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Biodiversity and Ecological Long-Term Plots in Southern Patagonia to support sustainable land management: the case of PEBANPA Network

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Abstract

Historically, interactions and trends between biodiversity, ecosystem function (EF) and land use practices in southern Patagonia (Argentina) have been largely undocumented and poorly understood. Since 2002, 1,214 permanent and semi-permanent plots within the PEBANPA Network have enabled researchers to monitor and assess functions and trends among vegetation parameters, biodiversity, forest dynamics, soil physicochemical characteristics, and land use management. The objectives of this manuscript are to communicate the role and rationale of the PEBANPA Network, summarize examples of the main results found within the network and provide guidance to decision makers with respect to advancing sustainable land management in southern Patagonia. As examples, rangeland health indices, seedling and sapling regeneration under different timber managed forests, litterfall and seeds production under silvopastoral use, and soil carbon content impacted by livestock grazing have all been assessed. Vegetation and environmental variables including soil respiration, soil water infiltration, soil water retention capacity, soil erosion, and litter cover were measured under different grazing intensities. Livestock and forestry production have caused changes in the original floristic patterns, with several areas experiencing desertification. Heavy stocking rates have caused the greatest impacts on grassland soil carbon (C) loss as a consequence of soil erosion. We were able to conclude that low - medium grazing intensities yield the most positive impacts for biodiversity and soil physicochemical characteristics. Studies regarding levels of seedling and sapling regeneration post-harvest of timber further supported the importance of long-term monitoring due to the strongest evidence of interactions occurring 20 to 30 years after harvest. Distribution patterns of vascular plants and epigaeic coleopterons diversity revealed statistically significant differences among geographical zones and dominant vegetation types. The PEBANPA Network helps southern Patagonia address the challenges of unsustainable land management and climate change through monitoring ecosystem function and services. Long-term monitoring of biodiversity and ecosystem function help decision makers better understand the impacts of land use practices, develop well-informed policies and secure present and future human well-being.

Keywords: Biodiversity; Carbon sequestration; Ecosystem services; Land use practices; Livestock grazing; Long-term monitoring

1. Introduction

Southern Patagonia (Argentina) is home to one of the few remaining well-conserved wilderness areas on the planet and where Nothofagus forests represent the southernmost forested ecosystem in the world. Internationally renowned for its mountain landscapes, glaciers, arid plateaus, and diverse wildlife, some ecosystem modification and degradation has occurred in Patagonia due to human-induced influences such as forest harvesting, livestock production and the introduction of invasive, exotic species. The inaccurate assessment of the region's carrying capacity in relation to unsustainable land use practices has contributed to the alteration and modification of the region's original ecosystem structure. Silvopastoral systems, which incorporate grasslands or pastures and trees for livestock grazing in the same land area has become an ecological, economic and social land use practice alternative for the region (Peri et al. 2016b). However, the majority of ranchers have been slow to adopt silvopastoral systems possibly due to lack of convincing evidence of positive economic returns or benefits from ecosystem services (ES) (Peri et al. 2016b). The functions and interactions between ecosystem services and land management practices have been poorly understood within the region due to the lack of long term monitoring and research (Lindenmayer et al. 2012).

Provisioning and cultural ES within the region have historically provided economic benefits for local populations. Since the late 1880 s, the production of ecosystem goods and services including timber extraction, livestock grazing (cattle and sheep), mining, and tourism have all further contributed to the region's economy. The region's forests have produced food, timber, fuel wood, and industrial products while livestock production has yielded meat, wool, leather, and dairy products. As a result of these production activities surpassing the ecosystem's natural carrying capacity, particularly during the period after European colonization, land degradation and biodiversity loss have recently occurred in Patagonia.

Throughout human history, societies have directly and indirectly benefited from ES; not only from provisioning and cultural, but also from regulating and supporting components. However, modern Western society has often taken ES for granted (Daily 1997; MEA 2005) without considering the synergies and trade-offs between conservation and economic development as natural landscapes experience further degradation (Vitousek et al. 1997; Levin & Lubchenco 2008; Seppelt et al. 2011). Historically, economic markets have largely focused on the provisioning services (forest products, livestock, etc.) of ecosystems while neglecting the interdependent roles and regressing conditions of regulating services (erosion and climate control), supporting services (nutrient cycling), and cultural services (recreation, local identity, tourism) (MEA 2005). Since regulating, supporting and cultural services are often not considered during the development of land management practices (Kinzig et al. 2011), biodiversity and habitat health have either declined or are at-risk of degradation (Myers 1996; Daily et al. 1997; Nahuelhual et al. 2007). Biodiversity loss threatens the health of each ES category, therefore placing present and future human well-being at-risk (Díaz et al. 2006; Meli et al. 2014; Felipe-Lucia & Comín 2015).

Long-term monitoring of all ES categories is required in order to better understand the functions and uses of each ES category (Boyd & Banzhaf 2007; Fisher et al. 2009). Developing and implementing sustainable land management strategies that consider future human well-being requires the analysis of synergies and trade-offs between biodiversity and ES provision (Tallis et al. 2008). Analyzing thresholds and trends for each ES category assists in identifying the optimal allocation of different land management practices at the landscape scale in Patagonia (De Groot et al. 2010). The intended analysis and consideration of trade-off decisions between ES and biodiversity can support effective conservation policies (McShane et al. 2011; Cordingley et al. 2016) and advance multifunctional landscapes such as agro-forestry-environmental practices. Furthermore, scientific monitoring can help stakeholders understand the trade-offs and spatial flows of different services, sustainable use of ES and the economic feedbacks within ES markets (Tallis et al. 2008). Consideration of natural capital and ecosystem health extends well beyond conservation issues and is equally important for decisions related to agriculture, energy, water security, health, and national security (Guerry et al. 2015).

According to climate models, mean maximum annual temperature is predicted to increase by 2 to 3°C by 2080 in the latitudinal range of 46º and 52º S (Kreps et al. 2012), therefore presenting additional challenges for the future. The projected changes in climatic variables will most likely have profound effects on ES, biodiversity and land use capacity throughout the globe, including Patagonia. Unsustainable land management and global climate change present long-term threats and risks to human well-being and local ecosystems, therefore necessitating changes in land-use management practices and policies (IPCC 2007).

The two traditional provisioning ES in Patagonia involve livestock grazing and wood harvesting (Peri et al. 2016a) supported by grasses, forbs, shrubs and trees found within the habitats and lands of Patagonia.

Since the relationship between ES and biodiversity is poorly understood and documented (Martínez Pastur et al. 2016a) in Patagonia due to lack of successful research, the establishment of long term monitoring and studies are required. Hundreds of forest research programs with permanent forest plots had been initiated in the 1950 s and 1960 s as a response to forest mismanagement in Argentina. The main objectives of past long term monitoring programs was to transition old-growth forests into normal-stage managed forests. The result of these initial long-term studies was a failure due to a combination of factors: (i) absence of land management planning by national and provincial governments; (ii) insufficient contribution and collaboration from the private sector; (iii) lack of societal interest in environmental conservation and long-term forest research; (iv) unwillingness of scientific and forest research institutions to finance long-term forest studies; and, (v) fragmented and fractured implementation and responsibility between several different scientific researchers. It is important to learn from these past mistakes in order to implement a successful and effective long-term ecological research program.

In 2002, the PEBANPA (Parcelas de Ecología y Biodiversidad de Ambientes Naturales en Patagonia Austral) Network was established to monitor these ecosystems and to produce scientific research focused on ecosystem function and ES (e.g. soil carbon stocks, nutrients, forestry), as well as on trends in biodiversity and the interactions between natural environments and land-use activities throughout southern Patagonia, Argentina. Long-term monitoring assesses bio-indicators, which therefore reveal the current state of the environment, particular stresses in ecosystems and early warnings of environmental changes ahead.

The present network of long-term ecological monitoring plots alone cannot achieve sustainable land management practices without sustained financial commitment and cooperation from research, administrative and forest entities to maintain these research platforms. If developed, supported and implemented correctly, these long term plots in Patagonia will foster a better understanding and provide effective decision making tools necessary for advancing sustainable land management objectives and addressing regional socio-economic-ecological challenges.

The objectives of this manuscript are to: (i) communicate the rationale of the PEBANPA Network; (ii) provide a brief description of the main results and methodologies applied regarding the recent trends of biodiversity, forest dynamics, soil carbon content, and land-use practices documented within the region; and,

(iii) include guidance for decision makers and stakeholders with respect to advancing sustainable land-use practices across Patagonia.

2. Materials and methods

2.1 PEBANPA Network: role and characterization

The PEBANPA Network was developed in Argentina by the National University of Southern Patagonia (UNPA), the National Agricultural Technology Institute (INTA) and the Southern Center for Scientific Research (CADIC), which is part of the National Scientific and Technical Research Council (CONICET). The PEBANPA Network contributes to the vegetation plot database (VegBank) of the Ecological Society of America's Panel on Vegetation Classification (http://vegbank.org), the collaborative project PREDICTS (Projecting Responses of Ecological Diversity In Changing Terrestrial Systems) (http://www.predicts.org.uk) and the international program GLORIA (Global Observation Research Initiative in Alpine Environments) (http://www.gloria.ac.at).

1,214 geo-referenced, permanent and semi-permanent plots in PEBANPA encompass native forests, grasslands, shrublands, and wetlands across environmental gradients in the provinces of Santa Cruz and Tierra del Fuego, Argentina. These plots make it possible for scientists to monitor and analyze (but not limited to) plant and insect biodiversity, invasive exotic species, forest structure and regeneration, and physicochemical soil characteristics within the region. Major climatic parameters (precipitation, temperature, wind intensity, radiation and humidity) and physiological responses of plants (photosynthesis, nutrients allocation, radiation and water use efficiencies, etc.) are additionally measured within the PEBANPA Network.

The mission of the PEBANPA Network is to share knowledge and provide a greater understanding of the functions of ecosystems under different conditions of use and therefore help foster a stronger socio-ecological balance for the region. The information gathered from the plots serves as a critical tool for improving our understanding of the ecological functions and environmental conditions of the region's ecosystems and the impact caused by land management practices and other anthropogenic drivers. The main purpose of this monitoring network is to analyze the relationship between ES and land management practices, and therefore utilize this research as a tool for advancing sustainable land management practices and policies throughout the region.

