



Social-Ecological Functional Types: Connecting People and Ecosystems in the Argentine Chaco

M. Vallejos,^{1,2,3*} S. Aguiar,^{1,4} G. Baldi,⁵ M. E. Mastrángelo,⁶ F. Gallego,⁷
M. Pacheco-Romero,^{8,9} D. Alcaraz-Segura,^{9,10,11} and J. M. Paruelo^{1,2,3,7}

¹Laboratorio de Análisis Regional y Teledetección (LART), IFEVA, Facultad de Agronomía, Universidad de Buenos Aires, CONICET, Buenos Aires, Argentina; ²Departamento de Métodos Cuantitativos y Sistemas de Información, Facultad de Agronomía, Universidad de Buenos Aires, Buenos Aires, Argentina; ³Instituto Nacional de Investigación Agropecuaria, INIA La Estanzuela, Ruta 50 km 11, Colonia, Uruguay; ⁴Cátedra de Ecología, Facultad de Agronomía, Universidad de Buenos Aires, Buenos Aires, Argentina; ⁵Instituto de Matemática Aplicada San Luis, Universidad Nacional de San Luis and CONICET, San Luis, Argentina; ⁶Grupo de Estudio de Agroecosistemas y Paisajes Rurales, Universidad Nacional de Mar del Plata, CONICET, Balcarce, Argentina; ⁷Grupo de Ecología de Pastizales, Instituto de Ecología y Ciencias Ambientales, Universidad de la República, Montevideo, Uruguay; ⁸Departamento de Biología y Geología, Universidad de Almería, Almería, Spain; ⁹Centro Andaluz para la Evaluación y Seguimiento del Cambio Global, Universidad de Almería, Almería, Spain; ¹⁰Departamen de Botánica, Facultad de Ciencias, Universidad de Granada, Av. Fuente-nueva s/n. 18071, Granada, Spain; ¹¹iecolab, Interuniversity Institute for Earth System Research (IISTA), University of Granada, Av. del Mediterráneo s/n. 18006, Granada, Spain

ABSTRACT

Sustainability science recognizes the importance of the integrated assessment of the ecological and social systems in land-use planning. However, most studies so far have been conceptual rather than empirical. We developed a framework to characterize the social-ecological systems heterogeneity according to its functioning through the identification of social-ecological functional types (SEFT). The SEFT framework builds on the plant, ecosystem and agent functional type approaches, taking a step forward to integrate the dimensions of social-ecological systems into an operational product to characterize administrative units in a hierarchical way. To illustrate this novel framework, we described the

heterogeneity of SEFT in the Argentine Chaco by clustering administrative entities. This area is a global deforestation hotspot and has diverse social actors that harness ecosystem services in multiple, and sometimes contrasting and conflictive, ways which determines an urgent need for land-use planning. We combined data from national census and remote sensing to identify SEFT by clustering census tracts based on 17 input variables that integrate key human, ecological and interaction processes across landscapes. We identified three classes and eight subclasses of SEFT. Ecological variables defined the first level of heterogeneity (classes), while human variables and the variables of interactions between the human and ecological components defined a second level of heterogeneity (subclasses). The degree of anthropization and mean annual productivity were important variables to explain the first two axes in the ordination (32% of the total variance). This framework offers a conceptually novel and comprehensive approach to understand the spatial heterogeneity of social-ecological systems functioning, which could play a pivotal role to support conservation or land-use planning in rural areas.

Received 10 January 2019; accepted 21 June 2019

Electronic supplementary material: The online version of this article (<https://doi.org/10.1007/s10021-019-00415-4>) contains supplementary material, which is available to authorized users.

Author's Contribution MV, SA, GB, MEM, FG and JMP conceived of or designed the study; MPR and DAS contributed new methods or models; MV analyzed data, performed research and wrote the paper and SA, GB, MEM, FG, MPR, DAS and JMP participated in the writing process.

*Corresponding author; e-mail: vallejos@agro.uba.ar

Key words: social–ecological systems; land-use planning; remote sensing; functional types; hierarchical analysis.

HIGHLIGHTS

- Social–ecological functional types (SEFT) are administrative units that share a similar social–ecological functioning
- SEFT were defined by clustering administrative units based on variables that integrate key human ecological and interaction processes across landscapes
- The degree of anthropization and mean annual productivity were the variables that captured most of the spatial variability of SEFT
- Ecological variables (for example primary productivity) defined a first level of heterogeneity and human variables a second one

INTRODUCTION

Solutions to environmental problems increasingly require systemic perspectives that integrate key aspects of the structure and function of ecological and social systems (Holling 2001). Although the full complexity of systems can never be characterized by maps (Hamann and others 2015), the definition of relatively homogeneous units in terms of its social–ecological functioning can contribute to land-use planning by spatially characterizing social and ecological dynamics together (Martín-López and others 2017). Traditionally, rural planning has characterized the spatial heterogeneity of landscapes through land zoning (that is, the delimitation of homogeneous areas) mainly based on biophysical properties (FAO 1996). Thus, human dimensions were seldom considered and biophysical properties were generally related to ecosystems structural attributes, whereas functional ones generally received less attention (Guerry and others 2015). The explicit spatial integration of these neglected properties of social–ecological systems could be an operational tool for understanding complex systems and defining evidence-based policies for sustainable development. This study develops a conceptual framework to map social–ecological systems according to their functioning. Using the Argentine Chaco as a case study, we applied this framework in order to identify social–ecological functional types (SEFT) by clustering the smallest

possible administrative unit at two nested levels. This area is a global deforestation hotspot and has diverse social actors that harness ecosystem services in multiple, and sometimes contrasting and conflictive, ways which determines an urgent need for land-use planning.

FUNCTIONAL FRAMEWORK TO CLASSIFY SOCIAL–ECOLOGICAL SYSTEMS

Functional characterizations are increasingly being considered a central aspect for sustainable management (Oliver and others 2015). According to Jax (2010), the functioning of a system refers to its ‘performance’ or ‘behavior,’ which is regulated by different mechanisms and interactions at multiple spatial and temporal scales. Previous studies have characterized functional types for ecological and human systems separately. For ecological systems, plant functional types were defined as groups of plants with a similar response to environmental conditions or with a similar effect on ecosystems (Walker 1997), so its use has spread, for example, to predict the responses of vegetation to global change (Bonan and others 2002). In a higher level of organization, ecosystem functional types were defined as ecosystems that regardless of their structure and composition have similar matter and energy dynamics (Paruelo and others 2001), and were useful for capturing the spatial and temporal heterogeneity of ecosystem functioning, as well as for improving the performance of general atmosphere circulation models (Müller and others 2014). For human systems, agent functional types were theoretically defined as groups of agents with a similar role and behavior regarding decision making related to land-use change (Arneith and others 2014). Although the usefulness of functional approaches for different levels of organization is widely acknowledged, a framework for classifying social–ecological systems according to its functioning, to our knowledge, has not been developed yet. As plant species, ecosystems and agents can be grouped according to common functional characteristics, social–ecological systems should be too.

Social–ecological systems are understood as systems where ecological and social components are strongly coupled through multiple mechanisms of interaction (Ostrom 2009). The social component benefits from the services provided by the ecosystem and, in turn, human agency modifies—directly or indirectly—the functioning and structure of ecosystems (Berkes and others 2003). As social–ecological systems cannot be identified or found in

nature (they are defined by the observer under a certain conceptual framework or question), their spatial limits are strongly dependent on the specific perspectives of the observer. Tracing these boundaries can be done in many different ways depending on the problem to be addressed and the data availability (Martín-López and others 2017). Although natural scientists frequently use landscape units or pixels as entities, social scientists focus on the individuals, households, farms or communities as units of analysis and demographers or decision makers base their analyses on administrative units to achieve better management efficiency.

