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Ecosystem services and disservices associated with pastoral systems from Patagonia, Argentina – A review

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Abstract – Pastoral systems worldwide secure rural livelihoods in the harshest environments on Earth. Their low productivity per area unit or head makes them the subject of much criticism with regard to their environmental impact, particularly in relation to global warming, desertification and land degradation. Such is the case of the traditional pastoral systems of Patagonia, a vast and isolated region where sedentary and mobile pastoralism coexist and contribute to shape landscapes and cultures. We argue that pastoral systems provide a wide range of ecosystem services that may compensate for their negative impact on the environment. We review the scarcely available evidence from Patagonia to identify ecosystem services and disservices associated with pastoralism, and pay special attention to the carbon balance: with C footprints between 10 to 40 kg CO_2-eq.kg^{-1} carcass, pastoral systems in dry Patagonia are below or within the range of semi-extensive livestock systems worldwide (35–45 CO_2-eq. kg^{-1} carcass). To inform development and policy, the assessment of trade-offs and synergies between ecosystem services needs to incorporate the intertwined social and ecological dynamics of complex pastoral systems, along resource regenerative trajectories.

Keywords: environment / sustainability / pastoralism / livestock / drylands / highlands / ecosystem services

Résumé – Services écosystémiques et dis-services associés aux systèmes pastoraux de Patagonie, Argentine – Revue bibliographique. Les systèmes pastoraux du monde entier garantissent des moyens de subsistance aux ruraux dans les environnements les plus difficiles de la planète. Leur faible productivité par unité de surface ou par habitant suscite de nombreuses critiques quant à leur impact environnemental, notamment en relation avec le réchauffement climatique, la désertification et la dégradation des terres. C'est le cas des systèmes pastoraux traditionnels de Patagonie, une région vaste et isolée où le pastoralisme sédentaire et nomade coexistent et contribuent à façonner les paysages et les cultures. Nous soutenons que les systèmes pastoraux fournissent un large éventail de services écosystémiques qui peuvent compenser leur impact négatif sur l'environnement. Nous passons en revue les données disponibles sur la Patagonie pour identifier les services écosystémiques et les dis-services associés au pastoralisme, en accordant une attention particulière au bilan carbone : avec des empreintes carbone entre 10 et 40 kg CO_2-éq/kg de viande, les systèmes pastoraux en Patagonie aride sont en dessous ou dans la gamme des systèmes d'élevage semi-extensifs dans le monde (35–45 éq-CO_2/kg de viande). Pour éclairer les options de développement et

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les politiques, l'évaluation des compromis et des synergies entre services écosystémiques doit intégrer l'entrelacement de dynamiques sociales et écologiques, dans des systèmes pastoraux complexes, au fil de trajectoires de régénération des ressources.

Mots clés : environnement / durabilité / pastoralisme / élevage / terres arides / hauts plateaux / services écosystémiques

1 Introduction

Pastoral systems worldwide provide livelihoods for rural families in a wide diversity of social-ecological contexts, but particularly in the harsh environments of arid rangelands and high mountain pastures. About 1 billion animals are herded by pastoralists, covering the basic needs for food, fibre, monetary incomes, workforce, energy, transportation and savings of millions of people (FAO, 2018). Pastoral herds play a central role at ensuring food and nutritional security of rural as well as urban families worldwide (*e.g.*, Randolph *et al.*, 2007), they are the backbone of the rural cultural inheritance in different regions (*e.g.*, Marsoner *et al.*, 2018) and represent a valuable investment/saving asset for rural peoples (*e.g.*, Paul *et al.*, 2020). This is also the case in Patagonia, where pastoral systems include both sedentary and mobile ranching systems relying on natural vegetation (Fig. 1A).

Worldwide, extensive livestock rearing is seen as responsible for negative environmental impacts such as vegetation and soil degradation, water pollution and greenhouse gas emissions (Modernel *et al.*, 2018). This bias also resulted in pastoral system being seen as a threat to environmental sustainability, especially when analysed with the methods and assumptions used to assess intensive or industrial livestock systems (*e.g.*, Lebacq *et al.*, 2013). There is evidence to suggest that pastoral systems generate both ecosystem services and disservices, hence the trade-offs between them need to be embraced to inform development strategies and policies (*e.g.*, Von Thungen *et al.*, 2021).

In virtue of the strong bonds between the social and ecological dynamics, pastoral systems can be conceptualized as complex systems, *i.e.*, they integrate processes across scales, multiple feedbacks, nested hierarchies and non-linearity (Tittonell, 2014). The ecological sub-system results in and is the result of the social sub-system, of its traditional ecological knowledge (*e.g.*, seasonal usage of lowlands and highlands), cultural values, social and productive organization (*e.g.*, mobility and landscape connectivity), and technologies (*e.g.*, local breeding). Pastoral communities in harsh environments such as the Patagonian steppes and mountains have developed adaptive strategies to cope with spatial and temporal variability in climate and natural resources. An important strategy is mobility: *i.e.*, nomadism, transhumance, semi-sedentarism. This lifestyle and its associated ecosystem services, which depend on traditional ecological knowledge and local institutions (Easdale and Aguiar, 2018; Oteros-Rozas *et al.*, 2013), is currently threatened by social, economic and environmental factors.