As shown in Figure 1, many relationships and feedbacks exist between natural drivers, human-induced drivers, societal needs, and ES. Feedbacks and gradients between systems, drivers and regions highlight the wide scope of research and analysis provided by the PEBANPA Network. The provisional, cultural, supporting and regulatory components within ecosystems reflect the wide variety of services and value provided to society. In order to achieve socio-ecological balance, appropriate scientific monitoring and inclusive participation between various levels of governmental, private, academic, scientific, and non-governmental institutions are required.

FIGURE 1

The plots spread throughout the PEBANPA Network reflect the full longitudinal and latitudinal gradients of ecosystems, temperature, rainfall and land-use intensities in Santa Cruz and Tierra del Fuego Provinces (Fig. 2). Of the 589 total plots currently existing in Santa Cruz Province, 234 plots are permanent, ranging from 46º00’ to 52º30’ S and covering an area of 243,943 km2. The 234 permanent plots are represented as follows: 84 plots in ñire (N. antarctica) forests; 58 in the Central Plateau; 10 in Andean vegetation and humid Magellanic grass steppe; 56 in mata negra thicket, shrub steppe Golfo San Jorge, and mountains and plateaus; and, 26 in dry Magellanic grass steppe and sub-Andean grassland. In addition, 355 other semi-permanent plots of biodiversity and forest structure in native forests belonging to the provincial ñire inventory were installed.

FIGURE 2

In Tierra del Fuego Province, 625 established plots currently extend between 52°00’ and 56°00’ SL. Biodiversity plots were distributed in different ecosystems: 23 plots in shrublands; 305 in lenga (Nothofagus pumilio); 84 in ñire and 56 in guindo forests (N. betuloides); 19 in mixed lenga-guindo forests; 109 in grasslands; and, 29 in peat-bogs. Some plots are tracked annually for more than ten years, covering gradients in temperature and rainfall intensity as well as the management and impacts of rangeland grazing and forest-use.

The Andes Mountains, the steppe and valleys characterize the three main ecosystems throughout Santa Cruz and Tierra del Fuego Provinces. 85% of Santa Cruz Province is composed of Patagonian steppe (shrublands and grasslands) and possesses a narrow, 100 km wide per 1000 km long section of native forest (Peri et al. 2013a). Tussock, short grasses and shrubs cover 25% of the Tierra del Fuego Province. Since the Andes mountains decrease in height and curve to the west, rainfall decreases from the north to the south. In locations where annual rainfall increases from 400 mm to 800 mm-1, forests occupy the area, covering an area of 733,907 ha in Tierra del Fuego Province (Peri et al. 2013a). The Nothofagus (southern beeches) forests of lenga, ñire and guindo are the dominant species in the southern most forests in the world, covering a total of 1,269,796 ha across both provinces (535,889 ha in Santa Cruz and 733,907 ha in Tierra del Fuego) (Peri et al. 2013a). A significant climate gradient exists in southern Patagonia. Since the Andes Mountains act as an orographic barrier, annual rainfall ranges from 800-1000 mm/year in the Andes Mountains and decreases to 200 mm/year in the eastern part of Santa Cruz Province, producing one of the most outstanding vegetation gradients on the planet (Peri et al. 2013a). The variations in local topographic and edaphic characteristics combined with a significant precipitation gradient substantially influence the distribution patterns of vegetation throughout the region. This cold temperate region possesses mean annual temperatures between 5.5 and 8.0º C and mean annual precipitation levels between 200 and 1,000 mm/year (Peri et al. 2013a). Temperatures are highest during the short Patagonian summers between the months of December and February. The summer days are long due to the region’s location at high latitudes. The windiest season within the region occurs between November and March, producing frequent and severe south-southwesterly wind storms reaching over 120 km/h (Peri & Bloomberg 2002).

2.2 Measurements in PEBANPA Network

Long-term monitoring of sites help support the goal of the PEBANPA Network to: (i) collect and obtain accurate, objective information that has the capacity to reflect changes in critical variables; and, (ii) monitor the progress of environmental and biological variables after alternative land management changes have been implemented.

(a) Plant diversity and biomass: At each sampling location, variables have been measured in a 20 m × 50 m quadrat (1000 m2). This plot size enables regional comparisons in diversity-associated factors for the broad vegetation types (e.g. grasslands, shrublands and forests). All quadrats were permanently marked and assessed at least once during the flowering period (spring-summer) for accurate plant identification. The cover data of each plant species was recorded using a modified Braun-Blanquet scale. Species were defined using origin (native, endemic, exotic), life-form (herb, graminoids, tussock grass, fern, shrub, dwarf shrub, tree), life-span (perennial, annual, biennial), and location of the plant's growth-point (bud) based on Raunkiaer classification system (geophyte, chamaephyte, phanerophyte, hemicryptophytes, cryptophytes, therophytes). Also, to detect changes in vegetation over time, survey was conducted using a point-quadrat lines procedure (Levy & Madden 1933) (two transects of 50 m in each plot, 500 hits per transect) at biomass peak (December-January) and recording the percentage of the ground covered by vegetation (plant life forms), bare soil, and litter. Estimates of annual net primary production (ANPP) for grasslands are based upon measurements of standing crop biomass (herb, graminoids, tussock grass, and dwarf shrub) by destructive harvest (two cuts at the end of each vegetation transect) using a quadrat of 1.0 m2 (Peri et al. 2013b).

(b) Arthropod diversity: The PEBANPA Network selected coleopterans as potential indicators for the largely unknown, insect biodiversity in Santa Cruz and Tierra del Fuego. Epigaeic arthropod samples were obtained by utilizing pitfall traps at the sites of 113 vegetation surveys, located across latitudinal (53º 40’– 55º 00’ S) and longitudinal (66º 30’– 68º 30’ W) gradients, coleopteran diversity in the Tierra del Fuego steppe was sampled. Coleopterans were captured at 106 sites with 85 species being identified within the study (Peri et al. 2013a). These were arranged in sets of five traps, one central and the remaining four at 5 meters from the first, and at 90 degrees from each other. Each trap (12 cm diameter and 14 cm height) was filled to a third of their volume with soapy water (300 ml) to trap and kill arthropods which fell in. Traps were left open at ground level for one week before being collected, and the contents of the five traps were joined and taken as a single sample unit. Samples were taken to the laboratory, where we classified and quantified individuals under a binocular dissecting microscope (x10-x20) within taxonomic groups, as Coleoptera, Hymenoptera and Orthoptera in the Class Insecta, and Pseudoescorpiones, Scorpionida and Solifuga in the Class Arachnida. All individuals were identified to genus or species level when possible, using standard keys in collaboration with specialists. In those taxa for which species or genus could not be determined, due in part to a scarcity of systematic studies of Patagonian insects, we employed the recognizable taxonomic unit or morphospecies concept (Oliver & Beattie 1993). The use of morphospecies instead of formal taxonomic species is valid to estimate species richness with average errors below 15% in assessment of biodiversity inventories, monitoring or preliminary ecological studies (Oliver & Beattie 1993). Likewise, morphospecies have been demonstrated to be a good tool for insect diversity studies in Patagonian ecosystems, such as Nothofagus forests (Lencinas et al. 2014). Specimens were deposited in the permanent reference collection at CADIC-CONICET in Ushuaia, Argentina.

(c) Forest ecology and management: In the particular case of native forest, PEBANPA aims to define the feasibility of a long-term sustainable forest management in southern Patagonia and to improve the economy of the forest companies by studying the biometry and forest yield during the harvesting processes (e.g. Martínez Pastur et al. 2009). Thus, permanent plots were designed to study the most adequate silviculture practices in secondary forests of lenga and guindo by the implementation of intermediate treatments through different thinning and pruning alternatives. Also, permanent plots were established to define most effective harvesting strategies and their impact over forest regeneration (Martínez Pastur et al. 2010). Similar to lenga, during recent years, interest in sustainable use of ñire forests increased significantly in Patagonia (Peri et al. 2016b). Long-term study research plots were established to monitor silvopastoral management as well as analyze different thinning intensities, the improvement of understory grass production, livestock carrying capacity, and to provide strategies to preserve the native tree strata over time.

The monitoring of these permanent plots included silvicultural and ecological parameters. The silvicultural parameters were: (1) tree and stand growth in managed and unmanaged stands under different overstory crown classes, or with different economic alternatives under implementation including prunings, or proposals to reduce the wind-throw risks or silvopastoral systems applications; (2) harvesting yield for sawmill or firewood-pole yield in secondary forests and old-growth forests harvested by using shelterwood cuts or different degrees of variable retention; and, (3) stability of remnant overstory after harvesting. The ecological parameters included: (1) flowering and seeding patterns, as well as regeneration dynamic in shelterwood cuts, variable retention and silvopastoral systems along crown cover and soil water content gradients; (2)

microclimatic variables measured by weather stations (Davis Weather Wizard III and accessories - USA) and data loggers (HOBO ONSET and Watchdog Spectrum - USA) to quantify air and soil temperatures, relative air humidity, wind speed and direction, rainfall and soil moisture (Watermark Spectrum and ECHO EC5 - USA); (3) biodiversity assessments, including birds, insects, vascular plants, ferns, mosses and fungi; and, (4) pasture productivity for different silvopastoral system alternatives, site classes and shade conditions (Peri et al. 2016b).

(d) Soil carbon: At each site, soil samples were collected from nine randomly selected points within a 20 m x 40 m quadrat using a hand auger (10 cm depth). Coarse root debris >2 mm from soil samples had been removed by sieving. To reduce the number of chemical analyses, individual soil samples were pooled into combined samples. From the nine samples collected within each quadrat, three composite samples were created so that each composite sample contained an equal proportion of soil from three auger holes (n = 3 for each site). The samples were finely ground to 2 µm using a tungsten-carbide mill. Measurements of soil carbon concentration (SOC) were derived from the dry combustion (induction furnace) method. The ground aggregates were also used to measure the percentage of nitrogen using a LECO auto-analyzer (St. Joseph, USA), major cations (Na, Al, P, K, Ca), pH, percentages of clay, silt and sand. The pH of soil samples was determined with an electronic meter immersed in a 1:5 mixture of soil and deionized water. When appropriate, soil carbon measurements were cross-referenced against soil pH measurements to ensure that the soil samples were free of soil inorganic carbon and thus composed of SOC.

