Degradation processes and adaptive strategies in communal forests of Argentine dry Chaco. Integrating stakeholder knowledge and perceptions

Santiago Miguel Cotroneo, Elizabeth Juliana Jacobo and Miguel Marcelo Brassiolo

*Facultad de Agronomía. Área de Agroecología, Universidad de Buenos Aires, Buenos Aires, Argentina; †Facultad de Ciencias Forestales. Instituto de Silvicultura y Manejo de Bosques. Cátedra de Agrosilvicultura, Universidad Nacional de Santiago del Estero, Santiago del Estero, Argentina

ABSTRACT
Forest replacement and degradation driven by crop expansion and livestock intensification are some of the main global socio-ecological threats, severely affecting the dry Chaco region (main dry forest in America). By involving stakeholders, whose actions are decisive in dealing with the problem under analysis, we assessed the interactions among processes of multiple dimensions and spatial scales, currently controlling communal forest degradation in 11 peasant communities of Taboada, Ibarra and Salavina departments, in Santiago del Estero province, Argentina. Then, by reconstructing historical processes undergone by these communities over the last century, we analyzed how different system settings have conducted to the system collapse (forests and community loss) or strengthened its adaptive capacity facing natural disturbances (droughts) and anthropogenic stressors (economic shocks, land disputes). This work unveils system attributes related to native resource management and economic diversification on the farm, family and community structure, and social networking with peasant organizations and other institutions, crucial for building social–ecological resilience. Alternative trajectories are shown towards degradation (throughout a downward spiral, often followed by peasant exodus and deforestation) or restoration. Our results would explain why forest (protection) law and state subsidies aimed at sustainable management have been insufficient and suggest some clues to reorient them.

Introduction
Dry forests are among the most converted and threatened biomes in the world (Hoekstra et al. 2005). The Dry Chaco (located mostly in Argentina, followed by Paraguay and Bolivia) holds the largest dry forest in the American continent (Eva et al. 2004), which is being deforested at alarming rates (Hansen et al. 2013) due to agricultural and cattle frontier advances (Fehlenberg et al. 2017). Deforestation, which involves the most drastic change in ecosystems and society (MEA 2005; IAASTD 2008), also increases pressure on the remaining forests, often degraded after a history of continuous grazing, selective logging, and other anthropic actions (MEA 2005; Morello et al. 2007; Pérez-Carrera et al. 2008). Thus, these processes threaten both native ecosystems and the peasants–indigenous peoples whose livelihoods depend on them.

The Argentine semiarid Chaco forest is largely (34%) located in the northwestern province of Santiago del Estero, main focus of this study. The region is an extensive plain which assembles xerophytic forests, savannas, and grasslands, often degraded by continuous grazing and timber extraction since the early 20th century (Adamoli et al. 1990). The native vegetation landscape is mainly inhabited by peasants (81% of the forest area in this province, calculated by combining geomatics and social methods by Rivas F, personal communication). Because of deforestation, this landscape is currently interrupted by large areas of soy monoculture and exotic pastures, held by few landowners (Paz 2014). In the last two decades, more than 2.3 million hectares have been deforested (Vallejos et al. 2015), while rural poverty has increased (Paolasso et al. 2012a) and approximately 4.2 thousand peasant establishments have likely disappeared (estimated as the decrease in total farms without fenced boundaries or less than 100 ha reported between CNA 2002, 2018) in Santiago del Estero. In semiarid Chaco, the largest losses occurred between 2000 and 2013 with 4.5 million ha deforested. In addition, Chaco deforestation compromises the provision of crucial ecosystem services such as flood regulation and climate regulation, which affect social wellbeing beyond the region (Barral et al. 2020). Although a national Forest Law (N°26331) was passed in 2007 aimed to protect native forests, local cultures, and promote sustainable use practices, this law could not stop deforestation or ameliorate historical ecological and social degradation (Volante and Seghezzo 2018).
An important body of research has been focused on deforestation consequences and its effects on the remaining forest. Ecological issues have been assessed at a regional scale such as carbon emissions (Gasparri et al. 2008; Baumann et al. 2017) and hydrological dynamics (Jiménez et al. 2020; Rodriguez et al. 2020). At a local–regional scale, habitat fragmentation (Correa et al. 2012; Torrella et al. 2013), biodiversity conservation (Giraudo 2009; Romero-Muñoz et al. 2020), changes in the structure and functioning of forest ecosystems (Tálamo and Caziani 2003; Torrella et al. 2013) have been addressed. At a local level, soil degradation (Rojas et al. 2016; Villarino et al. 2017), and social processes such as land grabbing and its related social conflicts (Jara and Paz 2013; Cáceres 2015), demographic and socioeconomic changes (Krapovickas 2010; Paolasso et al. 2012b), and loss of peasant and indigenous knowledge (Arenas 2012) have been considered. However, social, and ecological issues have recently been studied in an integrated way in semiarid Chaco. This research includes analysis of natural resources appropriation by peasant people (Aristide 2014) and sustainable use of forest carried out by indigenous people and peasant (Matteucci et al. 2016), evaluation of appropriation of ecosystem services by different social actors (Vallejos et al. 2020), assessment of trade-offs between social and ecological goals (Mastrangelo and Laterra 2015), development of a framework to characterize socio-ecological systems (Vallejos et al. 2019), and sustain-ability assessment through the integration of indicators of different domains (Seghezzo et al. 2020).

