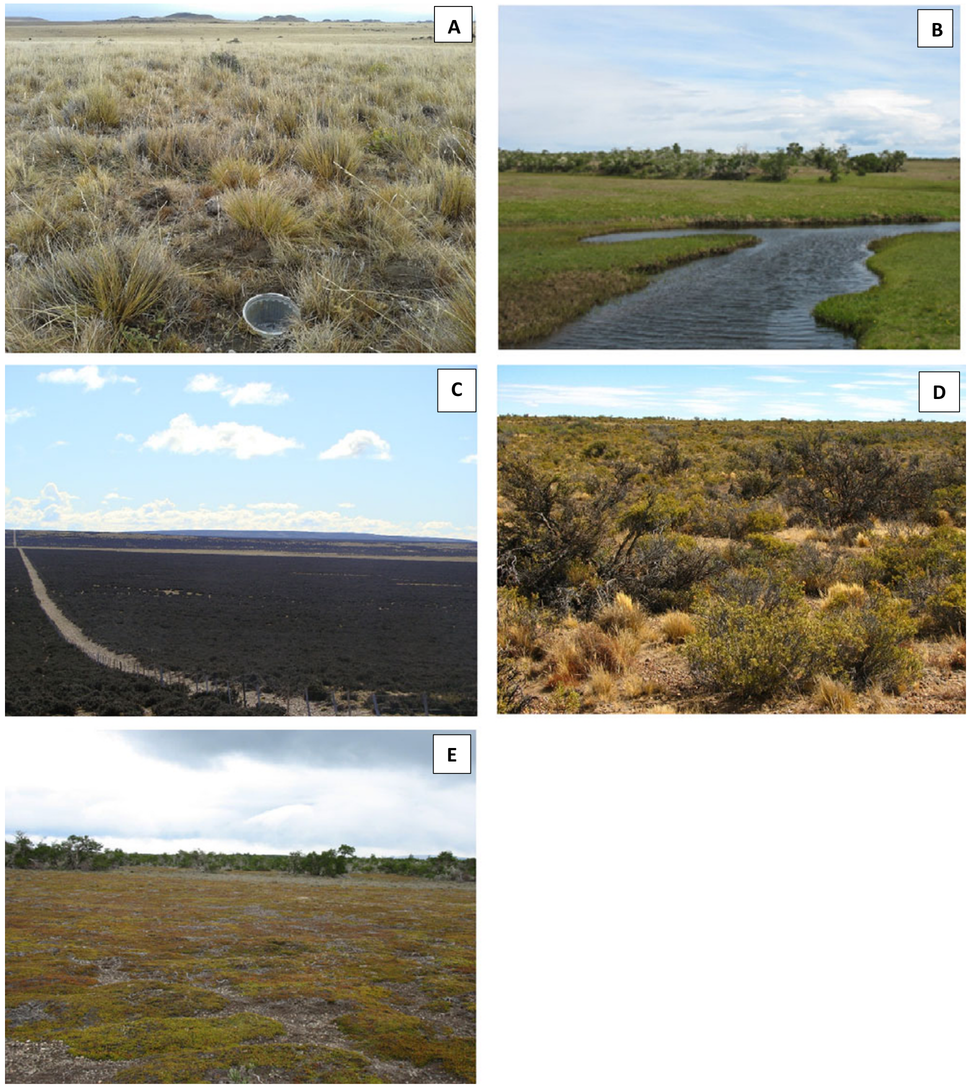


**Figure 2.** The main vegetation types in Santa Cruz (Argentina): (A) steppe grassland, (B) wetlands, (C) Mata Negra Matorral thicket, (D) mixed shrubland, and (E) murtillar dwarf-shrubland.

of vegetation patches. (b) The mixed shrublands (Figure 2D) are dominated mainly by tall shrubs, such as *Colliguaja integerrima*, *Chuquiraga*, *Anartrophyllum rigidum*, *Lycium* sp. and *Azorella prolifera*. The understory includes grasses such as *Bromus* sp., *Hordeum* sp., *Pappostipa* sp. and *Poa* sp. (c) Dwarf-shrublands (Figure 2E) are dominated by *Empetrum rubrum*, which mainly occurs on sites with acidic, coarse-textured and poor nutrient soils. Dwarf shrublands are often heavily disturbed due to overgrazing and fire.

Topographic variables were defined using GIS and the Shuttle Radar Topography Mission data (Farr et al., 2007), which produced the highest-resolution digital elevation model. Climatic variables, including temperature, precipitation and annual, monthly and seasonal climate indices were defined using the methods described in Hijmans et al. (2005). The regional climate is arid, cold and windy. Rainfall ranges from 192 to 219 mm $yr^{-1}$ (Table 1). Mean annual temperature ranges from 5.4 to 10.5 °C (Peri et al., 2016) (Table 1). The wind is predominantly from the south-southwest. Severe and frequent windstorms occur in spring and summer with wind speeds over 100 km $h^{-1}$. Altitude ranges from sea level to more than 1000 m.a.s.l. (Lencinas et al., 2021), with average values ranging from 390 to 612 m.a.s.l. depending on the vegetation type (Table 1). Steppe grasslands cover the largest extension in the province (representing 58.1% of the total area of the province or 142,085 $km^2$), followed by Mata Negra Matorral thickets (15.7%, 38,355 $km^2$) (Table 1).

## Provision of different ecosystem services at the landscape level

We selected eight proxies to quantify the level of ES provision from the different vegetation types: (i) Cultural ES including aesthetic, existence, local identity and recreational values; (ii) Regulating services which used net primary productivity and soil carbon as proxies and supporting services which were measured by characterizing habitat quality (maximum potential habitat suitability for the studied species); and (iii) Provisioning services which were characterized through livestock capacity and oil production.

Four maps were created for the cultural ES, three related to human interactions (e.g. physical or intellectual) with biotic systems, ecosystems and landscapes and another map that relates spiritual values to

**Table 1.** Area of the studied vegetation types, and ANOVAs results for mean annual temperature (MAT), mean annual precipitation (MAP) and altitude (ALT) comparing vegetation types in Santa Cruz province (Argentina)

| Vegetation type | Area (km$^2$) | df | MAT (°C) | MAP (mm yr$^{-1}$) | ALT (m.a.s.l.) |
|---|---|---|---|---|---|
| Wetlands | 2,164.5 | 46 | 6.15a | 198.8ab | 470.7ab |
| Murtillar dwarf-shrubland | 702.4 | 25 | 5.36a | 218.9b | 612.5b |
| Mata Negra Matorral thicket | 38,538.4 | 2881 | 7.32b | 192.5a | 525.2b |
| Mixed shrubland | 9,103.3 | 759 | 10.50d | 197.6a | 497.5b |
| Steppe grassland | 142,085.2 | 15,572 | 8.06c | 209.2b | 390.5a |
| F(p) | | | 506.27(<0.001) | 47.98(<0.001) | 147.60(<0.001) |