(e) Soil respiration: Soil respiration (from roots and micro-organisms) is measured in each site during spring season (November). CO2 resulting from soil respiration is measured using the soda lime method (Edwards 1982). This method has been used successfully in southern Patagonian ecosystems (Peri et al. 2015). Five sampling stations were randomly chosen in each study site. At each station, white opaque plastic respiration chambers (10 cm height x 21 cm diameter) with a well-sealed lid installed at a depth of 1 cm, were inverted over open jars (diameter of 7 cm) containing 50 g of previously dried (105ºC for 24 hours) and weighted soda lime granules. The area inside of the chamber was cleaned of all green plants and any organic living matter. After 24 hours, the soda lime jars were capped, transported to the laboratory, dried at 105ºC for 24 h, and reweighted. Two blank chambers per site of the same cut-off bucket with well-sealed lid were installed to account for minute gains of CO2 that occurred during oven drying (the only time that the blanks were left uncapped). Soil respiration (gCO2 h-1m-2) was calculated by multiplying field estimates by a correction factor of 1.69 to allow for loss upon drying of water produced by absorption of CO2 by soda lime (Keith & Wong 2006).

(f) Soil water infiltration: The soil water infiltration data was measured with the double-ring infiltrometer method (ASTM International D3385-09, USA). The method consists of driving two open cylinders, one inside the other, into the ground, partially filling the rings with water, and then maintaining the liquid at a constant level. The volume infiltrated during timed intervals is converted to an incremental infiltration velocity, expressed in cm/h and plotted versus elapsed time (measured every 15 min, one hour in total). The average incremental infiltration velocity of the test is equivalent to the infiltration rate.

(g) Soil water retention: The soil water retention capacity (mm/cm) is measured in the top layer of the soil, by taking soil profiles from 0-30 cm depth. The profiles are air dried and sieved (<2 mm) in the laboratory prior to the determination of water retention curves with Richard plates (Richards 1948). The water retention curves are determined for the sieved soil of each profile, according to the Richards method (Richards 1948), to determine the value of gravimetric moisture in soil, depending on the matric potential (-1500, -300, -100, -33 and -10 kPa). Gravimetric moisture at field capacity (-10 kPa) and gravimetric moisture at permanent wilting point (-1500 kPa) are calculated from the water retention curves to determine the available water retention capacity, which is calculated by: available retention capacity = field capacity - permanent wilting point.

(h) Soil erosion: The network monitors biological indicators such as water and wind erosion in order to assess soil stability and the water cycle for each site. Percentages of decomposition and blowout and active pedestals (0 to >10 cm) were classified and described to assess the level of wind erosion, and for water erosion, indicators of active rill, gullies and water flow patterns (0 to >10 cm) were also classified and described. The indicators are summed up in the evaluation matrix and were used to describe ecosystem's conditions, functions and trends.

(i) Grazing intensity: The average property size in Santa Cruz and Tierra del Fuego Provinces is 12,400 ha, with the largest property at 179,000 ha (Peri et al. 2013a). Mean sheep stocking rates are measured using 1 Corriedale ewe (49 kg of live weight, requiring 530 kg DM.yr-1) as a base calculation. The main grazing areas within Santa Cruz include the following locations: (i) central plateau; (ii) Andean vegetation and humid Magellanic grass steppe; (iii) mata negra thicket, shrub steppe Golfo San Jorge and mountains and plateaus;

and, (iv) dry Magellanic grass steppe and Sub-Andean grassland. In northern Tierra del Fuego, the main grazing areas are Magellanic steppe and steppe-forest ecotone. The stocking rate gradients for all areas range from 0.02 ewe.ha-1 yr-1 in the central plateau region to 1.60 ewe.ha-1yr-1 in the Andean vegetation in Santa Cruz and steppe-forest ecotone in northern Tierra del Fuego (Peri et al. 2013a). The estimation of carrying capacity is based on the biomass production of short grasses and forbs that grow in the space among tussocks of each ecological area and the requirements of 530 kg DM.yr-1 for 1 Corriedale ewe of 49 kg of live weight, representing a “Patagonian sheep unit equivalent (PSUE)” (Borrelli 2001).

(j) GIS Derived Independent Variables/Climate Parameters: The climate parameters for each site were estimated from a WorldClim data set (Hijmans et al. 2005). WorldClim contains geographic surfaces for 19 different climatic parameters that describe rainfall, temperature and variation in those parameters at a resolution of 0.008333° (approximately 1 km). Solar radiation (W m-2) was calculated from the Solar Radiation tool in ArcGIS version 9.3.1 (ESRI, California, USA), with topography data from the 3 arc second resolution NASA Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM) of the globe (Jarvis et al. 2008). We also calculated another composite climatic variable (W*) for use in statistical analyses because this integrates climatic conditions highly relevant to plant growth. W* represents mean annual water availability (Wynn et al. 2006), W* = (MAP - Q / (r L)) + 4000; where MAP is mean annual precipitation (mm/yr), Q is mean annual global solar radiation (J/m2/yr), r is the density of liquid water at 25ºC (1000 kg/m3), and L is the latent heat of evaporation of water at 25ºC (2.5 × 106 J/kg H2O).

(k) Rangeland health analysis: The PEBANPA Network produces qualitative and replicable rangeland health assessments based on the methods proposed and employed by US Bureau of Land Management (Pellant et al. 2005), the Nature Conservancy and Ovis XXI (Grass 2012). Rangeland health is dependent on properly functioning ecological processes that maintain the site's structure (US BLM 2001). The overall goal is to assess the conservation status and rangeland health with representative criteria and spatial variability. Under this framework, the PEBANPA Network assesses 13 biological indicators in order to evaluate the health of the specified ecological site (Grass 2012). Individual scores of each biological indicator (e.g. vegetation cover or soil erosion) are summed up together to make up the final score in order to analyze the rangeland health index. The observed score of the area is compared with the maximum possible reference score of 130, which describes the “most ideal functioning ecosystem”. The degree of departure from the maximum reference score indicates the level of rangeland health and conservation status.

3. Main results and trends

3.1 Rangeland

The results highlight the negative impacts of intensive grazing on the region under a traditional management of continuous grazing with fixed stocking rates in large paddocks. The ANPP ranged from 4.9 to 59.1 g m-2 yr-1 for overgrazed grassland in the mata negra thicket ecological area and moderate grazing in Sub-Andean grasslands, respectively (Fig. 3a). Overgrazing reduced ANPP up to three-folds in most ecological areas. Since all areas fall below a rangeland score of 70 (Fig. 3b), all ecological areas are experiencing damaged rangeland health and require conservation action planning. In comparison to the healthiest rangeland value set at 130, the regions of Sub-Andean grasslands (43) and humid Magellanic steppe (38) possess relatively the healthiest rangelands in the area. The central plateau (2), mata negra thicket (12) and shrub steppe Golfo San Jorge (16) possess the highest levels of soil degradation and desertification. These low RHI values require alternative land-use practices in order to restore and enhance the damaged landscapes within the main ecological areas.

FIGURE 3

In addition, in the grass steppe long term grazing intensities reveal the impacts on several variables under different levels of long-term grazing (Table 1). Areas under intensive grazing possessed lower percentages of vegetation and litter cover in conjunction with significantly higher levels of soil erosion and bare soil percentages, in comparison to other grazing intensities. Medium grazing intensities experienced significantly less soil erosion in comparison to high intensity grazing. In addition, medium grazing yielded the highest amounts of annual net primary production and soil organic matter. Low grazing intensities provide roughly similar effects on environmental variables as medium grazing intensities.

TABLE 1

3.2 Plant and arthropod diversity

Plant diversity contributes to healthy ecosystems and societies. The lack of plant diversity threatens the production capacity and services of livestock, agriculture, water resources, and medicinal products. The function of plant diversity impacts other natural services such as nutrient storage and recycling, soil organic matter and insect diversity. In the PEBANPA network, 345 plant species from 151 genera and 56 families were recorded in the quadrats surveyed across Santa Cruz Province, representing 16% of the flora of Patagonia (Peri et al. 2014). Local native plants accounted for 92.5% of the total species (47 endemic species), while alien taxa accounted for 24 species (Peri et al. 2013a). In Tierra del Fuego, 184 vascular plant species were surveyed, where 66% (122 species) were dicots, 32% (59 species) were monocots and 2% (3 species) were ferns. Among these were 24 exotic species, 15 dicots and 9 monocots (Peri et al. 2013a).

Studies of pattern of distribution on vascular plants on PEBANPA plots of Santa Cruz showed statistically significant differences among geographical zones (North, Center and South), as well as among dominant vegetation types (Fig. 4). In the three zones, Nothofagus forests and wetlands clearly differed from steppe, but shrub and grass steppe did not split in different groups. Similarly, in PEBANPA plots of Tierra del Fuego, vascular plant and epigaeic coleopteron pattern of distribution were compared. The analysis also showed statistically significant differences among geographical zones (North, East and South) as well as among dominant vegetation types (Fig. 5), with similar responses for both plants and coleopterons. In the North zone of Tierra del Fuego, ñire and lenga assemblages of plants and coleopterons were intermixed and conform a significantly different group, more concise in plants and more disperse in coleopterons (Fig. 5). Similarly, grassland, peatland and shrubland assemblages were similar among them, and these shaped another group more clearly separated from forests on plants, and less separated on coleopterons. In the East zone, lenga assemblages were clearly split from grasslands and ñire forests for both analyzed groups. In addition, grasslands and ñire forests also ordered in two subgroups for plants, but not for coleopterons. In the South zone, there was overlap between among different dominant vegetation types, with more concise groups for guindo and ñire forests, which are significantly different among them for both plants and coleopterons. Likewise, plant shrub assemblage conform a cohesive group inserted in grassland and peatland group, which was not clear in coleopteron assemblages. These analyses showed general greater similarities among forest types in North and South zones for both plants and coleopterons, while forest type diversity was different in East zone for both groups. On the other hand, assemblages of plants and coleopterons were quite similar among grasslands, peatlands and shrublands in the three zones. These results are important to delineate and propose strategies for sustainable management according to ES provision and conservation in South Patagonia environments.