It is increasingly recognized that addressing complex problems in socio-ecological systems (SES) calls for both the articulation of disciplines from social and natural sciences with an integrative, interdisciplinary approach (Berkes and Folke 1998; Redman et al. 2004; Liu et al. 2007; Ostrom 2009). In this regard, several research frameworks have been developed over the last decades (Binder et al. 2013). They differ from each other in disciplinary origin, purpose oriented to analysis or action, conception of uni–or bi– directional interactions between social and ecological systems, scales, interactions, and dynamics considered. The resilience approach, originating from systems ecology (Holling 1973), offers today a ‘conceptual umbrella’ under which different disciplines (from conservation biology to psychology, economics, and others) can be integrated (Adger 2006; Sterk et al. 2017) to deal with complex problems (e.g. Levine and Richmond 2014). The socio-ecological resilience framework (Folke 2006) provides a common language for understanding and organizing, into a multitier hierarchy, the relevant variables from various ‘domains’ (ecological, social, cultural, economic, and institutional) affecting SES (Wilson 2012; Kelly et al. 2015). This framework focuses on system dynamics and the ability to cope with change, in ways that continue to support human wellbeing and the ecosystems on which it depends (Folke et al. 2016).

Human activities transform ecosystems, and their dynamics influence the former, driving to multiple interplays and often ‘negative’ unforeseen outcomes. Complexity and uncertainty inherent to SES make it necessary to deal with change. In this context, resilience refers to the capacity of a SES to absorb or withstand perturbations and other stressors, maintaining its essential structure and functioning (Folke et al. 2003). Resilience reflects the degree to which the system is capable of self–organization, learning and adapting, avoiding undesired configurations. Conversely, reduced resilience increases vulnerability to disturbances that can drive to change into a qualitatively different regime (‘regime shift’). Moreover, gradual changes that lead to exceeding thresholds, both ecological and social, can also trigger the system to be always closer to collapse (Pelling and Manuel-Navarrete 2011; Bollettino et al. 2017).

Facing threats, a higher adaptive capacity, increases the system options to re–configure without a significant loss in crucial functions during periods of change and reorganization. Key principles to strengthen adaptive capacity by building resilience (Biggs et al. 2012) are related to: (i) Maintaining diversity and redundancy (of species, landscape types, actors and institutions); (ii) Managing connectivity (of resources and people); (iii) Managing slow variables (focusing on structural rather than circumstantial aspects, and avoiding undesired feedback loops); (iv) Encouraging learning (from crisis, incorporating interdependence and improving strategies facing uncertain futures); (v) Combining different types of knowledge (for learning, acquiring new information, skills or understanding); (vi) Broadening participation (allowing individuals in a community to make connections and decisions to self–organize, engage in projects and build networks with other social actors); and (vii) Promoting polycentric governance systems. For these purposes, the need to involve stakeholders in participatory approaches to analyze the past, manage the present and prepare for the future, is increasingly recognized (Walker et al. 2002; Matuk et al. 2020).

By integrating stakeholders’ knowledge and percep-tions, we assessed the interactions among factors and processes of multiple dimensions (ecological, social, cultural, productive, economic, and institutional) and spatial scales (farm, community, regional, national–global context), which nowadays control the degradation of communal forests in 11 peasant communities of Taboada, Ibarra and Salavina departments, Santiago del Estero province, Argentine semiarid Chaco (Objective 1). Then, by reconstructing historical processes of the last century and the effects of natural and anthropogenic disturbances on such communities, we analyzed the way in which these interactions and alternative system configurations have conducted to the
system collapse (loss of forests and communities) or strengthened its adaptive capacity (through building socio-ecological resilience) (Objective 2).

Materials and methods

Study area

The study area belongs to the semiarid Chaco region (Morello et al. 2012). The climate is subtropical, with a marked dry season during the winter (between May and September) and a wet season during the summer (between October and April). The average annual temperature is 20°C although historical absolute maximum temperatures have reached 49°C. The average annual rainfall is 640 mm, and the average annual water deficit is 300 mm. The relief is flat (with slopes of less than 0.5%), where xerophytic thorny forests predominate, and micro-relief shows small ancient riverbeds, covered by grasslands dominated by Elionurus matusicus. The native forest has four strata: upper arboreal, dominated by Schinopsis lorentzii (quebracho Colorado santiagueño) and Aspidosperma quebracho blanco; lower arboreal, mainly composed by species of the genera Protopis; shrubby, consisting of species of the genera Acacia, Atamasquea, Celtis, Larrea, Protopis and Schinus; and herbaceous, composed by C4 grasses of the genera Digitaria, Pappophorum, Setaria and Trichloris, dicotyledonous herbaceous (Acanthaceae, Malvaceae and Verbenaceae) and other plants of the Bromeliaceae and Cactaceae families. This landscape is currently anthropized, forming a complex matrix of depleted primary forests, secondary forests, shrublands and grasslands, interrupted by large agricultural and pasture patches.

