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Conceptual framework to define management strategies for silvopastoral systems in native forests

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ABSTRACT. Most of the native forests in Argentina are used for livestock production with little sustainable silvopastoral management. Our objective here is to discuss different management strategies where natural and human capital are combined to co-produce ecosystem services (ES) provided by silvopastoral systems in native forests, interacting with different ecosystem functions and biodiversity. Also, we provide perspectives that should be analyzed in a context of socio-ecological approaches in agro-forestry landscapes. Four types of theoretical strategies are proposed (win-win, win-lose, lose-win and lose-lose), which define the social-ecological and economic thresholds that determine the provision of ES and biodiversity in the long term. The evidence of the win-lose strategy occurs when the silvopastoral systems are managed mainly to increase economic profitability through increments in forage biomass aimed to increase livestock production in the medium and long term. Deferred deforestation was presented as a typical example of lose-lose strategy in the Chaco region based on short-term management strategies by only obtaining commodities (crops or livestock products) without considering the negative interactions with other ES and loss of biodiversity. The information provided in this work should assist stakeholders and researchers to identify thresholds of economic profitability and ecological resilience in ecosystems under management. The proposed approaches provide a utilitarian vision of ecosystem services and key aspects of social-ecological resilience.

[Keywords: agro-forestry landscapes, biodiversity, ecosystem services, forage biomass, livestock, resilience, social-ecological system]

RESUMEN. Marco conceptual para definir estrategias de manejo en sistemas silvopastoriles para los bosques nativos. La mayoría de los bosques nativos de la Argentina se utilizan para la producción ganadera con escaso manejo silvopastoril sustentable. El objetivo fue discutir diferentes estrategias de manejo en las que el capital natural y el humano se combinan para coproducir los servicios ecosistémicos (SE) que brindan los sistemas silvopastoriles en los bosques nativos, interactuando con la biodiversidad y con diferentes funciones de los ecosistemas. Además, proponemos perspectivas para ser analizadas en un contexto de enfoques social-ecológicos en paisajes agroforestales. Se proponen cuatro tipos de estrategias teóricas (ganar-ganar, ganar-perder, perder-ganar y perder-perder) que definen los umbrales social-ecológicos y económicos que determinan la provisión de SE y biodiversidad a largo plazo. La evidencia de la estrategia ganar-perder ocurre cuando los sistemas silvopastoriles se manejan principalmente para aumentar la rentabilidad económica a través de incrementos en la biomasa forrajera, a fin de elevar la producción ganadera en el mediano y el largo plazo. La deforestación diferida se presentó como un ejemplo típico de estrategia perder-perder en la región del Chaco, basada en un manejo a corto plazo, obteniendo sólo cultivos de alto valor comercial (cultivos o productos pecuarios) sin considerar las interacciones negativas con otros SE y la pérdida de biodiversidad. La información proporcionada en este trabajo debería ayudar a los tomadores de decisión e investigadores a identificar los umbrales de rentabilidad económica y resiliencia ecológica en los ecosistemas bajo gestión. Los enfoques planteados proveen una visión utilitaria de los servicios ecosistémicos y aspectos claves de resiliencia social-ecológica.

[Palabras clave: paisajes agroforestales, biodiversidad, servicios ecosistémicos, biomasa forrajera, ganadería, resiliencia, sistema social-ecológico]

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Introduction

Most of the native forests in Argentina (60% of a total of 48 million ha) are used for livestock production with little sustainable silvopastoral management at farm level (Peri et al. 2016a). There are evidences that both overstocking and inappropriate silviculture practices, coupled with the fragility of the environment, and other socioeconomic aspects led to degradation of native forest by reducing productivity, biodiversity and ecosystem services (Peri et al. 2017a; Barral et al. 2020; Domínguez-Núñez et al. 2020). In silvopastoral systems, woody perennials (trees, shrubs) are deliberately used on the same land management unit as livestock, with different spatial arrangements or temporal sequences. Thus, in the same land unit, these systems can incorporate exotic tree species or can manage the native forests into farming systems allowing the simultaneous production of wood and livestock. In silvopastoral systems, there are ecological and economic interactions between the different system components, which can generate synergies and trade-offs among ecosystem services (ES), biodiversity and/or ecosystem functions (Peri et al. 2021a).

The benefits provided by silvopastoral systems are based on the premise that these systems can be more productive, profitable and sustainable than crops, forestry or animal production monocultures based on exotic species (Peri et al. 2017a). The woody component in silvopastoral systems enhance nutrient uptake from the soil, which nourish grasses through the degradation of organic matter, improving both soil fertility and forage quality (Nair 2011; Gargaglione et al. 2014). In addition, trees enhance animal welfare through the attenuation of extreme weather conditions, provide wood (timber and fuel), reduce soil erosion and water loss, increase biodiversity and improve environmental aspects (e.g., aesthetics) (Shibu 2009; Soler Esteban et al. 2018).

Furthermore, in a context of climate change, silvopastoral systems are capable of fixing significant amounts of carbon (C) in the soil under improved pastures and in the standing tree/shrub biomass (Dube et al. 2012; Peri et al. 2017b). Reports of vegetation (above and belowground) C sequestration potential of silvopastoral systems worldwide ranged from 1.1 to 6.55 $Mg.ha^{-1}.year^{-1}$ depending on geographic location, tree densities, design and management (Nair et al. 2009). Given the vast area of land currently managed as ruminant production systems in native forests of Argentina, the potential for climate change mitigation through C sequestration is huge. In a global change scenario, where an increase in frequency and severity of droughts are predicted, trends suggest that more active and sustainable management of silvopastoral systems will be required to enhance joint production of timber and livestock, achieve income diversification, reduce financial risk, and increase resilience to adapt to stochastic weather events (Cubbage et al. 2012; Solorio et al. 2017; Zanotti et al. 2020).

A key property for the sustainability of forest ecosystems is the ecological resilience, which is the capacity of an ecosystem to absorb, recover and/or reorganize after a disturbance, maintaining their structural-functional integrity (López et al. 2011). The resilience approach assumes that ecosystems can be expressed as two or more alternative stable states and emphasizes the potential occurrence of state transitions based upon shifts between unique sets of organizing structures and processes. The state transitions are associated with the crossing of thresholds, beyond which the system significantly diminishes or loses resilience to the previous or original state. Each state has a specific resilience to different factors of disturbance. Then, the original resilience of the ecosystem is associated with the ability to maintain and/or recover the ecosystem identity (i.e., the reference state). Specifically, the forest resilience (i.e., reference state) is mainly associated with key processes, such as the recruitment of foundational tree species, which allow the tree stratum to be maintained and naturally recovered, and therefore allows to regenerate the structure and functioning of the rest of the forest ecosystem (López et al. 2011, 2013; Peri et al. 2017b). This natural regeneration process of the forest can be affected directly (e.g., by grazing and browse, trampling and/or death from regeneration stress, seedbeds lack due to overcutting), or indirectly when other key processes are 'degraded' and that limits natural regeneration (e.g., nutrient cycling, erosion soil, hydrological regulation) (Peri et al. 2021c).