Most studies on social–ecological systems in the literature have been conceptual rather than empirical (Herrero-Jáuregui and others 2018). However, there have been some efforts to develop approaches for mapping them by combining biophysical and social attributes. At the global scale, Ellis and Ramankutty (2008) used data on human population density, land use and land cover to derive a classification of anthromes (that is, anthropogenic biomes). More recently, Václavík and others (2013) integrated land-use intensity indicators with underlying environmental and socioeconomic factors to map global land system archetypes. On a regional level, Alessa and others (2008) identified social–ecological hotspots in the Kenai Peninsula of Alaska, as areas where there was a convergence between the social (human perceptions of the biological value of the landscape) and ecological (high net primary productivity) space. Based on the ecosystem services framework, Raudsepp-Hearne and others (2010) mapped the supply of ecosystem service bundles (that is, groups of services that appear together repeatedly) that allowed to identify emerging social–ecological dynamics across diverse landscapes in Quebec, Canada. With a similar approach, Hamann and others (2015) derived a classification based on the direct use level of local ecosystem services by households in South Africa, using national population censuses. Although the spatial integration of the human and ecological components has grown in recent years, there is still a lack of operational mapping approaches for characterizing the social–ecological system from a functional perspective.

In this study, we adopted the social–ecological system framework presented by the Resilience Alliance (2007, p. 8) as a basis to develop a more detailed framework to characterize the functioning of the social–ecological systems (see Figure 1). This framework emphasizes the interdependence and two-way feedbacks that exist between humans and the environment. In this framework, the social–

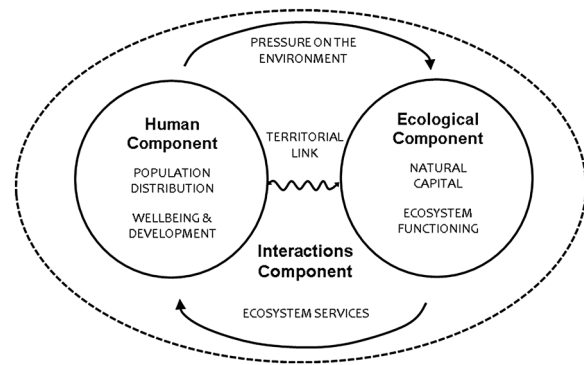


Figure 1. Conceptual diagram of the functional framework for assessing social–ecological systems. Each component (that is human, ecological and interactions) is comprised of two or three dimensions (for example, population distribution), which in turn should be characterized by one or more variables (for example, occupation of the territory) and its indicator (for example, population density) [Adapted and modified from Resilience Alliance (2007, p. 8)].

ecological system is composed of three interconnected components, which comprises two or three key dimensions. Within the human component, the population distribution is the way in which people are spatially arranged in the territory, whereas well-being and development integrate aspects related to housing, work, income, education, health status, governability and social connections, among others (OECD 2015). Within the ecological component, the natural capital refers to the stock of natural resources, which can provide people with free goods and services, while the ecosystem functioning refers to the fluxes of energy and matter that sustain the ecosystem over time and space (Jax 2010). Within the interaction component, the pressure on the environment reflects the impact of human activities on the ecosystem; the ecosystem services are the benefits people obtain from the natural environment (Millennium Ecosystem Assessment 2005), and the territorial link reflects the degree of decoupling between people and their surrounding environment (Liu and others 2007; Hamann and others 2015).

We define social–ecological functional types (SEFT) as administrative units that share a similar social–ecological functioning, that is, have similar dynamics in terms of (a) the socioeconomic aspects (human component), (b) biophysical aspects (ecological component) and (c) the two-way interactions between the previous subsystems (interactions component). This approach can be useful to explore complex systems, to understand

the spatial heterogeneity of social–ecological systems, to provide better inputs for modeling and as a tool to support conservation or land-use planning (for example, guiding participatory processes to regulate land use). The questions that guided this research are: (1) How to characterize SEFT using attributes of the social–ecological system functioning? (2) Which are the SEFT in the Argentine Chaco at the census tract resolution? (3) How are the attributes of social–ecological functioning correlated in the study area? (4) What are the spatial patterns among the SEFT classes at different levels of nesting?

METHODS

Study Area

The Humid and Dry Chaco ecoregions (hereafter, Chaco, see location in Figure A.1—Appendix A—Supplementary Material) (Olson and others 2001) of Argentina have a great biological and productive diversity (Baldi and others 2015), cultural richness (Leake 2008) and agricultural potential (Murray and others 2016), as well as high levels of poverty and inequality (Paolasso and others 2012). The social actors that occupy this region include large-scale capitalized farmers, small-scale farmers (*'puesteros'*), indigenous communities and mennonite colonists, among others (Baldi and others 2015). These actors interact with the environment in multiple ways by capturing ecosystem services and modifying the environment (for example, deforestation for industrial agriculture, silvopastures for livestock farming, selective logging or hunting and gathering). The rapid conversion of native forests to annual crops and pastures makes the Chaco region a global deforestation hotspot (Hansen and others 2013; Vallejos and others 2015). This transformation brought an increase in the production of commodities (for example, crops, meat) for the foreign markets, but at the same time is compromising the supply of multiple ecosystem services (Grau and others 2005; Paruelo and others 2011; Mastrangelo and Lateralra 2015), creating social inequalities (Lateralra and others 2019) and increasing social conflicts (Redaf 2011; Cáceres 2015; Aguiar and others 2016). Despite some legislation efforts (for example, Senado y Cámara de Diputados de la Nación Argentina 2007, Law N° 26,331), the territorial configuration responds more to an economic rationality, than to ecological, social and cultural criteria (García Collazo and others 2013; Aguiar and others 2018). The rapid changes are affecting the configuration of the

territory, not only in the ecological aspects (natural capital, ecosystem functioning), but also in the human aspects (population distribution, well-being and development) and in the interaction between both (pressure on the environment, ecosystem services and territorial link).

Data Sources and Preprocessing

The approach we followed to define SEFT consists of integrating human, ecological and interaction variables across rural landscapes to identify homogeneous administrative entities in terms of their social–ecological functioning. The resolution of the analysis was the 'rural census tract,' -that is, group of farms—an administrative unit designed to carry out the field surveys of agricultural censuses in Argentina. These divisions are delimited according to the way that population is distributed and settled in rural areas (divisions contain an average of 300 households), and also by the accessibility and distance between households, achieving a mean area of 180 km². Census data at this resolution are the finest and publicly available because the personal data protection prohibits the distribution of census data at finer resolutions in Argentina (Senado y Cámara de Diputados de la Nación Argentina 1968, Law N° 17,622). Because this study focused on rural land-use planning, census tracts corresponding to urban areas were eliminated. From 2188 rural census tracts, 22 were discarded due to missing or incongruent information (for example, area under irrigation larger than the total land), so we retained 2166 units.

For the classification of SEFT, we selected 17 descriptive variables, following the functional framework for assessing social–ecological systems described above (adapted and modified from the Resilience Alliance 2007, p. 8), that is, we selected variables and indicators according to the available data (Table 1) to characterize the dimensions of the three components of the framework (human, ecological and interactions). We gathered data from multiple governmental open-access databases, the 'National Census of Population, Households and Housing' (INDEC 2001) and the 'National Agricultural Census' (INDEC 2002). To characterize the ecosystem functioning, we used the 2002 seasonal dynamics of the enhanced vegetation index images derived from MODIS 005.MOD13Q1 product (16-day and 232 m resolution). Mean annual EVI and the intra-annual coefficient of variation were used as indicators of the primary productivity and its seasonality (difference in C gains between the growing and non-growing seasons), respectively.