Peasant communities in the region make multiple uses of the native forest, through practices whose origins go back to different historical periods of human occupation and land use. Despite its complexity (temporal, spatial and social, regarding the many actors involved), which far exceeds the scope of this work, certain milestones were key for the communities studied (for an overview see Morello et al. 2007). During the prehispanic period, subsistence activities were developed based on deep indigenous knowledge of the natural environment. They were mainly hunting, gathering, fire management, rainwater harvesting, and small-scale corn cultivation, probably associated with temporary stays on riverbanks bordering forests, subject to flood and drought cycles (Cione et al. 1979; Togo 2005). From the arrival of the conquerors, the natives were gradually displaced from their lands (during 17th, 18th, and 19th centuries), but changes were widespread later. Towards the end of the 19th century – beginning of the 20th century, most of the land was being managed by settlers. Productive activities were mainly forestry and livestock, and incipient agriculture. Forestry was developed by the obraje, a private investment dedicated to exploit native tree species, especially ‘quebracho Colorado santiagueño’, until depletion. The main workforce came from the peasants, mestizo people descendants of the first Spanish–Quechua settlers who arrived in the region (Scarpa 2000), and other migrants who arrived from neighboring provinces. Meanwhile, livestock (cattle and goat) breeding was developed by the estancias (large private ranches) and puestos, small, scattered settlements of peasants (often employees of the estancias), whose agriculture still reflected indigenous traditions. In most cases, labor relations occurred under different forms of exploitation and subjugation (Tasso 2004). In addition, several small colonies were established (many of them in our study region, such as Colonia Dora, Bandera and Icaño; Tasso 2004), the economy of which was based on agricultural activities, mainly cotton. The change of social actors living and managing the territory was driven by military campaigns and colonialist state policies, while the new commercial activities were enabled by the railroad and new routes to national and international markets. Between the middle of the 19th century and the middle of the 20th century, the provincial government sold large tracts (various 1000000 ha) of public land to private owners, at extremely low prices (Dargoltz 1980). Towards the middle of the 20th century, logging ceased to be highly profitable, the obrajes began to diminish, and many of the peasants (formerly workers) remained on these lands, although without regularizing their possession. By then, part of the forests had been degraded, and most of the grasslands had been transformed into shrublands, due to overgrazing. Meanwhile, the textile industry boom attracted powerful investors to large scale cotton cultivation, subduing the inhabitants’ vulnerability due to their precarious land tenure (Dargoltz 2003). Simultaneously, a favorable market drove the advance of the cattle frontier from other regions towards the southeast of the province, including Ibarra and Taboada departments. Later, a much stronger agricultural advance occurred in the 1990s, when an exceptionally wet cycle, direct seeding technologies, release of transgenic soybean varieties, and high global market prices were combined.

Currently, most of the farms in Santiago del Estero (82%) belong to communal lands or individual without fenced boundaries or smaller than 100 ha (CNA 2018), inhabited by peasant producers, whose self-supply largely depends on diverse productive activities (forestry, livestock breeding, gathering of fruits, honey and native herbs, wild animal hunting, extensive cropping, horticulture and poultry farming) enabled by traditional knowledge in a predominantly native-forest landscape. On the other hand, there are a few large farms (larger than 1,000 ha) dedicated to industrial agriculture (mainly soy monoculture) and extensive livestock (mainly cows fed with exotic pastures), which concentrate almost all (89%) of the deforested land. The
communal forests involved in this study are located in the southeastern region of Santiago del Estero, where agricultural expansion occurred with greater intensity (community locations are shown in Figure 1). The peasants who participated in this study are linked to each other through the peasant organization ‘Mesa Zonal Ámbito de Tierras Añatuya’ (MEZAT).

**Methodology**

Factors and processes that control forest degradation were organized (Objective 1) into a theoretical model, which was built based on workshops with stakeholders involved in this matter: peasants (men and women, mostly between 20 and 60 years old), field technicians and researchers of the National Institute of Agricultural Technology, researchers of the National Scientific and Technical Research Council and national universities, officials from government agencies, members of NGOs. Professionals included specialists from multiple disciplines of social and natural sciences. Medium and large-scale farmers were not included because they are the subjects of an agricultural model that promotes deforestation. To this end, we followed the methodology proposed by García (2006) for modelling complex SES. Such a methodology is a ‘procedural’ framework, in the sense that it provides a sequence of phases and planning guidelines, to inter – or – trans – disciplinary understanding of complex environmental phenomena. Its participatory approach allows the integration of the communities who reveal situations or events that are beyond the understanding of the researchers alone. The proposed methodology seeks, through a modelling exercise, to make the stakeholders involved more aware of their role in this reality. Therefore, it is self-reflexive and potentially transformative of the own reality under study. This framework is explicitly rooted in the general system theory and the complex adaptive systems theory, which are strong foundations for understanding SES dynamics, addressed in the second part of this work (Objective 2).

The model construction was carried out in multiple phases (adapted from Garcia 2006):

- Phase 1. Definition of system components: central process under study (community forest degradation), system boundaries (the area historically used by peasant communities), system elements of each dimension (ecological, social, cultural, productive, economic, and institutional), analysis levels (direct processes, indirect processes at a local level, at a regional level, and global context conditions), interactions (which define model structure (between elements) and temporal boundaries (1900–2015).
- Phase 2. Preliminary model construction. This was done in multiple steps, including:
  2.1. Review of previously studied processes linked to the central process under study.
  2.2. Construction of multiple preliminary models, elaborated from knowledge and perceptions from different stakeholders who participated in independent workshops. During the workshops, the elaboration of the models was made based on guiding questions: (What is community forest degradation? What processes affect it directly? Which ones indirectly? How do they relate to each other?).

![Figure 1](image-url)  
**Figure 1.** Left: location of the Chaco region (in grey) in the South American continent. Centre: South American Dry Chaco (Chaco Seco) region, in dark grey background. Black dots show accumulated deforestation up to 2018. Right: location of the communities involved in this study: (1) Campo Toledo, (2) Canal Melero, (3) Chilcán Bajada, (4) Costa de Icaño, (5) El Troncal, (6) Lago Muyoj, (7) La India, (8) Lote 28, (9) Lote 38, (10) Pozo Herrera and (11) Yanacón Bajada.
2.3. Data processing and analysis. Transcriptions of audio records were coded and analyzed using ATLAS-Ti software. The factors and processes were coded by dimension, and both direct and indirect interactions were identified among them, at different levels of analysis.