We hypothesize that the contribution of traditional pastoral systems to livelihoods and ecosystem services (Fig. 2), hence to some of the key sustainable development goals, may compensate for their negative effects on the environment. We focus our analysis on the relatively poorly studied pastoral systems of Patagonia, a vast region covering 1 043 000 km^2 and where transhumant, semi-sedentary and sedentary ruminant livestock-based activities represent the dominant livelihood for rural families, from the humid Andes to the dry steppes and irrigated valleys. Our objective was to take stock of the scarcely available evidence on ecosystem services and disservices associated with the regional diversity of pastoral systems, using first-hand evidence whenever possible, and make it available for further evidence-based trade-offs analysis, informing regional and international debates on livestock sustainability.

2 Diversity of pastoral systems in Patagonia

Extensive livestock farming is the main economic activity in Patagonia (750 000 ha; 8.5 million heads – ovine equivalents), including both family smallholder pastoralism and large-scale ranching. Smallholder pastoralism is the dominant farming type, rearing mixed-species herds of sheep, goats and cattle. Large scale ranches are more specialized in sheep and, to a lesser extent, cattle production (Fig. 1). Between smallholder pastoralism and ranching, there is a gradient of possible different livestock systems that combine elements of both family farming and commercial ranching. Argentina's Ministry of Agriculture proposes maximum benchmark land areas as part of their definition of what a family farm is for each agroecological region of the country. In dry Patagonia, a smallholder family farm is considered to own or manage less than 5000 ha of rangeland (*Coordinación de Agricultura Familiar: Resolución 186/14*).

The breeding of Merino sheep oriented to the production of fine wool is the most important livestock activity for both ranchers and pastoralists throughout Patagonia, followed by the Angora and Creole goat and, to lesser extent, Hereford and Creole cattle (Villagra *et al.*, 2013). For example, a regional study covering 106 smallholder households in north Patagonia and its diversity of systems (Fig. 1) showed that livestock contribution to household income was greater than 96%, especially by sheep, and that a sharp decline of wool prices resulted in outmigration of 42% of the rural population in the 1990s (Villagra *et al.*, 2015). Next to sheep, goat rearing is also common and it generally promotes the settlement of families in the driest areas of the region, where productivity is low and other farming activities are not possible. In wetter areas, goat rearing is a secondary activity yet less prone than other livestock activities to the risks associated with the macroeconomic situation of the country or the variability in the international wool and meat prices.

At the wettest end of the gradient, on the Patagonian forests (Fig. 1), farmers keep small to large herds of cattle (*e.g.*, less than ten to hundreds, exceptionally up to 700 Livestock Units),