Table 1. Variables Used for the Definition of Socio-ecosystem Functional Types at the Census Tract (CT) Resolution

Component	Dimension	Variable	Indicator	Metric	Abbreviation	Data source
Human	Population distribution	Occupation of territory	Population density	#Inhabitants/km ²	<i>Pop</i>	INDEC (2001)
	Well-being and development	Quality of life	Poverty	Unsatisfied basic needs	<i>Pov</i>	INDEC (2001)
		Employment	Permanent labor	#Permanent workers/1000 ha	<i>Lab</i>	INDEC (2002)
		Educational infrastructure	Number of schools	#Schools/km ²	<i>School</i>	Ministerio de Educación, Argentina (2012)
Ecological	Natural capital	Natural cover	Remnant native forest	Native forest area/CT area (%)	<i>Nf</i>	INDEC (2002)
	Ecosystem functioning	Productivity	Primary productivity (mean)	Annual mean of EVI (year 2002)	<i>PPm</i>	MOD13Q1-EVI - 2002
		Seasonality	Primary productivity (coefficient of variation)	Annual CV of EVI (year 2002)	<i>PPs</i>	MOD13Q1-EVI - 2002
Interactions	Pressure on the environment	Cultural practices	Surface with irrigation	Irrigated area/km ²	<i>Irrig</i>	INDEC (2002)
		Machinery	Number of tractors	#Tractors/1000 ha	<i>Tract</i>	INDEC (2002)
		Livestock intensity	Stocking rate	Livestock unit (cattle equivalent)/livestock area (ha)	<i>Cattle</i>	INDEC (2002)
		Loss of natural coverage	Natural cover transformation	Deforested area/CT area (%)	<i>Defor</i>	LART (2012)
	Ecosystem services	Agricultural production	Annual crops area	Annual crops area/CT area (%)	<i>Crops</i>	INDEC (2002)
		Livestock industrial production	Forage crops area	Forage crops area/CT area (%)	<i>Forage</i>	INDEC (2002)
		Cattle breeding activity	Cow pregnancy	#Pregnant cows/Total #cows (%)	<i>Calf</i>	INDEC (2002)
	Territorial link	Access	Transport network connectivity	Km of roads/km ²	<i>Roads</i>	Instituto Geográfico Nacional (2015)
		Type of management	Legal type of farmer	Area with legal type of farmer 'Physical Person'/CT area (%)	<i>Farmer</i>	INDEC (2002)
		Land tenure	Tenure regime	Area with land tenure regime 'Owner'/CT area (%)	<i>Tenure</i>	INDEC (2002)

These two indicators are descriptors of ecosystem functioning (Alcaraz-Segura and others 2006; Volante and others 2012) and have also been successfully used to quantify the provision of

ecosystem services (Puelo and others 2016). All variables were aggregated at the census tract resolution. We omitted the use of data from last National Agricultural Census of Argentina (2008), as

it turned out to be unreliable due to a non-exhaustive survey (Giarracca and others 2008).

Statistical Analyses

We explored the Pearson correlation between the 17 variables to analyze the sign and magnitude of the relationships between them. We standardized the variables and performed a hierarchical clustering analysis using Ward's method (Ward 1963) to identify SEFT classes and subclasses, in two nested levels of detail. Hierarchical clustering is useful to recognize discontinuities in the dataset of multiple variables, where the units of inferior-ranking clusters (subclasses) are members of larger and higher ranking (classes) (Legendre and Legendre 1998). Then, we performed a principal component analysis to understand the multivariate structure of data and to find which of the variables are more important to describe the heterogeneity of the data between the census tracts (Hair and others 2010). Once the SEFT subclasses were defined, we mapped them using QGIS development team (2016). Finally, we described each SEFT class and subclass in terms of the indicators conforming each class. Data analysis was done with R Core Team (2015), using the following packages: *'cluster'* (Maechler and others 2015), *'ggplot2'* (Wickham 2009), *'corrplot'* (Taiyun Wei 2013), *'rgdal'* (Bivand and others 2015), *'raster'* (Hijmans 2015) and *'sp'* (Pebesma and Bivand 2005).

RESULTS

Correlation Between Variables

Regarding the correlation between variables, of the 136 possible pairwise combinations, 75% were significant ($p < 0.01$). Of these, 66% presented positive relationships, while the remaining 34% were negative. The most significant positive correlation was the occupation of the territory (*Pop*) and the machinery (*Tractors*) ($r = 0.63$). The most significant negative correlations were between the natural cover (*Nf*) and the agricultural production (*Crops*), and between the productivity (*PPm*) and its seasonality (*PPs*) ($r = -0.40$, both) (Figure 2).

SEFT Classification

Rural census tracts were classified into three classes and eight subclasses of SEFT by using two cutting levels in the hierarchical clustering analysis. Class 1, 2 and 3 (defined by the first level) are composed by 550, 634 and 982 census tracts, respectively. Subclasses 1a, 1b, 1c, 2a, 2b, 3a, 3b and 3c (defined

by the second nested level) are composed by 157, 136, 257, 332, 302, 95, 252 and 635 census tracts, respectively (Figure 3). The principal component (PC) 1, (21.6% of the total variance), corresponds to an axis that varies from less-transformed census tracts with greater remnant native forests to more transformed tracts with higher population density. The PC 2, (10.9% of the total variance), corresponds to a gradient that goes from tracts with greater livestock pressure and higher mean annual productivity to tracts with greater agricultural activity and greater seasonality (Figure 4). Principal component analysis showed that seven axes were needed to explain 75% of the spatial variability between the census tracts (see complete analysis in Table B.1—Appendix B—Supplemental Material).

SEFT Mapping

We mapped the social–ecological functional types in the Argentine Chaco at the census tract resolution (Figure 5). Not all the census tracts are represented on the map because some tracts were discarded from the analysis (lack or inconsistency of data). We also described SEFT classes and subclasses in terms of the variables used for their classification (see Figure C.1 and C.2—Appendix B—Supplemental material).

Class 1 (*Agricultural functioning systems*) occupied census tracts in the western and central area of the study region, coinciding with foci of agricultural advance in the margins of the Dry Chaco, where rainfall is greater. This class covers an area of 62,000 km², and it has, on average, high population density (*Pop*), high levels of well-being and development (*Schools & Roads*), high land-use intensity (*Crops, Forage, Defor, Irrig & Tract*), high employment (*Lab*), high seasonality in the productivity (*PPs*) and low natural cover (*Nf*). Subclass 1a (*Small-scale intensive agriculture*) was located mainly in small-sized census tracts located in the province of Tucumán, where the sugarcane is the predominant crop. This subclass had the highest population density (*Pop*), employment (*Lab*), machinery (*Tract*) and agricultural production (*Crops*). Subclass 1b (*Traditional middle-scale agriculture*) was located mainly in the central southwestern region of the province of Chaco, where immigrant settlers deforested for cotton production in the mid-twentieth century and were then converted to the soybean production. This subclass has the highest loss of natural cover in the region (*Defor*) in the region. Subclass 1c, (*Expanding agribusiness*), was located in new foci of agricultural expansion in the eastern and western Dry Chaco.

