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Ecosystem services to support environmental and socially sustainable decision-making

Verónica E. Rusch[1,✉]; Graciela M. Rusch[2]; Andrea P. Goijman[3]; Santiago A. Varela[1] & Leonardo Claps[1]

[1] Estación Experimental Agropecuaria INTA Bariloche. San Carlos de Bariloche, Argentina. [2] Norwegian Institute for Nature Research (NINA). Sluppen, NO-7485 Trondheim, Norway. [3]Instituto de Recursos Biológicos. CIRN-INTA Castelar, Argentina.

Abstract. The theory of ecosystem services (ES) needs to be operationalized to contribute to practices leading to sustainable use of ecosystems, which includes solving trade-offs between private and public benefits and incorporating monetary and non-monetary values to help inform decisions. We developed a framework to analyse the impacts of farmers' management alternatives on *Nothofagus antarctica* (G. Forst.) Oerst. forest in northern Patagonia, and analysed synergies and trade-offs between private and public benefits based on three conceptual and methodological approaches: a) a state-and-transition model of ecosystem dynamics, and b) indicators of values of ecosystem service benefits based on the cascade model, implemented as c) a decision support tool based on a Bayesian network. We optimized a utility function for short (0-10 yr) and long (70-140 yr) term management decisions (levels of grazing, logging and tree planting) based on monetary and non-monetary indicators of benefits that fulfilled "farmer's satisfaction" objectives. We then assessed the consequences of these decisions on the fulfilment of public benefits as defined by the National Forest Law when projected into short (0-10 yr), intermediate (10-40 yr) and long (70-140 yr) time horizons. We found that when short-term decisions are projected into a long-time horizon, they lead to high losses of benefits, mainly linked to "regulating and maintenance" ES. On the other hand, long-term decisions improved the level of benefits in degraded systems but resulted in the degradation of well-preserved forests. The decisions that optimize farmer's satisfaction did not change with different weights of "farm income" in the utility function, indicating the absence of trade-offs between monetary and non-monetary benefits considered in the utility function. The tool developed helps to show long-term impacts of management, and discloses cause-effect relationships between levels of use and multiple benefits. It can therefore support measures aiming to raise awareness about degradation trends, and improve the functional understanding of the system wich can help to identify solutions for socio-economic and environmental sustainability.

[Keywords: forest law, public and private benefits, trade-offs, cascade model, influence diagram, *Nothofagus*]

Resumen. Los servicios ecosistémicos como soporte para la toma de decisiones ambiental y socialmente sustentables. La teoría de los servicios ecosistémicos debe hacerse operativa para poder contribuir a la formulación de prácticas que conduzcan al manejo sustentable de los ecosistemas. Esto incluye contribuir a resolver los conflictos entre beneficios privados y públicos, e incorporar valores monetarios y no-monetarios para poder informar la toma de decisiones. Desarrollamos un modelo para analizar el impacto de las decisiones de manejo de los productores en el bosque de *Nothofagus antarctica* (G. Forst.) Oerst. del norte de la Patagonia y analizamos las sinergias y los conflictos entre los beneficios públicos y privados en base a tres marcos conceptuales y metodológicos: a) un modelo de estados y transiciones de la dinámica del ecosistema, y b) indicadores de los servicios ecosistémicos generados sobre la base del modelo de cascada, implementado como c) un sistema de apoyo a la toma de decisiones basado en redes Bayesianas. Optimizamos la función de utilidad sobre decisiones de manejo (niveles de pastoreo, extracción de madera y plantación de árboles), para lo cual nos apoyamos en indicadores de beneficios monetarios y no monetarios que satisfacen los objetivos del productor a corto (0-10 años) y largo (70-140 años) plazo. Luego, determinamos las consecuencias de las soluciones cercanas al óptimo en términos de satisfacción de beneficios públicos de acuerdo con su formulación en la Ley Nacional de Bosques. Encontramos que cuando las decisiones que optimizan los beneficios a corto plazo se proyectan en el tiempo (70-140 años), resultan en pérdidas altas de beneficios, especialmente, los ligados a servicios ecosistémicos de "regulación y mantenimiento". Por otro lado, las decisiones que optimizan los beneficios a largo plazo mejoran el nivel de beneficios en los estados degradados, pero al mismo tiempo, desmejoran la condición del bosque en buen estado de conservación. Las decisiones que optimizan la satisfacción del productor no cambian con los distintos pesos de la variable 'ingreso predial', indicando que no existe conflicto entre los beneficios monetarios y no-monetarios en la función de utilidad. La herramienta desarrollada ayuda a visualizar los impactos a largo plazo y revela relaciones de causa-efecto entre los niveles de uso y los múltiples beneficios generados por el sistema. Por ello, puede asistir a formular medidas que generen conciencia sobre las tendencias de degradación y contribuir, de este modo, a identificar soluciones para lograr la sustentabilidad socioeconómica y ambiental.

[Palabras clave: ley de bosques, beneficios ecosistémicos públicos y privados, compromisos, modelo de cascada, diagrama de influencias, *Nothofagus*]

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✉ rusch.veronica@inta.gob.ar

Introduction

The theory of ecosystem services (ES) needs to be operationalized to contribute to practices leading to sustainable use of ecosystems. A fundamental tenet of the framework is that ecosystems provide a range of benefits that underpin multiple dimensions of human well-being (MEA 2005; TEEB 2010; see glossary in Annex 1), and that considering the value of these benefits will lead to better decisions about how ecosystems are managed. A series of concepts, indicators, and methodologies (Burkhard et al. 2012; Schröter et al. 2014) have been developed to support decision-making at various levels where a plurality of benefits is taken into account (Potschin et al. 2016). One major gap is how the concept can contribute to inform management for sustainable use, here understood as the levels of use that maintain the capacity of ecosystems to generate benefits in perpetuity. Assessments of the capacity of ecosystems to provide ES say little about the benefits people effectively derive from those services, and the flow of benefits say little about the sustainability of these benefit flows (Haase et al. 2014). To advance in this direction, tools that explicitly link management decisions with the condition of ecosystems and the level of ES generation, need to be developed (Mastrangelo et al. 2015).

ES science and practice recognize that decision-making based on single objectives is an important cause of unsustainable use. Different approaches have been developed to reveal the multiple benefits and values associated with ecosystems (Haines-Young and Potschin 2013) and how to analyse, assess and communicate trade-offs (Huan et al. 2011). Influence diagrams (ID) have increasingly gained importance to support decisions; they can be constructed as a Bayesian Belief Network (BBN) in which decision making problems can be modelled and solved combining available scientific data with expert knowledge (Marcot et al. 2001; Williams et al. 2009; Barton et al. 2012). Although ID have received limited attention until present (Kragt et al. 2011), they open significant opportunities to support ES based decisions. The approach is based on decision-analysis theory and adapted to the practical needs and constraints faced by decision-makers; enabling to articulate science with practice (Williams et al. 2009).

Making sustainable management decisions on ecosystems is challenging because the ecological functions that support ES are complex and responses are often non-linear (Carpenter et al. 2009). Also, the long-term consequences of management decisions are difficult to envisage, especially in forests where critical ecological processes happen over long time periods. Therefore, the analysis of ecological changes in time and of the impacts of decisions at different time horizons is critical. In the context of ES, an important framing is that of the cascade model, which conceptually links the ecological system with the derived ES and their use and/or enjoyment (hereon, benefits sensu Haines-Young and Potschin 2013; TEEB 2010) (Figure 1, Annex 1). Further, current conceptualizations of ES stress the various dimensions of value in human-nature interactions (Kenter 2016) and the need of multiple approaches to understand them (Jacobs et al. 2016). In this context, the analysis of trade-offs among different kinds of benefits can provide an opportunity to reveal potential conflicts among groups of people with different preferences and priorities, and prepare for a better base to make management decisions.