*F*: Fisher's test; (p): probability; df: degrees of freedom. Different letters in columns show differences among vegetation types according to Tukey's test at $p < 0.05$.

biotic systems, ecosystems and landscapes. For these maps, we used the methods and data of Martínez Pastur et al. (2016a). In short, this methodology used geo-referenced digital photos from a web platform that the public used to upload photos taken in the region. The social and biophysical importance of the cultural ESs in the landscape were evaluated through the quantification of the number of digital images that either local people and/or external visitors to the region uploaded to the Panoramio web platform. Then, we applied the Kernel density tool in a GIS, which allowed us to calculate the density of photos around each cell of a raster. Four proxies were considered: (i) aesthetic values were related to the interaction of people with the environment in relation to natural beauty, based on human perceptions and judgments, (ii) existence values were related to the degree of satisfaction that people get from knowing that a natural resource, like a species or an ecosystem, exists, (iii) local identity values were linked to images that depicted local culture and heritage, and (iv) recreation values were linked to images that captured the recreation value of the natural capital was captured in the image. To assess which social and biophysical variables best explained the spatial distribution of each cultural service (Martínez Pastur et al., 2016a) each map was rescaled from 0 to 100 using a linear scale by a function tool in ArcMap 10.0 software (ESRI, 2011). The significance of the explanatory variables in the explanation of the associations between cultural ES was tested with a Monte Carlo permutation test with 500 permutations per analysis. The inertia of the factors, which represents the explained variance, was used to identify the most important social and biophysical factors determining the associations between cultural ESs and landscape attributes (Martínez Pastur et al., 2016a).

Regulating services were estimated using net primary productivity (NPP) as a proxy (g.m$^{-2}$ yr$^{-1}$), after Zhao and Running (2010). The NPP data with a resolution of 30 arc seconds were acquired from the MOD17A3 data released by NASA's Earth Observation System Data and Information System. In these ecosystems, NPP varied from 30.9 to 714.2 g C/m$^2$/year (Peri et al., 2022). Using the GIS platform, a map with a resolution of 90 × 90 m was constructed to project the regulating services in the landscape. The human footprint index (HFI) was used as a proxy for the supporting services after Rosas et al. (2021c). In a GIS project, supporting services were calculated as the inverse of the Human Footprint Index (1-HFI) values to produce a natural habitat proxy map with a resolution of 90 m × 90 m. SOC was modeled for the first 30 cm of the soil profile by Peri et al. (2018) and mapped in a grid of 90 m× 90 m. In this work, for modelling, Peri et al. (2018) used a stepwise multiple regression to identify which variables among these uncorrelated variables helped to explain SOC variation at the landscape level. Briefly, the model was evaluated through the standard error of estimation (the r2-adj), defined as the average of the difference between predicted and observed values, and the mean absolute error, defined as the average of the difference between predicted and observed absolute values. From the SOC model, a SOC map was obtained for the entire Santa Cruz province, where the variables derived from the multiple linear regression models were integrated into a GIS using ArcMap 10.0 software.

The provisioning services were estimated using a sheep probability map of stocking density estimated from a model of probability of contact with sheep per ranch (0–1 probability km$^{-2}$) following Pedrana et al. (2011). Values close to 0 indicate a low probability of occurrence and values close to 1 high probability. In the GIS project, we applied the focal statistics tool to create a new raster by considering the values within a 10 km. We then applied a mask for forests and protected areas. Oil production was also included as a component of the "provisioning services" estimation, as it is an important economic activity in the region. Oil production was estimated based on oil well density (wells km$^{-2}$) (Rosas et al., 2021a). In a GIS project, we calculated the oil well density using a database of 21,426 registered and georeferenced oil wells. The oil well density map presented values from 0 (minimum density) to 8.44 wells km$^{-2}$ (maximum density), with a mean value of 0.09 wells km$^{-2}$. Maps were rescaled from the 0–100 linear scale using the same tool described above.

The different ES were then combined to obtain maps for three ES types (cultural, regulating/supporting and provisioning ES). All the rasterized maps were created using ArcMap 10.0 software (ESRI, 2011), and the resulting average values were rasterized again to obtain final values for each ES type from zero (lower provision of the service) to 100 (maximum provision of the service). This maximum provision value of 100 is rarely reached in the field.

### *Potential biodiversity mapping*

Potential biodiversity values for the region are based on the map and analysis of Rosas et al. (2022a) for Santa Cruz. Potential biodiversity refers to an area's capacity to support a diverse range of plant and animal species, often indicating the maximum theoretical biodiversity an ecosystem can maintain based on its environmental conditions (such as climate, energy, and resources). This map uses a large biodiversity database from the PEBANPA Network (Peri et al., 2016). In total, we used 118 maps (90 × 90 m) of potential habitat suitability for five taxonomic groups: one mammal (an endemic deer), 47 species of birds, 7 lizards, 10 darkling beetles and 53 plant species (Rosas et al., 2022a). Environmental Niche Factor Analysis (Hirzel et al., 2002) was used to map habitat suitability for each species based on potential physical environmental variables (climate, topography and other variables related to


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landscape attributes), which were rasterized at 90 m × 90 m resolution using the nearest resampling technique in ArcMap 10.0 (ESRI, 2011) using Biomapper 4.0 software (Hirzel and Le Lay, 2008). We then used the Cell Statistics tool to combine the 119 potential habitat suitability maps to obtain average values for each pixel, integrating the information for the different taxonomic groups. We first produced five taxonomic group maps: four were maps of potential biodiversity for birds, lizards, darkling-beetles and plants) and the 5th map describes potential habitat suitability for the endemic deer. Then, we created taxonomic group indices (G Indices) to weight each taxonomic group map, considering ecological and endemism values (Rosas et al., 2022a). These maps were rasterized to present scores that varied between 0 and 100 (average values of potential habitat suitability for all the studied taxa). A map of potential biodiversity (all taxa) was produced by summing values for each pixel of the five weighted maps of the taxonomic group indices in a single GIS project.

### *Data analysis*

We analyzed the different maps of ES and biodiversity using the hexagonal binning and univariate ANOVAs. Hexagonal binning is a method of aggregating individual data (pixel values) into polygonal regions (Battersby et al., 2017). This spatial methodology can simply and effectively represent complex data sets, improving the ability to analyze and visualize spatial patterns (Briney, 2014). For this, we calculated for each hexagonal area (250 thousand ha for the provincial scale) the average values of cover for the different vegetation types, environmental variables, ESs and the potential biodiversity (0–100). Explanatory variables, model outputs and statistical fit analyses are described in detail by Rosas et al. (2021a, 2021b, 2021c, 2022a, 2022b).