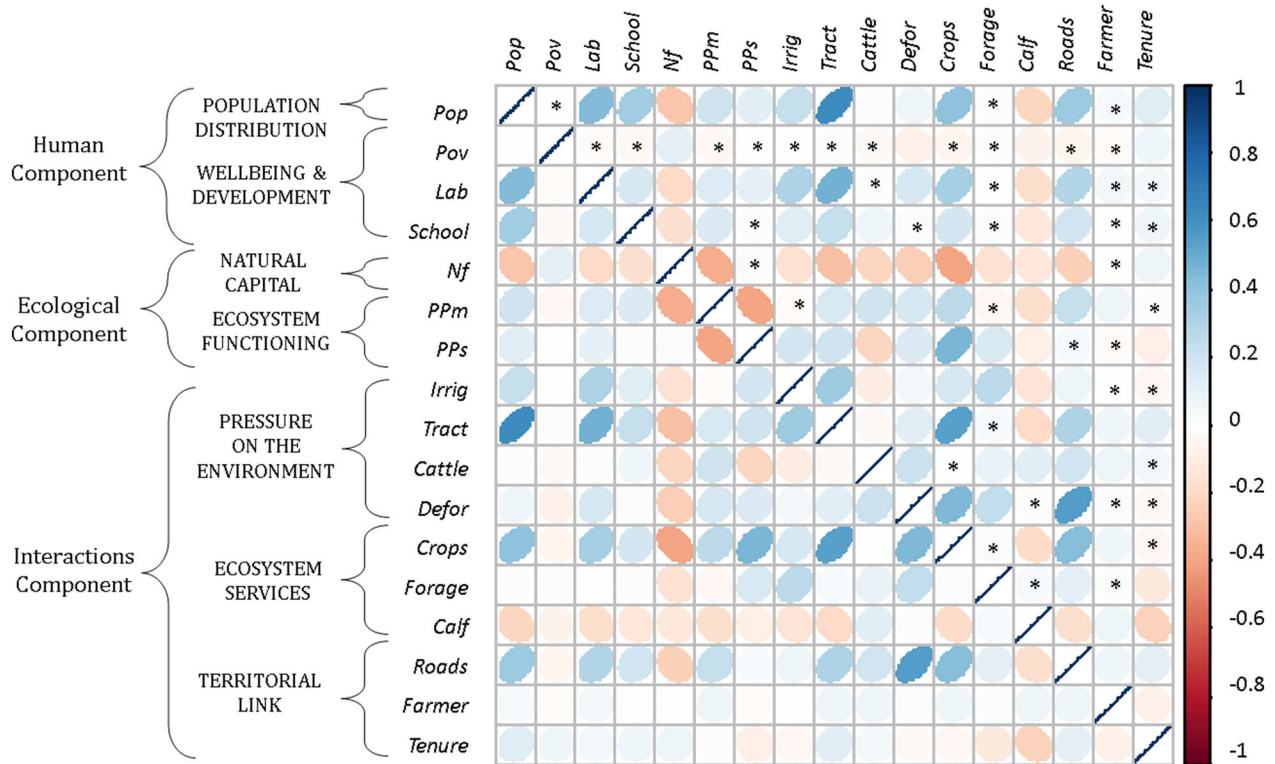


Figure 2. Correlation analyses between descriptive variables. The correlation coefficients are represented by ellipses (the more pronounced the shape of the ellipse, the greater the correlation) and colors (degrees of blue for positive correlations and degrees of red for negative correlations, the legend for correlation coefficients is at the left). The correlation significance is also shown (*are not significant correlations, p value > 0.01).

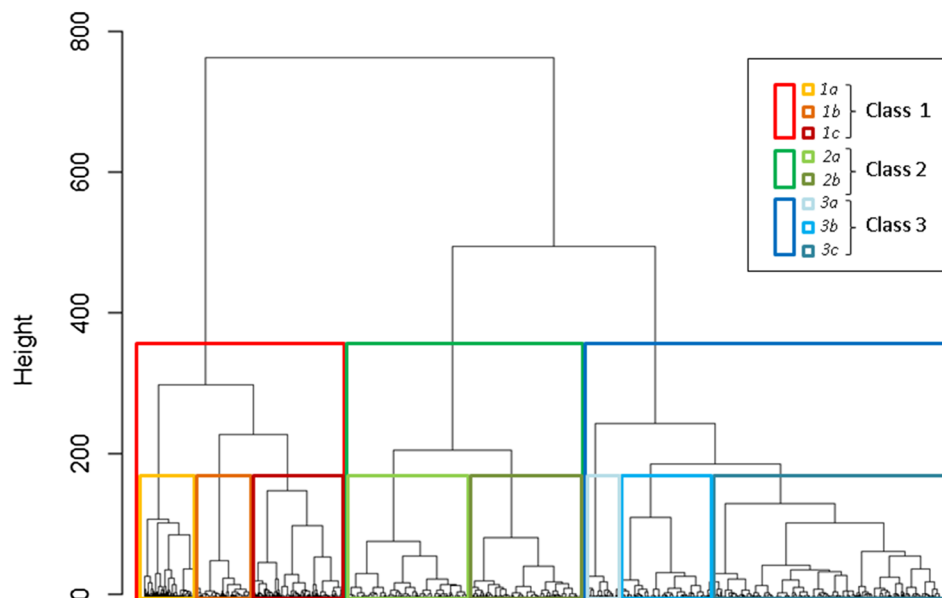


Figure 3. Hierarchical cluster analysis to identify social–ecological functional types. Three classes and eight subclasses were identified in the Argentine Chaco at the census tract resolution.

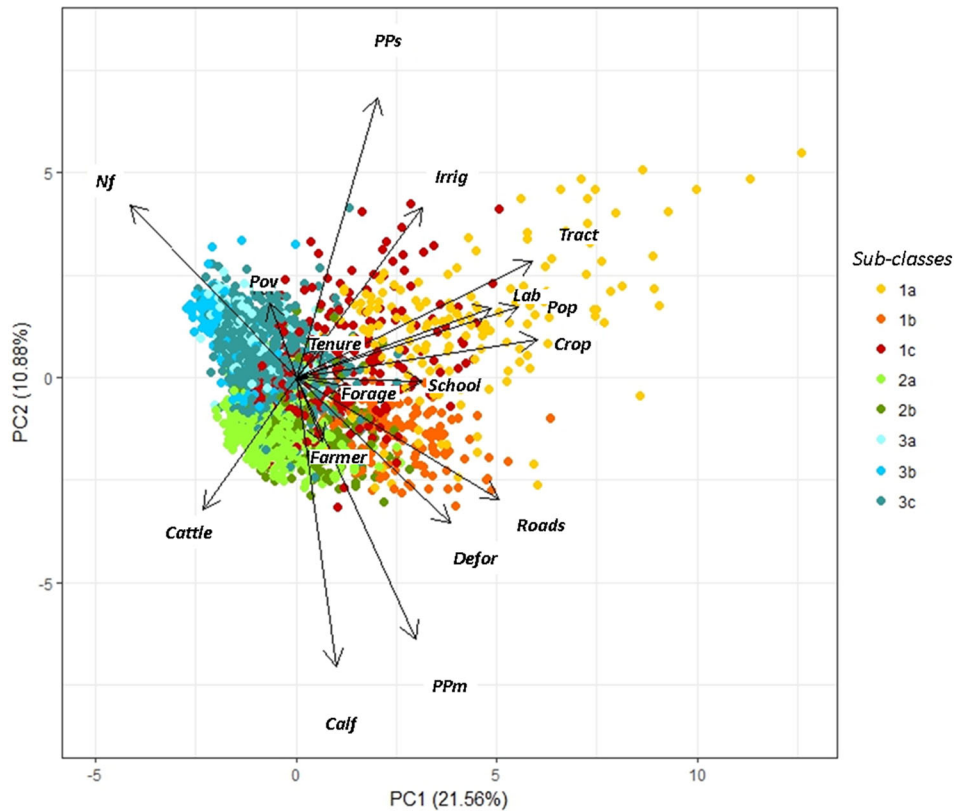


Figure 4. Principal component analysis (PCA) for the eight subclasses of SEFT. The first axis explains 21.6% of the variability of the data, whereas the second axis, 10.9%. Pop: population density; Pov: unsatisfied basic needs (poverty); Lab: permanent labor; School: number of schools; Nf: native forest area; PPM: mean net annual primary productivity; PPs: annual seasonality of net primary productivity; Irrig: irrigated area; Tract: number of tractors per area; Cattle: stocking rate; Defor: natural cover transformation; Crops: annual crops area; Forage: forage crops area; Calf: % cow pregnancy; Roads: roads density; Farmer: legal type of farmer; Tenure: tenure regime.