The degradation of the native forest cover is a pervasive problem in many regions, globally and in Argentina. In response to this problem, the national Forest Law (N° 26331 of "Minimum Standards of Environmental Protection of Native Forests") (InfoLeg 2007) was enacted with the aim to ensure the sustainable use of native forest while "increasing the overall provision of ecosystem goods and services that they provide without affecting negatively the quality of life of the population, the landscape, and the conservation of native biological diversity". The implementation of the Forest Law encompasses a zonation of native forests in three land-use zones: 'forest conservation', 'sustainable use' and 'conversion of forest cover allowed'. At the same time, the National Program for Native Forest Protection was established considering the design of financial and economic instruments to ensure the implementation of the Law. The focus of this study is on the 'sustainable use zone', which is the one with most implementation and management challenges, since the levels of use and management practices in this zone that comply with the Law have not yet been defined.

Here, we analyse the sustainability of and trade-offs between private and public benefits derived from ecosystem services generated by ñire (*Nothofagus antarctica* (G. Forst.) Oerst) forests with silvopastoral use in northern Patagonia. We integrate three conceptual and methodological approaches: a) a state-and-transition model (STM; Briske 2006; Rusch et al. 2015) of ecosystem condition and dynamics, b) indicators of ecosystem services and the benefits they generate based on the 'cascade' conceptual model (Haines-Young and Potschin 2013) (Figure 1), implemented as c) an influence diagram (ID) model, with a utility function and a management decision node (Williams et al. 2009) based on monetary and non-monetary values of benefits for the farmer. We optimize the farmer's satisfaction in short- (0-10 yr) and long- (70-140 yr) terms. We conduct a sustainability analysis by projecting the consequences on public and private benefits of the farmer's management decisions into three time horizons: (short (0-10 yr), intermediate (10-40 yr) and long (70-140 yr)).

Materials and Methods

The model system is a *N. antarctica* forest occurring in northern Patagonia under silvopastoral use. The *N. antarctica* ecosystem covers valleys of the Patagonian Andes from 36° to 56° S latitude. Currently, in the northern part of its distribution range, seven alternate states have been identified, which are characterized by the species composition and abundance of the tree, shrub and herbaceous vegetation (Rusch et al. in press). Transitions between states are driven by levels of cattle grazing, firewood extraction and wild fires (Rusch et al. 2015; Rusch et al. in press). These productive activities are the predominant land-use in the area and the main livelihood for the rural communities. The transitions between alternate states indicate a progressive degradation of the forest condition that, in the absence of fire, lose the tree cover and the capacity to recover forest characteristics in the absence of restoration or rehabilitation measures (Rusch et al. 2015; Rusch et al. in press). Alternate states imply different ecosystem conditions, which can be associated with different capacity to generate ES and their associated benefits.

Model structure

We implemented an ID, which provides a graphical representation of the decision problem; it readily allows for Bayesian updating and makes information uncertainty explicit. The ID consists of nodes (boxes), or variables, and arrows which represent causal links between variables (Marcot et al. 2001). Following the `cascade model' of ES, the ID was built with nodes representing the structural characteristics of the system (i.e., variables such as herbaceous cover, tree density, mean tree diameter, shrub cover, cane cover, presence of dead wood), which were linked to indicators of ES, and in turn, connected to nodes with indicators

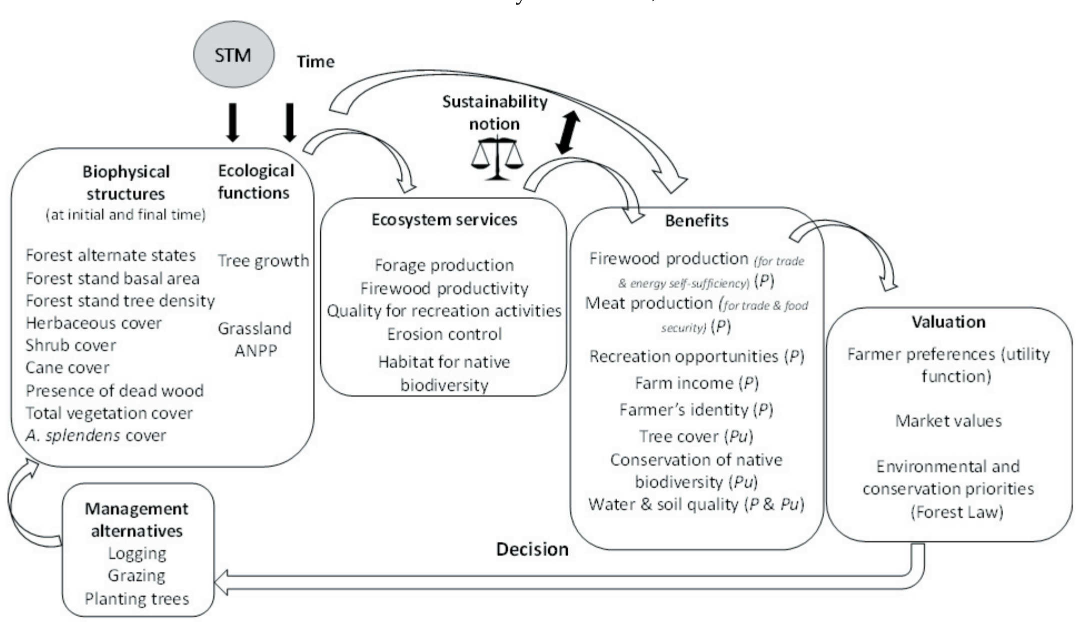

Figure 1. Main variables of the model reflecting the integration of state-and-transition model (STM), ecosystem services and decision making.

Figura 1. Principales variables del modelo reflejando la integración del Modelo de Estado y Transiciones (STM), los servicios ecosistémicos y la toma de decisiones.

of benefits (Figures 1 and 2, Table 1, Annex 2). Both economic and non-economic values were attached to benefits. A central element in the ID is the utility function that connects management alternatives to fundamental decision-making objectives, which in our case were based on the value of private (farmer) benefits (Figure 2 and Model parametrization, below). The model was implemented using the software Netica (www.norsys.com).