FIGURE 4

FIGURE 5

3.2 Forest dynamics and regeneration

Healthy forest structure and regeneration provide multiple benefits for both local ecosystems and society. Increased levels of biodiversity, soil quality, erosion control, long-term economic security, recreational benefits, and carbon sequestration are achieved as a result of healthy forest structure and regeneration. Forest product harvesting and end-use activities are improved for the long-term future due to the sustainable management of forests. However, historical silvicultural methods have emphasized economic gains over sustainable management through implementing practices focused on maximizing economic benefits and minimizing monetary costs (Alfonso 1942). With global forests disappearing due to economically driven human practices, forest related economic benefits will eventually suffer due to the unsustainable management of forests.

Forest ecosystems generally base their long-term sustainability in the natural maintenance of nutrient cycles (Perry et al. 2008), forest structure and biodiversity conservation (Lencinas et al. 2011; Soler et al. 2015, 2016). In Tierra del Fuego, the harvest levels have increased fivefold in the last 20 years (from 40 to 200 m3 ha-1) and is expected to be a growing trend in relation to costs, markets and technologies (Gea et al. 2004; Martínez Pastur et al. 2009). It is therefore necessary to establish guidelines aimed at conserving biodiversity associated with production forests (Lencinas et al. 2009a).The permanent PEBANPA monitoring plots in native forests have been established to evaluate and measure the economic, silvicultural and ecological parameters related to forest use, management and regeneration. The primary goals are to provide information for stakeholders in order to maximize product yield, improve conservation strategies and adopt sustainable forest management practices. Forest management for Tierra del Fuego and southern Patagonia are based mainly on silvopastoral use of ñire, and shelterwood cuts and thinnings for lenga. Both proposals had impacts over biotic and abiotic components of the original forests.

Details of different variables (density, damage, height, age, diameter breast height (DBH)) of seedling and sapling regeneration after forest harvesting methods, using a timescale of 1 – 50 years, are presented in Figure 6. In Tierra del Fuego province, three separate zones were evaluated, shelterwood (SC), gathering (G) and adjacent primary forests (PF) for 1, 5 - 10, 20 – 30, and over 50 years after harvest. Five plots were evaluated with study areas of 1 m2 for seedlings and 10 m 2 for saplings, (both at >1.3 m in height). High variability in density was assessed between plots including the same area and age. Differences were not discovered in average seedling density and age (16 seedlings/m2 and 5 years). However, PF possessed higher seedling density, (42.6 seedlings/m2) low height (9 cm) and lower average age (4 years) without saplings. Regardless of age, sapling density was significantly different between areas. While no significant differences were assessed for other variables, increasing trends between areas and age for saplings height were observed (PF = 3.9 m > G = 2.6 m; over 50 years = 5.1 m > 20-30 = 3.0 m > 10.05 = 1.6 m), 1.30 m diameter (PF = 3.0 cm > G = 1.7 cm; over 50 years = 4.2 cm > 20-30 = 2.3 cm > = 0.6 cm 5-10), and seedling height (19.8 cm PF = > G = 14.6 cm). The assessment reveals the need for long-term monitoring of post-harvest regeneration due to high variability over a 50 year timescale. For example, between year 1 and 5, both sapling and seedling regeneration variables show low levels of regeneration height and density. Few conclusions can be made on the impact of harvesting in different forests for the first 20 years due to the dry climate of the region. However, after 20 to 30 years as well as 50 years post-harvest, high levels of variability in seedling and sampling density, height and damage density occur.

FIGURE 6

(iv) Silvopastoral systems

Silvopastoral systems incorporate the services of both forests and pastures for livestock and wood production. Mixed livestock (cattle and sheep) production is the main activity and source of annual income on silvopastoral systems in ñire forests (Peri 2016a). Silvopastoral systems support cattle and sheep production while also providing a diverse array of wood products such as timber, firewood and poles (Peri 2005). Silvopastoral systems are designed to improve and conserve natural ecosystems while protecting agricultural production. In comparison to standard monocultures of forest and livestock production, silvopastoral systems produce higher yield per unit area, increase resource-use efficiency and help restore and conserve natural ecosystems (Peri et al. 2016a). Consequently, successful silvopastoral systems integrate economic and ecological interactions (positive and negative) between woody, non-woody and animal species. Nutrient enhancement, increased biodiversity, higher forage quality, improved soil fertility, carbon sequestration, watershed protection, animal welfare, and erosion control can be achieved while producing goods (e.g. timber, fuel, food, fodder, etc.) under silvopastoral systems. Estimated from provincial GIS cadastre and forest inventory, 102 medium and large landholdings (60 in Santa Cruz and 42 in Tierra del Fuego Provinces) with ñire forests have adopted silvopastoral systems (Peri & Ormaechea 2013) in the region. However, the vast majority of ranchers have been apprehensive about adopting an integral silvopastoral system management plan (Peri et al. 2016a) due to the possible lack of convincing evidence. Producing and communicating cost estimates of silvopastoral system implementation and an integral economic analysis of the values of healthy ecosystems and production provided by silvopastoral systems will be required for further adoption. Calculating and communicating the net-present-value (NPV) and the internal rate of return (IRR) of sustainable grazing practices with landowners and decision makers is critical for acceptance and success.

Litterfall production did not vary between years and was only different among uses during two years (Fig. 7). The ten year averages were 1556 and 940 kg ha-1 for PF and SP stands, respectively. On the other hand, seed production varied between years and uses (depending of the year). The PF averaged 15.5 million ha-1 in the ten years, while SP stands produced an average of 11.5 million ha-1 in the same period.

FIGURE 7

(v) Carbon content

World leaders have agreed to address climate change through advancing mitigation and adaptation strategies with the goal of limiting global temperatures to 2 degrees C above pre-industrial levels (IPCC 2014). This ambitious goal requires all efforts to be exercised and global leaders must recognize the role and impact of soil carbon sequestration. Land use change and agriculture practices contributed 24% of total anthropogenic greenhouse gases in 2010 (IPCC 2014). Soil contains two to three times more carbon than both the atmosphere and global vegetation stock combined and inadequate land-use management threatens the health and functionality of the soil carbon pool (Houghton 2007; Trumbore 2009). However, policy makers have focused more on above-ground biomass and have often overlooked and undervalued the role of soil carbon sequestration as a serious climate change mitigation strategy. The cost-effective, natural processes of soil carbon sequestration require healthy and productive soil, which provides multiple benefits for the agricultural economy. Effectively addressing climate change cannot be achieved without soil carbon sequestration, sustainable land use and strategic soil management. Through the natural processes existing within the Earth's carbon cycle, land-based carbon sequestration is currently the only feasible large-scale method to remove greenhouse gases from the atmosphere.

Soil physical and chemical properties and characteristics are influenced by the biological activity generated by available organic matter. As the aggregation and stability of soil increase with organic matter, increased water capacity, soil fertility, stronger resistance to erosion, and greater plant nutrient health are achieved. Increased structural stability and soil organic matter help prevent the desertification and erosion processes that are influenced by overgrazing of livestock, wind and water.

Table 2 illustrates the robust levels of mean carbon content within soils at depths of 30 cm in comparison to above-ground and below-ground levels of mean carbon content. Carbon content found within soils dwarfs the amount of carbon content found in above-ground and under-ground sites. Overall, ñire forests possess the highest levels of mean carbon content relative to the other main study areas within the PEBANPA Network. While stipa grasslands possess the lowest level of carbon content, it is imperative to conserve and sustainably manage all areas across the region.

TABLE 2

Figure 8 shows an example of the measured effect of long-term livestock grazing on C content of the plant-soil grassland system (to 30 cm) of Magellanic grass steppe and mata negra thicket areas. On these extensively managed grasslands, grazing intensity was the main management practice that affected ecosystem

C levels. This varied from 68 Mg C ha-1 at a heavy stocking rate (0.70 ewe ha-1 yr-1) to 125 Mg C ha-1 under low grazing intensity (0.10 ewe ha-1 yr-1) in grasslands, and from 124 to 160 Mg C ha-1 in shrublands for same stocking rate gradient (Fig. 8). A slightly higher total C content was detected in the low grazing intensity (0.10 ewe ha-1 yr-1) grassland compared with the non-grazed areas (125 vs. 120 Mg C ha-1) since non-grazed enclosures caused immobilization of C in excessive above-ground plant litter. Under low grazing intensity levels, total grassland C declined as grazing intensity increased, but the response was different according the ecological area. Thus, while for Magellanic grass steppe grassland under sheep grazing, this response showed that 0.35 ewe ha-1 yr-1 stocking rate was a critical value below which ecosystem C was severely restricted. For the mata negra thicket, the critical stocking rate was 0.20 ewe ha-1 yr-1. The effect of sheep on system C arose from the influence of grazing intensity on plant floristic composition. Thus, long-term grazing at heavy stocking rates has tended to decrease plant species diversity and plant cover, as well as increase bare areas. However, the biggest impact on grassland C ecosystem due to overgrazing was the C lost from soil (mainly the organic layer) as a consequence of soil erosion by strong winds.