Thresholds are an essential concept that should be considered in resilience management. The thresholds are used to describe 'breakpoints' between two regimes or alternate stable states in an ecosystem

(Briske et al. 2006). When a threshold along a controlling variable in a system is passed, the nature and extent of feedbacks change, such that there is a change in the direction in which the system moves. A shift occurs when internal key processes of the system (e.g., rates of birth, mortality, growth, consumption, decomposition, leaching, etc.) have changed such that the variables that define the state of the system begin to change in a different direction, towards a different attractor (Briske et al. 2006). Then, the thresholds crossing is associated with conditions or factors (e.g., extreme droughts and/or overgrazing) that modify the structure and key function of the silvopastoral system beyond the limits of ecological resilience (which allows to maintain the system in the current state, or return to the previous -or original- state), resulting in a transition to an alternative state. In some cases, threshold crossing brings about a sudden, large and drastic change in the responding variables (e.g., associated with the occurrence of drastic events such as fires, extreme droughts, eruption of volcanoes), whilst in other cases the response in the state variables is continuous and more gradual (e.g., associated with continuous and prolonged disturbance factors, such as overgrazing, recurrent and moderate droughts) (Christensen and Krogman 2012; Easdale and López 2016).

The objective of this work is to provide a conceptual framework to discuss different management strategies for silvopastoral systems in native forests where natural and human capital are combined to co-produce ecosystem services, interacting with different ecosystem functions and biodiversity. This framework has the potential to assist stakeholders and researchers to discuss how to assess, quantify and identify thresholds of economic profitability and ecological resilience in silvopastoral systems based on native forests. Likewise, we propose to advance some perspectives that should be analyzed in a context of social-ecological systems in agro-forestry landscapes. The proposed approaches provide a utilitarian vision of ecosystem services and key aspects of social-ecological resilience.

Conceptual framework for silvopastoral management strategies

The concept of ES has recently received increasing attention in scientific and policy contexts because of its capacity to bridge ecosystems and social systems (Reyers et al. 2013), as well as to integrate ecological, social-cultural and economic approaches to build knowledge and develop policies (Chan et al. 2012; Peri et al. 2021a). The cascade model proposed by Haines-Young and Potschin (2010) has been widely adopted as a conceptual model that guides how to assess ES by distinguishing the functional characteristics of ecosystems from services, and services from benefits (de Groot et al. 2010). Thus, the cascade framework links ecological processes with elements of human well-being following a pattern similar to a production chain. The Millennium Ecosystem Assessment (MEA 2005) classified ES in a) supporting services (the services that are necessary for the production of all other ES including soil formation, primary production, nutrient cycling), b) regulating services (climate, water and erosion regulation, disease regulation, pollination), c) provisioning services (products such as food, fiber, fuel, biochemicals, natural medicines, fresh water), and d) cultural services (spiritual enrichment, recreation, aesthetic). Silvopastoral systems provide multiple provisioning (e.g., food, wood, fodder, mulch, medicinal plants) and regulating services (e.g., maintenance of soil fertility, erosion control, microclimate improvement, biodiversity enhancement, watershed protection, carbon sequestration). Among these recognized categories of ES, cultural and regulating are those that have received less scientific attention in silvopastoral systems in Argentina, although their human demand will increase in the next years in industrialized and rural societies (Soler et al. 2018). In this context, the role of human capital and non-monetary values in the definition of ES management strategies is increasingly recognized (Jones et al. 2016), because these affect the supply of provisioning ES, the maintenance of ecosystem functions (regulation or support) and the conservation of biodiversity in anthropized environments (Peri et al. 2021a).

It is often assumed that a large variety of ES can be maintained through increased biodiversity and intact natural areas (Costanza et al. 1997; MEA 2005; Gamfeldt et al. 2013) that guarantee the maintenance of the ecological resilience of the system (Seidl et al. 2016). However, some management practices are aimed to increase provisioning ES (e.g., forage grasses, crops) at the expense of biodiversity (Lyytimäki and Sipilä 2009). In this sense, arises the concept of disservices in ecosystems under use (Lyytimäki and Sipilä 2009; Escobedo et al. 2011) by considering negative consequences of management practices on human well-being, profitability (e.g., increased costs) and ecosystem integrity (e.g., soil erosion), reducing the ecological resilience of the system. Traditionally, most silvopastoral management in native forests have been characterized by a short-term economic gain (e.g., monetary provisioning ES) without considering the potential negative unexpected effects (vulnerability to undesirable changes) on ecosystem functions and long-term economic profitability (Seidl et al. 2016). Likewise, long-term social-environmental vulnerability problems have not been considered, in terms of: greater frequency/exposure to social-environmental disturbances (for example, associated with climate and/or global change), as well as a decrease in resilience. All this undoubtedly compromises the long-term sustainability of silvopastoral systems.

The supply of ES depends on a variety of environmental and biodiversity co-factors (MEA 2005) that regulates the response capacity to external interventions (ecological resilience) and the productive biophysical capacity of the intervened forest ecosystems. This may impact on: 1) the generation of disservices, and 2) ecological resilience delimited by thresholds. Understanding these interactions and their consequences on ecological and economic stability (Tallis et al. 2008; Felton et al. 2019) determine challenges in the design of management proposals at multiple spatial and temporal scales (Figure 1).

In this context, four types of theoretical strategies are proposed (Figure 1 and 2), which define the social-ecological and economic thresholds that determine the provision of ES

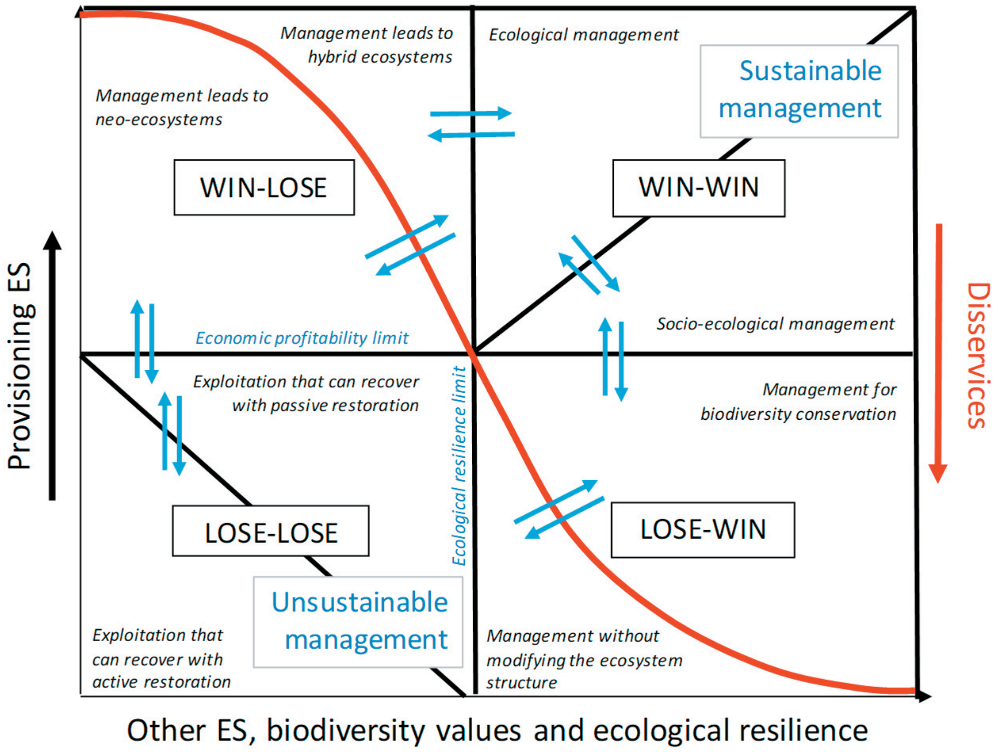

Figure 1. Schematic changes in the provision of ecosystem services (ES) and biodiversity in native forests, defined by the balance between ecological resilience and economic profitability under different silvopastoral management of anthropized environments. The plotted hypothetical curve (red) represents a non-linear response between the axes, in order to exemplify four contrasting situations of management and/or conservation of agricultural-livestock-forestry landscapes: lose-lose, win-lose, win-win, lose-win.