2.4. Data validation. The data obtained from the workshops were contrasted with scientific results of numerous projects and investigations that have been carried out in the same communities, ranging along several topics such as: edaphology, dasonomy, livestock, ecological restoration, wildlife conservation, economy, social psychology, community forest management, landscape matrix and ecosystem services (e.g. Giménez et al. 2008; Guzmán et al. 2012; Figueroa 2015; Abt-Giubergia 2015; Guzmán and Brasiolo 2015; Guzmán 2017; Rivas et al. 2017; Cotroneo et al. 2018, 2021a, 2021b).

- Phase 3. The final model was constructed. Based on the preliminary models and data validation, a synthesis model was built by successive approximations, until reaching a model agreed by the whole group of stakeholders.

To analyze system configurations and dynamics that have been conducted towards system reorganization or collapse (Objective 2), we used the resilience approach. We carried out a second round of workshops, where inquiries were made about the historical processes that were relevant to communal forest degradation, loss, or recovery during the last century. The data processing was the same as in the previous case but focusing the analysis on the system dynamics. We focused on disturbances, both regular (which are a part of the system’s own dynamics, e.g. drought) and extraordinary (beyond the system, e.g., agricultural expansion). System changes were considered between alternative states (system configuration varies while preserving its crucial processes), and regime shifts (or collapse). Critical changes in social–ecological systems could be determined by a small set of key variables or principles (about three to five), related to building resilience and adaptive capacity (Walker et al. 2006; Biggs et al. 2012). Accordingly, we focused our analysis on the identification and understanding of such system variables.

The elements and interplay in a given system are unique to that system, making resilience highly context-specific.

Thus, this work does not attempt to understand the processes linked to degradation (Objective 1) or the historical dynamics of the forest–community system (Objective 2) in the whole region, but rather in the specific communities involved in this study. All workshops, field trips and stays in the communities took place between 2013 and 2015.

Results

Multi–dimensional processes related to communal forests degradation

Processes linked to communal forest degradation are shown in Figure 2. Currently, the communal forest availability is less than that historically available. The loss of a portion of communal forest area determines the narrowing of the limits of the SES. The perceptions of all stakeholders involved in this study agreed that forest degradation of the managed area, currently embodies decrease or loss of trees in the upper layer, shrub encroachment, and important reduction of herbaceous cover, wildlife abundance, and biodiversity (plant and animal), forest connectivity, and soil degradation by compaction, salinization, and presence of gullies. To this structural changes, professionals added low recovery capacity of the forest under extreme degradation circumstances (typically shrublands) and peasants added low temporal stability (seasonal and interannual) of the forage offer and low multiple-use potential of the degraded forest. Both groups agreed on the fact that degradation had increased the system’s susceptibility to extreme climate events. It was affirmed that 50 years ago a drought event would have done no harm. Nowadays, drought increases pest incidence, exacerbates summer overgrazing, winter forage deficit, produces large deaths of lambs and goatlings and, facing a critical economic situation, it leads to heavy logging to offset lower income. Professionals in the natural sciences argue that a lower tree cover results in less shading and litter contributions to the ground. These changes, exacerbated by soil denudation and compaction by overgrazing favor the presence of shrublands (better adapted to water stress conditions) and they harm the grasses, feedbacking the problem. Susceptibility to climate variability is postulated as an emergent property of degraded forests and at the same time as a progressive process, since it exacerbates degradation under the light of climate events that are endogenous to the systems (such as drought). To address these structural and functional changes, professionals added less cultural capital (mainly knowledge and skills) related to the forest, lower capacity for social sustenance at community scale, and (in a broad sense) lower ecosystem services supply.

Peasants and professionals agreed on the point that the main direct causes of forest degradation are the privatization and loss of communal lands, deforestation in private land (for agribusiness) and native forest mismanagement in remaining communal lands. Both causes are linked because the reduction
of area of communal forest, in turn, increases pressure on the remaining forest, as much on tree overharvesting as on increases in livestock density and decreases in its mobility. Resource mismanagement includes the excessive extraction of some tree species (for wood and charcoal) and overgrazing. In the previous paragraph the feedbacks that link both processes to each other (through changes in the woody-herbaceous balance) and to drought events endogenous to the system were explained. However, peasants claim that the local climate has also changed (more severe droughts, higher variability of rainfall between nearby sites, more frequent late frosts, lower altitudes and longer periods of strong winds), making the problem even worse. Additionally, professionals added high recurrence of anthropic fires oriented to shrub control and low-quality native grasses regrowth, introduction of exotic grasses with invasive behavior, the increase in the population of a locust (‘langosta quebracha’, that feeds on the dominant trees) which turned into a pest as a result of agricultural expansion, landscape fragmentation, reduced mobility of wildlife due to habitat loss and extensive fencing, increasing poaching, drift of the fumigations with agrochemicals from adjacent agricultural fields, and the lack of management in remaining forests.