FIGURE 8

Discussion

The current structure of political, economic and social systems has long considered natural capital (ecological function) and economic development as two independent spheres. Short-term economic growth is often rewarded by current systems while ecosystems continue to experience degradation. There are cost estimates between $4.3 – 20.2 trillion in ES damages due to land use change (Costanza et al. 2014). Ecosystems are changing in an extremely complex fashion, some changes are occurring rapidly while other ecological processes are responding to disturbances several years (to decades) later (Sanchez-Carillo et. al 2016). There is a significant increase in global demand to adapt land management efforts in order to help alleviate the risk to both social well-being and ecosystem function health. Therefore, it is imperative to understand the responses, dynamics and consequences of ecological processes through long-term ecological research (Sanchez-Carillo et. al 2016). The long-term monitoring of biodiversity indicators enables decision makers and stakeholders to better understand the historical changes in ecosystem functions, predict future declines and avert further damage through sustainable land management practices (Hudson et al. 2014). PEBANPA main results in grasslands highlight the negative impacts of intensive grazing on the region. The introduction of extensive livestock grazing has markedly reduced vascular plant diversity and cover, decreased the availability and desirability of forage, facilitated the encroachment of invasive and exotic species, as well as increased soil degradation and desertification within Patagonian rangelands (Aguiar & Sala 1998; Bertiller & Bisigato 1998). Heavy and unsustainable grazing conditions threaten the future of livestock health and productivity, therefore threatening the long-term health and well-being of the local economy. Desertification of the region's soil also decreases the capacity of soil carbon sequestration, a recognized climate change mitigation strategy. Depending on the functionality and condition of the ecosystem, ranches are eligible to receive "Full" or "Restore" conservation certification status for their products under the GRASS protocol (Grass 2012). "Full Brand" certified products originate from farms that possess positive biological indicators and implement adaptive management practices, which minimize degradation and maximize environmental performance potential. "Restore Brand" products also incorporate adaptive management practices, but possess negative biological indicators during the rehabilitation and regeneration process. Corporate social responsibility and sustainable products are quickly growing in demand by international consumers and sustainable product certification will become increasingly important for local ranchers to consider.

We found that the critical role of insects within the global and regional ecosystem is often overlooked and undervalued, perhaps due to the human perception of their small size, large populations or the potential dangerous they can present. Arthropods' critical roles as pollinators and natural managers of soil quality as well as their place at the bottom of the food chain necessitate greater conservation efforts and ecosystem management strategies (Lencinas et al. 2015). Insect richness and health are sensitive to resource health of local ecosystems (Werner & Raffa 2000). The evaluation of insect and arachnid abundance and richness serve as a strong indicator of the impacts and effects of human activities on biodiversity and environmental quality on a landscape level (Kim 1993; Niemelä 2001; Lewis & Whitfield 1999).

Furthermore, regional systematic soil monitoring through the establishment of permanent plots is critical in order to evaluate the conditions and changes in soil organic matter and progress of carbon sequestration. The widely distributed, geographical grid within the PEBANPA Network serves as a useful tool for monitoring, verifying and reporting soil organic matter and soil carbon sequestration levels necessary for regional and international agendas and requirements. Furthermore, the scientific inventories conducted within the PEBANPA Network allows stakeholders to better understand the drivers and causes for soil degradation and options for improvement. The PEBANPA Network enables stakeholders and decision makers to identify the impacts and relationships between climate variables, land use practices, soil organic matter, nutrients, and soil carbon sequestration at the regional level.

As biodiversity and natural landscapes as well productivity throughout Patagonia continue to change and degrade, it becomes increasingly important to pursue sustainable solutions. The decision to simply designate wilderness areas as partial reserves will not address the mounting challenges regarding the impacts on the region's biodiversity caused by climate change and unsustainable land use practices. The first step is to inform decision makers, enterprises and stakeholders of the functions, interactions and trends associated between natural systems and human activities. Objective and reliable data raises awareness, strengthens understanding and can help to develop responsible and well-informed decisions. Obtaining high quality data can help institutions and stakeholders identify policy strategies, assess trade-offs (benefit-cost analysis) and achieve policy objectives (Martínez Pastur et al. 2016b). After implementation of sustainable management practices, the PEBANPA Network has the capacity to monitor the effectiveness and impacts of the alternative management policies. Long-term monitoring of the progress (or lack thereof) of a specific land management policy enables decision makers and stakeholders to make policy adjustments in hopes of yielding positive results. Communicating the processes, trends and progress to the international community can also enhance global collaboration.

The following three overarching strategies are recommended for researchers and policy makers to achieve success in sustainable management policy at a landscape level: (i) produce objective evidence that reveals the impacts of land use practices and decision making on ecosystem services; (ii) foster inclusion and the intellectual capital of leaders in government, private sector, landowners, and society during the strategic development and implementation process; and, (iii) build institutional capacity and reform policies that link short-term economic goals with societal long-term health and prosperity (Guerry et al. 2015).

The PEBANPA Network's role in the long-term monitoring of functions, trends and interactions between land use and ecosystem services can guide policymakers and stakeholders in restoring biodiversity and ecosystem function in order to secure a healthier social well-being within Southern South America-Patagonia. Livestock and timber production can be implemented in a sustainable manner at a landscape scale while restoring the region's ecosystems and sustaining economic viability. The most successful results achieved by sustainable land management and/or climate change mitigation and adaptation policies will be aided by long-term research, stakeholder collaboration and political will.

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Figure Legends.

Fig. 1 - The role and rationale of the PEBANPA Network.

Fig. 2. Distribution of PEBANPA plots located in Santa Cruz (left) and Tierra del Fuego (right) Provinces.

Fig. 3. (A) Annual net primary production (ANPP) for grasslands of standing crop biomass (herb, graminoids, tussock grass, and dwarf shrub) and (B) the rangeland health index (RHI) values in main ecological areas in Southern Patagonia using PEBANPA Network data. HMS – humid Magellanic steppe, DMS – dry Magellanic steppe, MNM – mata negra thicket, SAG – Sub-Andean grasslands, CP – central plateau, SSSJ – shrub steppe Golfo San Jorge. The perfect RHI is set at 130. It is important to mention that typical rangeland health evaluations assess a total of 15 biological indicators, totaling a maximum perfect score of 130. The ecological areas assessed in the PEBANPA Network did not include two biological indicators (biological crust and litter cover).

Fig. 4. Ordination of PEBANPA plots of Santa Cruz by non-metrical multidimensional scaling (NMDS) for vascular plant diversity at three zones (North, Center and South), classified by dominant vegetation type (Nothofagus forests, wetlands, shrub steppe and grass steppe).

Fig. 5. Ordination of PEBANPA plots by non-metrical multidimensional scaling (NMDS) for vascular plant and Coleoptera diversity at three zones (North, East and South) of Tierra del Fuego, classified by dominant vegetation type (N. antarctica, N. betuloides, N. pumilio forests, grasslands, peatlands and shrublands).

Fig. 6. Seedling and sapling regeneration interactions between different areas in the timber managed forests: adjacent primary forests (PF), gathering (G), shelterwood cuts (SC)) and years after harvest (1 – 50+ years).

Fig. 7. Total litterfall (A) (adapted from Bahamonde et al. 2015) and seeds production (B) (adapted from Bahamonde et al. 2011 and 2013) in N. antarctica primary forest (PF) and under silvopastoral use (SP) measured during 10 years. The values are average of stands growing in two site classes (IV and V). Bars represent the standard deviation of the mean. * $p < 0.05$; ns not significant.

Fig. 8. Effect of long-term livestock grazing on C content of the plant-soil grassland system (to 30 cm) of Magellanic grass steppe (•) and mata negra thicket (▼) areas, Patagonia, Argentina. The baseline (dash line) corresponds to an undisturbed vegetation area (non-grazed). The carrying capacity (ewe ha-1 yr-1) estimation is based on the biomass production of short grasses and forbs that grow in the space among tussocks of this ecological area and the requirements of 530 kg DM yr-1 for 1Corriedale ewe of 49 kg of live weight.