## Results and discussion

### *Cultural ecosystem services*

The importance of the various vegetation types that populate the steppe for the supply of cultural ES is low, but it varies in subtle and important ways (Table 2). For example, mean aesthetic and recreational values were highest in wetlands. This result is consistent with previous studies, as there is a positive effect of water presence on aesthetic values and recreation (Abildtrup et al., 2013; García-Llorente et al., 2012). Also, the positive effect of vegetation on social preferences toward wetlands can be interpreted as an expression of phytophilia, which is the phenomenon of people generally preferring green views over arid or semiarid landscapes (López-Santiago et al., 2014). Existence values were highest in the dwarf-shrublands, and local identity values were highest for Mata Negra Matorral thicket and steppe grasslands (Table 2). Similarly, Martínez Pastur et al. (2016a) reported that the grassland ecosystem positively influenced local identity in Tierra del Fuego because of the historical and cultural importance of ranching.

Cultural ESs (Figure 3) were primarily influenced by accessibility and landscape characteristics (Martínez Pastur et al., 2016a). High values were associated with features possessing significant aesthetic, recreational or ecotourism appeal, such as mountains or lakes. Hotspots were observed in areas where natural marvels are present, including penguin colonies, National Parks and Natural Reserves, whereas cold spots were most prevalent in regions lacking road access. Homogeneous flat landscapes, such as the steppe grasslands, also registered low scores for cultural ES, possibly in part due to limited accessibility and absence of roads. This pattern may be attributed to the limited ability of people to reach these natural ecosystems, underscoring the importance of both demand and supply factors (Yahdjian et al., 2015). Finally, homogeneous flat landscapes, like the steppe, are extensive across the studied region, and these landscapes may harbor a great variety of vegetation types.

### *Regulating and supporting ecosystem services*

The importance of the various vegetation types in regulating and supporting ES is shown in Table 3. For example, wetlands had the highest SOC, NPP and habitat quality values (Table 3). This is consistent with Ma et al. (2023) who also report that SOC supports the capacity of the land to sustain plant productivity. The strong and direct relationship between rainfall and SOC may be related to the NPP and mean soil water content (Peri et al., 2018). The high habitat quality of wetlands is consistent with Rosas et al. (2002a) who reported that plant and bird species had the highest potential biodiversity values, mostly related to humid steppes and shrublands associated with higher NDVI values.

According to Rosas et al. (2022b) regulating ES (e.g. NPP) was highest in the south, with a tendency to increase across a gradient of rainfall from east to west (Figure 4). The northwest corner of the province was also a hotspot for regulating services, and here, mixed shrubland was the main vegetation type (Figure 4). Also, according to Rosas et al. (2022b), NPP values were greater in valleys and decreased with altitude, with the lowest values recorded in alpine grasslands. The map of SOC showed a continuous decline from the northeast and central areas of Santa Cruz province, dominated by shrublands (Peri et al., 2018), to the south and southwest, where rangelands dominate (Figure 4). There were, however, subtle variations due to the fact that dwarf-shrubland and wetlands, both

**Table 2.** ANOVAs for aesthetic, existence, local identity and recreation ES comparing vegetation types in Santa Cruz province (Argentina)

| Vegetation type | df | Aesthetic | Existence | Identity | Recreation |
|---|---|---|---|---|---|
| Wetlands | 46 | 15.4bc | 20.8bc | 9.9b | 46.1c |
| Murtillar dwarf-shrubland | 25 | 8.9a | 25.5c | 4.0ab | 32.4ab |
| Mata Negra Matorral thicket | 2881 | 11.9b | 13.2a | 7.1b | 38.6c |
| Mixed shrubland | 759 | 11.8b | 16.7bc | 1.8a | 36.1b |
| Steppe grassland | 15,572 | 12.3b | 15.3b | 6.8b | 28.3a |
| $F(p)$ | | 2.27(0.059) | 16.63(<0.001) | 50.78(<0.001) | 180.17(<0.001) |

*Note: Numbers varied between 0 (minimum provision) and 100 (maximum provision).*
$F$ = Fisher's test, ($p$) = probability, df = degrees of freedom. Different letters in columns show differences among vegetation types according to Tukey's test at $p < 0.05$.


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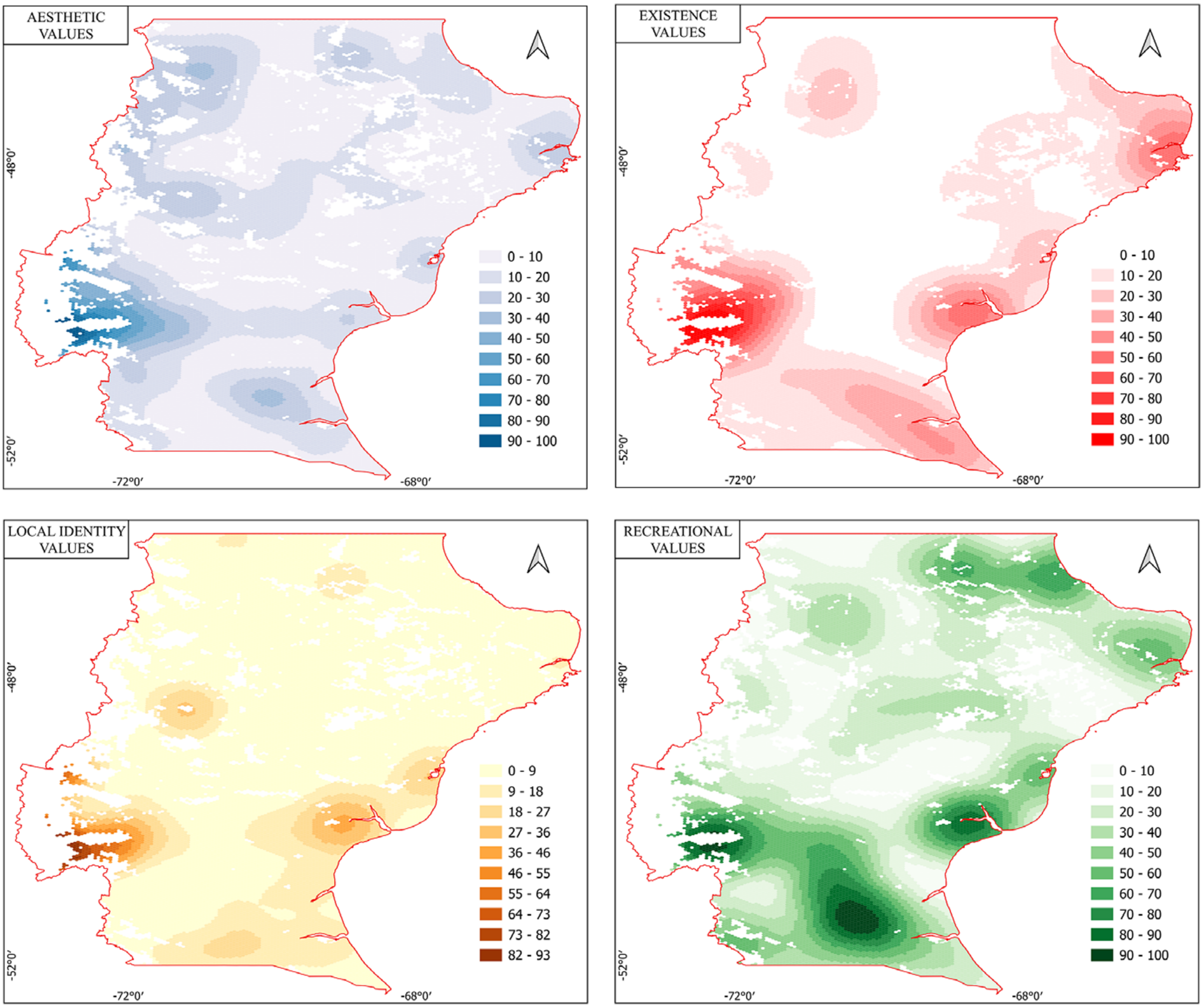