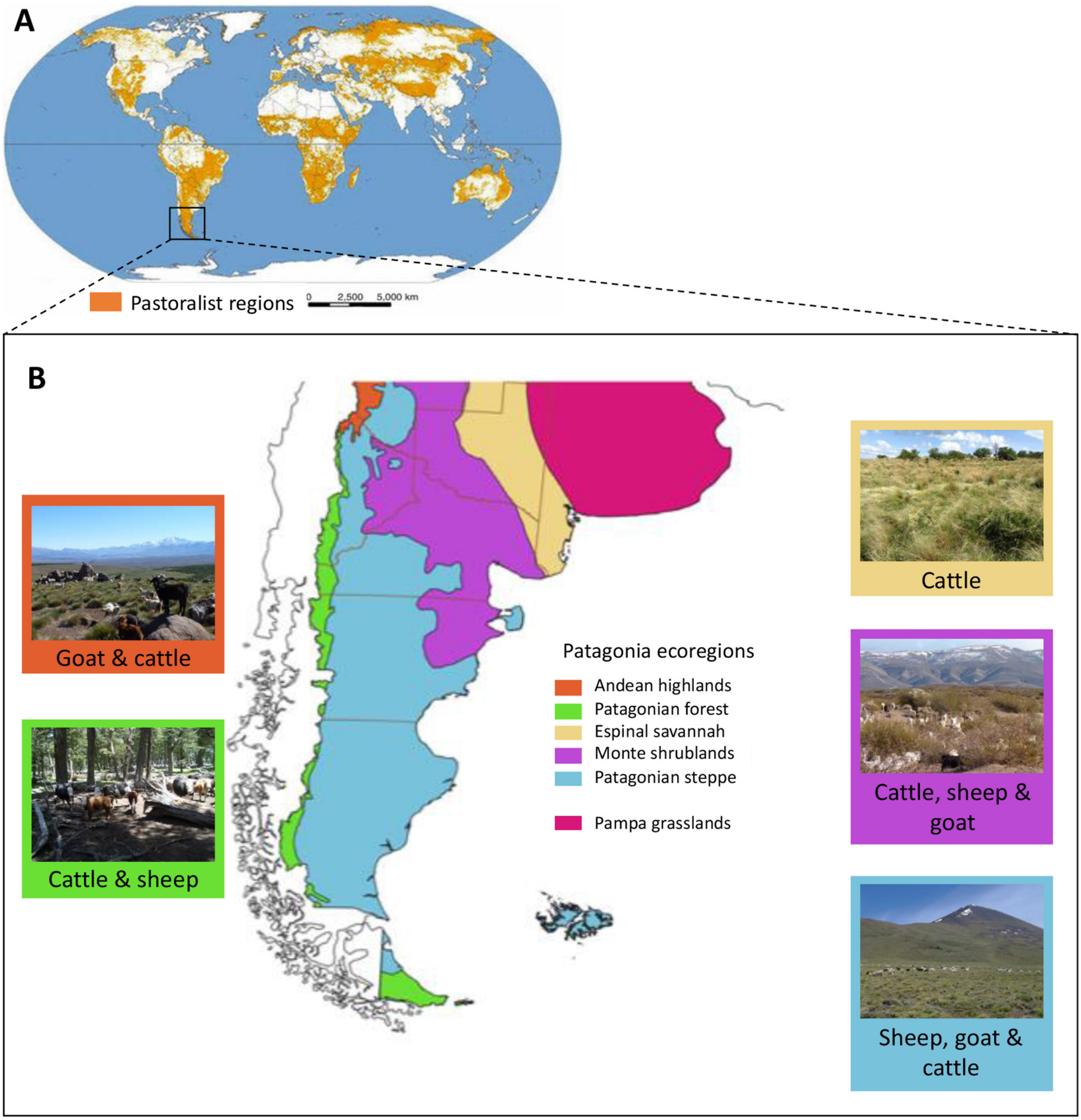

Fig. 1. (A) World pastoralist regions highlighting the Patagonia region (adapted from Dong, 2016). (B) Livestock systems in Patagonia ecoregions (adapted from ANP, 2020) with illustrative pictures. The Pampa's region, and the northern parts of the Monte and Espinal regions (not shown in picture) are not part of Patagonia.

Fig. 1. *(A) Régions pastorales mondiales et mise en évidence de la région de Patagonie (adapté de Dong, 2016). (B) Systèmes d'élevage dans les écorégions de Patagonie (adapté de l'ANP, 2020) avec des images illustratives. La région de la Pampa et les parties septentrionales des régions de Monte et Espinal (non représentées en photo) ne font pas partie de la Patagonie.*

following a strategy characterised by large head numbers but low productivity per head (*i.e.*, livestock as savings). Winter grazing takes place in valley bottoms and foothills (500 to 900 m.a.s.l.), while summer grazing makes use of the high forest, shrublands and alpine-type meadows (1000 to 1800 m. a.s.l.), areas which are covered in snow for most of the rest of the year. In the past, people used to open grazing areas through fires, although this practice has been reverted over the last century, especially since forest use became regulated by law (*e.g.*, Gowda *et al.*, 2012).

In North-West Patagonia, transhumant goat-based pastoralism interconnects contrasting and fragmented ecosystems through seasonal movements. Dry winter lowlands (Patagonian steppe and Monte shrublands – Fig. 1) connect with wet summer highlands (Andean highlands and Patagonian forests – Fig. 1) through regional networks in which the social and ecological phases of these movements are synchronized, defining an annual transhumant cycle (Pérez León *et al.*, 2020). Summer highlands are typically meeting areas where pastoralists exchange or sell breeds (*i.e.*, creole goats) and livestock products such as cheese or meat, textile and leather handicrafts, and engage in different joint activities such as marking and shearing, organise logistics (*e.g.*, travel to town), festivals or religious gatherings. Key components of the transhumance system are also the herding or migratory roads, which are common lands that interconnect the different communal pasturelands (Lanari *et al.*, 2012).

3 Key ecosystem services and disservices associated with pastoral systems

Here we summarise the available regional evidence on the effects pastoral systems may have on ecosystem services and disservices associated with (i) watershed protection and nutrient cycling (support and regulation), (ii) plant and soil biodiversity conservation (support and regulation), (iii) the carbon balance (which may be both a service or a disservice), and (iv) cultural ecosystem services (Fig. 2). The choice of ecosystem services to investigate responds to what is available so far in the literature. The ecosystem services forage or animal production (provision) are by large the best studied in Patagonia, hence we will consider them only with regards to their trade-offs against other ecosystem services.

3.1 Watershed protection and nutrient cycling at landscape level

Stocking rate, directly related to grazing pressure, is the main management variable regulating grazing impacts on ecosystem services in Patagonia (Oñatibia, 2021). Stocking rates can be lower, equal or higher than field carrying capacity (varying broadly between 0.10 to 0.35 sheep ovine equivalents ha^{-1}), resulting in low, moderate or overgrazing. Limiting stocking rates to field carrying capacity (*i.e.*, moderate or appropriate grazing) can provide watershed protection by regulating soil cover and the amount, timing and quality of water and sediment flows and soil water infiltrability. Overgrazing negatively affects these structural attributes, with consequent water run-off and soil erosion (López *et al.*, 2013).

Signs of overgrazing are conspicuous in Patagonia and attributed to both domestic and wild herbivores, mostly through classical lineal analysis of NDVI trends from satellite imagery series (*e.g.*, Gaitán *et al.*, 2017, 2019; Mazzonia and Vazquez, 2009; Marino *et al.*, 2020; Oliva *et al.*, 2020). Yet recently published data from long-term grazing experiments indicate that moderate and adaptive grazing regimes (*i.e.*, following recommended stocking rates) may actually result in greater short- and long-term productivity and stability (Oliva *et al.*, 2020). Moreover, the analyses of long-term NDVI trends in satellite imagery using wavelets – instead of linear trends – to capture cyclical dynamics (Easdale *et al.*, 2018, 2019) show that processes of vegetation recovery are also frequent throughout Patagonia, in spite of recurring droughts and ash falls affecting vast regions in the last two decades (Solano-Hernandez *et al.*, 2020).