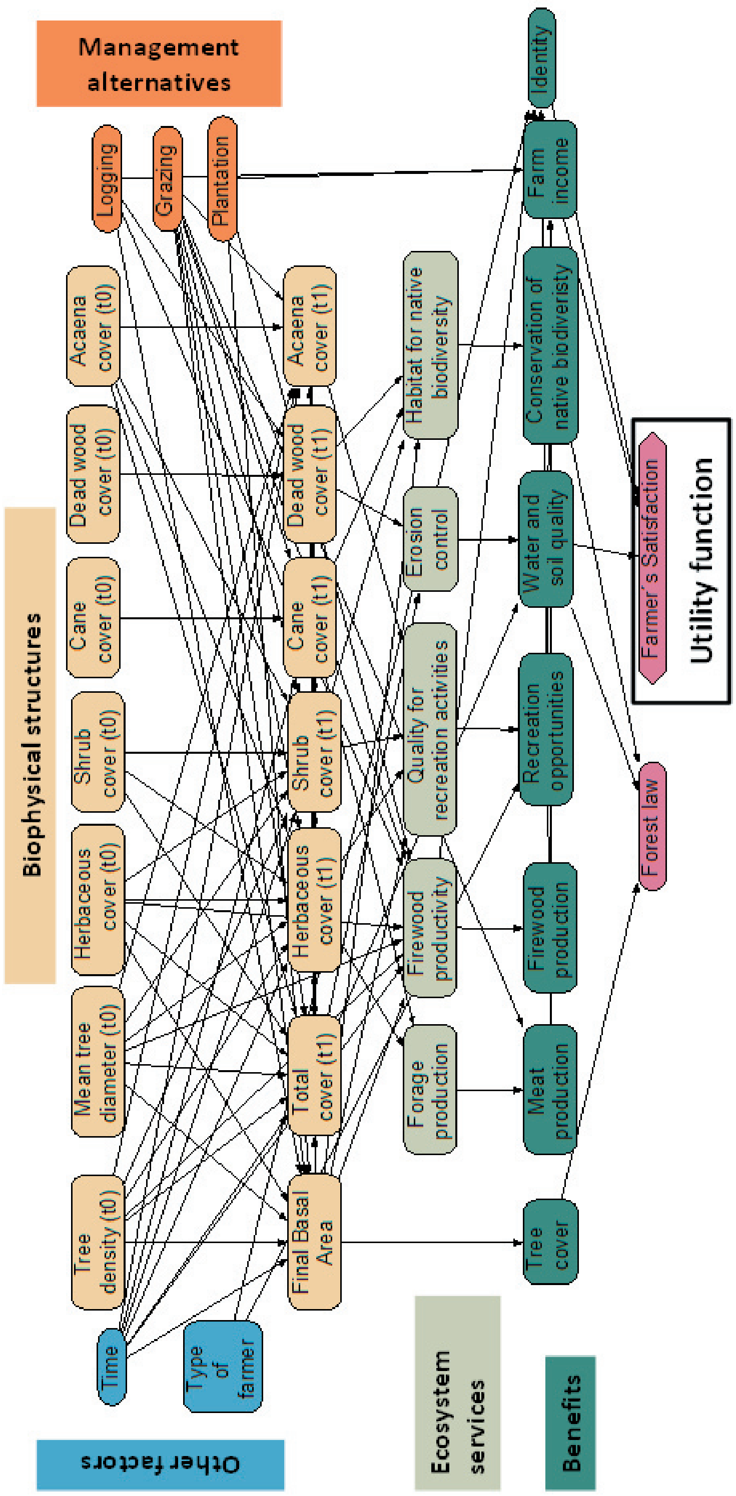

Figure 2. Structure of the model. Boxes are variables and arrows relationships (conditional probabilities).
Figura 2. Estructura del modelo. Las cajas representan variables y las flechas relaciones (probabilidades condicionadas).

Table 1. State variables included in the influence diagram and their levels. The value of variables was standardized on a scale between 0 and 1 to be able to report the results in Table 2. *P*: private benefits; *Pu*: public benefits; R: relative value.

Tabla 1. Variables de estado incluidas en el diagrama de influencias y sus niveles. Los valores de las variables de estados se estandarizaron según una escala entre 0 y 1 para poder reportar los resultados en la Tabla 2. *P*: beneficios privados; *Pu*: beneficios públicos; R: valor relativo.

Variable	Units	Variable levels in the influence diagram
Management alternatives		
Logging (*L*)	m^3 ha^{-1} $yr.^{-1}$	0; 0-2,5; 2,5-5; 5-7,5; 7,5-10; 10-15 null, very low, low, intermediate, high, very high
Grazing (*G*)	R	0; 0-1; 1; >1 null; low; intermediate; high
Planting –trees- (*Pl*)	established saplings/ ha	0; 400 no, yes
Biophysical structures		
Basal Area	%	0; 0,1-8; 8-15;15-25;24-40; 40-70
Tree density	Ind /ha	0-1; 1-50; 50-200; 200-450; 450-700; 700-1000; 1000-1500; 1500-2000
Tree diameter (mean)	cm at breast height	0-1; 1-10; 10-20; 20-30; 30-40; 40-65
Hebaceous cover	%	0-15;15-50;50-75; 75-100
Shrub cover	%	0-10;10-30;30-60; 60-100
C. culeou (cane) cover	%	<1; >1
Dead wood	%	<1; >1
Total cover	%	0; >1
Acaena cover	%	<10, >10
Ecosystem services		
Forage production	kg DM ha^{-1} yr^{-1}	<1000; 1000-2500; >2500
Firewood productivity	m^3 ha^{-1} yr^{-1}	0; 0-2,5; 2,5-5; 5-7,5; 7,5-10; 10-15
Quality for recreation activies	R	low; intermediate; high
Erosion control	R	low; intermediate; high
Habitat for native biodiversity	R	0 to 10
Benefits		
Firewood production (*P*)	m^3 ha^{-1} yr^{-1}	0; 0.1-1.25; 1.25-2.5; 2.5-5; 5-7.5; 7.5-10; 10-15
Meat production (*P*)	R	null; low; intermediate; high
Recreation opportunities (*P*)	% (see detail in the text)	low; intermediate; high
Farm income (*P*)	\$ ha^{-1} yr^{-1}	-500-0, 0-500; 500-1000; 1000-1500; 1500-2000; 2000-2500; 2500-4000
Identity (*P*)	R	low, high
Tree cover (*Pu*)	m^2 ha^{-1}	>8% basal area
Conservation of native biodiversity (*Pu*)	R	0 to 10
Water & Soil quality (*P*, *Pu*)	R	very low; low; intermediate; high
Utility function & trade off analysis		
Farmer's satisfaction		0-0,01; 0,01-2; 2-4; 4-6; 6-8; 8-10
Forest law (environmental and biodiversity priorities)		null, very low, low, intermediate, high
Other factors		
Time	Yr	0: 0-10: 10-40; 40-70; 70-140
Kind of producer	Small-Medium (see detail in the text)	

We used a systematic approach to identify the most important private and public benefits generated by the system, and their indicators (Table 1, Figure 2) through an expert workshop (with 13 technical experts on the ñire forest system with expertise in historical mapping, ecosystem dynamics and forest use and economy held in San Carlos de Bariloche, Argentina on 15-18 Sept. 2014), following the CICES classification of ES (Haines-Young and Potschin 2013). The fundamental objectives in the utility node (farmer's satisfaction) were based on the benefits for the farmer (Figure 2). The utility function was optimized to identify management decisions which rendered the highest level of farmer's satisfaction of these objectives (Clemen and Reilly 2001; Williams et al. 2009). Public benefits (see below) as defined in the Forest Law were also modelled, but not included in the utility node.

We first simulated the management alternatives that optimized the utility function in the short- (0-10 yr) and long- (70-140 yr) terms; hereon 'short-term' and 'long-term decisions', respectively. Then, we assessed the consequences of these decisions on private and public benefits when projected into three time horizons (short (0-10 yr), intermediate (10-40 yr) and long (70-140 yr)). Finally, we conducted a sensitivity analyses: a) to identify which model variables had the highest impact on the utility function and b) to explore the influence of the relative weights of the variables in utility function on management decisions.

Model parametrization

a) Management variables that are the basis for the decisions. Firewood extraction ('Logging' = L), cattle grazing intensity ('Grazing' = G), and planting of tree saplings ('Planting' = Pl) were the three management practices included in the model (level ranges of the three management variables are listed in Table 1). Logging (L) has six levels and was estimated as the annual volume of firewood harvested per hectare (m^3/ha). In the case of grazing, intensity is a ratio between grassland aboveground net primary productivity (ANPP) and the annual dry matter feed requirements of cattle. It has four levels: 0 (no grazing), 0-1 (low), 1 (intermediate) and >1 (high), indicating whether grazing intensity is null, below, equal to or higher than the capacity of the system to produce fodder. For Planting (Pl), there are two levels: 0 (no planting = no) and 400 *N. antarctica* saplings established after ten years (= yes). Planting is not a common practice in the region, but since recruitment of trees is limited by grazing and grassland cover (Rusch et al. 2015; Rusch et al. in press), it was considered a necessary practice to maintain tree cover under certain uses. The combination of the three management variables and their levels form the decision node of the model, in total 48 management alternatives or decisions.

b) Key benefits. The key private benefits (P) derived from the system (Figure 2 and Table 1) are: firewood and meat for the market and self-sufficiency, recreation and tourism opportunities and farmer's identity. Sustainable firewood production depends on forest stand productivity. In our case the benefit of firewood was a direct function of L and dependent on stock (available wood) (Rusch et al. 2016). Meat production was estimated by combining three levels of grassland above ground primary productivity (ANPP) and the four levels of *G*, from which we determined four livestock unit densities (LU) (estimated mean values: 0; 0.064; 0.13 and 0.24 LU/ha). LU estimates were used to calculate meat production (low, medium and high levels).