Figura 1. Esquema de cambios en la provisión de los servicios ecosistémicos (ES) y la biodiversidad de los bosques nativos, definidos por el balance entre la resiliencia ecológica y rentabilidad económica bajo diferentes esquemas de manejo silvopastoril de ambientes antropizados. La curva teórica (roja) representa una respuesta no linear entre los ejes para ejemplificar cuatro situaciones contrastantes de manejo o conservación de paisajes forestales-agrícola-ganaderos: perder-perder, ganar-perder, ganar-ganar, perder-ganar.

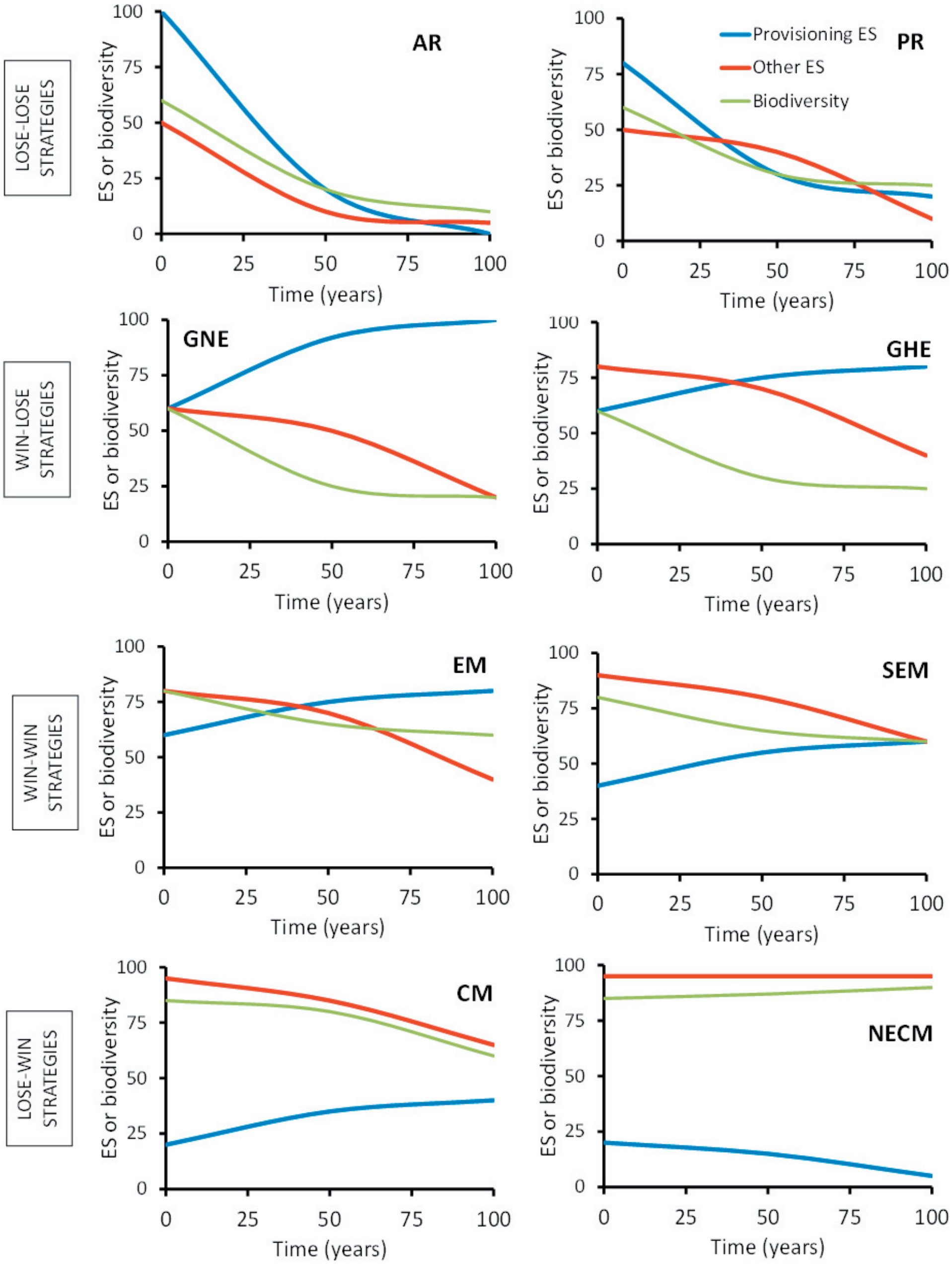

Figure 2. Theoretical changes in the supply of ecosystem services (ES) and maintenance of biodiversity under different management strategies for silvopastoral use of anthropized environments over time. AR=silvopastoral use with active restoration; PR=passive restoration; GNE=management with generation of neo-ecosystems; GHE=management with generation of hybrid ecosystems; EM=ecological management; SEM=socio-ecological management; CM=conservation management; NECM=management without conversion of ecosystems. Time 0 years represent the start-up converted forest, and shows the provision of the different ES according the management objectives. The curves were defined using data of biodiversity and ES evolution for unmanaged and managed *Nothofagus* forests along the full management cycle (e.g., Spagarino et al. 2001; Deferrari et al. 2001; Martínez Pastur et al. 2002, 2013, 2021).

Figura 2. Cambios teóricos en la provisión de los servicios ecosistémicos (ES) y el mantenimiento de la biodiversidad frente a diferentes estrategias de manejo silvopastoril en ambientes antropizados a lo largo del tiempo. AR=uso silvopastoril con restauración activa; PR=restauración pasiva; GNE=manejo con generación de neo-ecosistemas; GHE=manejo con generación de ecosistemas híbridos; EM=manejo ecológico; SEM=manejo socio-ecológico; CM=manejo para la conservación; NECM=manejo sin conversión de los ecosistemas. El año cero representa el momento de la conversión de los bosques, y muestra la provisión de los ES de acuerdo con los objetivos del manejo planteado. Las curvan fueron definidas de acuerdo con datos de biodiversidad y la evolución de los ES para bosques manejados y no manejados de *Nothofagus* a lo largo de su ciclo de manejo (e.g., Spagarino et al. 2001; Deferrari et al. 2001; Martínez Pastur et al. 2002, 2013, 2021).

and biodiversity in the long term. Given the array of possible regime shifts, we adopt a broad definition of a threshold as a breakpoint between two regimes (or alternative estates) of an ecosystem. It is intended to be inclusive to provide a conceptual framework and context for analysis of different kinds of thresholds and different kinds of regime shifts or alternative states with different ecological resilience, but it will also allow us to address the concept of social-ecological resilience discussed at the end of this proposal (López et al. 2017).