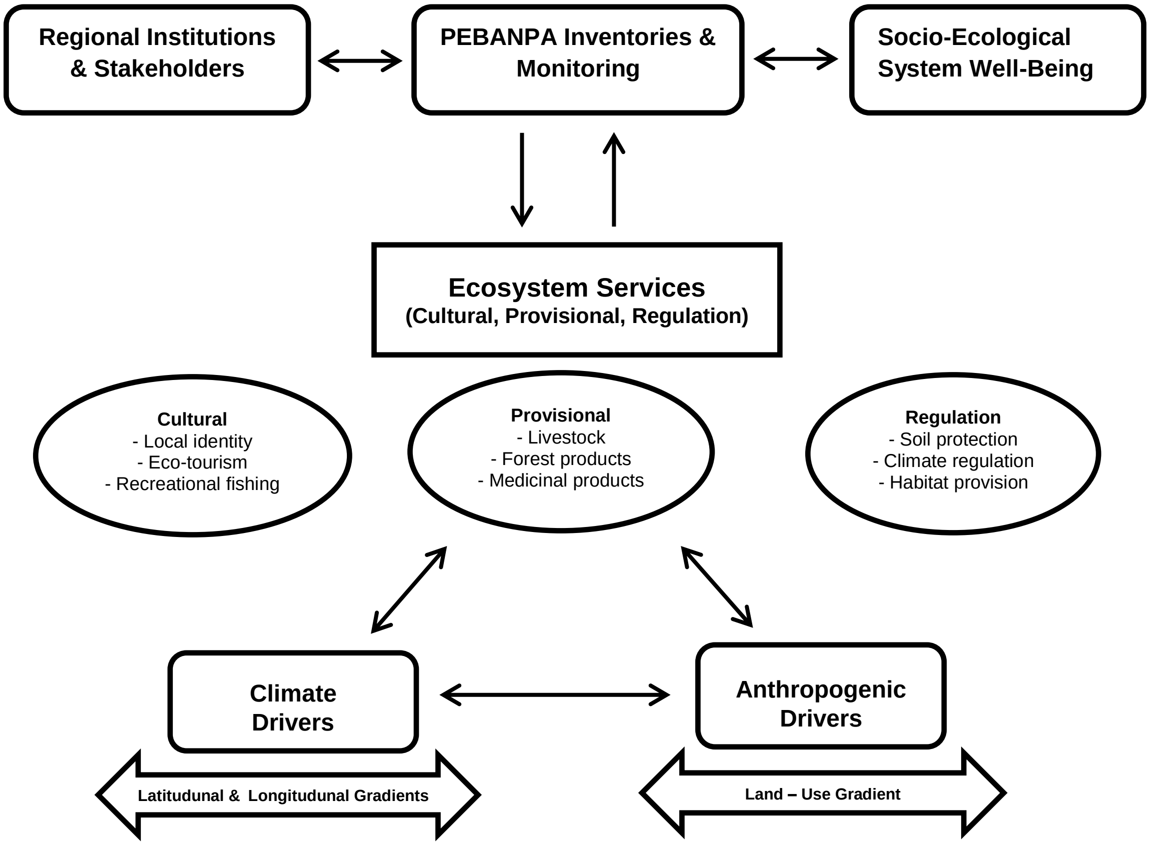
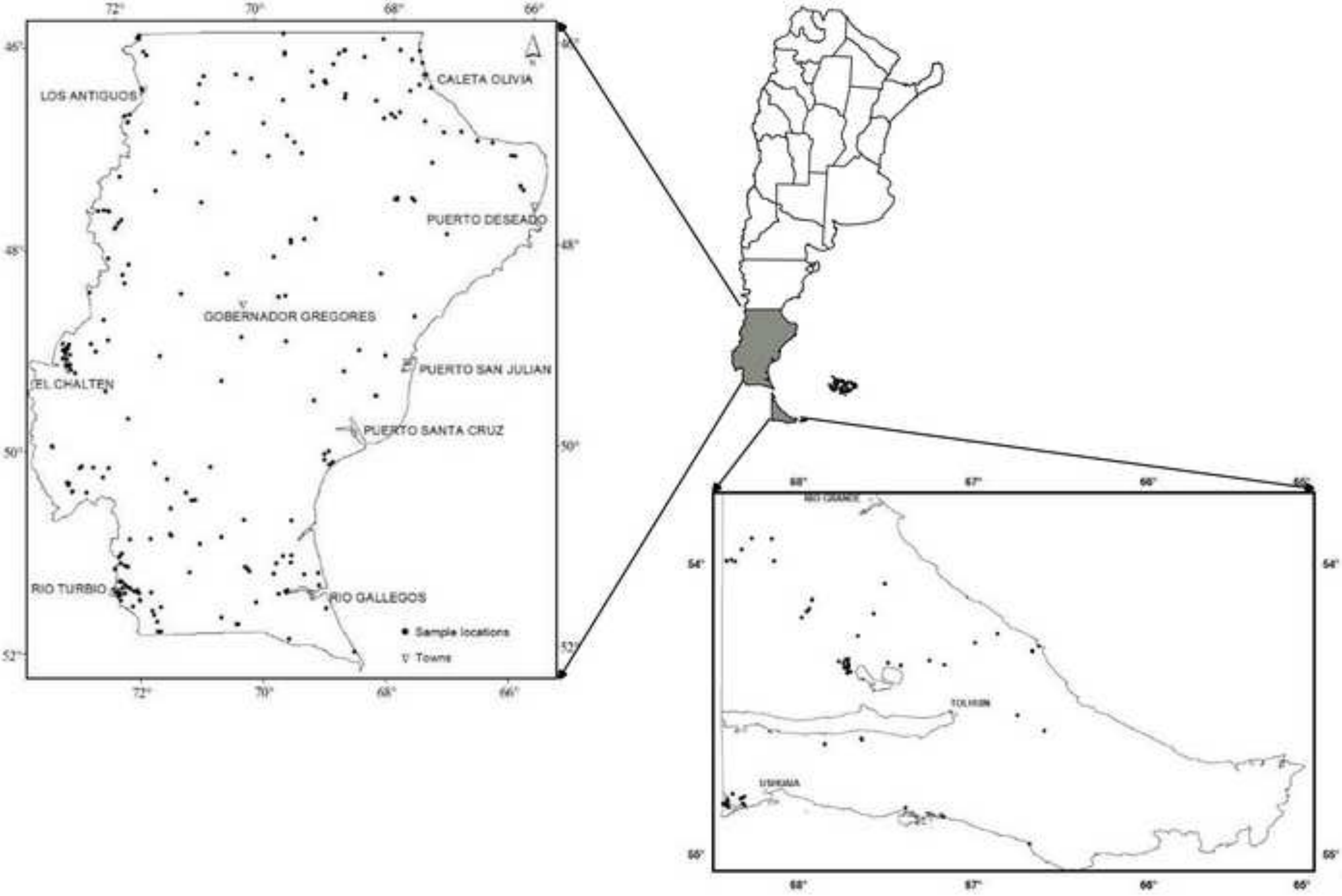

Regional Institutions & Stakeholders
PEBANPA Inventories & Monitoring
Socio-Ecological System Well-Being
Ecosystem Services
(Cultural, Provisional, Regulation)
Cultural
- Local identity
- Eco-tourism
- Recreational fishing
Provisional
- Livestock
- Forest products
- Medicinal products
Regulation
- Soil protection
- Climate regulation
- Habitat provision
Climate Drivers
Anthropogenic Drivers
Latitudunal & Longitudunal Gradients
Land – Use Gradient

Figure 2



72°
70°
68°
66°
46°
48°
50°
52°
N
LOS ANTIGUOS
CALETA OLIVIA
PUERTO DESEADO
GOBERNADOR GREGORES
PUERTO SAN JULIAN
EL CHALTEN
PUERTO SANTA CRUZ
RIO TURBIO
RIO GALLEGOS
Sample locations
Towns
68°
67°
66°
65°
54°
55°
RIO GRANDE
TOLHUIN
USHUAIA

Figure 3

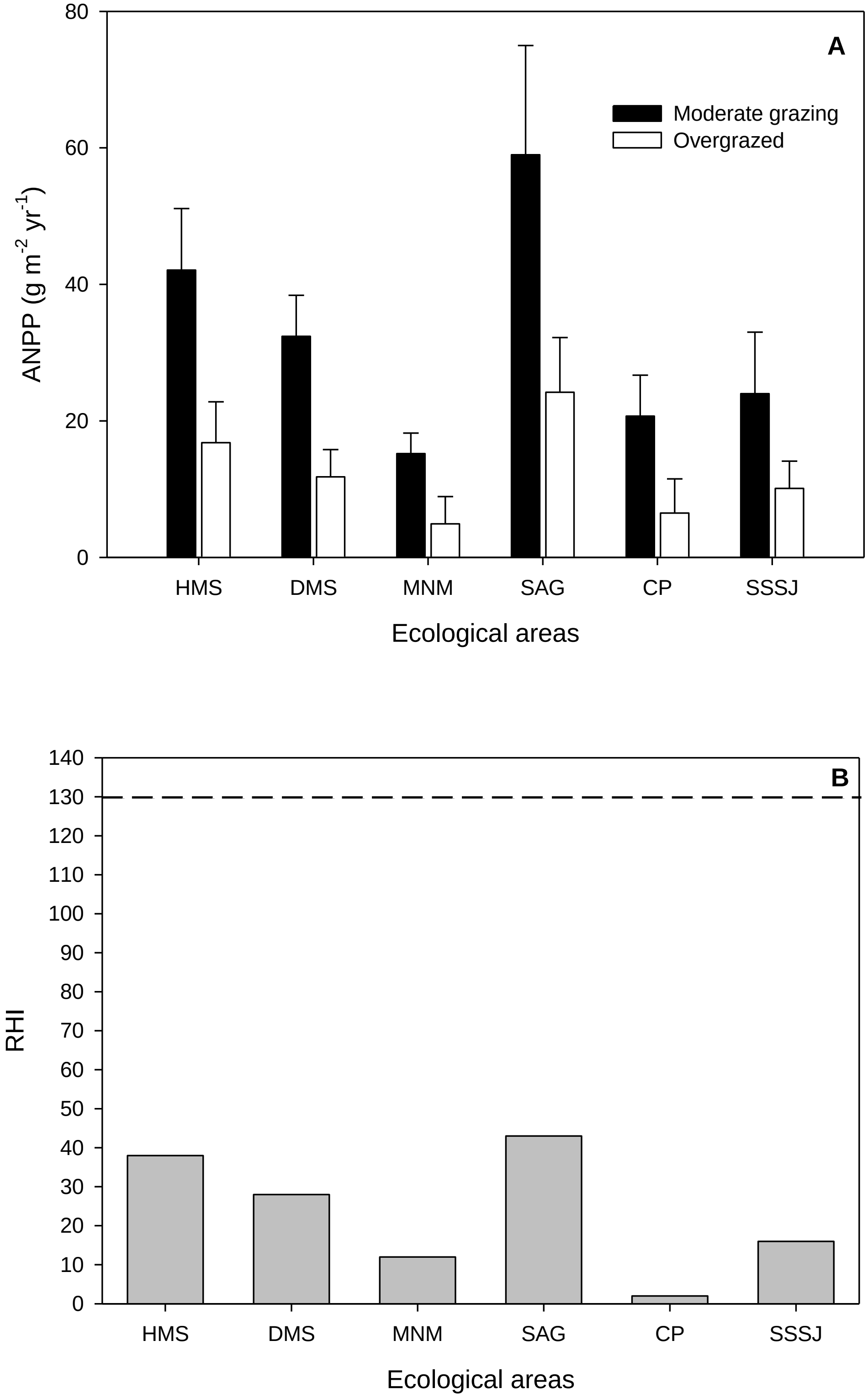

A
Moderate grazing
Overgrazed
ANPP (g m-2 yr-1)
0
20
40
60
80
HMS
DMS
MNM
SAG
CP
SSSJ
Ecological areas
B
RHI
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
HMS
DMS
MNM
SAG
CP
SSSJ
Ecological areas