Recreation opportunities and tourism depend on the forest characteristics for these activities and 'type of farm' (see "other factors" in Table 1). Small farms (i.e., not hiring labour) are less likely to offer those activities whereas 38.5% of 'medium' farms engage in providing some kind of tourism-related services (Cardozo 2014). In addition, the kind of services offered by farms without water bodies (river or lake) within the property is small. Activities include camping facilities, sale of homemade food and other supplies for the camps and horse riding opportunities. We set four levels of benefits from tourism and recreation activities, from no activity to offering all services listed above. 'Farmer's identity' was evaluated in a qualitative way. It is related to being a cattle raiser (Cardozo 2014) and depends on engaging in livestock ranching (i.e., associated to grazing), and we also included food and energy self-sufficiency as components of this variable.

Three public benefits (*Pu*), related to the protection of the environment, are explicitly defined in the Forest Law: 'maintenance of forest cover', 'conservation of native biodiversity' and 'water and soil quality' (Figure 2 and Table 1). The indicator of 'maintenance of forest cover' was according to the Federal Commission of Environment (COFEMA, 2012), which defines the forest land-cover class for mapping purposes as land units with canopy cover higher than 20%. Since tree basal area is the structural variable included in the model on which wood production is based (Rusch et al. 2016) (Figure 2), we converted tree cover to tree basal area based on Peri et al. (2015), and considered compliance to the Forest Law if basal area was larger than 8 m^2/ha. The indicator of 'conservation of native biodiversity' was based on indicators of habitat quality for forest elements of key ecological importance (Rusch et al. 2005). The maintenance of clean water and soil quality and (hereon, 'water and soil quality') depends on total vegetation cover and to the presence of dead wood, as proposed by the Universal Soil Loss equation (Wischmeier and Smith 1978). Water and soil quality was also considered a private benefit as soil quality is recognized as important to maintain forage production.

c) Valuation of benefits. Based on former ecosystem services research (MEA 2005; TEEB 2010; Jacobs et al. 2016) and on knowledge about the system, we assumed that farmer's satisfaction relied on both income from farm activities and non-economic benefits generated by the forest. Farm income (operating profit) was estimated based on meat and firewood costs and sales, income from tourism and recreation activities, and the costs of tree planting. All prices were based on market prices in the nearest city in September 2015. Transport costs were not included in the calculation. The unit on which the economic value of livestock and firewood production was estimated is a livestock-rearing farm with a size of 500 ha, with wire fence, the typical management practice for the region. Yearly total farm income had seven levels, varying from -500 to 4000 Argentinean Pesos (ARP).$ha^{-1}.yr^{-1}$ (Table 1). The economic value of meat production was calculated as the farm income based on the four levels of this variable (see above), resulting in 0; 46.4; 78.1 and 372.4 ARP.$ha^{-1}.yr^{-1}$, respectively. Income from firewood production was calculated based on the six levels of wood extraction: 0; 1.25; 3.75; 6.25; 8.25 and 12.5 $m^3.ha^{-1}.yr^{-1}$ (Table 1), which rendered the following operating results: 0; 84; 793; 1368; 1965 and 2931 ARP.$ha^{-1}.yr^{-1}$. Costs of planting *N. antarctica* saplings (240 ARP.$ha^{-1}.yr^{-1}$) included plant purchase (4000 plants/yr), costs of planting and wire fencing of the planted area. The economic value of recreation opportunities is very variable, and the data uncertain. Income was estimated as 0, 25, 50 and 75 ARP.$ha^{-1}.yr^{-1}$ for the four levels of recreation activity, respectively.

In relation to non-monetary values, 'farmer's identity' (Table 1) was considered an important cultural value that can affect the farmer's decisions on management alternatives. It was defined with two levels (high and low satisfaction) and is related to the opportunities that the ecosystem provides to conduct livestock rearing activities (Cardozo 2014), which in addition provides meat for self-consumption. We recognize the limited knowledge about these benefits and of their relative importance at present. The fulfilment of the Forest Law was considered as a public benefit with non-monetary value.

d) Time. The time variable in the ID has four time ranges within which the responses to management and to natural processes are expected to occur (Table 1). The amplitude of the ranges reflects, in each case, the degree of uncertainty about when the change is expected to take place (Rumpff et al. 2011). The time ranges were determined considering major ecological switches in the dynamics of the silvopastoral system. Zero to ten years was considered an adequate time to predict the response of herbaceous vegetation to grazing. The cane (*Chusquea culeou* E. Desv), a dominant understorey species in the forest, presents massive diebacks at intervals of 70 years (Marchesini et al. 2009), drastically changing forest structure, so we assumed a high probability of dieback to take place within the time range of 40-70 yr. In the same way, 140 years is the life span of *N. antarctica* trees (average 120 years) (Hansen, INTA pers. comm.), and we considered high probability of *N. antarctica* trees to die within the range between 70-140 yr. Time was used in three different analyses. First, to model changes in state variables supporting the generation of benefits; the changes result from the combination of time and management alternatives (see arrows entering to boxes of state variables at time "1", Figure 2). The variable time, was treated as a continuous variable for firewood production calculation (Rusch et al. 2016). Secondly, the utility function was optimized at two time horizons: i.e. short (0-10 yr) and long- (70-140 yr) term decisions, respectively. Finally, the outcomes of the decisions that optimized the utility function were projected at three time horizons: short (0-10 yr), intermediate (10-40 yr) and long (70-140 yr) (Table 2).

e) Utility function and expected level of satisfaction of farmer's objectives. We constructed an additive utility function 'farmer's satisfaction' (Clemen and Reilly 2001) that combined farmer's fundamental objectives and their preferences (relative weights). The utility function included three fundamental objectives: 'income', a value of 'farmer's identity', and the value of maintaining 'water and soil quality'.

The additive utility function is simply a weighted average of the objectives; the corresponding weights were initially estimated, to the best of our knowledge, as