The traditional management of several forest landscapes in Argentina was based on short-term management strategies (lose-lose strategy) by only obtaining wood and livestock products without considering the potential negative interactions with other ES, the loss of biodiversity or the generation of ecosystem impacts on humans. This strategy maximizes the profitability in the short term, despite the other ES or ecosystem values or the consequences in the long term. However, in recent years, new management strategies have been implemented in order to maintain main ecosystem functions and biodiversity in anthropized landscapes (win-win strategy) that guarantee the supply of provisioning ES in the long term and allow achieving sustainability and economic profitability. This strategy reduces the losses of biodiversity and ES supply in the same areas under management, determining long-term consequences in the decision-making process.

The lose-lose and win-lose strategies aim to maintain economic profitability at the expense of ecological resilience (i.e., causing the decrease or loss of the forest original resilience and, thus, threshold crossing) (Figure 1 and 2). The lose-lose strategy tends to increase economic profitability in the short-term, at the expense of loss or decrease of forests' ecological resilience caused by a great loss of biodiversity and functional diversity (Peri et al. 2021c), promoting the loss of other ES, which ultimately decreases economic profitability at the medium- and long-term as a consequence of resource exploitation and ecosystem degradation (Seidl et al. 2016). However, the change from exploitation (lose-lose) to management (win-lose) of the forest landscape would allow to increase the economic profitability in the long term. In this situation, two types of practices are proposed: a) active restoration through tree plantation or sapling protection (individual fences) in forests heavily harvested where the regeneration process of tree species has been disrupted (Peri et al. 2017b), and b) passive restoration (natural recovery) through use suppression in silvopastoral systems that still retain its ecological resilience to the reference state (intensively harvested stands with incipient natural regeneration) but requiring time for the ecosystem to recover.

The win-lose strategy enhances the provisioning ES in the medium and long term, obtaining significant economic profitability from the system compared to natural ecosystems. However, there is a considerable decrease in other ES and biodiversity, and therefore, a decrease in the ecological resilience to the reference state. Consequently, restoration or management practices can drive transitions to states with better structural and functional levels, but distinct to the reference state. Two types of silvopastoral management can be identified in this situation: 1) generation of neo-ecosystems (Hobbs et al. 2006) that differ from the characteristics of the reference forest (primary forest), for example silvopastoral management in *Nothofagus antarctica* (ñire) forests with forage species introduction (Peri et al. 2016b), and 2) generation of hybrid ecosystems, with moderate anthropic interventions that preserve values of the reference forest. For example, a silvopastoral system that only manage the forest canopy cover by a planned thinning or design scheme to increase the solar radiation availability in the understory to favor the growth of few forage species, but decline ecological resilience by reducing soil fertility and biodiversity (Peri et al. 2016b; Mauricio et al. 2019).

On the contrary, the win-win and lose-win strategies aim to maintain the ecological resilience of the system in the long term (Figure 1 and 2). The win-win strategy aims to manage the provisioning ES from silvopastoral systems at distinct spatial-temporal scales, allowing greater long-term economic profitability, maintaining other ES and biodiversity. For this, two types of management can be identified: 1) ecological management that increase provisioning ES in the long-term by maintaining characteristics of the reference forests in the managed stands, e.g., variable retention that combines dispersed retention and forest aggregates in a landscape production matrix (Martínez Pastur et al. 2019), and 2) social-ecological management where less use of provisioning ES is based on multi-purpose and diversified production

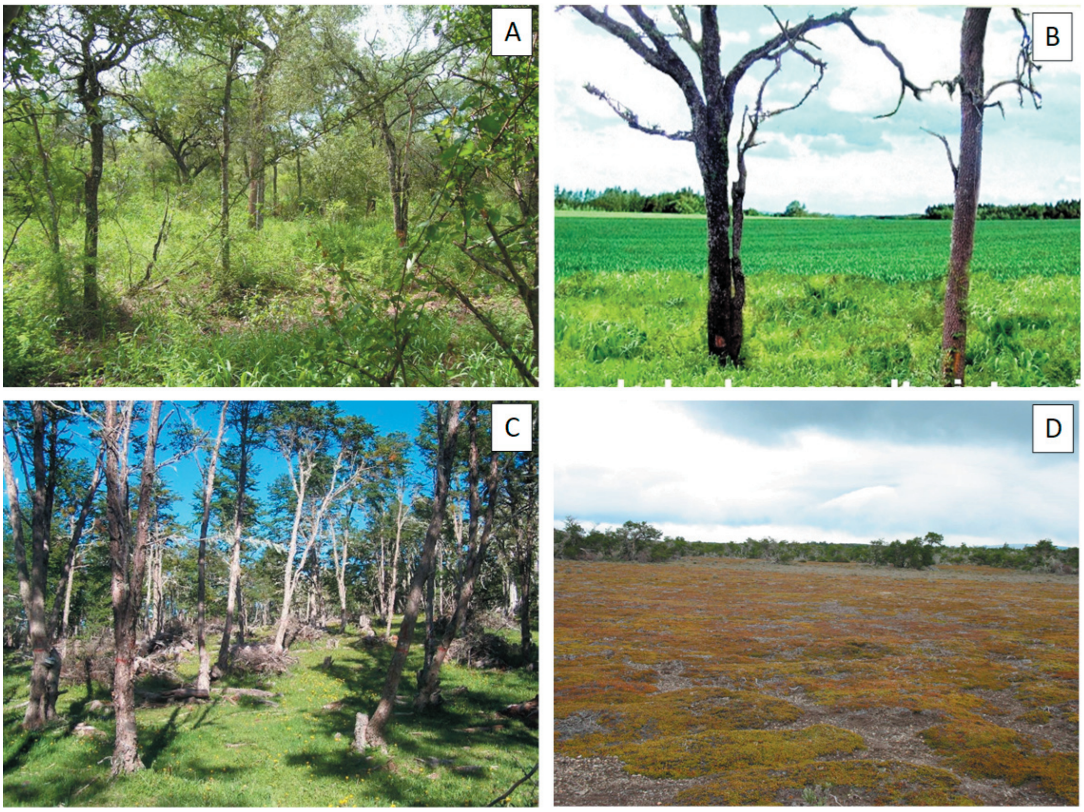

Figure 3. Examples of win-win (A) and lose-lose (B) strategies in the Chaco Region, and win-lose (C) and lose-lose (D) strategies in Patagonian ñire forest.

Figura 3. Ejemplos de una estrategia ganar-ganar (A) y perder-perder (B) en la región del Chaco, y de ganar-perder (C) y perder-perder (D) en bosques de ñire en la Patagonia.

strategies preserving biodiversity and other ES, for example different-scale diversified agroforestry systems (e.g., extensive livestock raising, beekeeping, collection of native fruits, fungi and medicinal plants, either within the same farm or landscape level) (see also Figure 4).

Finally, the lose-win strategy, where the main objective of ecosystem management is the conservation of other ES and biodiversity, with minimal use of provisioning ES. These types of management allow to preserve characteristics of the reference forest in the long-term at expense of the economic profitability. Two types of management can be proposed: 1) conservation management with very low forest interventions, e.g., forest management in watersheds for water retention and quality (Lin et al. 2020), and 2) non-conversion of ecosystems by using minimum provisioning ES (e.g., ecotourism, bird watching, fungi collection or non-wood forest products [Lovrić et al. 2020]). Therefore, the definition of these strategies (lose-lose, win-lose, win-win, and lose-win) aims to facilitate the identification of the key components (e.g., natural and artificial related to human uses) that define the different types of forest management under silvopastoral use considering the ecological resilience and economic profitability of the anthropized landscapes.