Figure 4

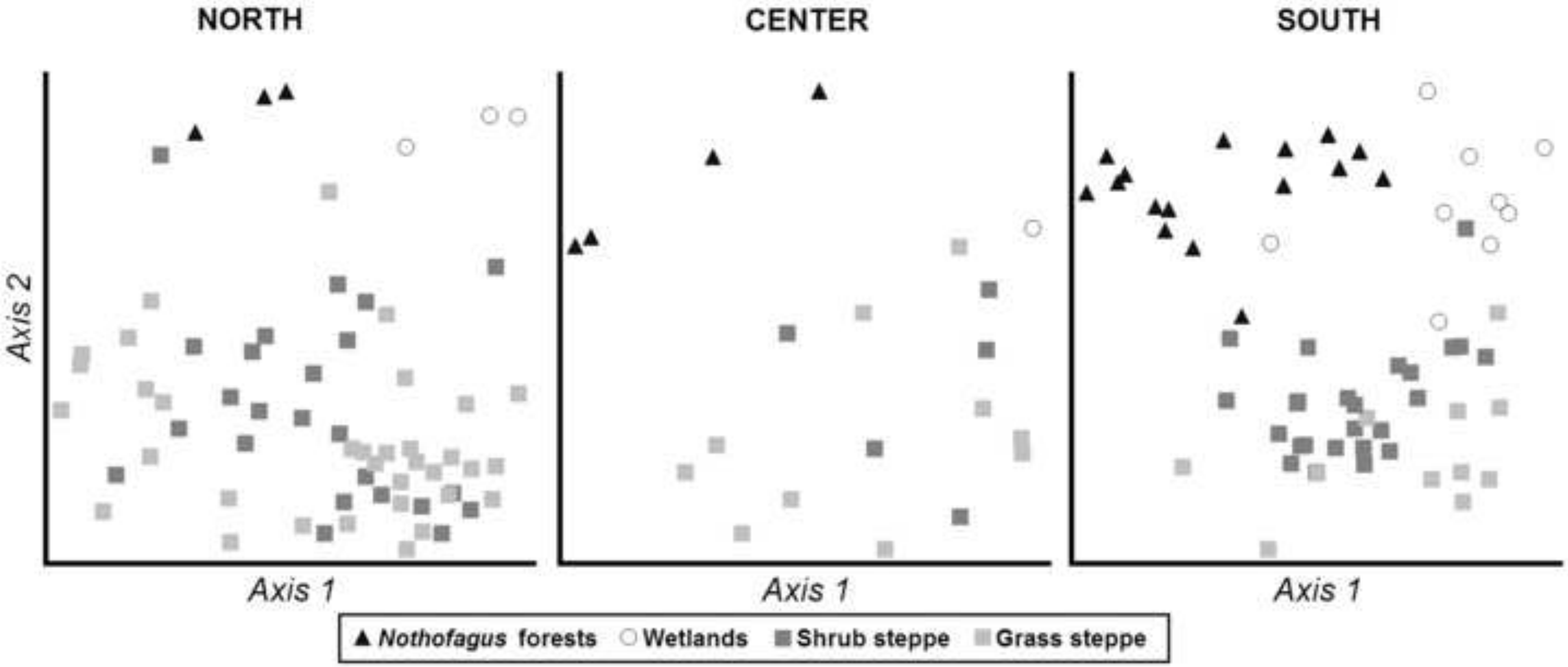
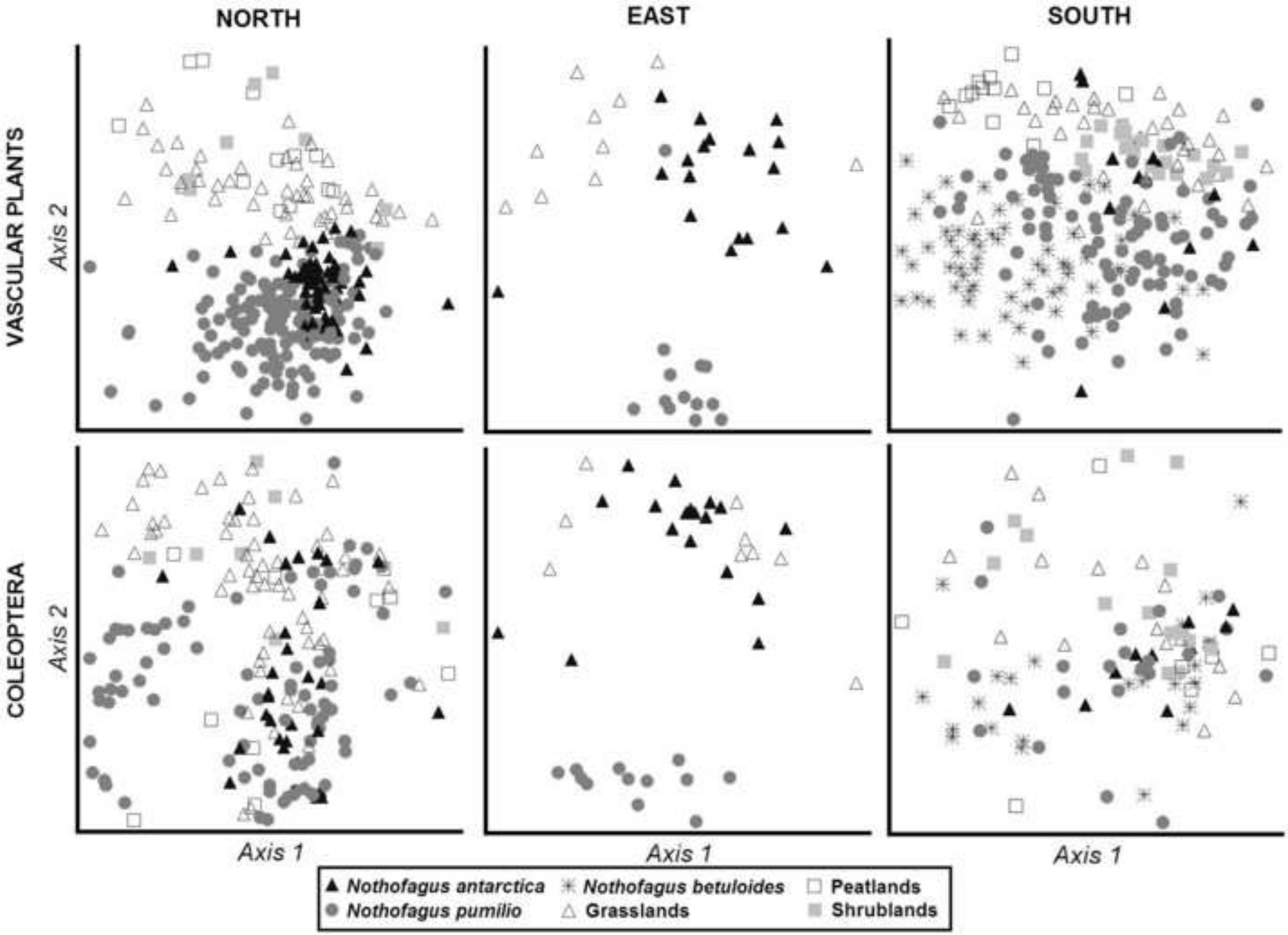

NORTH
CENTER
SOUTH
Axis 2
Axis 1
Axis 1
Axis 1
▲ *Nothofagus* forests
○ Wetlands
■ Shrub steppe
■ Grass steppe

Figure 5



NORTH
EAST
SOUTH
VASCULAR PLANTS
COLEOPTERA
Axis 2
Axis 2
Axis 1
Axis 1
Axis 1
▲ Nothofagus antarctica
● Nothofagus pumilio
✳ Nothofagus betuloides
△ Grasslands
☐ Peatlands
■ Shrublands

Figure 6

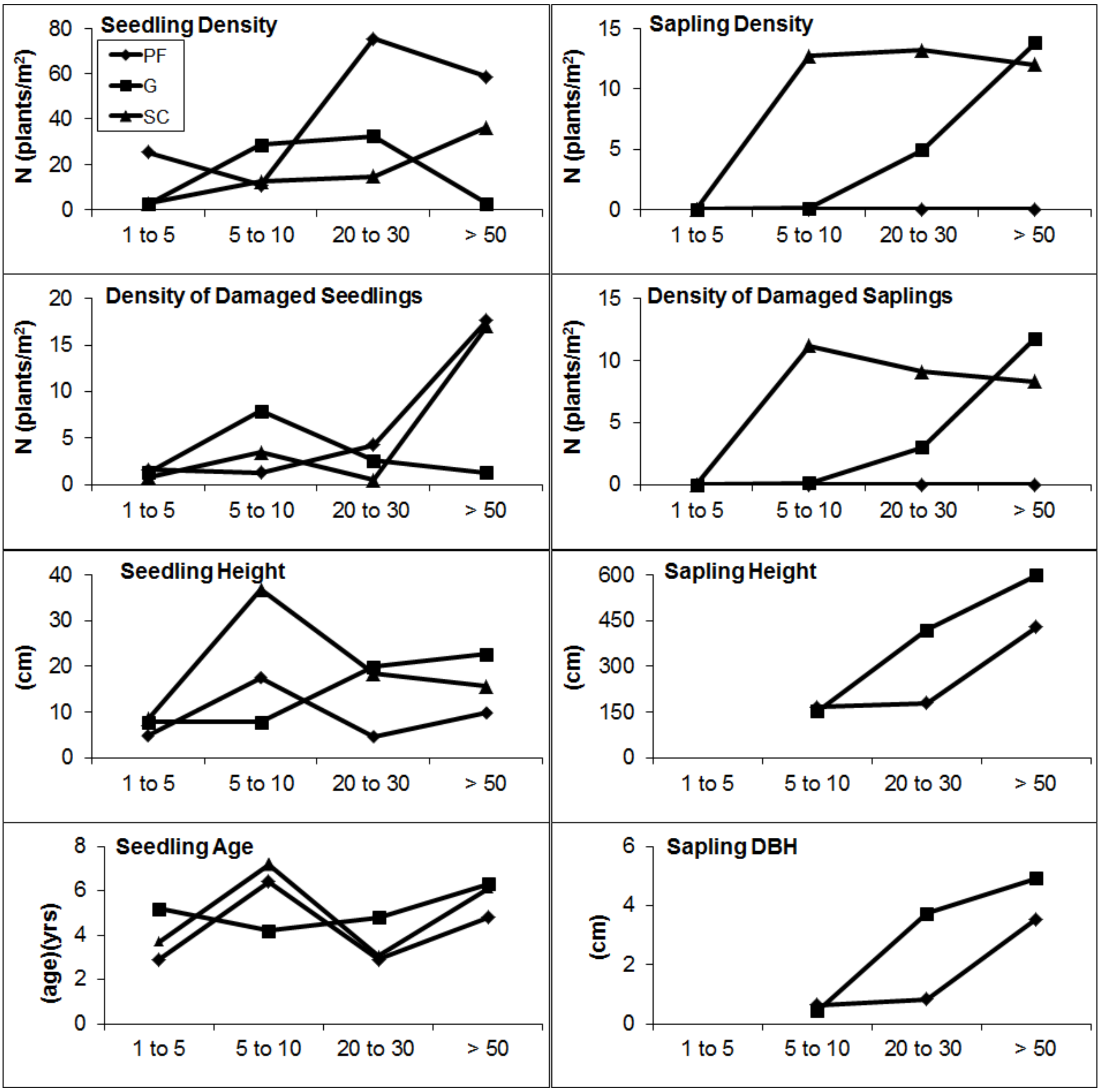

Seedling Density
N (plants/m²)
80
60
40
20
0
PF
G
SC
1 to 5
5 to 10
20 to 30
> 50
Sapling Density
15
10
5
Density of Damaged Seedlings
Density of Damaged Saplings
Seedling Height
(cm)
Sapling Height
600
450
300
150
Seedling Age
(age)(yrs)
8
6
4
2
Sapling DBH