Variable	Time (yrs.)	Option Decision State	*Short term decisions*			*Long term decisions*			*Max. extraction*	*No manag.*	Option Decision State	*Short term decisions*			*Long term decisions*			*Max. extraction*	*No manag.*
			1st	2nd	3rd	1st	2nd	3rd				1st	2nd	3rd	1st	2nd	3rd		
			Gh, Lvh	*Gi, Lvh*	*Gh, Lvh, Pl*	*Gi, Lh*	*Gn, Lh*	*Gl, Lh*	*Gh, Lvh*	*Gn, Ln*		*Gi, Lvh*	*Gi, Lvh, Pl*	*Gl, Lvh*	*Gi, Lvl*	*Gi, Lvl, Pl*	*Gi, Ln*	*Gh, Lvh*	*Gn, Ln*
Farmer´s satisfaction	0-10		**7 (47.1)**	**7 (46.3)**	**7 (46.2)**	7 (40.7)	5 (44.7)	5 (44.8)	7 (47.1)	3 (49.6)		**7 (49.7)**	**7 (48.8)**	**7 (47.2)**	3 (51.2)	3 (49.6)	3 (54.8)	7 (47.3)	1 (64.8)
	10-40		7 (48.5)	7 (48.8)	7 (47.3)	7 (44.7)	5 (45.7)	5 (45.2)	7 (48.5)	3 (56.9)		Imp.	Imp.	Imp.	5 (56.0)	5 (57.3)	5 (48.3)	Imp.	3 (56.4)
	70-140		7 * (49.2)	7 * (48.3)	7 * (46.1)	**7 (53.7)**	**5 (45.9)**	**5 (45.1)**	7* (49.2)	3 (61.0)		Imp.	Imp.	Imp.	**5 (64.7)**	**5 (57.0)**	**5 (51.9)**	Imp.	3 (59.2)
Farm income	0-10		**9 (87.0)**	**7 (84.9)**	**9 (78.3)**	7 (77.7)	9 (63.9)	7 (89.1)	9 (87.0)	0 (67.5)		**9 (83.5)**	**9 (77.0)**	**9 (84.5)**	1 (64.5)	1 (69.9)	0 (55.5)	9 (84.1)	0 (63.4)
	10-40		9 (86.7)	7 (85.7)	9 (78.1)	7 (70.3)	9 (64.4)	7 (80.0)	9 (86.7)	0 (66.7)		Imp.	Imp.	Imp.	1 (66.0)	1 (66.9)	0 (56.6)	Imp.	0 (65.6)
	70-140		9 * (83.4)	7 * (84.0)	9 *(73.7)	**7 (66.7)**	**9 (63.9)**	**7 (75.5)**	9 * (83.4)	0 (67.4)		Imp.	Imp.	Imp.	**1 (77.2)**	**1 (54.8)**	**0 (55.9)**	Imp.	0 (64.9)
Farmer´s identity	0-10		**8 (51.6)**	**8 (55.0)**	**3 (46.6)**	8 (55.2)	3 (77.7)	3 (50.4)	8 (51.6)	3 (77.4)		**8 (66.7)**	**8 (66.7)**	**8 (54.2)**	8 (68.4)	8 (68.4)	8 (68.5)	8 (56.5)	3 (83.0)
	10-40		3 (56.0)	8 (51.3)	3 (46.6)	8 (53.6)	3 (80.0)	3 (51.1)	3 (56.0)	3 (79.7)		Imp.	Imp.	Imp.	8 (69.6)	8 (70.5)	8 (70.3)	Imp.	3 (82.6)
	70-140		3 * (61.9)	8 * (64.0)	3 * (57.9)	**8 (63.6)**	**3 (80.8)**	**3 (53.4)**	3 (61.9)	3 (81.0)		Imp.	Imp.	Imp.	**8 (75.0)**	**8 (76.3)**	**8 (75.1)**	Imp.	3 (83.0)
Forest law	0-10		**9 (46.1)**	**9 (66.6)**	**9 (46.0)**	9 (67.4)	9 (71.3)	9 (69.9)	9 (46.1)	9 (79.3)		**0 (54.7)**	**0 (56.9)**	**0 (55.2)**	6 (57.1)	6 (55.6)	6 (60.1)	0 (54.3)	6 (65.6)
	10-40	***SI***	6 (47.1)	9 (44.8)	6 (48.0)	9 (48.7)	9 (76.2)	9 (53.6)	6 (47.1)	9 (77.4)	***SIII***	Imp.	Imp.	Imp.	9 (66.3)	9 (66.0)	9 (75.4)	Imp.	9 (72.3)
	70-140		0 * (55.5)	0 * (39.4)	6 * (53.3)	**6 (47.0)**	**9 (88.7)**	**6 (50.5)**	0 * (64.9)	9 (84.6)		Imp.	Imp.	Imp.	**9 (50.9)**	**9 (84.3)**	**9 (58.7)**	Imp.	9 (59.1)
Tree cover	0-10		**9 (60.4)**	**9 (61.7)**	**9 (60.9)**	9 (63.4)	9 (63.5)	9 (64.0)	9 (60.4)	9 (67.7)		**1 (28.8)**	**1 (31.3)**	**1 (29.4)**	5 (33.5)	5 (31.9)	5 (35.3)	1 (28.5)	5 (35.2)
	10-40		7 (25.3)	7 (24.0)	7 (24.2)	9 (31.1)	9 (33.5)	9 (31.5)	7 (25.3)	9 (41.4)		Imp.	Imp.	Imp.	1 (24.5)	3 (25.1)	5 (31.5)	Imp.	5 (31.8)
	70-140		0 * (45.1)	0 * (23.7)	3 * (34.0)	**5 (22.6)**	**9 (39.5)**	**5 (27.2)**	0 * (45.1)	9 (44.2)		Imp.	Imp.	Imp.	**1 (34.9)**	**5 (30.2)**	**1 (28.0)**	Imp.	1 (28.0)
Habitat quality for native biodiversity	0-10		**4 (30.5)**	**7 (45.8)**	**4 (30.2)**	7 (47.1)	7 (62.9)	7 (57.1)	4 (30.5)	8 (67.1)		**3 (53.1)**	**3 (55.4)**	**3 (53.7)**	6 (44.2)	6 (43.7)	6 (48.2)	3 (52.8)	6 (47.9)
	10-40		2 (37.7)	4 (34.5)	2 (40.3)	2 (20.5)	6 (33.1)	4 (44.1)	2 (39.7)	8 (28.8)		Imp.	Imp.	Imp.	6 (26.6)	6 (28.7)	6 (31.5)	Imp.	6 (48.7)
	70-140		2 * (79.2)	2 * (61.8)	2 * (41.3)	**2 (55.9)**	**7 (35.5)**	**2 (40.2)**	2 * (79.2)	10 (36.8)		Imp.	Imp.	Imp.	**4 (38.3)**	**8 (35.2)**	**4 (31.6)**	Imp.	4 (27.5)
Water and soil quality**	0-10		**9 (54.8)**	**9 (54.9)**	**9 (54.6)**	9 (55.7)	9 (55.6)	9 (55.7)	9 (54.8)	9 (62.4)		**4 (47.5)**	**4 (47.5)**	**4 (50.5)**	4 (47.6)	4 (47.6)	4 (47.7)	4 (56.3)	4 (53.6)
	10-40		9 (68.1)	9 (72.5)	9 (68.5)	9 (74.0)	9 (70.6)	9 (71.1)	9 (68.1)	9 (78.8)		Imp.	Imp.	Imp.	9 (78.5)	9 (78.5)	9 (78.5)	Imp.	9 (71.4)
	70-140		9 * (78.6)	9 * (78.6)	9 * (78.6)	**9 (78.6)**	**9 (78.6)**	**9 (78.6)**	9 * (78.6)	9 (88.4)		Imp.	Imp.	Imp.	**9 (78.5)**	**9 (78.5)**	**9 (78.5)**	Imp.	9 (76.9)

Table 2. Relative level of satisfaction of private and public benefits (probability of occurrence between brackets) according to the best three management decisions (1st, 2nd and 3rd) that optimize farmer satisfaction considering short- and long-term decisions (0-10 and 70-140 years, highlighted in bold format). Time: the time horizon on which the outcomes of management decisions are projected. SI and SIII: two states of forest condition with differences in tree and grassland cover. Max extract and No Manag: extreme levels of use, maximum extraction and no management. G=grazing; L=logging; Pl=plantation. Variable level codes: n=null; vl=very low; l=low; i=intermediate; h=high; vh=very high. It is partially impossible (52.2%) to maintain the management alternative during all the period as the rate of logging is greater than existences. Imp.: probability more than 60%. ** Also a variable included in the estimation of 'farmer´s satisfaction'.