**Figure 3.** Cultural ecosystem services (aesthetic, existence, local identity and recreational values) modeled for grasslands and shrublands in Santa Cruz province (Argentina) based on Martínez Pastur et al. (2016a). Numbers varied between 0 (minimum provision) and 100 (maximum provision).

**Table 3.** ANOVAs for regulating (NPP: net primary productivity, and SOC: soil carbon stock), supporting (Habitat) and provisioning (Livestock) values of steppe grasslands and shrublands in Santa Cruz province (Argentina)

| Vegetation type | df | NPP | SOC | Habitat | Livestock |
|---|---|---|---|---|---|
| Wetlands | 46 | 37.6c | 64.4d | 73.7bc | 51.8bc |
| Murtillar dwarf-shrubland | 25 | 33.8c | 63.8d | 64.7ab | 34.3a |
| Mata Negra Matorral thicket | 2881 | 13.4a | 35.6c | 68.9b | 62.4c |
| Mixed shrubland | 759 | 22.5b | 29.9a | 61.3a | 67.4d |
| Steppe grassland | 15,572 | 13.7a | 32.1b | 75.0c | 44.8b |
| *F*(*p*) | | 684.07(<0.001) | 341.86(<0.001) | 177.57(<0.001) | 422.95(<0.001) |

*Note: Numbers varied between 0 (minimum provision) and 100 (maximum provision).*
*F* = Fisher's test, (*p*) = probability, df = degrees of freedom. Different letters in columns show differences among vegetation types according to Tukey's test at $p < 0.05$.

vegetation types with low vegetation cover, presented higher SOC values, presumably due to more limited decomposition/anoxia (Peri et al., 2024). The supporting services of habitat quality decreased as the human footprint increased, mainly due to roads (Rosas et al., 2021c). Therefore, the highest values for supporting services are found in the center and west of the province (Figure 4). Complex geomorphology (center) and flooding at the base of the Andes on the western margin of the province may explain the lack

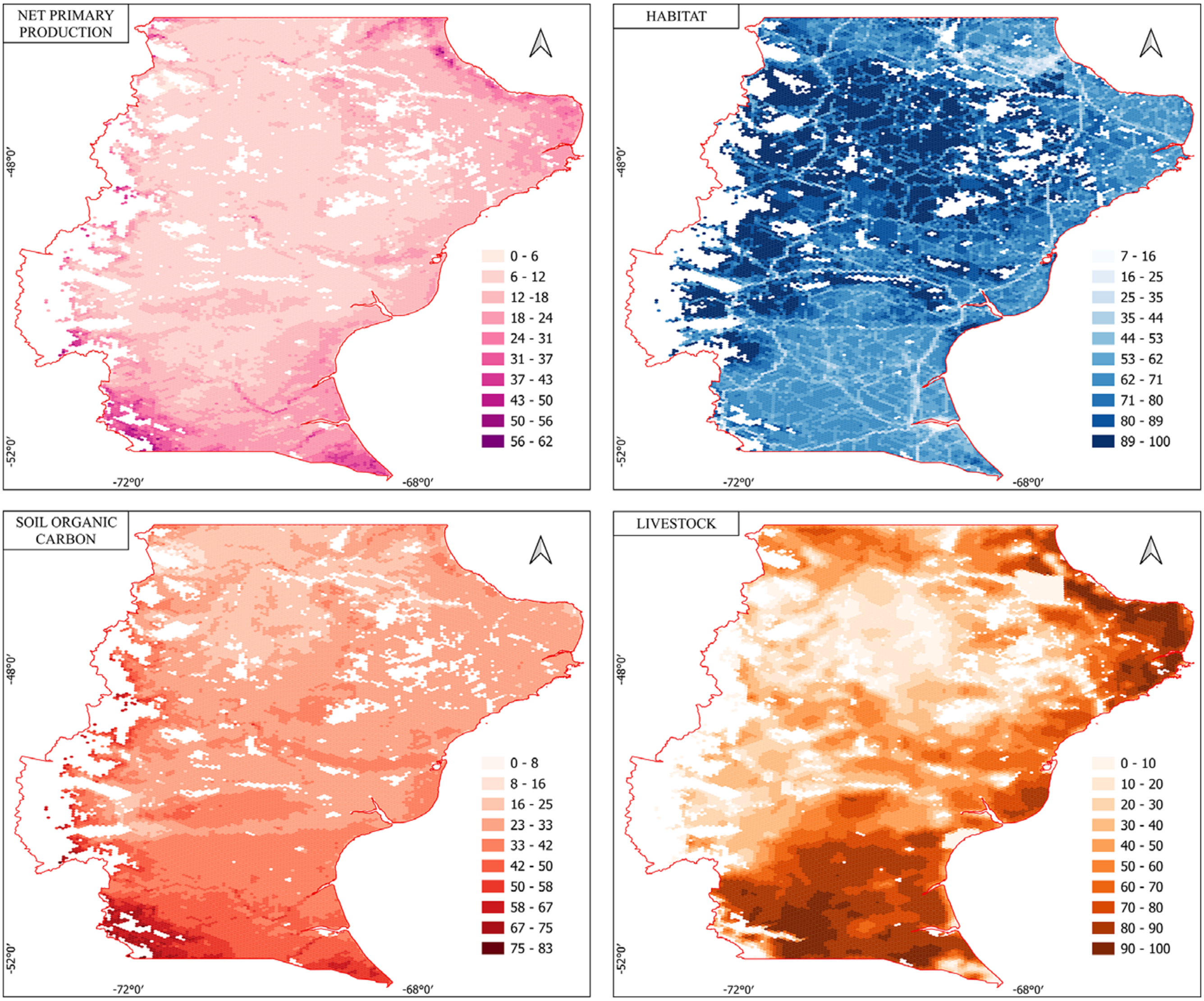


**Figure 4.** Regulating (net primary productivity, soil carbon stock), supporting (habitat) and provisioning (livestock) ecosystem services for grasslands and shrublands in Santa Cruz province (Argentina). Numbers varied between 0 (minimum provision) and 100 (maximum provision).

of transport infrastructure, low values of ranching activity, and the high levels of supporting services in these locations (Rosas et al., 2021c).