Grazing intensity and management determine different patterns of livestock impacts on nutrient cycling (Tab. 1). In the silvo-pastoral systems found in the Andean forest zone (Fig. 1), overgrazing generates more negative than positive effects at stand level, while low to moderate grazing leads to null or positive impacts on C and N flows and stocks in different components of soil and vegetation. Heterogeneous distribution of patches of silvo-pastoral use within the landscape allowed the maintenance of diversity and the provision of multiple ecosystem services, including nutrient cycling through faster litter decomposition and animal dejections (Chillo *et al.*, 2018). In Patagonian irrigated valleys, where diverse types of agricultural systems coexist with pastoralism, circular farming and crop-livestock integration have been proposed to reduce dependence on external nutrient inputs at local and regional level, considering the coexistence of farms with nutrient demands and farms with a potential excess of manure (Basso, 2018).

In the Patagonian steppe, where water and nutrients are scarce, forage supply and C and N storage were highest in areas under moderate grazing, compared to ungrazed and overgrazed areas, and they were positively correlated indicating the absence of trade-offs between them (*e.g.*, Oñatibia *et al.*, 2015). Comparable findings were reported by Buono *et al.* (2011) and Oliva *et al.* (2012, 2020). These findings are promising as they point to possible synergies or neutral effects of moderate pastoral grazing on nutrient stocks and flows, specially under so-called “holistic management” (Cibils *et al.*, 2014). Yet, our general impression following the literature review is that this field is still very poorly studied in Patagonia, especially in the drier zones, and hence more knowledge is needed to arrive at sound conclusions and recommendations. What can be considered an “appropriate” grazing regime or stocking rate varies widely across time and space in Patagonia, but it always implies that stocking rates should be equal to the estimated grassland receptivity.

As grazing may prevent fires, especially in woodland ecosystems, it may also contribute to maintaining soil physical properties, avoiding post-fire hydrophobicity and reducing soil erosion susceptibility (Neary and Leonard, 2020). In the Monte shrublands (*cf.* Fig. 1) for example, where wildfires are more frequent, grazing reduces the occurrence of fires (Kröpfl *et al.*, 2015). While herbivore impact on fire propagation depends on the context (Blackhall *et al.*, 2017), drivers of current wildfires in Patagonia include also climate change and urbanization (Gowda *et al.*, 2012).

3.2 Plant and soil biodiversity conservation

Grazing has been reported to have different direct effects, positive or negative, on species richness, cover and biomass of palatable grasses, and null impact on cover and biomass of shrubs in Patagonian drylands (Cipriotti *et al.*, 2019; Oñatibia *et al.*, 2018). However, excluding livestock does not appear to be the most sensible measure to manage plant biodiversity. Compared to grazing exclusion, continuous moderate grazing maintains plant density of palatable species, reduces standing-dead biomass proportion, and promotes green biomass of grass