Tabla 2. Nivel relativo de satisfacción de los beneficios privados y públicos (probabilidad de ocurrencia entre paréntesis) en función de las tres mejores decisiones de manejo (1st, 2nd and 3rd) que optimizan la satisfacción del productor según decisiones a corto y largo plazo (0-10 y 70-140 años, resaltadas en negrita). Time: el horizonte de tiempo en el cual se proyectan los resultados de las decisiones. SI y SIII: dos estados de condición de bosque con diferentes coberturas arbórea y herbácea. Max extract y No Manag: niveles de uso extremo, de máxima extracción y sin manejo. G=pastoreo; L=extracción de leña; Pl=plantación. Códigos de niveles de variables: n=nulo; vl=muy bajo; l=bajo; i=intermedio; h=alto; vh=muy alto. *Es parcialmente imposible (52.2%) mantener el manejo alternativo durante todo el período ya que la tasa de cote de leña es mayor que el de las existencias. Imp.:probabilidad mayor a 60%. **Esta variable también está incluida en la estimación de la "satisfacción del productor".

0.6 for income, and 0.2 for 'farmer's identity' (Cardozo 2014) and 'water and soil quality', respectively. The utility function assigns values of 0 and 1 to the worst and best levels, respectively, on each particular objective.

To calculate the expected value of the decision (e.g., farmers' satisfaction of each decision, Netica provides calculations by the uncertainty-weighted outcome values [Williams et al. 2009]):

$$E(D_j) = \sum_{i=1}^{n} U(x_i) * p(x_i)$$

where D_j represents each alternative decision, $U(x_i)$ is the relative satisfaction given by a level of each fundamental objective (xi), and $p(x_i)$ is its associated probability. Thus, the expected level of satisfaction of a decision is the sum across levels of the fundamental objectives, weighted by their probability of occurrence.

Model inputs and outputs

a) Initial conditions of the system. We conducted the analyses starting at two ubiquitous alternate states of forest condition (`Biophysical structures' in Table 1): SI) *N. antarctica* forest with *C. culeou*, and SIII) *N. antarctica* forest with grassland. SI is a relatively dense forest maintaining characteristics of a well-conserved forest, and SIII is a highly-modified forest with high grassland and low tree cover (Rusch et al. in press).

Hence, the initial conditions (evidence) corresponding to the state variables in SI and SIII, respectively, were set as follows: a) mean *N. antarctica* density was set as a fixed value of 1000 and 200 ind/ha; b) herbaceous cover was 15-50% and 75-100%; c) *C. culeou* cover: >1 and <1, and d) deadwood cover: <1 and >1. For both SI and SIII, mean diameter was 25 cm, kind of producer was: medium; shrub cover: intermediate; *Acaena splendens* Gillies ex Hooker et Arnott. cover: <10. The model was run for a site quality where trees of *N. antarctica* reach 8 m and mean growth rate at breast height is 0.2 cm/yr (Ivancich 2013).

b) Sustainability and trade-off analyses. We assumed that farmers make decisions primarily based on short-term satisfaction because ecological long-term impacts are difficult to foresee, and long-term economic benefits are more uncertain. Hence, we first optimized the utility function for short-term (0-10 yr.) satisfaction of the fundamental objectives (short-term decisions). We then selected the three management decisions that rendered the highest levels of farmer's satisfaction and assessed the consequences of these decisions on the different private and public benefits, when projected into three time horizons: t_{+1} 0-10, 10-40, and 70-140 yr (Table 2). At a second step, we conducted similar analyses, but optimizing farmer's satisfaction within a time frame of 70-140 yr (long-term decisions). Thirdly, we assessed the consequences on benefits of two extreme management practices: no-farm management and the highest levels of grazing and logging. Management alternatives with logging levels higher than the productive capacity of the firewood stock were excluded from the analysis. To enable the comparison among different benefits, the levels of the variables were relativized to a common scale, 0-10, where 0 is the minimum value and 10 the maximum one. Certain management practices might not be implemented (i.e., logging if there are no trees left). For these cases, we indicate the probability of occurrence of the "impossible" situation (Table 2).

c) Sensitivity analysis. We developed sensitivity analyses (Clemen and Reilly 2001; Williams et al. 2009) to identify which variables in the ID had the greatest influence on the decisions by changing each variable's minimum and maximum values and observing the change on the probabilities of a given decision (as a proxy for its expected values). We built tornado diagrams, which help visualize how sensitive the decisions are to the variation in the different variables. A tornado diagram is a special bar chart which is the graphical output of a comparative sensitivity analysis. It is meant to give an idea of which factors are most important to the evaluated decision. It can also be useful as part of the analytical project's results, giving decision makers some insight into the uncertainties and their potential impact. A variable with a wide bar is called value sensitive, meaning it can cause a large change in the value of the objective function.

Since we had little information about the importance that farmers attribute to the different objectives (i.e., the weights in the utility function), we conducted a sensitivity analysis of the utility function to explore the influence of 'farm income' on the expected value of the optimal management alternative (axis "y") by assigning random weights to each component (sum of weights constrained to 1). We simulated 50 combinations for each of the two states of forest condition (SI and SIII) to evaluate the best short- and long-term decisions.

Results

In Table 2 we show three short- and long-term decisions that optimized farmers' objectives for ecosystem conditions SI and SIII (12 decisions). We also present the consequences of these decisions for private and public benefits when projected into short, intermediate and long-term time horizons.

Short-term satisfaction of farmer's objectives

Starting from the ecosystem condition SI, the three decisions with highest probability to satisfy the farmer's short-term objectives, included high (1) and intermediate (0-1) levels of grazing and very high levels of logging (10-15 $m^3.ha^{-1}.yr^{-1}$) (Table 1); one alternative decision includes planting of trees. All decisions resulted in the same overall level of farmer's satisfaction (7/10), but 1st and 3rd decisions led to higher levels of income, and 1st and 2nd led to high levels of satisfaction of farmer's identity when projected into a time horizon of 0-10 yr. The three short-term decisions resulted in high levels of benefits associated with water and soil quality. The overall levels of farmer's satisfaction, income, and water and soil quality were maintained relatively constant when the outcomes were projected into short- (0-10 yr), intermediate (10-40 yr) and long-time-horizons (70-140 yr). Nevertheless, the likelihood of maintaining the practice in the long- term declined because of forest loss (partially impossible in Table 2). All other private and public benefits ('farmer's identity' maintenance of tree cover and conservation of native biodiversity) that resulted from short-term decisions, declined with time.

When SIII was the initial condition of the system, the three closest short-term decisions that satisfied farmer's objectives included intermediate (1) and low (0-1) levels of grazing and very high levels of logging (10-15 $m^3.ha^{-1}.yr^{-1}$). All decisions that optimized short-term farmer's satisfaction rendered high levels of satisfaction (overall satisfaction: 7, income: 9 and farmer's identity: 8), but only when projected into 0-10 yr. However, these decisions resulted in lower levels of environmental benefits in the short-term, which could not be maintained when projected into 10-40 yr and 70-140 yr time horizons.

Long-term satisfaction of farmer's objectives

The management decisions that optimized farmer's short- and long-term satisfaction differed. Starting from the ecosystem condition SI, the best three long-term decisions included intermediate, low and null levels of grazing combined with high levels of logging (Table 1); none of the alternatives included planting of trees. The decisions resulted in different levels of farmer's overall satisfaction (7 or 5) and different levels of income (7 or 9). Only 1st decision led to higher levels of values associated to farmer's identity (8). The three best long-term decisions resulted in high levels of benefits associated with water and soil quality when projected into all-time horizons.