This was the subclass with the highest livestock industrial production (*Forage*) and the greatest irrigated area (*Irrig*) of the whole region.

Class 2 (*Extensive stockbreeding functioning systems*) is located mainly in the eastern portion of the study region, coinciding with the Humid Chaco, where agricultural aptitude is low due to the water surplus during the rainy season, and the predominance of low and flooded land. This class covers an area of 124,000 km², and has, on average, high productivity (*PPM*), low seasonality (*PPs*), low deforestation rates (*Defor*), high proportion of cattle breeding activities (*Calf*) and high stocking rates (*Cattle*). Subclass 2a (*Cattle breeding dominance*) was located in the eastern and southern part of the Humid Chaco, where the floods are mostly of fluvial origin (Paraguay and Paraná Rivers floodplains). This subclass had the highest proportion of cattle breeding activities (*Calf*) of the whole region. Subclass 2b (*Livestock farming dominance*) was located in the northern and eastern part of the Humid Chaco.

This subclass had the highest stocking rate (*Cattle*) of the whole region. Within Class 2, it is observed that subclass 2a has lower primary productivity mean (*PPM*) and higher seasonality (*PPs*) than subclass 2b, because in 2a, there is naturally more pasture than in 2b. The deforestation rates are lower in part because the amount of native forests is lower too.

Class 3 (*Forest functioning systems*) occupy most of the western zone of the study region, coinciding with the central and southern portion of the Dry Chaco, where rainfalls are low and the lands are marginal for agriculture. This class covers an area of 340,000 km², and has, on average, high native forest area (*Nf*), low productivity (*PPM*), low pressure on the environment (*Irrig*, *Tract*, *Cattle*, *Defor*), low population density (*Pop*), low levels of well-being and development (*Pov*, *Lab*, *Schools*) and low access (*Roads*). Subclass 3a (*Subsistence activities dominance*) was located in census tracts with predominance of indigenous communities or small

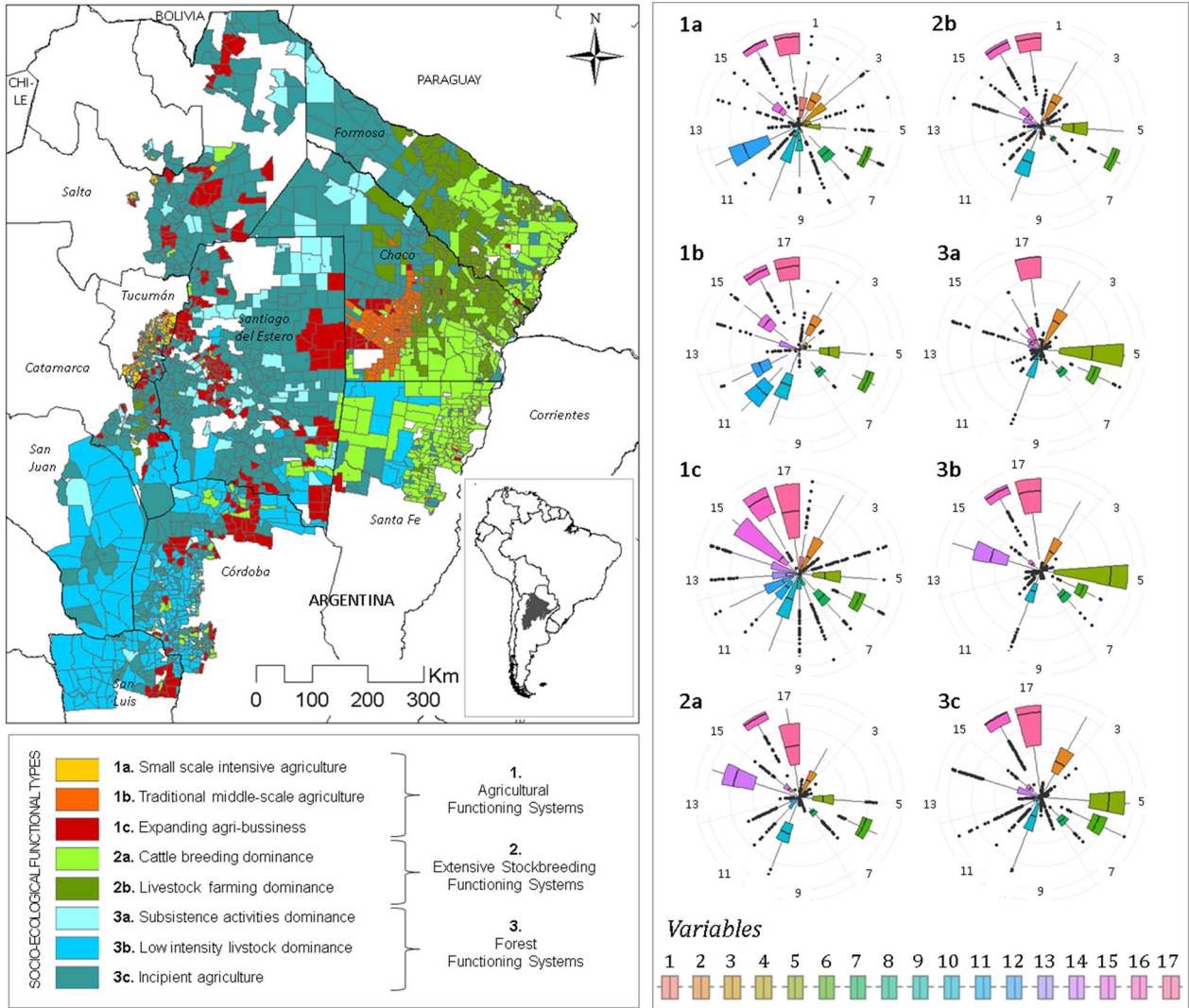


Figure 5. Social–ecological functional types in the Argentine Chaco at census tract resolution (corresponding to the year 2002). Eight subclasses of SEFT are shown in the map: 1a, 1b, 1c, 2a, 2b, 3a, 3b and 3c. The polar diagrams at the right of the figure illustrate the contribution of the 17 variables for each subclass of SEFT. All the variables are scaled from 0 to 1. Variables: 1. Pop (population density); 2. Pov (poverty); 3. Lab (permanent labor); 4. School (number of schools); 5. Nf (native forest area); 6. Ppm (mean annual primary productivity); 7. PPs (annual seasonality of primary productivity); 8. Irrig (irrigated area); 9. Tract (number of tractors per area); 10. Cattle (stocking rate); 11. Defor (natural cover transformation); 12. Crops (annual crops area); 13. Forage (forage crops area); 14. Calf (% cow pregnancy); 15. Roads (roads density); 16. Farmer (legal type of farmer); 17. Tenure (land tenure regime).

farmers. This subclass had the lowest dominance of physical person as legal type of farmer (*Farmer*). This means that other legal types of farmer are dominant (for example, societies, cooperatives, nonprofit institutions, national public entities). Subclass 3b (*Low intensity livestock dominance*) was located in census tracts in the southern part of the Dry Chaco, corresponding with the Arid Chaco. This subclass had the lowest productivity (*PPm*) in the whole region, and the highest proportion of cattle breeding activity (*Calf*) of Class 3. Subclass 3c (*Incipient agriculture*) was located in census tracts in

the northern part of the Dry Chaco, where agriculture is expanding. This subclass had the highest productivity (*PPm*) and agricultural production (*Crops*) within Class 3, but also has the highest levels of structural poverty in the whole region (*Pov*).

DISCUSSION

Mapping SEFT allowed us to characterize and understand the heterogeneity of the social–ecological systems in the Chaco. We identified three classes and eight subclasses, in a nested level of

detail at the census tract resolution. These classes represent relatively homogeneous units in terms of its social–ecological functioning. Our results showed that ecological variables defined the first level of heterogeneity (classes), while human and interaction variables defined a second level of heterogeneity (subclasses). This supports not only the importance of considering the human dimension when zoning the territory but also suggest a hierarchy of the controls that determine the spatial distribution of SEFT.