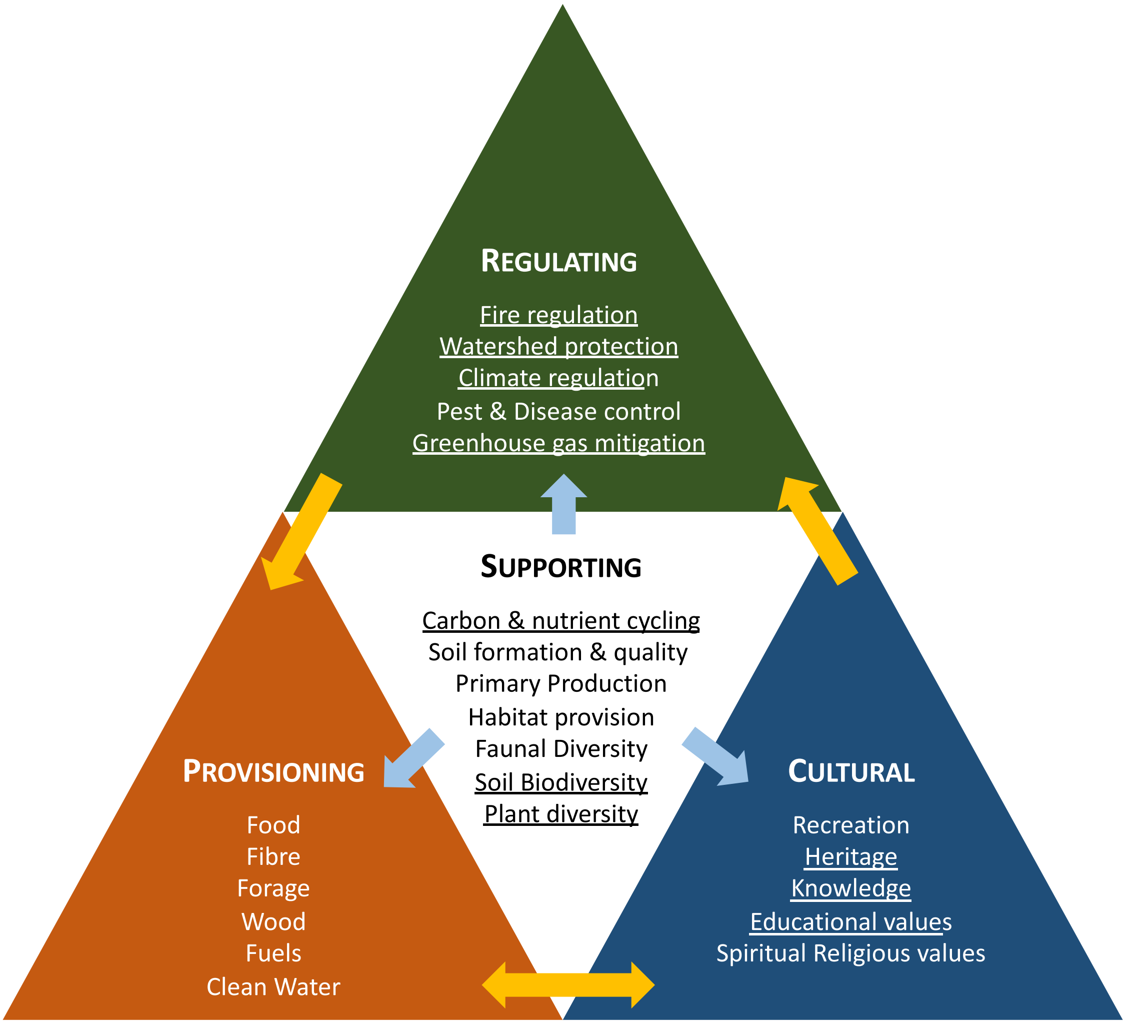

Fig. 2. Four types of ecosystem services relevant to pastoral social-ecological systems. Underlined are those that were covered in this review for Patagonia. Arrows represent both effects and influences.

Fig. 2. *Quatre types de services écosystémiques pertinents pour les systèmes socio-écologiques pastoraux. Ceux qui ont été traités dans cette revue bibliographique sur la Patagonie sont soulignés. Les flèches représentent à la fois les effets et les influences.*

tussocks (*e.g.*, Oñatibia and Aguiar, 2019). Reduction of paddock sizes (*NB*: a "paddock" may be as large as 500–1000 ha in dry Patagonia) also contributes to the decrease of spatial heterogeneity of grazing impacts, as vegetation variables (*e.g.*, total and specific plant cover, vegetation patchiness) in smaller paddocks reach a plateau at short distance of watering points compared to larger paddocks (Oñatibia and Aguiar, 2018).

Mainly negative impacts of cattle grazing on plant biodiversity have been reported in Patagonian ecosystems (Fig. 3). Recent studies in northern Andean mixed forests of *Nothofagus dombeyi* and *Austrocedrus chilensis* suggest that cattle grazing affects plant biomass, reduces shrub cover and the number of native plants, differentially affects flowering and fruiting periods of palatable and non-palatable species, and enhances exotic plant species (*e.g.*, Ballari *et al.*, 2020, De Paz and Raffaele 2013). Experiences in southern Patagonian *Nothofagus antarctica* forests, however, showed that, through active ecosystem management, cattle production can coexist with native plant biodiversity (Peri *et al.*, 2016). This study shows that when cattle were introduced, some species of native vascular plants were lost from grazed plots, and simultaneously new ones appeared. Although this generated similar values of biodiversity in terms of both richness and cover in these landscapes (Fig. 4), the loss of native species cannot be compensated for its biodiversity value, and specific measures (*e.g.*, grazing exclosures) must be taken to preserve native vascular plant diversity.

Synergies between provision and cultural ecosystem services through grazing management have also been reported in the Andean forest region of Patagonia. Chillo *et al.* (2018) showed perceivably positive changes in the floristic and functional diversity of herbaceous vegetation associated with grazing, for example through the appearance and dominance of exotic and native grasses with high cultural and productive value.

Moreover, in grazed areas of northern Patagonian forests, changes in community specific leaf area and weighed N content resulted in greater plant growth and cover (less soil erosion) and faster litter decomposition (higher nutrient

Table 1. Examples of reported negative, positive or null impacts of livestock systems on nutrient cycling.
Tableau 1. *Exemples d'impacts négatifs, positifs ou nuls des systèmes d'élevage sur le cycle des nutriments.*

Variable	Negative impact	Positive impact	Null impact	References
C and N stock in green above ground biomass		grass-MG	shrub-UG, MD, OG	Oñatibia *et al.* (2015)
C and N stock in standing dead biomass	grass-OG		shrub-UG, MD, OG	
C and N stock in litter	OG			
C and N stock in roots			UG, MD, OG	
total N, NH4+ and NO3−	OG			Enriquez *et al.* (2014)
C stock in roots + SOC (= total below ground C storage)			LG, MD, OG	Larreguy *et al.* (2014)
SOC	OG			Larreguy *et al.* (2014)
SOC			UG, MD, OG	Golluscio *et al.* (2009)
SON	OG			
^{13}C SOM	OG			
^{15}N SOM		UG		
N and C mineralization	OG			
SOC content	OG			Enriquez *et al.* (2015)
SOC stock	OG			
Above and below ground biomass and C storage	OG			
Organic matter decomposition		SVP		Bahamonde *et al.* (2012)
Litterfall	SVP			
SOC	SVP-OG			Chillo *et al.* (2018)

LG, MG and OG: low, moderate and overgrazing; UG: ungrazed sites; SVP: sylvo-pastoral system; SOC: soil organic carbon; SON: soil organic nitrogen; SOM: soil organic matter.