Evidence of win-lose strategy in silvopastoral systems

The evidence of the win-lose strategy occurs when the silvopastoral systems are managed mainly to increase economic profitability through increments in forage biomass aimed to increase livestock production in the medium- and long-term. The productivity and nutritive value of a pasture in a silvopastoral system is dependent on the interaction of environmental and management factors, and, in turn, determines animal reproduction efficiency and production.

For example, in the western Chaco Region, silvopastoral systems in mixed native forests and degraded open woodlands are

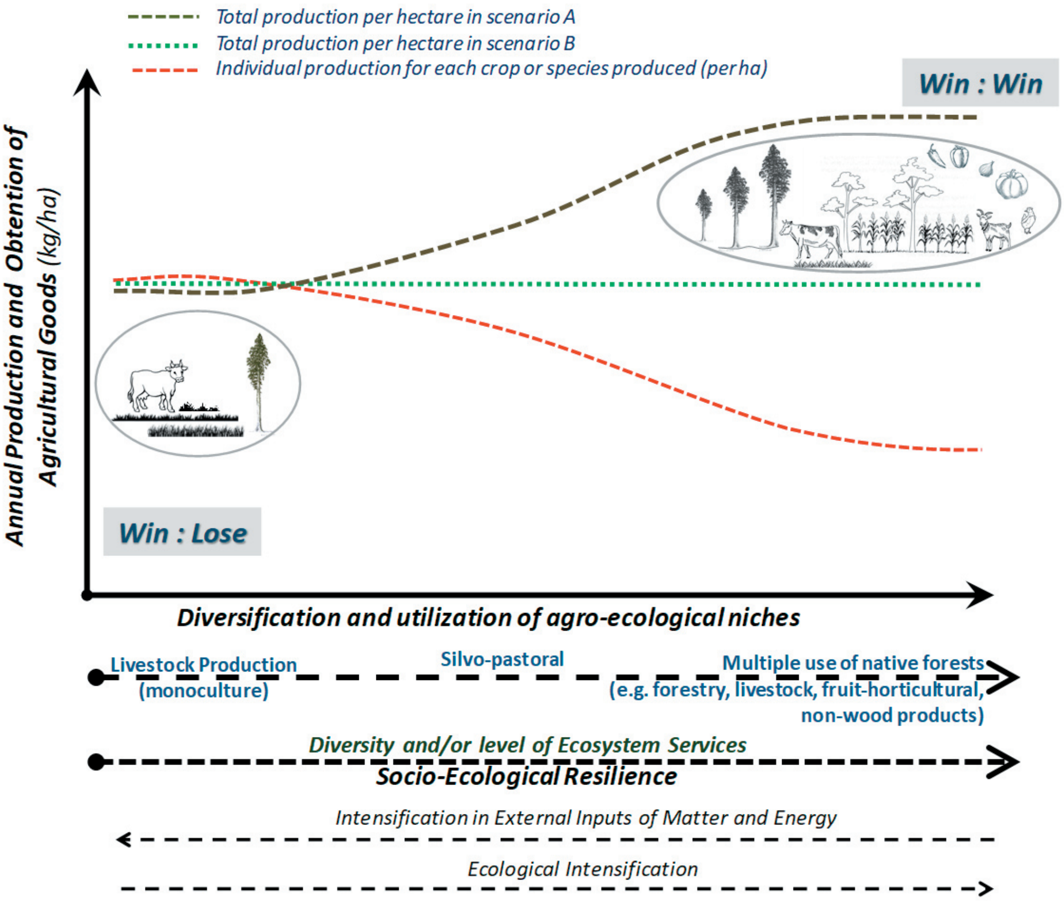

Figure 4. Theoretical model of the response between provisioning of agricultural goods per hectare and the increase in diversification and agro-ecological niches use, and its relationship with socio-ecological resilience (modified from Peri et al. 2021c). Red dotted line shows the response of species production as agro-ecological diversification increases; the dark green dotted line (scenario A) shows how production per hectare would be as agro-ecological diversification increases; the light green dotted line (scenario B) represents a scenario where socio-ecological resilience increase despite agricultural production per hectare with greater agro-ecological diversification (López et al. 2017).

Figura 4. Modelo teórico de respuesta entre la provisión de bienes agrícolas por hectárea y el incremento de la diversificación de nichos agro-ecológicos, y su relación con la resiliencia socio-ecológica (modificado de Peri et al. 2021c). La línea roja punteada muestra la respuesta de las especies a medida que la diversificación agro-ecológica aumenta; la línea verde oscura punteada (escenario A) muestra cómo podría ser la producción por hectárea a medida que la diversificación agro-ecológica aumenta; la línea verde claro punteada (escenario B) representa un escenario donde la resiliencia socio-ecológica aumenta más allá de la producción agrícola por hectárea con una alta diversificación agro-ecológica (López et al. 2017).

being designed to specifically address the problem associated to dense shrub thickets and overstocked forests caused by livestock overgrazing, over-logging, changes in the fire regime and fencing (Kunst et al. 2006). This process known as 'native woody plant encroachment' or 'ticketization' is a process that has occurred in many parts of the world, especially in African savannas (Sankaran et al. 2005). The proliferation of the shrub stratum reduces forage availability due to competition for resources (space, solar radiation and water) and, at the same time, difficult livestock and personnel movements due to high stem density and thorns. In this context, silvopastoral systems are established to generate hybrid ecosystems, using the mechanical treatment called 'low intensity roller-chopping' (RBI) based on a mechanical disturbance that improves forage productivity (Cabral et al. 2003; Kunst et al. 2008). Research reports a forage yield increase >500% of native grass species in comparison with untreated areas (Passera et al. 1996), increasing economic profitability. Tree individuals of DBH>10-15 cm are left standing in different patterns and densities, while, at the same time, shrubs are crushed and left as debris that can degrade naturally, harvested for firewood or burnt. The elimination of the shrub layer negatively impacts the survival of tree seedlings and saplings <10-15cm DBH, decreasing the regenerative ability of native forests in the long-term (del Moral et al. 2007). Because the woody species have the ability to resprout (Bravo et al. 2010), these interventions must be recurrent (2-5-years intervals) to be able to avoid the recovery of the shrub stratum and also ensure the maintenance of a profuse herbaceous layer (Kunst et al. 2008). Hence, recurrent interventions may disrupt native tree regeneration. In addition, after a roller-chopping treatment, forage yields and livestock stocking rates usually increase by seeding exotic species such as *Panicum maximum* (C_4 summer growth perennial grass adapted to shade) and *Cenchrus ciliaris* simultaneously with the roller chopping (Kunst et al. 2014; Baldassini et al. 2018). This practice has the potential risk of the proliferation of highly competitive alien grasses, ultimately leading to plant invasion in the understory. Therefore, this practice is highly unstable and dependent on external inputs aimed to maintain the system supplying high levels of provisioning ES, as recurrent mechanical interventions, thereby compromising tree regeneration in the long-term.