Class 1 is associated with *Agricultural functioning systems*, where there is a high pressure on the environment, high seasonality of the productivity and intermediate levels of well-being. Class 2 is associated with *Extensive cattle functioning systems*, where there is a high livestock production, a lower pressure on the environment in relation to the first class, high mean annual productivity and low seasonality of the productivity. Class 3 is associated with *Forest functioning systems*, where there is a high native forest area, high structural poverty, predominance of de-capitalized producers and low mean annual productivity. Class 2 and 3 are clearly associated with biogeographical areas (Humid and Dry Chaco, respectively), while Class 1 is interspersed mainly over Class 3, reflecting the advance of agriculture mainly in the Dry Chaco. In this region, agriculture is expanding over areas with less suitability, and land clearing dynamics are associated with the proximity to already cleared areas, defining a frontier-advancement pattern which suggests the prevalence of a contagion process (Volante and others 2016). In the last two decades, agriculture has drastically expanded into the Chaco ecoregion, due to favorable political and economic factors in Argentina, increasing soybean prices and new genetically modified varieties, between other aspects (Pengue 2005; Cáceres 2015; Piquer-Rodríguez and others 2018). Although it was not possible to capture the current state of social–ecological systems in this study, we can assume that the expanding agri-business (that is, Subclass 1c) has spread out in many census tracts of the study area in the present.

The degree of anthropization and mean annual productivity were important variables to explain the first two axes in the ordination (32% of the total variance). Biophysical and social variables showed a low-to-moderate level of covariation, evidencing their high complementarity for the definition of the SEFT classes. In fact, the seven of axes needed to explain 75% of the spatial variability in the principal component analysis reveals the complex and multidimensional nature of so-

cial–ecological systems. Although in this case the reduction in dimensionality was not possible, we support the use of multivariate analyses in order to understand the structure of the data and, hence, the importance of each variable for the definition of SEFT.

When studying the correlation of variables at the census tract resolution, we observed that census tracts located in disadvantaged environments (that is, with low productivity) were also those that showed less pressure on the environment (low population density, technification level and natural cover transformation). Moreover, we observed that in these areas, where agri-business agriculture is not feasible and the natural cover has not been replaced, the levels of well-being and development are low (high poverty, low employment and educational infrastructure). This reflects a clear connection between land quality and poverty, suggesting a long-term ‘accumulation by dispossession’ process (Harvey 2004; Cáceres 2015), where smallholders are on poor land because they have been expelled by large farmers. This process of marginalization of the less capitalized stakeholders in lower-quality lands entails a potential risk of poverty traps (Aghion and Durlauf 2005), as marginal producers make use of the surrounding forest intensifying the degradation of natural resources, which in turn feeds back the level of poverty (Duraiappah 1998). This situation is difficult to overcome without an appropriate redistribution of wealth, and the implementation of incentives for marginalized lands. The results presented here could be used to identify the areas prone to poverty traps to apply specific interventions oriented toward promoting rural development and halting environmental degradation.

The identification of SEFT using administrative units as entities is useful for land-use planning because it represents the space where interests and problems relevant to local stakeholders connect with decision makers (Martín-López and others 2017). Studying social and ecological aspects together at lower resolutions (for example, land-holding level) also matters because of its direct link with the unit in which stakeholders make decisions. This would require the collection of primary data from interviews and field surveys, and the use of high spatial resolution satellite information. The choices over scale, extent and resolution critically affect the type of patterns that are observed, because patterns that appear at one level of resolution or extent may be lost at lower or higher scales (Gibson and others 2000). So, the observed patterns cannot be extrapolated to other scales

(Peterson and others 1998). Complex systems must be analyzed and managed by performing a simultaneous analysis at various scales and approaches (Viglizzo and others 2005; Cumming and others 2006). At a regional scale, coarse resolutions are enough to answer questions about the general patterns of interaction between social and natural systems, but to study smaller geographic areas, more detailed resolutions will be required (Gibson and others 2000).

Despite the complexity of social–ecological systems, it is possible to assess them in a degree of simplicity necessary for understanding, but also with the required complexity to develop policies for sustainability (Holling 2001). Nevertheless, conceptualizing the systems functioning is a matter of both scientific knowledge and values. The definition of the system limits, the selection of variables and the classification methods are always dependent on the observer and his/her specific interests or problems to be tackled. Depending on the objectives and resolution of the study other criteria for the selection of variables may be used. Once the classification has been conducted and distinct modes of functioning were identified, the question of which of those modes of functioning is preferable (or desirable) is still a matter of evaluation by human observers (Theobald and others 2005). Each mode of functioning can be considered as ‘proper functioning’ for its kind of system and state, or not. Each productive system has ‘winners’ and ‘losers’ among the parts involved and impacted, and also in terms of the services that human may derive from the system (Jax 2010). Although the definition of SEFT is not absolutely neutral (since the choice of the unit to be classified, the variables for its classification and also the number of classes are made by humans), the advantage of using SEFT for understanding the social–ecological heterogeneity of the territory lies in the transparency of the process. Therefore, it could be a useful tool to guide participatory processes in land-use planning and to define sustainable policies in more transparent and integrative ways (for example, seeking for consensus with regard to the expansion of particular activities in a SEFT class), as a function of the overall performance or functioning of the system.

Land-use planning implies a public policy that must reconcile the process of economic development and the conservation of natural capital through the regulation of land use, with the ultimate goal of increasing the human well-being and the equity in the distribution of cost and benefits associated with land use. The identification and

mapping of SEFT constitutes a social–ecological-based zoning process, where territorial units have a similar behavior or functioning in terms of its social–ecological vulnerability, adaptability and resilience (Chapin and others 2009). The framework developed here might help decision makers to understand the social–ecological context to establish restrictions, incentives or to promote an effective spatial arrangement of activities. For example, the area of the triple border of the Santiago del Estero, Chaco and Santa Fe provinces shares the same biophysical characteristics. However, provincial boundaries define different SEFT due to differences in the human aspects or the interaction between the biophysical and ecological components (Figure 5). Whereas in eastern Santiago del Estero SEFTs associated with an expanding agribusiness were dominant, in western Chaco dominant SEFT were associated with more traditional middle-scale agriculture. In northern Santa Fe, in contrast, dominant SEFT were associated with subsistence activities or cattle breeding. All these SEFT present contrasting socio-ecological arrangement and, consequently, different potential roles or functions in the region (for example, providing commodities for exports, meat or areas for conservation). The presences of distinct SEFT would also indicate differences in stakeholders and actual or potential conflicts. Such discrimination clearly indicates the need of different intervention policies. In short, the use of SEFT facilitates a more inclusive understanding of the territory in a comprehensive and transparent framework and could be useful to identify areas within which to develop similar management policies in accordance with the objectives of the land-use planning. Improving access to scientific information could help decision makers anticipate potential consequences of rural land-use change and in doing so, avoid unintended ecological and social effects. Finally, the developed framework can be applied to understand the heterogeneity, complexity and trends of social–ecological systems in other regions of the world.

ACKNOWLEDGEMENTS

This research was supported by Consejo Nacional de Investigaciones Científicas y Técnicas (Argentina), Universidad de Buenos Aires (Argentina). This work was carried out with the aid of a grant from the Inter-American Institute for Global Change Research (IAI) CRN III 3095, which is supported by the US National Science Foundation (Grant GEO-1128040), and an associated complementary project financed by CONICET. The project

CGL2014-61610-EXP, which is supported by Dirección General de Investigación Científica y Técnica, Ministerio de Economía y Competitividad (Spain) also provided fundings for the research. We would also like to thank anonymous referees and the editors, who have made valuable comments to a previous version of the manuscript, and to Dr. Ignacio Gasparri who also made useful comments.