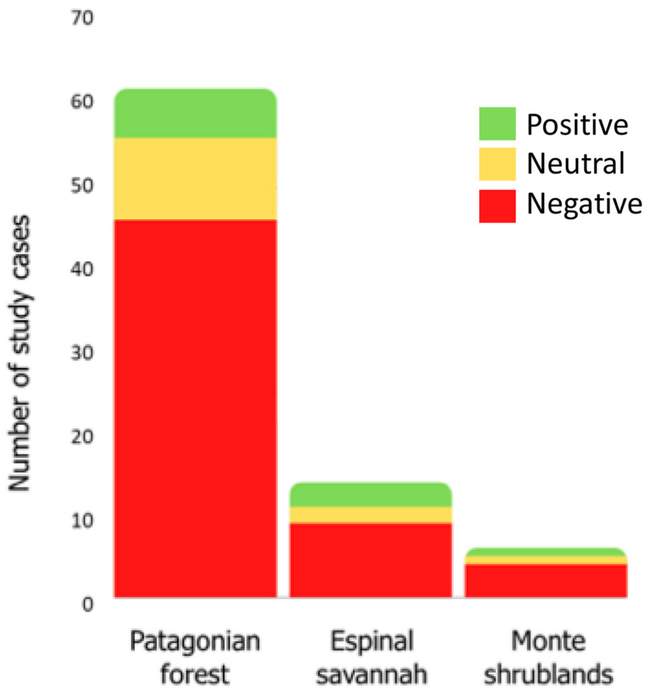

Fig. 3. Effects of cattle on plant biodiversity of Patagonian ecosystems. Adapted from Mazzini *et al.* (2018).
Fig. 3. *Effets des bovins sur la biodiversité végétale des écosystèmes de Patagonie. Adapté de Mazzini et al. (2018).*

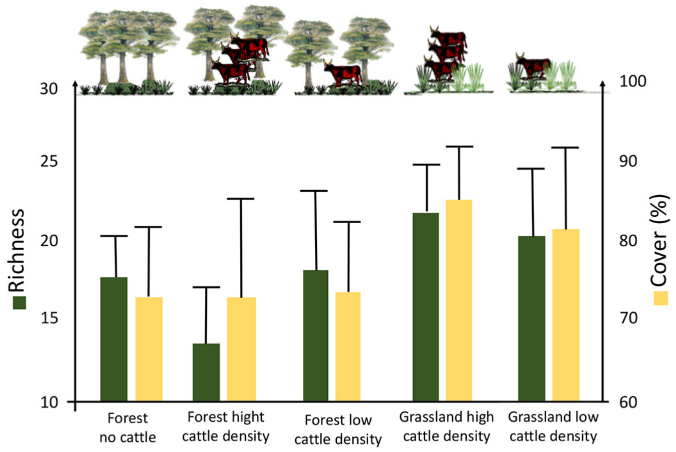

Fig. 4. Impact of different livestock grazing pressure over vascular plants (richness and cover) in *Nothofagus antarctica* forests and grasslands. Adpted from Peri *et al.* (2016).
Fig. 4. *Impact de différentes pressions de pâturage exercées par le bétail sur les plantes vasculaires (richesse et couvert) dans les forêts et les prairies à Nothofagus antarctica. Adapté de Peri et al. (2016).*

supply), which consequently determined greater forage productivity (Chillo *et al.*, 2018). Yet high cattle stocking rates in forests may prevent forest regeneration, as the dominance of exotic grasses tend to outcompete tree seedlings (Rusch *et al.*, 2016), compromising all ecosystem services associated with forest in the long term. Grazing regimes in

Table 2. Livestock impact on biological indicators of soil biodiversity.
Tableau 2. *Impact des systèmes d'élevage sur les indicateurs de biodiversité du sol.*

Biological indicator	Negative impact	Positive impact	Null impact	Observed change	References
MBC	PCP-MG	IC-OG			Prieto *et al.* (2011)
PA	IC		PCP		
DA, BA, APA, ALPA			PCP, IC		
Heterotrophic bacterial abundance		PCP, IC-OG			
Heterotrophic fungal abundance	PCP-MG	IC-OG			
APA	PCP, IC				Olivera *et al.* (2014)
ALPA	PCP-MG, OG	IC-OG			
BA	PCP		IC		
PA			PCP, IC		
DA		IC	PCP		
MBC	PCP-OG	IC			
MBC		MG			Toledo *et al.* (2017)
Bacterial community structure				IC-OG *vs.* LG/MG; PCP-LG *vs.* MG/OG	Olivera *et al.* (2016)
Microbial community structure and networks		network-GS		Structure GS *vs.* NGS	Marcos *et al.* (2019)
Arbuscular mycorrhizal (AMF) fungi spore abundance	OG		MG		Dudinszky *et al.* (2019)
AMF diversity index	OG		MG		

MBC: microbial biomass carbon; PA, DA, BA, APA, ALPA: protease, dehydrogenase, β-glucosidase, acid and alkaline phosphatase activity; PCP: plant-covered patches; IC: nearest inter-canopy areas; LG, MG and OG: low, moderate and overgrazing; NGS and GS: non-grazed and grazed sites.