When SIII was the initial condition of the system, the optimal long-term decisions included intermediate level of grazing combined with very high, very low or null levels of logging (Table 1). Only 2nd decision included planting of trees. These decisions resulted in the same level of farmer's satisfaction (5) and farmer's identity (8). Levels of income in the three decision were low (0 or 1), but benefits related to the environment (Forest Law) were high (9). Habitat quality for biodiversity had high values only in the case of 2nd decision. The three decisions resulted in high levels of benefits associated with water and soil quality (9).

Comparing short- and long-term decisions in SI, farmer's satisfaction was lower when decisions were long-term compared to short-term. However, the levels of income were comparable (ranges between 7 and 9), although there were generally lower probabilities associated to levels of income when the decisions were short-term. The lower level of overall satisfaction resulting from long-term decisions was due to low values of 'farmer's identity', especially in 1st and 2nd decisions (*Gi,Lh*; *Gn,Lh*, respectively) (Table 2, Annex 3). The levels of overall environmental benefits (related Forest Law and to farmer's appreciation of water and soil quality) were relatively high and the probability of occurrence of these levels was comparatively higher than those of short-term decisions.

Conservation of native biodiversity is the benefit with the lowest score and lowest associated probability of occurrence, especially when projected into intermediate and long-term horizons. In SIII, the levels of all benefits improved considerably when farmer's satisfaction was optimized with a long-term decision compared to short-term ones.

Effects of maximum extraction and no management

In SI, maximum extraction levels (high grazing and very high logging) resulted in high levels of most benefits with short-term decisions, but these benefits either declined or could not be fulfilled when projected into a long-time horizon (Table 2). In SIII, the level of farmer's satisfaction was high, but only when the outcomes were projected into a short time horizon. All environmental benefits scored very low and, no benefits were generated when projected into intermediate and long-time horizons. The no-management option rendered low levels of farmer's satisfaction, including no benefits from income, but it results in high level of environmental benefits both in SI and SIII, although the levels achieved are higher in SI.

Key variables in the ID model

Sensitivity analysis of variables' effect on management decisions. The sensitivity analysis shows a high degree of consistency among the different management decisions in terms of which variables caused the highest impact on the decision (we show the graphical outcome of only one decision). 'Farm income' was the variable with highest impact when decisions involved 'Grazing intermediate and Logging Very High' (Figure 3). Meat production causes high variability for some cases with low levels of grazing (not shown).

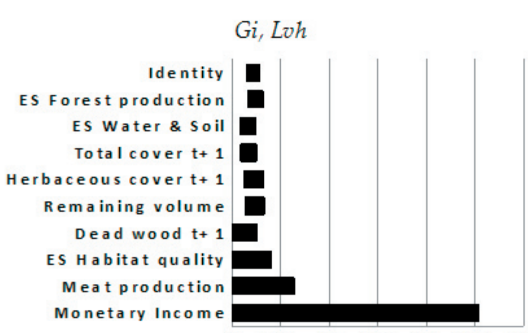

Figure 3. Example of one-way sensitivity analysis of different variables affecting the probability distribution of the management alternative included Grazing intermediate (Gi) with very high Logging (Lvh). . Bars express the range of the values.

Figura 3. Ejemplo de análisis de sensibilidad a una vía de las diferentes variables que afectan la distribución de probabilidades de la decisión de manejo incluyendo un pastoreo intermedio (Gi) y una extracción de leña muy alta (Lvh).

Sensitivity analysis of utility function weights. Results from random weighting on the fundamental objectives show that the best decisions in SI and in SIII (Figure 4) do not change with the weight of income in the utility function for either very short-or very long-term decisions (i.e., the same decision has the highest value independently of the relative weight of income). However, the expected value of the decisions that included planting, declined with higher weights of income. With long-term decisions, no grazing and high logging was one of the alternatives that optimized the utility function. Remarkably, at low weights of income (and high weight of farmer's identity), the expected value of the decision satisfying the utility function (no grazing and high logging) declined drastically. In the case of SIII, the management alternatives that optimized the utility function had higher expected values if the weight of income was low (Figure 4, SIII b).

Discussion

Integrated valuation of ecosystem benefits

Following the ecosystem services cascade, we identified important benefits that underlie silvopastoral farmers' management decisions. Farmers' benefits had instrumental values (sensu Díaz et al. 2015), both monetary (i.e., income from livestock, firewood and recreation activities) and non-monetary (i.e., food and energy self-sufficiency, water and soil quality, and farmer's identity related to a livelihood based on livestock ranching).

Combining different dimensions of benefits in trade-off analysis is a central challenge in ES research, which aims to embrace multi-functionality and plural benefits. Modelling the silvopastoral system dynamics as an ID required the development of semi-quantitative indicators of incommensurable values such as "farmer's identity". We derived these values by estimating the levels of importance attached to the characteristics of the silvopastoral system assumed to underlie the attribution of these values. Decision making, however, is determined by several personal, historical, and context elements, that were difficult to include in simple models like these. In addition, there are other limitations when constructing an additive utility function, such as that the levels of the different variables defining satisfaction

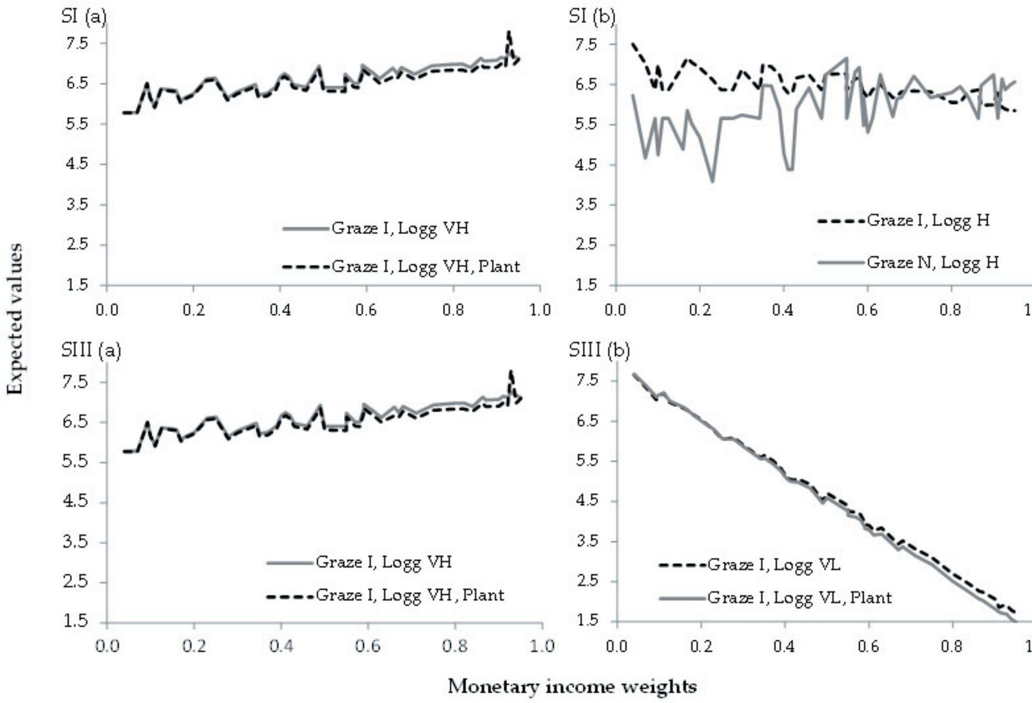

Figure 4. Response profiles of expected utility of two probable management decisions of *Nothofagus antarctica* forest in alternate state SI and SIII, in relation with income weights at: a) very short, and b) very long term decisions optimization. See abbreviations in Table 1.

Figura 4. Perfil de respuestas de la utilidad esperada para dos decisiones de manejo probables para el bosque de *N. antarctica* en los estados alternativos SI y SIII en relación a los ingresos a: a) muy corto, y b) muy largos horizontes de decisión. Abreviaturas, en la Tabla 1.

interact and could show non-linear responses (Selin and Davey 2012).