In Southern Patagonia, the understorey dry matter (DM) production in ñire silvopastoral systems ranges from 140 to 3760 kg DM/ha, and mainly depends on the interaction of soil water availability and light intensity reaching to the forest floor, determined by specific environmental site conditions and the intensity of the thinning (Peri 2005; Fertig et al. 2009; Peri et al. 2017a; Martínez Pastur et al. 2018). For pasture growing in moderate water stress site conditions, there is a positive exponential relationship between DM production and the light reaching understorey, decreasing from 2800 kg DM/ha in the open (100% photosynthetic photon flux density-PPFD) to 500 kg DM/ha under severe shade (5% PPFD). In this situation, trees in silvopastoral systems reduce soil moisture by creating a rain shadow, direct interception of rainfall and root competition for water. However, under severe water stress site conditions, understorey DM production increased from 5 to 47% PPFD reaching a maximum value of 1400 kg DM/ha around 50-60% PPFD, and then declined with a reduction in tree number. In these dry conditions, intermediate crown cover may conserve soil moisture through a reduction in evapotranspiration mainly by reducing wind speed (up to 80% reduction compared with adjacent open area) within the stand (Bahamonde et al. 2009). The results suggest that silvopastoral use of ñire forests at intermediate crown covers are established to generate hybrid ecosystems that may be desirable to increase forage production. In addition, it has been demonstrated that forage DM production and quality in ñire silvopastoral systems is improved by introducing high productive forage species such as legumes that provide a source of nitrogen and high-quality forage for animal grazing. Peri et al. (2012) reported that pasture total annual yield increased by 20-40% as well as quality of pasture (crude protein, %CP and in vitro digestibility), depending on light availability, through the introduction of mixed improved pastures with white clover (*Trifolium repens*). These results highlighted the adaptation of white clover to ñire silvopastoral systems and their ability to improve the quality of natural pastures.

EVIDENCE OF LOSE-LOSE STRATEGY IN SILVOPASTORAL SYSTEMS

Most of Argentina's native forests are subjected to livestock use of varying intensity and with varying levels of planning, from extensive community forestry farming to intensive models. The latter converts forests into savannas and parks in few years through a deferred deforestation by totally removing the shrub layer and leaving a negligible proportion of mature trees for livestock shading (less than 100 mature trees per hectare) without regeneration that slowly fall down at short- to medium-term. Between 2012 and 2018, the total area of native forest loss in the provinces of Chaco, Salta, Formosa and Santiago del Estero was approximately 1 million ha, of which 28% corresponded to deferred deforestation justified under 'silvopastoral use' (Mónaco et al. 2020). Therefore, deferred deforestation is a typical example of lose-lose strategy in the Chaco Region based on short-term management strategies by only obtaining commodities (crops or livestock products) without considering the generation of disservices and negative interactions with other ES, loss of biodiversity (Martínez Pastur et al. 2020) and significant decrease in ecological resilience. This produced a strong expansion of the real estate market for sale off land with forests at low prices, where companies after clearing with authorization for agriculture and livestock production, sold the land at substantially higher prices. Currently, the value of cleared land is three times higher than that of the land covered by native forest, and even discounting clearing costs, the profit is still very positive (Mónaco et al. 2020).

In ñire forests of Patagonia, lose-lose strategy can be represented by livestock overgrazing, fire use for land conversion, intensive logging (e.g., clear-cuts) and extreme droughts, or a combination of these factors that generate significant structural-functional changes in the ecosystem leading to a degraded state (Peri et al. 2017b). An example of this situation in Santa Cruz province, are mature (>120 years-old) ñire forests of very low canopy cover (<10% or basal area <8 m^2/ha) without natural regeneration due to soil loss by wind erosion, and high occupation (cover >30-40%) of murtilla (*Empetrum rubrum*). Generally, these are shrubby forests (<5 m height of dominant trees), exposed to strong winds, growing in sandy or sandy loam soil and in sites with evidence of intense fires that determine the loss of the thin organic soil layer and facilitate the occupation of murtilla. This type of exploitation determines that the lack or absence of ñire regeneration due to soil loss by wind erosion and occupation of murtilla limits forest continuity, and protection strategies (e.g., active regeneration) are necessary to guarantee the forest cover structure in the medium-term.

Evidence of lose-win strategy in silvopastoral systems

The lose-win strategy occurs mostly in lands destined to conservation purposes, which can be national parks or private nature reserves located in fields usually acquired by non-governmental organizations (NGO). Two contrasting situations can be characterized by this strategy. The first situation can be exemplified by indigenous or local 'criollos' people that inhabit national parks, and raise livestock mainly for self-consumption, with low economic profitability and mainly unsatisfied basic needs. When demographic growth of those families is accompanied by growth of the herds they raise and forest harvesting for timber or firewood (win situation), sustainable grazing and wood harvest turns into overgrazing and unsustainable management that can lead to native forest degradation and biodiversity loss (lose situation). This can be compensated by encouraging other activities such as ecotourism and management for biodiversity conservation grounded on their traditional ecological knowledge (TEK). However, for indigenous communities like Wichís in the Chaco Region, the win situation to improve their livelihoods is different because their sense of economic wellbeing is not framed in the western perception of productivity (Gordillo 1993).

Another example of lose-win strategy would be when a territorial ordering of landscapes is carried out, in which basin headwaters and strategic areas associated with a key ecosystem service are conserved. However, for territorial ordering, integration among sectors and policy-makers, as well as the balance of power relationships among stakeholders, are crucial for the conservation and sustainable use of native forest, long-term human wellbeing and sustainable development (Peri et al. 2021a). This, in the short term, reduces the area to produce and, therefore, the economic income of the producers of these landscapes is reduced. But in the long-term, environmental disturbances (or disasters) such as floods or avalanches are prevented, and the economic, social and environmental consequences this entails, are avoided (e.g., as avalanches in Tartagal-Salta, and then it was decided to regulate the forest law).

Evidence of win-win strategy in silvopastoral systems

There are evidences of the win-win strategy in Latin America, where several silvopastoral systems designs restore soil fertility and biodiversity, increase forage and wood biomass, promote animal welfare, diversify income and meet food security needs associated with environment conservation (Mauricio et al. 2019). In Argentina, articulation of public policies for silvopastoral management has been developed in a joint institutional agreement between the Ministerio de Agricultura Ganadería y Pesca (Ministry of Agriculture, Livestock and Fisheries, MAGyP) and the Ministerio de Ambiente y Desarrollo Sostenible (Ministry of Environment and Sustainable Development, MAyDS), and the Instituto Nacional de Tecnología Agropecuaria (National Agricultural Institute, INTA). This general agreement named Forest Management with Integrated Livestock (Manejo de Bosque con Ganadería Integrada, MBGI) aims mainly to: 1) contribute to sustainable use of native forests as a tool of development and according to sustainability criteria and minimum standards established by Law No. 26331, 2) strength the provinces by promoting capacity building for implementing MBGI plans, and 3) establish a monitoring system. The conceptual framework of MBGI technical agreement is based on the provision of ES by forests and on an adaptive management scheme to define the interventions.

MBGI proposes seven technical guidelines to meet the objectives and guide management plans.

Technical guideline 1

MBGI incorporates a comprehensive land use planning by considering the minimum contents for Sustainable Management Plans for Native Forests in which the specific goals and objectives for each component of the system are clearly defined and the interventions are designed with respect to a reference forest state. The plan is the document that synthesizes the spatial-temporal organization of resources for sustainable use of timber and non-timber forest products and services provided by the ecosystem. Therefore, the plan must include a detailed initial characterization of the farm (baseline) including ecological, legal, social and economic aspects, as well as a forest inventory to identify ecological sites and current forest state.