Andean forests must be carefully designed to maintain forest coverage in the long term (Raffaele *et al.*, 2011).

In the soil, biodiversity supports and regulates multiple processes and is therefore crucial for ecosystem functioning and services (El Mujtar *et al.*, 2019). Grazing affects soil physico-chemical properties, and hence biodiversity, but impacts differ according to grazing strategies and intensities (Byrnes *et al.*, 2018). In Patagonia, the evaluation of grazing impact on soil biodiversity is scarce and so far mostly focused on differences in microbial biomass and activity, *e.g.*, between plant-covered patches and inter-canopy areas (Marcos and Olivera, 2016). These impacts can be positive, negative or null (Tab. 2), and more research is needed to explore such trade-offs or synergies.

3.3 Carbon balance

The carbon balance is addressed in a separate sub-section since it is the summary of several other aspects in the pastoral management system and, at the same time, it is one of the few ecosystem services with a potential market price. Understanding the C balance in the pastoral systems of Patagonia constitutes a particular area of raising political interest at the moment (MAyDS, 2020). There is a generalized concern about the contribution of livestock activity to global warming, as livestock are responsible for 14.5 to 22% of the global anthropogenic greenhouse gas (GHG) emissions (Gerber *et al.*, 2013). However, these emissions can be partially or totally offset by C sequestration through improving the C balance at landscape level (Assouma *et al.*, 2019). The potential to stabilize or increase the soil organic carbon (SOC) stock is highly dependent on climatic conditions, soil characteristics and grazing management (Abdalla *et al.*, 2018). On the other hand, C footprints are not restricted to the farm level but to the whole production chain. Globally, the C footprint for extensive and intensive meat production is around 38.4–42 kg CO_2-eq. kg^{-1} carcass, respectively (Opio *et al.*, 2013). However, C stored in natural reservoirs and their potential of C sequestration should be considered too in assessing C footprints of products from grazing ecosystems (Toro-Mujica *et al.*, 2017).

In Patagonia, Peri *et al.* (2020) reported a regional total C footprint of 10 to 41 kg CO_2-eq. kg^{-1} for lamb meat (carcass), and of 8 to 19 kg CO_2-eq kg^{-1} for fine-grade wool. The highest C footprints were found in ecologically degraded sites with lower plant productivity. Soils of the Patagonian steppe store large amounts of SOC due to their high extension in the territory (FAO and ITPS, 2018), but have low capacity to fix C associated to their above and below ground biomass (Tab. 3). However, the wetland meadows frequently occurring in the Patagonian steppe and locally known as *Mallines*, exhibit a positive balance between the sequestration of atmospheric C and the emissions of other GHG, such as methane and nitrous oxide (Enriquez *et al.*, 2020). They may be considered as key C sink environments despite their small extension in the territory (Tab. 3). Grazing with stocking rates beyond field carrying capacity can in the long term significantly reduce above and below ground biomass and C stocks in Patagonian steppes (*e.g.*, Larreguy *et al.*, 2017) and in wetland meadows (*e.g.*, Enriquez *et al.*, 2020), which slowly contributes to a desertification process.

Table 3. Carbon content and stocks in soil, below and above ground biomass in Patagonian ecosystems according to grazing intensity.
Tableau 3. *Teneur et stocks en carbone dans le sol, biomasse souterraine et aérienne dans les écosystèmes de Patagonie selon l'intensité du pâturage.*

System	Condition	Pool	Magnitude	Unit	Depth (cm)	References
Steppe	UG	SOC	35	S	0–200	Nosetto *et al.* (2006)
	LG	SOC	60	S	0–25	Laclau (2006)
		SOC	~9	C	0–5	Gaitán (2002)
		SOC	11–12	C	0–5	Chartier *et al.* (2013)
		POM	4	C	0–10	Fariña (2018)
		AGB	7–10	S		Laclau (2006)
		BGB	2	S		Laclau (2006)
	HG	SOC	34	S	0–200	Nosetto *et al.* (2006)
		SOC	~6	C	0–5	Gaitán (2002)
		SOC	6–8	C	0–5	Chartier *et al.* (2013)
		POM	4–5	C	0–10	Fariña (2018)
		AGB	5	S		Laclau (2006)
		BGB	2	S		Laclau (2006)
		AGB	4–5	C		Mazzarino *et al.* (1998)
	UG to HG	AGB	5	C		Mazzarino *et al.* (1998)
		BGB	1	S		Oñatibia *et al.* (2017)
	N/I	SOC	38	S	0–30	FAO and ITPS (2018)
		SOC	13–39	S	0–10	Bran *et al.* (2011)
		SOC	10	C	0–10	Gaitán *et al.* (2019)
Meadow	LG	SOC	93	C	0–20	Enriquez *et al.* (2015)
		SOC	117	C	0–10	Chimner *et al.* (2011)
		SOC	66	C	0–20	Cardoso *et al.* (2010)
		SOC	61	C	0–15	Jaramillo (2019)
		POM	83	C		Enriquez and Cremona (2018)
		C–AGB	3	S		Enriquez *et al.* (2015)
		C–BGB	53	S	0–20	Enriquez *et al.* (2015)
	HG	SOC	48	CC	0–20	Enriquez *et al.* (2015)
		POM	38		0–20	Enriquez and Cremona (2018)
		C–AGB	0.4	S		Enriquez *et al.* (2015)
		C–BGB	22	S	0–20	Enriquez *et al.* (2015)
	N/I	SOC	117	S	0–30	Enriquez *et al.* (2020)
		SOC	264	S	0–100	
Monte	UG	SOC	10	C	0–20	Kröpfl *et al.* (2013)
	HG	SOC	14	C	0–20	Kröpfl *et al.* (2013)
	LG to HG	SOC + AGB + BGB + Litter	16–28	S	0–30	Larreguy *et al.* (2017)
		SOC	4–12	C	0–10	Prieto *et al.* (2011)