## Provisioning ES

Sheep probability (stocking density) fluctuated from 34.3 in Murtillar dwarf-shrubland to 67.4 in the mixed shrubland (Table 3). Variability in sheep production can be attributed to differences in grassland conditions that in turn can be related to NPP variation due to long-term grazing management and climate conditions along vegetation types (Paruelo et al., 2004; Piñeiro et al., 2006). The map of livestock density across Santa Cruz (Figure 4) shows high values in the ecotone between *Nothofagus antarctica* forest, the grasslands in the west and in the south, and in river valleys and wetlands corresponding to the most productive habitats for livestock production (Peri et al., 2021b). The model of livestock occurrence probability was consistent with the regional/spatial analysis of Peri et al. (2021b) in which meat production ranged from 0.25 to 0.69 g lamb $m^{-2}$ $yr^{-1}$ and greasy wool production from 0.10 to 0.19 g $m^{-2}$ $yr^{-1}$. While variation in lamb production was mainly driven by temperature seasonality, NVDI and desertification, the most important variables for explaining variation in greasy wool production were isothermality, temperature seasonality and NVDI (Peri et al., 2021b).

## Biodiversity values

The Mata Negra Matorral thicket showed the highest potential biodiversity compared with other vegetation types (Table 4). Similarly, Peri et al. (2024) reported that the biodiversity was high in shrublands (64.1% in Mata Verde shrublands and 63.7% in mixed shrublands), comparable even to values found in open deciduous forests (*N. antarctica* forest, with 60.4%). Rosas et al. (2022a) determined at the provincial level that mean potential biodiversity showed higher values in shrublands and steppe grasslands in humid areas. The map of potential biodiversity (Figure 5) indicates the lowest values (1–51%) in areas near the mountains and glaciers in


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**Table 4.** ANOVAs for potential biodiversity (BIO), total cultural ecosystem services (CUL-ES), total provisioning (PRO-ES) and total regulating and supporting ecosystem services (R&S-ES) of grasslands and shrublands in Santa Cruz province (Argentina)

| Vegetation type | df | BIO | CUL-ES | PRO-ES | R&S-ES |
|---|---|---|---|---|---|
| Wetlands | 46 | 47.2a | 25.8c | 19.8a | 49.8d |
| Murtillar dwarf-shrubland | 25 | 38.6a | 19.8bc | 28.4ab | 46.2c |
| Mata Negra Matorral thicket | 2881 | 65.9d | 19.8b | 33.1b | 31.8a |
| Mixed shrubland | 759 | 53.3b | 18.6ab | 38.3c | 33.3b |
| Steppe grassland | 15,572 | 57.7c | 17.5a | 24.2a | 33.4b |
| *F*(*p*) | | 255.48(<0.001) | 22.74(<0.001) | 429.93(<0.001) | 223.1(<0.001) |

*Note: Numbers varied between 0 (minimum provision) and 100 (maximum provision).*
*F* = Fisher's test, (*p*) = probability, df = degrees of freedom. Different letters in columns show differences among vegetation types according to Tukey's test at $p < 0.05$.

the western part of the province. According to Rosas et al. (2022a), medium values (52–62%) are observed in the steppe grasslands in the eastern region, while high biodiversity values are primarily concentrated in steppe grasslands located in three distinct geographic locations: the extreme south, the extreme north and the central part of the province. The elevated biodiversity in these three regions may be attributed to landscape heterogeneity, as all three locations exhibit complex geomorphology (e.g. Rosas et al., 2021a, 2021b, 2021c), which may result in a variety of niches and ecotones (Riesch et al., 2018). This geological complexity may also have hindered the construction of roads in these areas, thereby reducing human access and limiting ecological disturbances within these ecosystems. Consequently, this limited accessibility may have contributed to the higher biodiversity values observed in these specific locations.

### *Synthesis*

The estimates of stocks (e.g. SOC, habitat value) and flows (e.g. NPP, sheep occurrence probability) of natural capital presented in Figures 3 and 4 were integrated to generate maps illustrating three broad categories of ES (cultural, supporting/regulating and provisioning services) and biodiversity values (Figure 5). These synthesis maps reflect the underlying stocks and flows of natural capital that produce ESs, while also highlighting areas where trade-offs and synergies among different ES occur. For example, the total regulating-supporting, total provisioning and total cultural ESs varied with vegetation type (Table 4). While total regulating and supporting ESs, and total cultural ESs were highest in wetlands, total provisioning ESs occurred in mixed shrublands (Table 4). The provision of ESs presented medium values in some shrublands (e.g. Mata Verde shrubland and Murtillar dwarf-shrubland, 43.6–45.3%), and wetlands (47.7%); and minimum values in the other shrubland types (Mata Negra Matorral thicket and mixed shrubland) and steppe grasslands (29.7–30.9%) (Peri et al., 2024). The map combining cultural services showed high values associated with the road network and mountainous regions (Rosas et al., 2022b). Although total cultural ESs are relatively evenly distributed across the province, with low to medium values (less than 30%), total regulating and supporting ESs are most prominent in the western and central parts of Santa Cruz (Figure 5). The very high values for provisioning ESs (Figure 5) observed in the north (>70%) due to oil production, medium values (40–50%) in the south and southwest, areas characterized by more humid grasslands linked to livestock production, are consistent with models reported by Rosas et al. (2022b). These results confirmed the hypothesis that the provision of the different ES was not independent of interactions dependent on vegetation types. Also, human activities generate synergies and trade-offs between provisioning ES and biodiversity.

### *Recommendations for management and conservation*

The intensification of land use has demonstrated that optimizing certain ESs, such as provisioning services, is likely to diminish ecological diversity and system stability (Cardinale et al., 2012), as well as overall biodiversity (MEA, 2005). In recent years, scientific and policy agendas on biodiversity have shifted to incorporate ES assessments, recognizing the critical importance of monitoring ESs to evaluate the effectiveness of policy frameworks (Liquete et al., 2016; Schwantes et al., 2024).

The spatial analysis of ESs and biodiversity values presented here further emphasizes that the benefits derived from nature extend far beyond the direct supply of provisioning services such as fuel, food and fiber. Notably, the observed spatial overlaps and mismatches between the supply and demand for different categories of ESs, namely cultural, regulating/supporting and provisioning services, highlight both opportunities and challenges for integrating ES considerations into land use and biodiversity planning. For instance, areas with high biodiversity in the north, center and south of the province also serve as key regions for regulating services, making the development of land management strategies to secure both in these zones relatively straightforward. Conversely, for services like provisioning and cultural services, which are both closely linked to road access, more detailed analyses of value, potential trade-offs and associated costs for conservation or enhancement may be necessary.