The indirect causes of local scale forest degradation identified by all stakeholders are the precarious tenure of land, which allowed it to be bought by large landowners after a long period of land dispute, and family structural change, related to emigration of women and children to the cities. On its own, family fragmentation enforces a decrease in the farm workforce, the diversity of productive activities (especially those necessary for self-supply, associated with woman’s knowledge about multiple uses of the forest and the transformation of primary products into processed ones), knowledge transfer to the young ones, and an increase in the money demand associated with breadwinners moving to the city. Peasants include as indirect causes of degradation, a lower income due to the abandonment of their own agriculture for commercial purposes and the lower demand for rural labor. Migration from the countryside to the city (even of entire families) also induces changes in the community organization, proposed as a key control of degradation by professionals in social sciences. This organization is an intimate structure, with certain rules of coexistence and shared values. It establishes common space use, territory boundaries, distribution of individual zones (for instance, fences and exclosures), the role of the elderly and seniors on the knowledge transfer to the youngsters, and solidarity bonds as an exchange...
mechanism. Community dynamics is reflected in multiple actions, ranging from daily food (for example, a common and staggered use of the meat production of different families is practiced in the face of a limited conservation capacity without electricity), to the defense of the land (mediated by the peasant organization). It is claimed that this structure brings resilience to the community in order to preserve its identity, territory, and ways of life.

As indirect causes from the regional–national scale, both groups identified the expansion of agricultural frontiers as the main cause for forest degradation. Professionals included the province’s precarious land tenure structure and the poor rural infrastructure (lack of schools, roads, and electricity) as pressure factors towards rural emigration. Meanwhile, only the peasants included the break of state support for peasant agriculture (in particular, linked to the ‘cotton crisis’) as a determinant of the rural exodus. Different stakeholders agreed that peasant emigration inevitably leads to land clearing and monoculture, considered this as the most extreme ecological degradation situation. All of them highlighted the role of the state that, both present (by promoting the expansion of a national agro export model in the region) and absent (in the face of land conflicts), plays a decisive role in the loss of tenure, migration, and the limited capacity of the forest law to stop deforestation. The context conditions considered relevant to the prior mentioned processes were the commodity market that favors the expansion of agricultural frontiers, cultural homogenization, and climate change, all of them of global nature.

States and transitions of the forest–community system

Initial state setting

Families’ settlement in the study zone occurred around 1930. Initially, there was the extraction of wood, wildlife hunting, native plant gathering, and livestock as usual practices (the cattle followed extensive grasslands, many kilometers long), as well as agricultural and horticultural farming extensive for self–supply (corn, pumpkin, watermelon, sweet potato and bean). Then, small-scale commercial cotton farming (5–10 hectares) was added. At that time, natural vegetation was an unmanaged, extensive, and diverse forest and grassland, enough for the supply of goods and provide income to the communities that inhabited it. Productive diversification exercised a diversified, light pressure on the ecological system. During wet years agricultural activity increased, lowering the pressure on the exploitation of natural vegetation whose recovery was favored by humidity conditions during the summer. Peasants declare that in that context there was no need to pull significant livestock or forest pressure since income (in the form of money) and self-sufficiency (of food and other goods) depended on multiple activities. The money came from family farming (cotton sales), temporary jobs in nearby farms, livestock, and forestry activities. Self–supply depended on raising cattle, goats, and sheep (extensive) and poultry farming (peri–domestic) subsistence cultivation, hunting and gathering. The whole family lived and worked in the field and multiple cultural activities involved the entire community that shared a continuous forest matrix. At that stage, the coordination among communities was low, restricted to nearby settlements since there were still no peasant organizations (Figure 3, state A).

External disturbances: ‘cotton crisis’ and first agricultural frontier advance

Since 1960–1970 multiple factors led to a crisis that set the beginning of the end of family cotton production: drought, floods, plagues, cotton price drop, and subsidies elimination. Although profits were declining, cotton activity continued until around 1985 – even when it no longer generated money – because of this activity’s strong roots in which cultural tasks involved the entire family and neighbors. Peasants refer to a progressive state subsidy percent dependency (tillage with state machinery, seeds and welfare plans for farmers with children) and regret the loss of practices related to land labor with their own tools and animal traction, which were not recovered when the state removed subsidies. The loss of family agriculture and the lower demand of rural labor force from neighboring establishments reduced family incomes drastically (Figure 3, transition start A–B). Simultaneously, as a consequence of earlier advances from industrial agriculture, the very first conflicts about land tenure (in Suncho Pozo, 1965) emerged, which worsened and became irreversible in 1988 (in Los Juríes). The lack of peasant organizations facilitated the fact that many families from isolated communities were rapidly displaced (Figure 3, transition A–D) and their lands were immediately deforested and replaced by monocultures. The area of communal forests has started decreasing (Figure 3, continuation of transition A–B). An example of this process is documented in Cotroneo et al. (2021a), who described how a community here studied (Lote 28) with a population of around 32 families occupying an area of 1600 ha was reduced to its current 600 ha, after a long legal procedure over land titling. In the lands, some families remained with devastated incomes, in less extensive and threatened forests (Figure 3, state B). According to the communities involved in this study, this combination of processes started with the ‘cotton crisis’, and deepened by land conflicts, generated a breakdown of the socio-ecological equilibrium.
**Intensification of disturbances over weakened systems: second advance of industrial agriculture**

In 1996 transgenic soy varieties were liberated, and from then on a second advance from industrial agriculture was produced, much more intense than the first one. Between 1996 and 2006 the highest deforestation rates were registered (during that period 1,150,000 hectares were cleared in Santiago del Estero), mainly in the east side of the province, where our study area is located. Between 2007 and 2008 the Forest Law was passed and regulated with the aim of organizing deforestation and promoting sustainable management. Its effectiveness from that time to the present turned out to be controversial among the stakeholders involved, most of whom consider that, although this law is necessary, it has been ineffective (between 2009 and 2019 800,000 hectares were deforested in the province) (see updated data in monitoreodesmonte.com.ar, calculated from Vallejos et al. 2015). Communal forests shrank and their fragmentation, interrupting circulation roads, also lengthened the distance to rural schools and increased the social isolation of impoverished peasants, promoting the emigration of part of the families (mainly women and school-age children) to towns and cities (Figure 3, transition B–C).