REFERENCES

- Aghion P, Durlauf SN. 2005. Handbook of Economic Growth. Amsterdam: North Holland.
- Aguiar S, Texeira M, Paruelo JM, Román ME. 2016. Conflictos por la tenencia de la tierra en la provincia de Santiago del Estero. Su relación con los cambios en el uso de la tierra. In: Transformaciones agrarias argentinas durante las últimas décadas: una visión desde Santiago del Estero y Buenos Aires. FAUBA. Buenos Aires. pp 199–225.
- Aguiar S, Mastrangelo ME, García-Collazo MA, Camba-Sans G, C.E. M, Ciuffoli L, Schmidt M, Vallejos M, Langbehn L, Cáceres D, Merlinsky G, J.M. P, Seghezzi L, Staiano L, Texeira M, Volante J, Verón S. 2018. ¿Cuál es la situación de la Ley de Bosques en la Región Chaqueña a diez años de su sanción? Revisando su pasado para discutir su futuro. *Ecología Austral*, en prensa.
- Alcaraz-Segura D, Paruelo JM, Cabello J. 2006. Identification of current ecosystem functional types in the Iberian Peninsula. *Global Ecology and Biogeography* 15:200–12.
- Alessa L, Kliskey A, Brown G. 2008. Social-ecological hotspots mapping: A spatial approach for identifying coupled social-ecological space. *Landscape and Urban Planning* 85:27–39.
- Arneth A, Brown C, Rounsevell MDA. 2014. Global models of human decision-making for land-based mitigation and adaptation assessment. *Nature Climate Change* 4:550–7.
- Baldi G, Houspanossian J, Murray F, Rosales AA, Rueda CV, Jobbágy EG. 2015. Cultivating the dry forests of South America: Diversity of land users and imprints on ecosystem functioning. *Journal of Arid Environments* 123:47–59.
- Berkes F, Folke C. 1998. Linking social and ecological systems: management practices and social mechanisms for building resilience. New York: Cambridge University Press.
- Berkes F, Colding J, Folke C. 2003. Navigating Social-Ecological Systems. Cambridge: Cambridge University Press.
- Bivand R, Keitt T, Rowlingson B. 2015. Rgdal: Bindings for the Geospatial Data Abstraction Library. R package version 1.0-6. <http://CRAN.R-project.org/package=rgdal>. Accessed 1 July 2019.
- Bonan GB, Levis S, Kergoat L, Olson KW. 2002. Landscapes as patches of plant functional types: An integrating concept for climate and ecosystem models. *Global Biogeochemical Cycles* 2 16:1–18.
- Cáceres DM. 2015. Accumulation by Dispossession and Socio-Environmental Conflicts Caused by the Expansion of Agribusiness in Argentina. *Journal of Agrarian Change* 15:116–47.
- Chapin FS, Folke C, Kofinas GP. 2009. A Framework for Understanding Change. In: Principles of Ecosystem Stewardship. New York, NY: Springer New York. pp 3–28.
- Cumming GS, Cumming DHM, Redman CL. 2006. Scale Mismatches in Social-Ecological Systems: Causes, Consequences, and Solutions. *Ecology and Society* 11:1–14.
- Duraiappah AK. 1998. Poverty and environmental degradation: A review and analysis of the nexus. *World Development* 26:2169–79.
- Ellis EC, Ramankutty N. 2008. Putting people in the map: anthropogenic biomes of the world. *Frontiers in Ecology and the Environment* 6:439–47.
- FAO. 1996. Agro-ecological zoning guidelines. Rome: Food and Agriculture Organization of the United Nation. Soil Resources, Management and Conservation Service.
- García Collazo MA, Panizza A, Paruelo JM. 2013. Ordenamiento territorial de bosques nativos: Resultados de la zonificación realizada por provincias del norte Argentino. *Ecología Austral* 23:97–107.
- Giarracca N, Teubal M, Palmisano T. 2008. Paro agrario: crónica de un conflicto alargado. *Realidad Económica* 237:33–54.
- Gibson CC, Ostrom E, Ahn TK. 2000. The concept of scale and the human dimensions of global change: a survey. *Ecological Economics* 32:217–39.
- Grau HR, Aide TM, Gasparri NI. 2005. Globalization and Soybean Expansion into Semi-arid Ecosystems of Argentina. *AMBIO: A Journal of the Human Environment* 34:265–6.
- Guerry AD, Polasky S, Lubchenco J, Chaplin-Kramer R, Daily GC, Griffin R, Ruckelshaus M, Bateman IJ, Duraiappah A, Elmqvist T, Feldman MW, Folke C, Hoekstra J, Kareiva PM, Keeler BL, Li S, Mckenzie E, Ouyang Z, Reyers B, Ricketts TH, Rockström J, Tallis H, Vira B. 2015. Natural capital and ecosystem services informing decisions: From promise to practice. *PNAS* 112:7348–55.
- Hair J., Black WC, Babin BJ, Anderson RE. 2010. Multivariate Data Analysis. A Global Perspective. 7th Edition, Pearson Education, Upper Saddle River.
- Hamann M, Biggs R, Reyers B. 2015. Mapping social-ecological systems: Identifying ‘green-loop’ and ‘red-loop’ dynamics based on characteristic bundles of ecosystem service use. *Global Environmental Change* 34:218–26.
- Hansen MC, Potapov PV, Moore R, Hancher M, Turubanova SA, Tyukavina A, Thau D, Stehman SV, Goetz SJ, Loveland TR, Komareddy A, Egorov A, Chini L, Justice CO, Townshend JRG. 2013. High-resolution global maps of 21st-century forest cover change. *Science (New York, NY)* 342:850–3.
- Harvey D. 2004. The New Imperialism: Accumulation by Dispossession. *Socialist Register* 40:63–87.
- Herrero-Jáuregui C, Arnaiz-Schmitz C, Reyes MF, Telesnicki M, Agramonte I, Easdale MH, Schmitz MF, Montes C, Aguiar M, Gómez-Sal A. 2018. What Do We Talk about When We Talk about Social-Ecological Systems? A Literature Review. *Sustainability* 10:2950.
- Hijmans RJ. 2015. Raster: Geographic Data Analysis and Modeling. R package version 2.4-18. <http://CRAN.R-project.org/package=raster>. Accessed 1 July 2019.
- Holling CS. 2001. Understanding the Complexity of Economic, Ecological, and Social Systems. *Ecosystems* 4:390–405.
- INDEC. 2001. Censo Nacional de Población, Hogares y Viviendas 2001.
- INDEC. 2002. Censo Nacional Agropecuario 2002.
- Instituto Geográfico Nacional. 2015. Red vial. <http://www.ign.gob.ar/NuestrasActividades/InformacionGeoespacial/CapasSIG>. Accessed 1 July 2019.