## Final remarks and conclusions

The findings of this study provide valuable insights for land use planning in Santa Cruz, integrating considerations of ESs and biodiversity values. With the recent increase in tourism, cultural ESs have gained greater prominence (Martínez Pastur et al., 2016a) and could play a key role in the sustainable exploitation of the region's natural capital. Nonetheless, traditional activities such as livestock production remain vital, especially for the intangible cultural ESs, including local identity and cultural values. A significant challenge lies in reconciling the need to maximize provisioning services, which are closely linked to cultural identity, while preserving the capacity of the steppe grasslands to continue providing regulating and supporting services (Ahtikoski et al., 2011).


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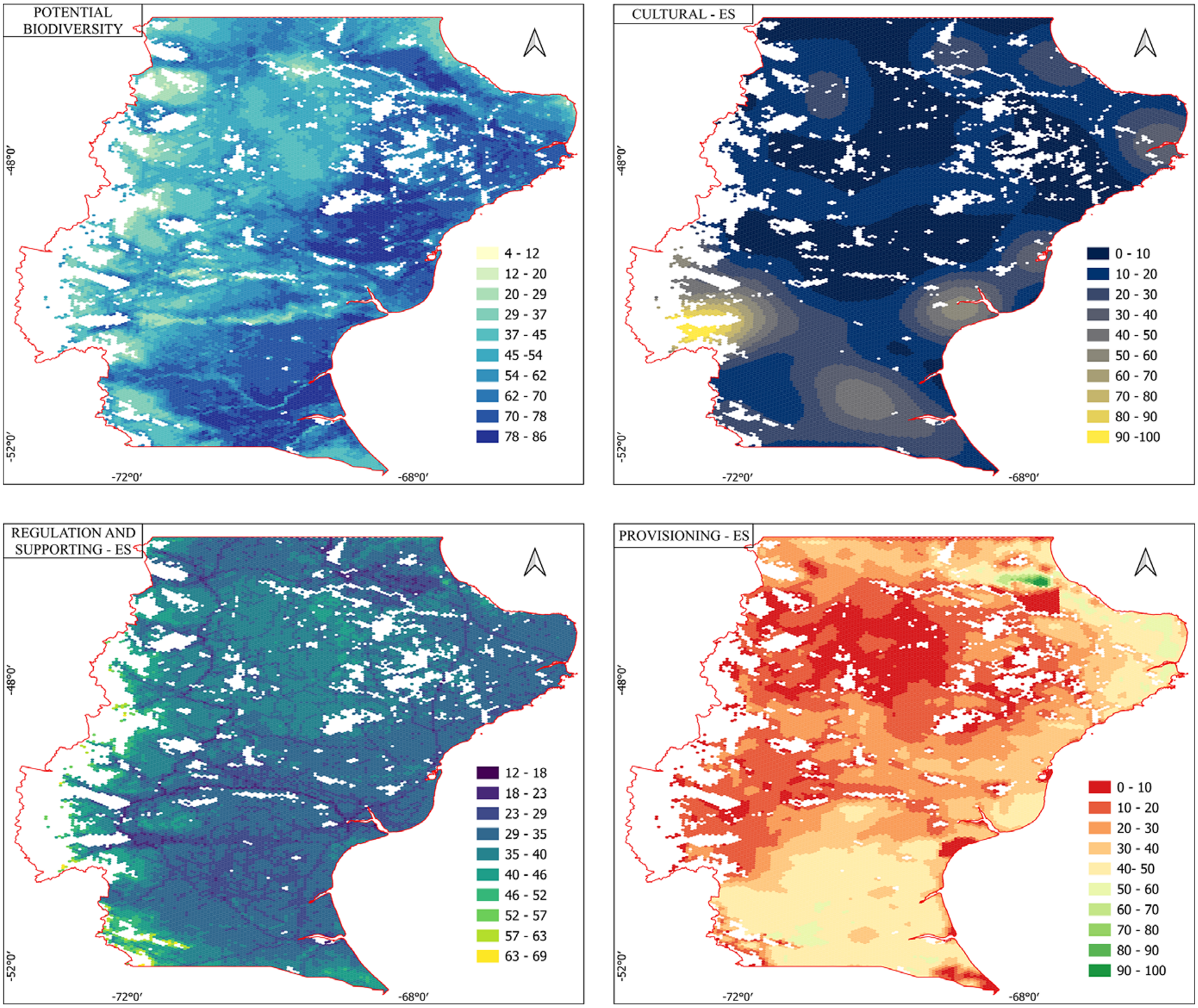


**Figure 5.** Potential biodiversity and combination maps for cultural, regulating/supporting and provisioning ecosystem services for grasslands and shrublands in Santa Cruz province (Argentina). Numbers varied between 0 (minimum provision) and 100 (maximum provision).

Implementing adaptive grazing management, with stocking rates aligned to forage availability and net primary production, may yield more sustainable long-term economic benefits without degrading the steppe grasslands or compromising the natural capital that contributes to human well-being through cultural ESs such as ecotourism and the Patagonian sense of place. In this context, sustainable land management, particularly regarding grazing practices, must incorporate the consideration of other ESs, especially the regulating and supporting services, into management plans. One strategy is to maintain high levels of biodiversity within managed ecosystems, which might positively influence provisioning ESs (Duru et al., 2015; Duarte-Guardia et al. 2024). Preserving heterogeneity at the landscape scale might also enhance ecosystem resilience and stability in response to global environmental change drivers (e.g. Geijzendorffer and Roche, 2013).

A thorough understanding of the processes underlying ES supply, as well as the trade-offs with biodiversity conservation, is a valuable tool to support spatial planning and land management decisions (Carvalho Santos et al., 2015).

Enhanced decision-making in land management necessitates empirical data on the effects of landscape-scale conservation approaches on trade-offs between biodiversity and ESs(Cordingley et al., 2016). Our findings underscore opportunities to integrate biodiversity conservation with the preservation of ESs. The trade-offs identified in this analysis represent areas where further research could deepen understanding and potentially contribute to the development of more effective management strategies.

**Open peer review.** For open peer review materials, please visit http://doi.org/10.1017/dry.2026.10038.

**Data availability statement.** Data are available from the institutional repository at https://repositorio.inta.gob.ar/

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## References

**Abildtrup J, Garcia S, Olsen SB and Stenger A** (2013) Spatial preference heterogeneity in forest recreation. *Ecological Economics* **92**, 67–77. https://doi.org/10.1016/j.ecolecon.2013.01.001.