**Downward spiral of degradation**

The demand for subsistence money in the city and the fall in the prices of peasant products simultaneously with the rise in the price of products bought
in the city, deteriorated the family economy. The diminished productive diversity associated to the change in family structures concentrated pressure over one or two system components (livestock or forest production, carried out by men who remained on the farm), all of which resulted in degraded forests (Figure 3, state C). Such degradation exacerbated the effects of overgrazing which, during the first half of the century, had already transformed many grasslands and forests into low-productive shrublands. The degraded system became increasingly susceptible to internal economic shocks and endogenous disturbances, such as drought. This hastened the downward spiral, progressively increasing the degradation (Figure 3, transition C–D). At first, consumption of valuable trees and forage resources was observed. This was followed by the pure tree exploitation for charcoal production on highly degraded lands that were already unproductive for other purposes, and finally the abandonment of the land or its sale for less money, finally leading to deforestation and monoculture (Figure 3, state D), which means the forest–community system collapsed.

Adaptive strategies
Because of the land conflicts, peasant organizations emerged in the study area (‘Comisión Central Campesina’, in 1985, and later ‘MEZAT’) and in the province (‘Movimiento Campesino de Santiago del Estero’, in 1990) that first allowed to resist land conflicts, and then incorporate adaptive strategies towards the system reorganization. By the time the peasant organizations were created, their main referents had a union experience in the cities where they had stayed for some years. Coordination among organizations and other actors like NGOs, universities and state organisms were considered key factors to make an impact on public policies, co–production of knowledge and access to investments aimed at forest management and restoration (Figure 3, transition start B–E or C–E). For instance, until 2014, the Forest Law only contemplated granting subsidies for the management of forests in private lands, therefore leaving communal forests aside. Communities involved in this study, organized, and networked with public institutions and NGOs, managed to intercede in law rules, opening access to these funds for peasant communities, from then on.

One of the most used management practices is the exclosures, built up to temporarily exclude livestock from the forest (all peasants interviewed who received state subsidies used part of the money for this purpose). This practice makes it possible to achieve productive and conservation objectives at the same time. Regarding production, exclosures are a tool to defer forage to dry season and to carry out agricultural and forage crops in small, deforested patches (generally located at the edges of the forest, within the same exclosure). Regarding conservation, exclosures reversed forest degradation by overgrazing and tree overharvesting. A few years after grazing rest during the wet season, it has been demonstrated that forest herbaceous cover was rehabilitated, primary productivity increased (Cotroneo et al. 2018), soil seed bank of forage species was recovered, and soil structure was regenerated (decrease in bulk density and increase in porosity and air capacity) (Cotroneo et al. 2021b). In addition, exclosures protect tree regeneration. Most families have one or more closures that span multiple types of forest in order to diversify their uses. Complementary forest management strategies are introduced to drive heavily degraded shrublands (through root thinning and pruning, and in extreme situations through multi-year exclosures) into secondary forests of Acacia spp. and Prosopis spp. used as forage banks. Selective forest harvesting was also implemented maintaining the natural irregular structure of the forest, and leftovers used from that harvest in order to produce charcoal in small, and occasionally, mobile kilns. A great part of subsidies received is destined to water harvesting structures for human consumption (wells, collector roofs and cisterns) and for animals (dams). In large communities, seasonal closing of livestock access to water is used to rotate grazing and rest distant forest areas that do not have exclosures (Figure 3, continuation of transition B–E or C–E). Adaptive management carried out by communities maintains a high functional diversity of the forest, maximizing both provision and regulation of ecosystem services (Conti et al. 2018).

At farm and community scale, productive diversification recovery and management introduction allow native forest restoration and return stability towards endogenous climate fluctuations, such as drought or external shocks, such as economic ones (Figure 3, state E). At a peasant organization scale, new trading channels are generated, which allow more equitable benefits to be obtained through direct sales to consumers. The link between NGOs and public institutions also favors the access to urban sale spaces and mechanisms to guarantee the health and quality of food since the protocols at national level are mainly oriented to industrial processes. Similarly, some communities manage improvements to access to water mains, health, and education, although the achievements also depend on local political agreements and their effects are miniscule compared to the general abandonment of rural infrastructure, imposed by public policies at a regional and national scale.
Discussion

Understanding resilience at the community level requires understanding the complex interplay between various domains that characterize socio-ecological systems (Buikstra et al. 2010; Wilson 2012; Berkes and Ross 2013). Our results support that community resilience will be stronger than long as these different domains are well-developed and balanced (Kelly et al. 2015). The earliest abrupt change observed in systems replaced by monoculture (regime shift A–E) would reflect the high system vulnerability associated to extreme imbalances between domains. At that point, the extensive rich natural system, local culture, stable economy, and high social capital at community level were not enough to face economic (soybean expansion) pressures. On the other hand, our results support that weakening factors within one domain can also weaken factors in other domains (Kelly et al. 2015), as reflected by gradual losses in both ecological and social (forest degradation and partial family migration; Figure 3, transition B–C and transition start C–D), following the initial economic weakening (given by family agriculture loss; A–B). Sequential and progressive losses in different domains tend to lead, through cascading effects, to an often undesirable regime shift (Kinzig et al. 2006). These processes are the result of the advancement of industrial agriculture on communal forest lands, which shrinks and weakens the peasant agroecosystem, highlighting the incompatibility of both production models.