Technical guideline 2

The MBGI plans include an exclusive area (>10% of farm area) for biodiversity conservation, the maintenance of forest connectivity, the preservation of species gene pool and the protection of the associated fauna. By considering the importance of biodiversity conservation in productive landscapes, it is of great value to preserve livestock-free areas within the management unit. Ideally, these areas should be located away from roads and intensive productive sites. Forest connectivity should be considered at watershed- or landscape-scale rather than at the farm-scale. The rest of the property is destined to the management of the shrub layer, such as the practice of 'low intensity roller-chopping' (RBI) in the Chaco Region. Nevertheless, the shrub layer is controlled but leaving a remnant of shrub cover of at least 30% for each stand intervened or successive thinning for ñire forests in the Patagonian region.

Technical guideline 3

MBGI considers the importance of all strata of the vertical forest structure in the ecosystem functioning and its space-time complexity. In this sense, the native shrub stratum functionality is recognized in the nutrient cycle, forage contribution, soil protection, microclimatic amelioration, biodiversity, water cycle, source of non-wood products and wildlife protection. For the management of the shrub cover (a remnant >30% cover per hectare) to increase the forage allowance within forests, technical parameters of the machinery used in the Dry Chaco are established (e.g., maximum width of 2.5 m, maximum length of 10 m). In addition, exclusive area for forage reserve must be located outside of the native forest on the property. The forage species implanted to increase forage supply must be non-invasive species and in areas compatible with the farm economic objectives of sustainability.

Technical guideline 4

The organization of activities includes a forest management plan in which the proposed silviculture scheme is based on the natural forest dynamics as to ensure the stands regeneration. The resulting structure from forest use must be representative of the region reference forest, both in the composition of species (in terms of its richness and abundance) and in the diameter distribution. In turn, it establishes that remnant trees provide other forest functions such as seed production, fauna habitat, and nutrient cycling. For example, in 'Quebrachal' (*Schinopsis lorentzii*, *Aspidosperma quebracho-blanco*) forests growing in 'high' ecological sites of the semi-arid Chaco Region, the minimum basal area that must be maintained is around 6 m^2/ha, with a balanced irregular tree size distribution, and harvesting volume must not exceed the forestry possibility. To encourage the successful application of forest management within the MBGI framework, it is desirable to promote the value addition of wood and non-wood forest products, and to evaluate employment conditions.

Technical guideline 5

Livestock management plan must be specifically adapted to the real possibilities of the system (carrying capacity) by adjusting animal stocking rate to forage productivity over time (inter-annual variability), planning of forage reserves and productive efficiency, allowing in all cases, the regeneration of the forest to avoid the adverse effects caused by overgrazing.

Technical guideline 6

Contingencies plan in MBGI must contain a system for forest fires prevention and control, and strategies of water reserves for livestock consumption to prevent situations of negative impacts of prolonged droughts on the system.

Technical guideline 7

Water management plan establishes the design for efficient water use that includes water supply sources and its spatial distribution to improve animal performance (animal welfare, live weight gain) and to reduce the negative impacts of livestock on the forest (regeneration browsing, trampling) in concentrated drinking points.

These MBGI technical guidelines require definitions by provincial government agencies to provide local operational meaning by maintaining the balance and integration of the productive, environmental and social aspects under principles of sustainability. Not all the silvopastoral systems under MBGI guidelines can be a win-win strategy. Most of the current applications, from northern to southern forests, are based on win-lose strategy maximizing provisioning ecosystem services. For this reason, new proposals of silvopastoral systems must be designed and tested under MBGI guidelines considering: a) an increase of livestock density compared to unmanaged stands, b) an improvement of timber quality of the remnant trees according to the market needs, c) support in-situ at least of 80% of the original biodiversity, including the key umbrella species, and d) maintain the other provision of ES according to the uses of local people, including the aboriginal communities and the respect of heritage values. Thus, MBGI can be an example of a win-win strategy if the proposed management integrate all the ecosystem functions and values, as a productive alternative to land use change, where the native forest is included in the productive matrix. In this context, forest use must be adjusted considering stand growth rates that contemplate the maintenance of a minimum stock and remaining cover, the preservation of habitat for biodiversity conservation and other support and regulation services of the system.

Under MBGI management, the creation of a complete array of forest successional stages and structures (e.g., phase dynamics within the reference state, according to the state and transition model [Peri et al. 2017b]), including sectors with connected old-growth forest and other legacies as original understory vegetation is recommended to achieve the persistence of the system and the maintenance of major environmental values as the original resilience of forests. Native forests are usually immersed in a landscape spatial matrix that alternates rangelands, wetlands, crops and other woodlands, depending on the geographic zone. Biodiversity is partially share among these environments (e.g., 79-93% of their vascular plant species are usually common to all environments of the landscape matrix [Lencinas et al. 2008]). Also, variations in forest structure through modifications in overstorey canopies (more closed or open canopies) generate differences in richness and relative abundance of different organisms, which could be minima as for understory vascular plant, insect and bird richness and density (Peri et al. 2017a; Lencinas et al. 2018). Aspects such as forest types and reference states, intervention thresholds, action protocols, special conservation values and the establishment of biological corridors aimed at increase forest connectivity should be developed at the provincial level. Regarding the low-impact management strategy, sequential interventions (spatial-temporal rotation) of all the components of the system are proposed to be managed within the limits of the forest resilience (i.e., without crossing ecological thresholds, beyond which the forest resilience to different disturbance factors is diminished or lost).

Furthermore, this win-win strategy of silvopastoral use provides better carbon (C) sequestration and storage in forests than degraded ecosystems or land conversion to crop (Peri et al. 2017c). Well-managed silvopastoral systems outperform both grasslands/pastures and forests in terms of C by increasing soil and biomass C storage. For example, in the Chaco Region, the soil organic C (100 cm depth) stored in a silvopastoral system (*Prosopis alba* trees with *Chloris gayana* pasture) was higher than an adjacent grazing beef cattle pasture (84.7 *vs.* 64.6 Mg C/ha), and in Patagonia, the total C stored in silvopastoral systems showed an intermediate value of 148.4 Mg C/ha, compared with primary ñire forest and adjacent open grasslands (Peri et al. 2017c). This regulating ES is essential for the contribution to reducing greenhouse gas emissions under a climate change scenario.

Considering the multiple aspects that the MBGI involves under an adaptive management, it is necessary to evaluate and monitor different variables related to the social-economic and environmental dimensions. Peri et al. (2021b) in Patagonia and Alaggia et al. (2019) in the Chaco Region developed a set of indicators to assess sustainable management of native forests under MBGI at a farm scale. Multi-criteria methods were used to integrate different perspectives regarding environmental, social and economic aspects of the forest's management. In a participatory process (extensive consultation with experts and workshop for prioritization of indicators), 17 indicators (7 environmental, 4 social-economic, 6 productive) for the Chaco Region and 23 indicators (12 environmental, 5 social-economic, 6 productive) for Patagonia were agreed by consensus of specialists for monitoring at the farm scale. The indicators respond to the basic principles of sustainability: 1) the productive capacity of the ecosystem must be maintained or improved, 2) the integrity of the ecosystem and its ecosystem services should be maintained or improved, and 3) the communities well-being associated with forest use must be maintained or improved. The importance of monitoring indicators will allow government agencies with competence in native forests management (provincial technical committees in the application of the MGBI) to evaluate the impact of the management plans on the state of forests conservation and on farmer's life quality associated with forest use.