**Ahtikoski A, Tuulentie S, Hallikainen V, Nivala V, Vatanen E, Tyrväinen L and Salminen H** (2011) Potential trade-offs between nature-based tourism and forestry: A case study in northern Finland. *Forests* **2**(4), 894–912. https://doi.org/10.3390/f2040894.

**Battersby SE, Strebe DD and Finn MP** (2017) Shapes on a plane: Evaluating the impact of projection distortion on spatial binning. *Cartography and Geographic Information Science* **44**(5), 410–421. https://doi.org/10.1080/15230406.2016.1180263.

**Briney, A**, 2014. Binning in GIS. GISLounge. http://www.gislounge.com/binninggis/.

**Cardinale BJ, Duffy JE, Gonzalez A, Hooper DU, Perrings C, Venail P, Narwani A, Mace GM, Tilman D, Wardle DA, Kinzig AP, Daily GC, Loreau M, Grace JB, Larigauderie A, Srivastava DS and Naeem S** (2012) Biodiversity loss and its impact on humanity. *Nature* **486**(7401), 59–67. https://doi.org/10.1038/nature11148.

**Carvalho-Santos C, Sousa-Silva R, Goncalves J and Honrado JP** (2016) Ecosystem services and biodiversity conservation under forestation scenarios: Options to improve management in the Vez watershed, NW Portugal. *Regional Environmental Change* **16**(6), 1557–1570. https://doi.org/10.1007/s10113-015-0892-0.

**Cordingley JE, Newton AC, Rose R, Clarke R and Bullock J** (2016) Can landscape-scale approaches to conservation management resolve biodiversity-ecosystem service trade-offs? *Journal of Applied Ecology* **53**(1), 96–105. https://doi.org/10.1111/1365-2664.12545.

**Daily GC** (1997) *Nature's Services*. Washington DC, USA: Island Press.

**Duarte-Guardia S, Peri PL, Martinez-Pastur G, Lasagno R, Lencinas MV, Thomas E and Ladd B** (2024) Value of biodiversity on Patagonian rangeland: Estimation via a hedonic Price index. *Rangeland Ecology and Management* **92**, 122–128. https://doi.org/10.1016/j.rama.2023.10.005.

**Duru M, Therond O, Martin G, Martin-Clouaire R, Magne MA, Justes E, Journet EP, Aubertot JN, Savary S, Bergez J and Sarthou JP** (2015) How to implement biodiversity based agriculture to enhance ecosystem services: A review. *Agronomy for Sustainable Development* **35**(4), 1259–1281. https://doi.org/10.1007/s13593-015-0306-1.

**Eldridge DJ, Wang C, Liu Y, Ding J, Li Y, Wu X and Li C** (2024) Nature's contribution to people in drylands. *Cambridge Prisms: Drylands* **1**, e2. https://doi.org/10.1017/dry.2024.2.

**ESRI** (2011) *ArcGIS Desktop: Release 10*. Redlands, USA: Environmental Systems Research Institute Inc.

**Farr TG, Rosen PA, Caro E, Crippen R, Duren R, Hensley S, Kobrick M, Paller M, Rodriguez E, Roth L, Seal D, Shaffer S, Shimada J, Umland J, Werner M, Oskin M, Burbank D and Alsdorf D** (2007) The shuttle radar topography mission. *Reviews of Geophysics* **45**(2), RG2004. https://doi.org/10.1029/2005RG000183.

**García-Llorente M, Martín-López B, Iniesta-Arandia I, López-Santiago CA, Aguilera PA and Montes C** (2012) The role of multi-functionality in social preferences toward semi-arid rural landscapes: An ecosystem service approach. *Environmental Science & Policy* **19-20**, 136–146, https://doi.org/10.1016/j.envsci.2012.01.006

**Geijzendorffer IR and Roche P** (2013) Can biodiversity monitoring schemes provide indicators for ecosystem services? *Ecological Indicators* **33**, 148–157. https://doi.org/10.1016/j.ecolind.2013.03.010.

**Hernández-Blanco M, Costanza R and Moritsch M** (2025) Payment for ecosystem services 2.0: The Natural Capital Trust of Costa Rica. *Ecosystem Services* **76**, 101787. https://doi.org/10.1016/j.ecoser.2025.101787.

**Hijmans RJ, Cameron SE, Parra JL, Jones PG and Jarvis A** (2005) Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology* **25**(15), 1965–1978. https://doi.org/10.1002/joc.1276.

**Hirzel AH, Hausser J, Chessel D and Perrin N** (2002) Ecological-niche factor analysis: How to compute habitat- suitability maps without absence data? *Ecology* **83**(7), 2027–2036. https://doi.org/10.1890/0012-9658(2002)083[2027:ENFAHT]2.0.CO;2.

**Hirzel AH and Le Lay G** (2008) Habitat suitability modelling and niche theory. *Journal of Applied Ecology* **45**(5), 1372–1381. https://doi.org/10.1111/j.1365-2664.2008.01524.x.

**Lencinas MV, Soler R, Cellini JM, Bahamonde H, Pérez Flores M, Monelos L, Martínez Pastur GJ and Peri PL** (2021) Variation in alpine plant diversity and soil temperatures in two mountain landscapes of South Patagonia. *Diversity* **13**(7), 310. https://doi.org/10.3390/d13070310.

**Liquete C, Cid N, Lanzanova D, Grizzetti B and Reynaud A** (2016) Perspectives on the link between ecosystem services and biodiversity: The assessment of the nursery function. *Ecological Indicators* **63**, 249–257. https://doi.org/10.1016/j.ecolind.2015.11.058.

**López-Santiago CA, Oteros Rozas E, Martín-López B, Plieninger T, González E and González JA** (2014) Using visual stimuli to explore the social perceptions of ecosystem services in cultural landscapes: The case of transhumance in Mediterranean Spain. *Ecology and Society* **19**(2), 27. https://doi.org/10.5751/ES-06401-190227.

**Ma Y, Woolf D, Fan M, Qiao L, Li R and Lehmann J** (2023) Global crop production increase by soil organic carbon. *Nature Geoscience* **16**(12), 1159–1165. https://doi.org/10.1038/s41561-023-01302-3.

**Martínez Pastur G, Peri PL, Huertas Herrera A, Schindler S, Díaz Delgado R, Lencinas MV and Soler R** (2017) Linking potential biodiversity and three ecosystem services in silvopastoral managed forest landscapes of Tierra del Fuego, Argentina. *Int J Biodiv Sci Ecosyst Ser Manage* **13**(2), 1–11. https://doi.org/10.1080/21513732.2016.1260056.

**Martínez Pastur G, Peri PL, Lencinas MV, García Llorente M and Martín López B** (2016a) Spatial patterns of cultural ecosystem services provision in Southern Patagonia. *Landscape Ecology* **31**(2), 383–399. https://doi.org/10.1007/s10980-015-0254-9.