In this regard, two ‘undesired’ feedback loops are warned, as they drive gradual changes that trigger a critical transition (C–D). The first feedback we found between ecosystem degradation processes (tree-grass depletion and shrub encroachment), induced by overgrazing and indiscriminate logging, exacerbated by extreme climate events, is a well-known process in drylands (Asner et al. 2004). The second feedback amplifies the first by linking social changes and economic pressure with ecosystem degradation. For years, it was postulated that ecosystem degradation and rural poverty, usual in drylands (MEA 2005), necessarily lead to a ‘downward spiral’ where systems become gradually less productive as inhabitants increase their pressure on them to survive (WCED 1987; Ekbom and Bojó 1999). This statement partially matches our results since economic pressure does not arise from poverty, but from partial family migration and productive specialization derived from it. Anyway, this turns out to be alarming because peasants in that situation are often forced to undersell or leave their land, concluding in the complete family migration and deforestation. The higher vulnerability prior to an undesirable regime change was already noted in other SES (Abel et al. 2006). Apparently, to avoid passing ecological thresholds (e.g. linked to massive deforestation) it would be necessary to avoid passing other sociocultural thresholds, as pointed out Kinzig et al. (2006) for other dry forests. In addition, our results challenge that ‘downward spiral’ as the only possible trajectory of the system, being avoidable such as other authors claim, based on extensive empirical evidence (Scherr 2000).

Despite the threat of industrial agriculture, our results suggest that alternative trajectories leading to system reorganization are possible and related to crucial components of resilience in socio-ecological systems. At community–forest level, diversity and functional redundancy were nurtured by management and rehabilitation of native resources and productive diversification of the farms. The multiple-resource use strategies enable economic diversification helping rural households to reduce poverty and vulnerability (Thulstrup 2015; Martin and Lorenzen 2016; García Jácome et al. 2020) and to cope with economic shocks and climate variability, critical in drylands (Ellis 1998; Block and Webb 2001; Mortimore and Adams 2001; Wu et al. 2014). Such shocks are precisely the ones promoting the aforementioned ‘undesired’ feedback loops, which would be avoided by focusing on the management of structural variables of the system (Biggs et al. 2012), discussed above. However, that system configuration would be strongly interdependent with important social factors. At the same level, economic diversification depended on the presence of women and young people on the farm (Abt–Giubergia 2015). As in other cases, women command a large part of the multiple forest uses that support a high household self-sufficiency (Fortmann and Rocheleau 1985; Djoudi and Brockhaus 2011), strengthening the non–monetary family economics, key in the studied systems (Cotroneo et al. 2021a). Moreover, young people participate in almost all activities, providing workforce while learning.

The permanence of young people is central since they receive the local knowledge, mainly about native fauna and flora, including deep knowledge about forage plants (Jiménez-Escobar 2019). The high ecological knowledge in the main local socio-productive practice (Roger 2020), is necessary for reconciling use and conservation of natural resources, both in the Chaco (Cotroneo et al. 2021a) as in other regions (Toledo and Barrera Bassols 2008). However, the outmigration of young people due to isolation and economic constraints, is a worrying problem not only in the studied community but also in others, dependent on forests threatened by degradation (Kelly et al. 2015). The erosion of social memory, given by the loss of local environmental knowledge, skills and learning pathways, threatens crucial components of resilience. Local knowledge is a main indicator of
adaptive capacity in communities managing forests (Lee and Krasny 2017). The emigration of young people and even entire families also undermines resilience by weakening the collective identity of the communities (Abt–Giubergia 2015), in which the shared ways of perceiving and acting serve as a barrier to outside threats (Leap and Thompson 2018) as cultural homogenization (indirect cause of degradation; Figure 2).

A recent paper (Cotroneo et al. 2021a) analyzed the processes associated to the sustainability of an agroecosystem located in the study area. This paper reveals key synergies between management and natural asset conservation (most of its area is conserved forest), a complex social network (with peasants, ONGs and public institutions) and a high level of self-sufficiency sustained by diversified productive activities. About 81 species are used, accounting for an overall of 41 uses (food, medicinal, veterinary, forage, energy, and biotic regulation). This paper provides evidence that adaptive strategies adopted are key to the good quality of peasant life in semiarid Chaco.

In the upper levels of social structure, self-organization gave rise (from the initial setting) to new system components whose emergence was (and still are) essential to avoid collapse. Certain circumstances of resources (as deteriorating forests, too small for users to perceive) and users (with prior organizational experience) would make self-organization more likely (Ostrom 1999). This matches the early circumstances of the resources in the studied systems, when the first agricultural advance shrunk the communal forest area (Figure 3, transition A–B); thus, community resources became limiting and began to significantly degrade. Organizational experience prior to the first agricultural advance was not enough to react quickly, with significant costs for many communities. However, networking between communities, collective actions as a peasant organization, and cooperation with NGOs and other social actors of the public sector, increased from the crisis period (Figure 3, transition B–E), similarly to what Janssen et al. (2006) observed in various case studies. As in other communities, organizations served to gain visibility and denounce deforestation (Vega et al. In press), take joint legal action, preserve territory (Jara and Paz 2013; Cáceres 2015), conquer means to manage it (Osbahr et al. 2010), and achieve access and influence on public policies (Cassidy and Barnes 2012). This highlights the importance of social networks in the upper levels of social structure and institutions, which play an important role in problem-solving and balance power among interest groups (Resilience Alliance 2007). Our results suggest that, by combining these attributes, communities have gained adaptive capacity. Therefore, they would currently have a wider range of options to cope with disturbances and other stressors of the threatening context (Figure 3, state E). However, this situation does not prevail in several communities of Santiago del Estero.