- Jax K. 2010. *Ecosystem Functioning*. Cambridge: Cambridge University Press.
- LART 2012. Laboratorio de Análisis Regional y Teledetección. 'Monitoreo de desmonte' Project. <http://monitoreodesmonte.com.ar/>. Accessed 1 July 2019.
- Laterra P, Nahuelhual L, Vallejos M, Berrouet L, Arroyo Pérez E, Enrico L, Jiménez-Sierra C, Mejía K, Meli P, Rincón-Ruiz A, Salas D, Špirić J, Villegas JC, Villegas-Palacio C. 2019. Linking inequalities and ecosystem services in Latin America. *Ecosystem Services* 36:100875.
- Leake A. 2008. Los pueblos indígenas cazadores-recolectores del Chaco Salteño: población, economía y tierras. Salta, Argentina: Fundación Asociana: Instituto Nacional de Asuntos Indígenas, Universidad Nacional de Salta.
- Legendre P, Legendre L. 1998. *Numerical ecology*. Amsterdam: Elsevier.
- Liu J, Dietz T, Carpenter SR, Alberti M, Folke C, Moran E, Pell AN, Deadman P, Kratz T, Lubchenco J, Ostrom E, Ouyang Z, Provencher W, Redman CL, Schneider SH, Taylor WW. 2007. Complexity of coupled human and natural systems. *Science* (New York, NY) 317:1513–16.
- Maechler M, Rousseeuw P, Struyf A, Hubert M, Hornik K. 2015. cluster: Cluster Analysis Basics and Extensions. R package version 2.0.3. <http://CRAN.R-project.org/package=cluster..> Accessed 1 July 2019.
- Martín-López B, Palomo I, García-Llorente M, Iniesta-Arandia I, Castro AJ, García Del Amo D, Gómez-Baggethun E, Montes C. 2017. Delineating boundaries of social-ecological systems for landscape planning: A comprehensive spatial approach. *Land Use Policy* 66:90–104.
- Mastrangelo ME, Laterra P. 2015. From biophysical to social-ecological trade-offs: integrating biodiversity conservation and agricultural production in the Argentine Dry Chaco. *Ecology and Society* 20:art20.
- Millennium Ecosystem Assessment. 2005. *Ecosystems and human well-being: synthesis*. In: Island Press; Washington D.C., USA. Oxford University Press, New York, USA.
- Ministerio de Educación, Argentina 2012. (Data unpublished).
- Müller OV, Berbery EH, Alcaraz-Segura D, Ek MB, Müller OV, Berbery EH, Alcaraz-Segura D, Ek MB. 2014. Regional Model Simulations of the 2008 Drought in Southern South America Using a Consistent Set of Land Surface Properties. *Journal of Climate* 27:6754–78.
- Murray F, Baldi G, von Bernard T, Viglizzo EF, Jobbágy EG. 2016. Productive performance of alternative land covers along aridity gradients: Ecological, agronomic and economic perspectives. *Agricultural Systems* 149:20–9.
- OECD. 2015. *How's Life? 2015: Measuring Well-being*. Paris: OECD Publishing.
- Oliver TH, Heard MS, Isaac NJB, Roy DB, Procter D, Eigenbrod F, Freckleton R, Hector A, Orme CDL, Petchey OL, Proença V, Raffaelli D, Suttle KB, Mace GM, Martín-López B, Woodcock BA, Bullock JM. 2015. Biodiversity and Resilience of Ecosystem Functions. *Trends in Ecology & Evolution* 30:673–84.
- Olson DM, Dinerstein E, Wikramanayake ED, Burgess ND, Powell GVN, Underwood EC, Damico JA, Itoua I, Strand HE, Morrison JC, Loucks CJ, Allnutt TF, Ricketts TH, Kura Y, Lamoreux JF, Wettengel WW, Hedao P, Kassem KR. 2001. *Terrestrial Ecoregions of the World: A New Map of Life on Earth*. *BioScience* 51:933.
- Ostrom E. 2009. A General Framework for Analyzing Sustainability of Social-Ecological Systems. *Science* 325:419–22.
- Paolasso P, Bolsi A, Gasparri I, Longhi F. 2012. La pobreza en el nordeste argentino: cambios y persistencias durante la primera década del siglo XXI. In: *Estudios y contribuciones en homenaje a la doctora Norma Cristina Meichtry*. Resistencia: Ed. Con Texto. p 111–136.
- Paruelo JM, Jobbágy EG, Sala OE. 2001. Current Distribution of Ecosystem Functional Types in Temperate South America. *Ecosystems* 4:683–98.
- Paruelo JM, Verón SR, Volante JN, Seghezze L, Vallejos M, Aguiar S, Amdan L, Baldassini P, Ciuffolli L, Huykman N, Davanzo B, González E, Landesmann J, Picardi D. 2011. Conceptual and Methodological Elements for Cumulative Environmental Effects Assessment (CEEA) in Subtropical Forests. The Case of Eastern Salta, Argentina. *Ecologia Austral* 21:163–78.
- Paruelo JM, Teixeira M, Staiano L, Mastrángelo M, Amdan L, Gallego F. 2016. An integrative index of Ecosystem Services provision based on remotely sensed data. *Ecological Indicators* 71:145–54.
- Pebesma EJ, Bivand RS. 2005. Classes and methods for spatial data. R package version 3.1–1. <http://CRAN.R-project.org/package=sp>.
- Pengue W. 2005. Transgenic crops en Argentina: the ecological and social debt. *Bulletin of Science, Technology and Society* 25:322.
- Peterson G, Allen CR, Holling CS. 1998. Ecological Resilience, Biodiversity, and Scale. *Ecosystems* 1:6–18.
- Piquer-Rodríguez M, Butsic V, Gärtner P, Macchi L, Baumann M, Gavier Pizarro G, Volante JN, Gasparri IN, Kuemmerle T. 2018. Drivers of agricultural land-use change in the Argentine Pampas and Chaco regions. *Applied Geography* 91:111–22.
- QGIS Development Team. 2016. QGIS Geographic Information System. Open Source Geospatial Foundation Project.
- R Core Team. 2015. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. <http://www.R-project.org/>.
- Raudsepp-Hearne C, Peterson GD, Bennett EM. 2010. Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. *Proceedings of the National Academy of Sciences* 107:5242–7.
- Redaf. 2011. *Conflictos sobre Tenencia de Tierra y Ambientales en la Región del Chaco argentino*. 2º Informe Datos relevados hasta Agosto de 2010 Red Agroforestal Chaco Argentina Observatorio de Tierras, Recursos Naturales y Medioambiente.
- Resilience Alliance. 2007. *Assessing and managing resilience in social-ecological systems: Volume 2 supplementary notes to the practitioners workbook*.
- Senado y Cámara de Diputados de la Nación Argentina. 1968. Ley 17.622 'Marco legal de las estadísticas oficiales', Boletín Oficial de la República Argentina.
- Senado y Cámara de Diputados de la Nación Argentina. 2007. Ley N° 26.331 'Presupuestos Mínimos de Protección Ambiental de los Bosques Nativos', Boletín Oficial de la República Argentina.
- Theobald DM, Spies T, Kline J, Maxwell B, Hobbs NT, Dale VH. 2005. Ecological support for rural land-use planning. *Ecological Applications* 15:1906–14.
- Václavík T, Lautenbach S, Kuemmerle T, Seppelt R. 2013. Mapping global land system archetypes. *Global Environmental Change* 23:1637–47.
- Vallejos M, Volante JN, Mosciaro MJ, Vale LM, Bustamante ML, Paruelo JM. 2015. Transformation dynamics of the natural

- cover in the Dry Chaco ecoregion: A plot level geo-database from 1976 to 2012. *Journal of Arid Environments* 123:3–11.
- Viglizzo EF, Pordomingo AJ, Buschiazzi D, Castro MG. 2005. A methodological approach to assess cross-scale relations and interactions in agricultural ecosystems of Argentina. *Ecosystems* 8:546–58.
- Volante JN, Alcaraz-Segura D, Mosciaro MJ. 2012. Ecosystem functional changes associated with land clearing in NW Argentina. *Agriculture, Ecosystems & Environment* 154:12–22.
- Volante JN, Mosciaro MJ, Gavier-Pizarro GI, Paruelo JM. 2016. Agricultural expansion in the Semiarid Chaco: Poorly selective contagious advance. *Land Use Policy* 55:154–65.
- Walker BH. 1997. Functional types in non-equilibrium ecosystems. In: Smith TM, Shugart HH, Woodward FI, editors. *Plant Functional Types: their Relevance to Ecosystem Properties and Global Change*. Cambridge. p 369.
- Ward JH. 1963. Hierarchical Grouping to Optimize an Objective Function. *Journal of the American Statistical Association* 58:236–44.
- Wickham H. 2009. *ggplot2: elegant graphics for data analysis*. New York: Springer. p 2009.