**Millennium Ecosystem Assessment (MEA)** (2005) *Ecosystems and Human Wellbeing: Current State and Trends*. Washington DC: Island Press.

**Oñatibia GR** (2021) Grazing management and provision of ecosystem Services in Patagonian Arid Rangelands. In Peri PL, Nahuelhual L and Martínez Pastur G (eds), *Grazing Management and Provision of Ecosystem Services in Patagonian Arid Rangelands. In: Ecosystem Services in Patagonia: A Multi-Criteria Approach for an Integrated Assessment*. Cham: Springer, pp. 47–74. https://doi.org/10.1007/978-3-030-69166-0_3.

**Paruelo JM, Golluscio RA, Guerschman JP, Cesa A, Jouve VV and Garbulsky MF** (2004) Regional scale relationships between ecosystem structure and functioning: The case of the Patagonian steppes: *The case of the Patagonian steppes. Global Ecology and Biogeography* **13**(5), 385–395. https://doi.org/10.1111/j.1466-822X.2004.00118.x.

**Pedrana J, Bustamante J, Rodríguez A and Travaini A** (2011) Primary productivity and anthropogenic disturbance as determinants of upland goose *Chloephaga picta* distribution in southern Patagonia. *Ibis* **153**(3), 517–530. https://doi.org/10.1111/j.1474-919X.2011.01127.x.

**Peri PL, Gaitán J, Díaz B, Almonacid L, Morales C, Ferrer F, Lasagno R, Rodríguez-Souilla J and Martínez Pastur G** (2024) Vegetation type mapping in southern Patagonia and its relationship with ecosystem services, soil carbon stock, and biodiversity. *Sustainability* **16**(5), e2025. https://doi.org/10.3390/su16052025.

**Peri PL, Lencinas MV, Bousson J, Lasagno R, Soler R, Bahamonde H and Martínez Pastur G** (2016) Biodiversity and ecological long-term plots in Southern Patagonia to support sustainable land management: The case of PEBANPA network. *Journal for Nature Conservation* **34**, 51–64. https://doi.org/10.1016/j.jnc.2016.09.003.

**Peri PL, Lencinas MV, Martinez Pastur G, Wardell-Johnson GW and Lasagno R** (2013) Diversity patterns in the steppe of Argentinean Southern Patagonia: Environmental drivers and impact of grazing. In Morales Prieto MB and Traba Díaz J (eds), *Steppe Ecosystems: Biological Diversity, Management and Restoration*. New York, USA: NOVA Science Publishers, Inc, pp. 73–95.

**Peri PL**, **Rosas YM**, **Ladd B**, **Toledo S**, **Lasagno RG and Martínez Pastur G** (2018) Modelling soil carbon content in South Patagonia and evaluating changes according to climate, vegetation, desertification and grazing. *Sustainability* **10**(2), e438. https://doi.org/10.3390/su10020438.

**Peri PL**, **Martínez Pastur G and Nahuelhual L** (2021a) *Ecosystem Services in Patagonia: A Multi-Criteria Approach for an Integrated Assessment*. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-69166-0.

**Peri PL**, **Rosas YM**, **Rivera E and Martínez Pastur G** (2021b) Lamb and wool provisioning ecosystem services in southern Patagonia. *Sustainability* **13**(15), e8544. https://doi.org/10.3390/su13158544.

**Peri PL**, **Rosas YM**, **Rivera E and Martínez Pastur G** (2022) Human appropriation of net primary production related to livestock provisioning ecosystem services in southern Patagonia. *Sustainability* **14**(13), 7617. https://doi.org/10.3390/su14137617.

**Piñeiro G**, **Oesterheld M and Paruelo JM** (2006) Seasonal variation in aboveground production and radiation-use efficiency of temperate rangelands estimated through remote sensing. *Ecosystems* **9**(3), 357–373. https://doi.org/10.1007/s10021-005-0013-x.

**Riesch R**, **Plath M and Bierbach D** (2018) Ecology and evolution along environmental gradients. *Current Zoology* **64**(2), 193–196. https://doi.org/10.1093/cz/zoy015.

**Rosas YM, Peri PL and Martínez Pastur G** (2021a) Assessment of provisioning ecosystem services in terrestrial ecosystems of Santa Cruz Province, Argentina. In Peri PL; Martínez Pastur G; Nahuelhual L, *Ecosystem Services in Patagonia: A Multi-Criteria Approach for an Integrated Assessment*. Cham: Springer International Publishing, 19–46. https://doi.org/10.1007/978-3-030-69166-0_2.

**Rosas YM**, **Peri PL**, **Lencina MV**, **Lasagno R and Martínez Pastur G** (2021b) Improving the knowledge of plant potential biodiversity-ecosystem services links using maps at the regional level in southern Patagonia. *Ecological Processes* **10**(1), e53. https://doi.org/10.1186/s13717-021-00326-0.

**Rosas YM**, **Peri PL**, **Pidgeon AM**, **Martinuzzi S**, **Politi N**, **Pedrana J**, **Díaz Delgado R and Martínez Pastur G** (2021c) Human footprint defining conservation strategies in Patagonian landscapes: Where we are and where we want to go? *Journal for Nature Conservation* **59**, 125946. https://doi.org/10.1016/j.jnc.2020.125946.

**Rosas YM**, **Peri PL**, **Lencina MV**, **Lizarraga L and Martínez Pastur G** (2022a) Multi-taxon biodiversity assessment of southern Patagonia: Supporting conservation strategies at different landscapes. *Journal of Environmental Management* **307**, 114578. https://doi.org/10.1016/j.jenvman.2022.114578.

**Rosas YM**, **Martínez Pastur G and Peri PL** (2022b) *Servicios ecosistémicos Y Biodiversidad de los Recursos Naturales de Santa Cruz*. Buenos Aires, Argentina: Editorial INTA, p. 120.

**Schwantes AM**, **Firkowski CR**, **Affinito F**, **Rodriguez PS**, **Fortin M-J and Gonzalez A** (2024) Monitoring ecosystem services with essential ecosystem service variables. *Frontiers in Ecology and the Environment* **22**(8), e2792. https://doi.org/10.1002/fee.2792.

**Trier Bjerring A**, **Peri PL**, **Christiansen R**, **Vargas-Bello-Pérez E and Hansen HH** (2025) Rangeland grazing management in Argentine Patagonia. *International Journal of Agriculture and Biology* **24**(5), 1041–1052. https://doi.org/10.17957/IJAB/15.1531.

**Yahdjian L**, **Sala OE and Havstad KM** (2015) Rangeland ecosystem services: Shifting focus from supply to reconciling supply and demand. *Frontiers in Ecology and the Environment* **13**(1), 44–51. https://doi.org/10.1890/140156.

**Zhao M and Running SW** (2010) Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. *Science* **329**(5994), 940–943. https://doi.org/10.1126/science.1192666.