UG, LG, and HG: ungrazed, light, and high grazing intensity, respectively. SOC: soil organic carbon; POM: particulate organic matter; AGB: above ground biomass; BGB: below ground biomass; OM: organic matter; N/I: no information or specification; S: C stock t.ha^{-1}; C: C content g.kg^{-1}.

With data from a representative sheep farm in North Patagonia (2500 ha and 442 sheep, Villagra *et al.*, 2015), we calculated emission rates in the order of 36 ton CO_2-eq.year^{-1} for enteric fermentation (which represents about 55% of total GHG emissions in small ruminant meat production – Opio *et al.*, 2013), and 1600 ton CO_2-eq.year^{-1} for soil respiration. We also calculated an above and below ground net primary production C fixation (Enriquez *et al.*, 2015; Milchunas *et al.*, 2005) of 5500 ton CO_2-eq.year, that would offset at least three times the estimated emissions. Overall, "carbon trade-offs" related to livestock activity in Patagonia region are likely to be highly dependent on the ecological context (Fig. 1) but also on the initial condition of the grassland (*i.e.*, grassland evaluation is needed), environmental aspects (*i.e.*, relative to the geographic region, with wide climatic and geological variability), management strategies (*i.e.*, intensification level, management practices), and the scale of analysis considered (*i.e.*, farm, local, regional levels).

3.4 Cultural ecosystem services

Pastoral livelihoods contribute to creating and conserving traditions, knowledge and the local culture. Patagonia landscapes have been shaped by human communities since at least 12 500 BP (Ceballos, 1982) and for the last 200 years with their domestic animals (Gasteyer and Flora, 2000). Pastoral livelihoods have developed ecological knowledge on local resource management, medicinal and edible plants, firewood, fungi and animal species (*e.g.*, Ladio and Lozada, 2009). For example, the conservation of local genetic resources and their ancestral knowledge include the *criolla* or *linca* sheep – of great importance for rural women –, the *chiva criolla* (creole goat) and the *Gallina araucana* local fowl (Lanari *et al.*, 2012). The use of mammals and bird species as ethno-indicators of ecosystem quality is traditional knowledge amongst Patagonian pastoralists and also a part of their cultural heritage (Castillo and Ladio, 2017).

The different types of pastoral systems coexisting in Patagonia as described here rely on traditional forms of collective organization and natural resource governance that date from the introduction of domestic livestock in the region (Coronato *et al.*, 2015). Even when new generations of pastoral families became sedentary, the land they managed is not always fenced or clearly demarcated, yet grazing trajectories and spots are known and respected within the community (Von Thungen, 2010). Such local by-laws and traditional institutions are also a cultural asset associated with rural livelihoods and value systems in Patagonia (Nuñez *et al.*, 2020). Through the maintenance of such livelihoods, traditions (gastronomy, language, music, art, etc.), institutions and value systems, pastoralism undoubtedly contributes to safeguarding cultural ecosystem services in Patagonian landscapes.

4 Conclusions

Pastoral socio-ecological systems are essential to sustaining livelihoods in the world's harshest environments, and they support rural families on almost half of the world's terrestrial surface. They have the potential to provide a wide array of ecosystem services and protect the natural resource, base of the marginal environments where they coexist with deeply rooted pastoral cultures. In such sense, pastoralism is more than just another type of rural livelihood. It is a social-ecological system closely bound to its natural environment and the sentinel of local biocultural diversity. Yet pastoral systems are poorly understood in terms of their contribution to ecosystem services, climate change or biodiversity conservation, as the limited available evidence from Patagonia indicates. Scarce and atomized information limits our ability to assess and improve the contribution to the United Nations sustainable development goals from this vast and remote pastoral region, of high international conservation and environmental interest.

We found that pastoral socio-ecological systems of Patagonia sustain resilient livelihoods and traditional cultures, contribute to conserve biodiversity, protect landscape functionality and ecosystem services and exhibit trade-offs and possible synergies around the carbon balance. With C footprints between 10 to 40 kg CO_2-eq.kg^{-1} carcass, pastoral systems in dry Patagonia are below or within the range of semi-extensive livestock systems worldwide (35–45 CO_2-eq.kg^{-1} carcass). Would Patagonia ecosystems be better off, healthier or more functional, without pastoralists? This is a rhetorical question, but it is part of an ongoing debate in the region. Pastoralists have been the custodians of the landscapes and biocultural diversity we inherited. It seems only logical to aim at minimizing, yet embracing, the socio-ecological trade-offs associated with their activities.

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