Social-Ecological Resilience approach and management

Social-ecological resilience is an emergent property of a social-ecological system, and is related to three key aspects: 1) the system's ability to absorb or respond to a disturbance factor and remain in the same state or equilibrium regime, 2) self-organization capacity (in comparison with a lack of organization or the organization driven by external factors), and 3) the ability to learn and adapt to future changes and/or new disturbance factors or social-environmental drivers (Holling and Gunderson 2002; López et al. 2017). Social-ecological resilience is an emergent property because it does not depend on one factor or system component (e.g., such as ecological resilience), but rather depends on various factors and/or their interaction or synergy (e.g., learn ability about natural dynamics, people's ability to foresee and anticipate change).

The social-ecological resilience is a complex property to evaluate and quantify (Folke 2006). But the structural-functional diversity and redundancy at both the ecological subsystem (e.g., species richness and evenness, process diversity of an ecosystem) and the social subsystem level (diversity of rural family composition, types of crops and productive uses, appropriate technologies and knowledge of the environment) can be used as proxies to estimate the resilience level of a given social-ecological system (Easdale and López 2016; López et al. 2017). Functional diversity is associated to the range of options that a given system has to respond to one or more disturbance factors. Specifically, functional diversity is the variety of functional traits, behaviors and action modes by which a system can respond to several drivers. Likewise, functional redundancy is the existence of multiple similar units, but not identical, functionally replaceable with each other, to fulfill a common function or interest (Salas-Zapata et al. 2012; López et al. 2017).

For the sustainable management of social-ecosystem at farm- and social-ecological landscape-levels, the resilience must be thought at different scales. Specifically, it is essential to maintain key processes and relationships in social-ecological systems to increase their resistance, recovery and adaptation ability to a great variety of external or internal disturbances at a range of ecological and social scales. Management practices should be aimed to actively maintain a diversity of functions, steering systems away from thresholds of potential concern, increasing the ability of the system to maintain structuring processes and feedbacks under a wide range of conditions, and increasing the capacity of a system to cope with change through learning and adaptation (Bestelmeyer and Briske 2012; López et al. 2017). The design of multipurpose agro-forestry is an alternative that allows to make compatible environment conservation (e.g., farms dominated by forest ecosystems) with forestry and livestock production, tourism and welfare. To do this, the social-environmental dynamics and problems that a region or territory go through must be understood.

Structural-functional diversification can involve an increase in total production per land unit over production at species level (each product) per land unit (Figure 4). For instance, simplified social-ecological systems (e.g., intensified livestock production in forests transformed into savannas or parks) based on the use of one species (e.g., livestock, pasture) have a greater supply of provisioning ES (meat or calves) at the expense of a structural-functional simplification of the system. These simplified systems are an example of the win-lose strategy in which short-term economic profitability is benefited over social-ecological resilience to distinct social-environmental drivers, as well as other ES and biodiversity (e.g., medium and long-term benefits) (Figure 1 and 2).

In contrast, the social-ecological resilience approach tends to manage complex systems aiming to maximize diversity at farm- and landscape-scale. Although in these complex systems the production at species-level per land unit can decrease (e.g., due to interspecific resource competition), total production per land unit would increase (Scenario A, Figure 4). This is because in multipurpose systems a greater diversity of agro-ecological niches is used, not only below ground (e.g., because root systems of different morphology allow to explore distinct soil depths), but also above ground. In this case, biotic interactions as facilitation, pollination and seed dispersal are maximized (Figure 4). Thus, a multipurpose forestland should have intermixed space-time configurations, which contemplate diverse uses such as wood and livestock production, fruit-horticultural crops, beekeeping, collection of fruits and foliage from native plants, leather, wool, among others. This win-win strategy will allow to increase total production and, at the same time, increase social-ecological resilience and the supply of ES (Figure 4) (López et al. 2017; Peri et al. 2017b). In some cases, a greater diversification does not imply an increase in total production per land unit (Scenario B, Figure 4), but it can increase social-ecological resilience to social-environmental drivers. This win-win strategy not only includes functional agro-ecological diversity, but also the diversity of knowledge and technologies of the people who live and manage the lands, and the diversity of social networks that sustain those landscapes. In this sense, for the same landscape or territory it is essential to maintain a great cultural diversity and of scientific and local knowledge, which will undoubtedly help to face new social-environmental challenges. Likewise, it is essential to maintain a great diversity of social-ecosystems types, which will provide society with a great diversity of ecosystem services and a high social-ecological resilience to diverse social-environmental drivers.

Final remarks

The conceptual framework developed in the present work, together with evidences of different management strategies for silvopastoral systems in native forests, is a tool that can assist 1) to guide the definition of social-ecological and economic thresholds that modulate the provision of ES and biodiversity in the long term in these productive systems, 2) to analyze the influence of markets and policies on land managers and the influence of consumer demand on values of the ES that originate from silvopastoral systems, 3) to support communication across disciplines, knowledge systems, and between science and policy makers for sustainable use of native forest with integrated livestock, and 4) to provide a base framework information for future research that seeks to quantify the impact of these management strategies on the provision of ES and biodiversity. Also, a key function of the presented conceptual framework is to organize structure to help clarify complex relationships in native forests under silvopastoral use, to reframe biodiversity-related issues and to provide an analytical template for empirical research and operational strategies and applications. In this context, many challenges and opportunities arise for public policies, scientific institutions and rural extension agencies to promote more sustainable and diversified farming systems. There are differences in the motivation between landowners in the forest regions of Argentina that determined the contrasting spatial-temporal design of the silvopastoral systems, aiming to improve their economic profits, animal welfare, self-consumption of wood in rural properties, soil conservation and land use efficiency. Understanding the importance of the spatial-temporal aspects in silvopastoral systems allow us to achieve a better strategic planning for sustainable forest use. Also, to achieve objectives of increasing productivity while conserving other ES in native forests under silvopastoral use, farm management plans should necessarily manage connectivity at the landscape level and consider the social-productive context. The incorporation of corridors has been recognized as a strategy in planning for habitat configuration, and may be used to plan biodiversity conservation in consolidated areas under silvopastoral use. Another topic that must be explored are the legacies (retention strategy) that must be maintained in the managed landscapes to assure the provision of ES and biodiversity below critical levels.

To expand win-win strategies in silvopastoral land use systems and farmer adoption, a multi-agency, interdisciplinary and participatory strategy is required. The problems associated with forest product harvesting, processing and marketing, together with the strategy of producing added-value wood and animal products, which also are key factors for silvopastoral system development. Therefore, legal framework, policy and planning appear to be key areas for silvopastoral system development in the region.

It is essential that management plans include strategies that consider both farmer's and household's knowledge and the co-construction of knowledge between scientific and rural settlers, which constitute a basis for the social-cultural diversity of a territory. Therefore, to reinforce social-ecological resilience, the resilience of the people who live and work in agro-forestry systems, and social networks, should be enhanced. Diversified landscapes in which distinct social actors and productive sectors interact with diversified social networks will have greater social-ecological resilience to different social-environmental drivers.

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