Only peasants who are organized participated in this study. This decision could have biased the results obtained because they share values and certain ideological affinity, thus they probably have a similar understanding of socio-economic and political dynamics of changes. However, this decision has been fruitful for the purpose of the study because organizations provide significant resources to cope with external disturbances as well as deal with internal differences.

Economic factors still exert strong pressure on community forests in the region. The national agro–export model oriented to commodities, the agricultural and cattle frontier expansion, and the private grabbing of lands with precarious tenure are essentially driven by economic goals. Many studies stressed that economic factors are among the most important affecting degradation and resilience at community level (Gray and Moseley 2005; MEA 2005), both in a ‘negative’ or ‘positive’ way. On the one hand, economic incentives linked to specific policies (in this study: soybean price, release of transgenic soybean varieties, promotion of no–till technologies, unregulated deforestation) often exacerbate land degradation (Ohaete and Peco 2005). Such ‘negative’ factors are widely recognized in the academy (Román and González 2016), when debate and controversial perceptions about Forest Law effectiveness still persist (Nolte et al. 2017; Volante and Seghezzo 2018). Central in the debate is the concern about unceasing deforestation, which occurs today in breach of the law. In that matter, the first necessary action seems to be improving law enforcement and compliance. Our results disclose complex processes that suggest that these public policies are not enough to stop deforestation. Top–down attempts given by legal deforestation bans (Forest Law) have been unsuccessful (probably because they did not consider the complexity associated with land tenure problems; Aguiar et al. 2018), compared to the more recent initiatives of social coordination supported by networks of individuals, organizations, and institutions at multiple organizational levels. The consolidation of new systems of institutions and governance (Folke et al. 2005; Schultz et al. 2015), still incipient in the Chaco region, could be essential to reduce deforestation.

On the other hand, ‘positive’ economic factors linked to how communities can successfully address land degradation processes are stressed (Kelly et al. 2015). Peasant silvopastoral practices have proven to be highly effective in the restoration and conservation of native forest (Aristide 2014; Cotroneo et al. 2018) and synergistic with the economic diversification on the farm (Costanza and Neuman 1993; Trillo et al. 2014; Abt–Giubergia 2015). However, this would
depend on easier and increased access from peasants to the funds provided by the law for the forest sustainable management (Aguilar et al. 2018). Despite managing more than 81% of the remaining forest, communities have received less than 5% (since 2014) of the funds. Even so, the access to that portion was possible due to changes in institutions and governance systems. Regarding the economic factors affecting forest degradation at community–family level, recovery of monetary economics would seem necessary. Today, the profitable options for sustainable forestry, livestock and agriculture are almost null. From the learning obtained from the cotton production period, it can be concluded that resuming family agriculture in small areas would allow income diversification and reduce pressure on the remaining forest. Today, agricultural activities are hardly carried out mainly because of the difficulty of tilling a small portion of land without machinery, and re–tilling it when rain fails. When cultivation is achieved, a pair of hectares (small clearings that frequently lie idle) of extensive horticultural crops for sale, improves the economic situation. Accordingly, a necessary action seems to be the recovery of peasant agriculture. Despite requiring access to external subsidies (probably a minimum state support) from the cotton crisis, it was also learned (as expressed by several communities during the workshops) that excessive subsidization would be harmful. Abel et al. (2006) pointed out that it can inhibit the capacity to self–organize, foundational for resilience. Accordingly, in studied communities it generated the abandonment of traditional practices and the loss of skills that were not recovered after the subsidy was interrupted.

According to Mochizuki et al. (2018), infrastructure would be an important factor for community resilience. Reversing rural infrastructure abandonment (drinking water, health, education, transport, communication) seems crucial to avoid peasant migration (Cardona 2006) to the city outskirts, where people probably live in worse conditions than in the countryside (Matteucci et al. 2016). This last aspect is possibly the most important because – as we observed first-hand through this study’s communities and along the long of Chaco – forest is preserved only when it is dwelled, and people dwell on it only to a minimal wellbeing threshold. More likely, solely an active policy to preserve the countryside inhabited by people in decent conditions will allow stopping Chaco’s degradation and loss of native ecosystems.

Regarding the participatory approach to the problem, this study highlights the potential of integrating different forms of knowledge and stakeholders to better understand and contribute to the solution of complex socio–ecological problems (Turnhout et al. 2013). According to Balvanera et al. (2020), it is among the main challenges (and opportunities) of science–policy interface on ecosystems and people. Although it is increasingly recognized the need to involve the peasants along with the other stakeholders (with their diverse interests and perceptions) (Ceddia et al. 2015; Matuk et al. 2020; ZEPHIROVICH et al. 2020), from the diagnosis of the problem to the elaboration and implementation of public policies, though this type of participatory processes is still rare in large–scale programs and policies (van der Hel 2016; Piquer–Rodriguez et al. 2018). Addressing this challenge is a necessary way to improve approaches to the global environmental crisis.

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ORCID
Santiago Miguel Cotroneo http://orcid.org/0000-0002-5636-9603
Elizabeth Juliana Jacobo http://orcid.org/0000-0002-5622-7963
Miguel Marcelo Brasiolo http://orcid.org/0000-0003-2845-8390

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