Besides, one assumption is that the benefits perceived from nature can be quantified and compared with each other on a common constructed scale. Despite these limitations, we consider that the model and the analyses in our study provide useful insights about potential conflicts among a set of important benefits perceived by silvopastoral farmers in the region, and between private and public benefits. It also points to often overlooked benefits from nature and how the generation of these benefits can be hampered in time with certain levels of use. The study shows important knowledge gaps about farmers' preferences and on how they deal with conflicting benefits, which could be bridged by applying participative valuation methods.

Another challenge when comparing values with a quantitative approach is that the optimization of the utility function depends on values of each individual objective, represented by the weights, and reflecting different preferences on numerous benefits. In our study, the sensitivity analysis of these weights demonstrated that the results were robust in terms of the decision (levels of use and activities) that rendered the highest level of overall satisfaction. At the same time, income was the variable with highest impact on optimal satisfaction.

Trade-offs of private and public benefits

When optimizing the utility function, we found that no management decisions rendered the highest level of farmer's satisfaction, indicating some incompatibility among the different benefits perceived by the farmer; farmer's identity and income appear to be such a case. However, "farmer's identity" is defined as a complex variable that includes the benefits associated to a livelihood based on livestock ranching, and the attachment to forest (Cardozo 2014). This does not allow to fully disentangle them.

Considering that economic decisions tend to be based on short-term gains and neglect long-term risk (Orstein and Ehlrich 2000), it is likely that the management alternatives that optimize short-term satisfaction are prioritized by farmers. Compared to farmer's short-term decisions, long-term decisions rendered lower levels of overall satisfaction; which was due to lower levels of income, especially in SIII (degraded forest), but also to lower levels of benefits linked to farmer's identity. At the same time, the results indicate that if only farm income was important for the farmer's decisions, the importance of livestock rearing activities could be reduced. Farmer's optimal long-term decisions generally resulted in higher levels and higher probabilities of satisfaction of overall environmental benefits.

We also identified trade-offs between private and public benefits as defined in the Forest Law, but both forest condition (whether SI or SIII) and scope of the decision determined the magnitude of these trade-offs. Especially, in the case of short-term decisions and outcomes, farmer's satisfaction and public benefits generally agreed in the forest dominated vegetation (SI), but private and public benefits were largely incompatible in the grassland-dominated state (SIII). There was also higher level of agreement between private and public benefits when farmer's decisions were made in the long-term.

Conservation of native biodiversity is the benefit most negatively affected by silvopastoral use, especially when short-term benefits are optimized. These results indicate that the generation of these benefits are largely incompatible with the levels of use that optimize farmer's benefits. In SI, high levels of all environmental benefits can only be achieved with no management, indicating that specific biodiversity protection measures, such as set asides and/or protected areas, need to be designed to target the conservation of these features.

Sustainability analysis: long-term impacts of decisions

By analysing the long-term impacts of management decisions, we were able to explore several dimensions of the sustainability of silvopastoral systems based on the use of *N. antarctica* forests. In all cases (short- and long-term decisions in the two forest conditions), the environmental benefits or the probabilities of maintaining optimal practices, declined with time. This was a consequence of the disappearance of forest cover due to overharvesting and high grazing intensity. This result indicates a progressive degradation of the forest resource, despite the low rates. It also indicates the income levels associated to current use are unlikely to be maintained beyond the time-frame of this study (up to 140 yr), likewise because income relies on levels of use that are incompatible with tree cover maintenance. However, degradation trends may be difficult to detect if the starting point of the forest in its best condition, because overall farmer's satisfaction and income are largely maintained in SI, even in the long term. In state SIII of the forest, the levels of use that optimise short-term farmer's satisfaction lead to severe degradation of the forest system, hampering the likelihood of maintaining both income and farmer's identity, beyond a time horizon of 10 years. If long-term decisions are optimised, the delivery of environmental benefits increases considerably, but the level of overall farmer's satisfaction is low and income, very low. In addition, the no-management option in SIII can deliver high levels of environmental benefits, even when decisions are optimized in the long term, indicating the low capacity of the system to recover naturally. Starting at SI, the highest levels of environmental benefits are achieved with management consisting of intermediate levels of grazing, planting and very low levels of logging, but the level of income in this management alternative is very low. There is a clear need for restoration of these areas, in which tree planting appears to be a required practice. Instruments targeting this objective could be designed to strengthen the technical capacity of practitioners and farmers, including improving knowledge about future benefits of tree planting, and provision of financial support and investment, especially, since income levels are expected to be very low.

The analysis of mismatches between the capacity to generate ES (supply) and level of use (ES flow or demand), (see balance draw in Figure 1), is a basis to understand levels of sustainable use, which is seldom addressed in ES modelling. Our approach contributes to overcome these limitations in several ways: first, the state-and-transition model makes explicit cause-effect relationships of ecosystem condition and change with management alternatives. With the implementation of the model as a decision-support tool (ID), the levels of benefits are clearly identified, and included as the basis for decision-making.

Ecosystem services and models of sustainability to implement the Forest Law.

One of the aims of this study, was to better inform the implementation of the Forest Law in Argentina, which explicitly addresses the sustainable use of the native forest, including the maintenance of the ecosystem services that the forests generate. In this sense, an analysis based on ES and the benefits derived from this forest, seems highly appropriate. However, levels of use (the flow of ES) are seldom linked to their impact on ecosystem condition (Figure 1) in ES analysis. By establishing casual relationships between the level of use and ecosystem condition, our approach goes beyond commonly used approaches (e.g., Gómez-Baggethun et al. 2016), further contributing to understand management-induced ecosystem change and to inform practice.

Different instruments could help to successfully implement the Forest Law. Although Payments for Ecosystem Services (PES) have initially been thought of as an alternative, our findings indicate that income was not always a factor that would make the farmer change decisions on management alternatives. Other interventions targeting other factors such a better understanding of long-term impacts of management alternatives, changes in attitudes and priorities (as awareness of global sustainability relevance) or the development of practices that allow maintaining activities and satisfaction in the long-term with less impact on the forest, could be better equipped to target environmental, social and economic sustainability.

Conclusions

Limitations registered in the present study highlight future research needs, including estimates of income that better account for factors such as availability of labour and accessibility to markets, better understanding of cultural and non-monetary economic benefits, and direct knowledge about farmers' choices in the face of different benefits. In this respect, the different management alternatives could be used as a starting point for participatory assessments of farmers' choices (Huan et al. 2011) to help bridge the knowledge gaps about their values identified in our study. Likewise, research directed to a more qualified understanding of farmers' preferences would provide insights on the nature of trade-offs, which is essential to inform measures aiming to promote changes in farmer's decisions. An advantage of implementing the model as a BBN is that it enables to incorporate uncertainty explicitly and allows updating by future learning.

The tool developed in this study helps to show long-term impacts of use on ecosystem condition, and discloses cause-effect relationships between levels of use and impacts on benefits. It can therefore support measures as education and extension programmes aiming to raise awareness about degradation trends, and of the dynamics of the system that can help identify solutions for socio-economic and environmental sustainability. Furthermore, the tool can be valuable to help government authorities to achieve better level of implementation of the Forest Law when including farmers' interests, multiple objectives and long-term consequences on the ecosystem condition. Further, our results highlight the need to incorporate a temporal perspective in the analysis of benefits because short- and long-term decisions differed in terms of the best management alternatives, and in the level of satisfaction of farmers' objectives and of the public benefits according to the Forest Law. It is important to adapt the model to incorporate management alternatives that render high satisfaction in the short-term, and that at the same time are compatible with long-term sustainability objectives.

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