Figure 7

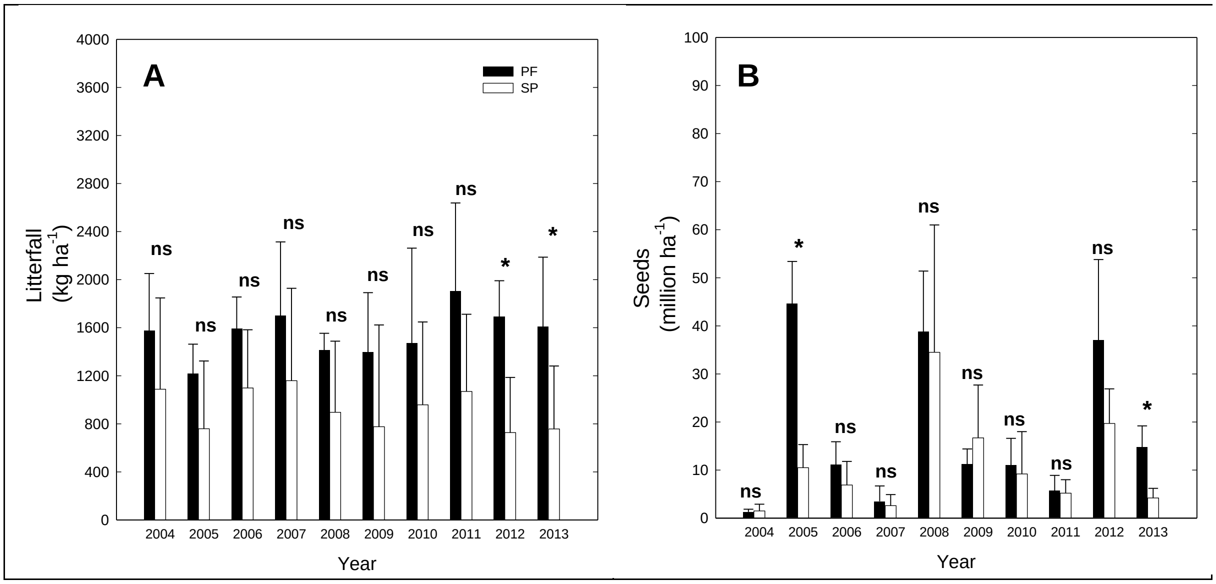

A
PF
SP
Litterfall (kg ha-1)
4000
3600
3200
2800
2400
2000
1600
1200
800
400
0
ns
ns
ns
ns
ns
ns
ns
ns
*
*
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
Year
B
Seeds (million ha-1)
100
90
80
70
60
50
40
30
20
10
0
ns
*
ns
ns
ns
ns
ns
ns
ns
*
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
Year

Figure 8

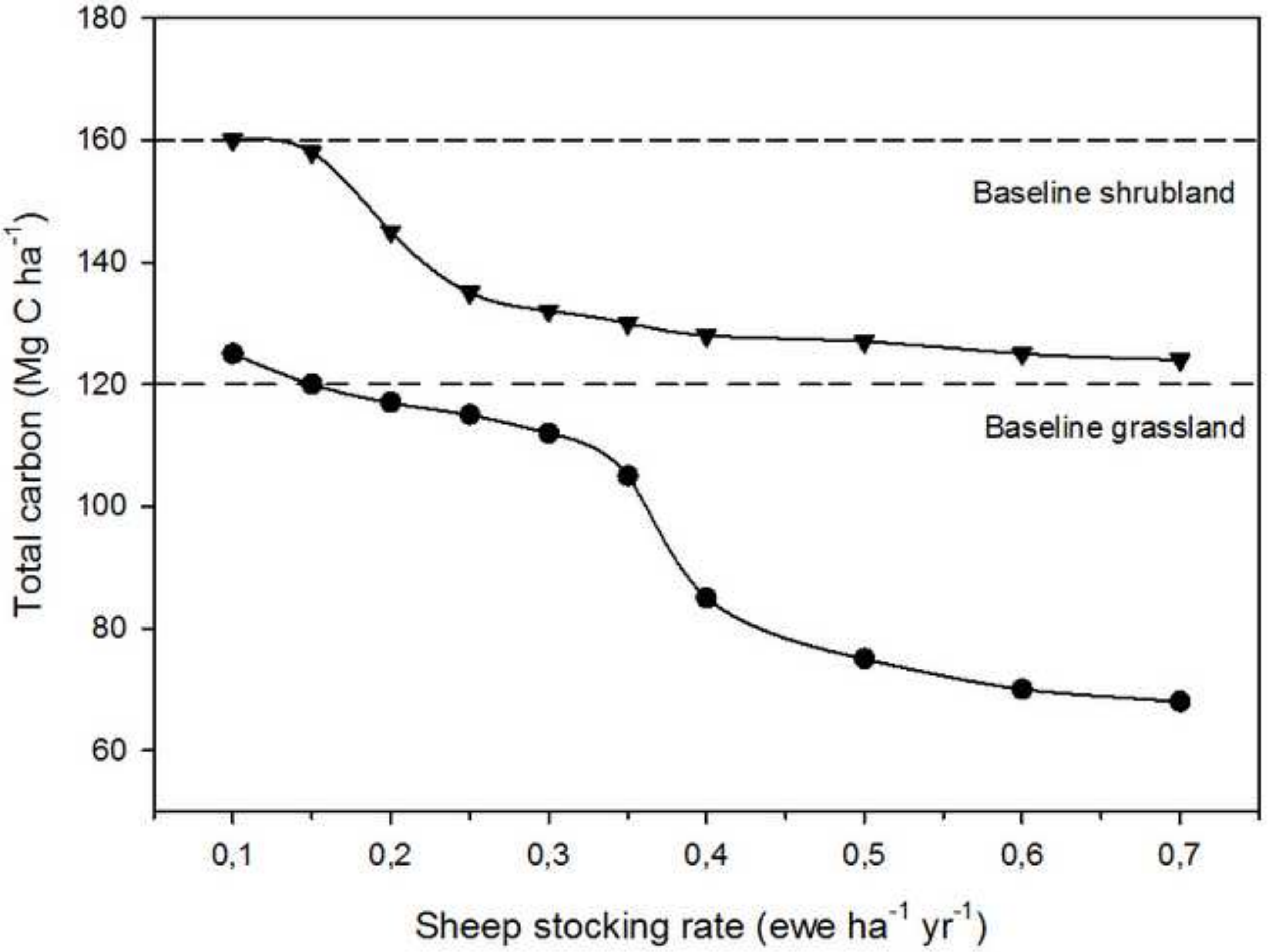

180
160
140
120
100
80
60
Total carbon (Mg C ha^{-1})
Baseline shrubland
Baseline grassland
0,1
0,2
0,3
0,4
0,5
0,6
0,7
Sheep stocking rate (ewe ha^{-1} yr^{-1})

Table 1 – Mean values of vegetation and environmental variables (± SD) impacted by contrasting long-term grazing intensity levels in dry Magellanic grass steppe.

Variables	Low Grazing	Medium Grazing	Intensive Grazing
Vascular species	27.7 (2.52)	25.3 (2.52)	16.7 (1.53)
Soil water infiltration (cm/h)	1.72 (0.06)	1.70 (0.97)	1.62 (0.08)
Soil water retention capacity (mm/cm)	1.70 (0.22)	1.65 (0.23)	1.40 (0.17)
Soil organic matter (%)	3.44 (0.27)	3.96 (0.42)	3.20 (0.24)
Soil nitrogen (%)	0.17 (0.01)	0.24 (0.02)	0.14 (0.01)
Soil respiration (g C/m2/h)	0.65 (0.05)	0.55 (0.04)	0.44 (0.03)
Bare soil (%)	5.90 (1.73)	10.2 (1.80)	22.5 (2.25)
Litter cover (%)	17.9 (1.95)	9.90 (2.45)	4.50 (1.15)
Vegetation cover (%)	76.4 (4.86)	79.9 (8.63)	73.0 (12.5)
Annual Net Primary Production (g m-2 yr-1)	29.1 (3.49)	32.4 (5.38)	11.6 (1.64)
Soil erosion (%)	0 (0.0)	3 (0.30)	15.0 (1.20)

Table 2 – Mean carbon content (± SD) levels in soil and above-ground/below-ground biomass.

Site	Stipa Grasslands	Festuca Riparian	Junellia tridens shrublands	N. antarctica forests
Above-ground	4.35 (0.31)	6.15 (0.63)	8.75 (0.93)	41.6 (5.3)
Below-ground	3.87 (0.27)	7.56 (0.58)	6.97 (0.78)	33.5 (2.8)
Soil (depth 30 cm)	97.5 (11.2)	168.3 (18.8)	144.2 (15.9)	184.1 (20.8)
Total	105.72	182.02	159.92	259.23

* Study area characteristics: In Magellanic Patagonian steppe Stipa chrysophylla and Festuca pallescens are dominant tussock species commonly associated with cool season Poadusenii and Carexandina short grasses. In Santa Cruz Province there is a thicket area dominated mainly by Mulguraea tridens covering 2.8 million hectares among the grasslands of the Magellanic steppe and the steppe of the Central Plateau Grass steppe with 65% S. chrysophylla, 3% P. dusenii, 1% F. pallescens and 1% C. andina. Grass riparian with 70% F. pallescens. 70% Shrub cover of thicket area dominated mainly by Mulguraea tridens. Mature (195 years) pure even-aged stand of Nothofagus antarctica grown at site class III where the mean total height of dominant tree (H) reached 10.2 m (basal area of 56 m2/ha; 895 trees/ha) (Peri et. al. 2010-2011).