Trends in
Ecology & Evolution

CellPress
OPEN ACCESS

Review

Reconciling livestock production and wild herbivore conservation: challenges and opportunities

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Increasing food security and preventing further loss of biodiversity are two of humanity's most pressing challenges. Yet, efforts to address these challenges often lead to situations of conflict between the interests of agricultural production and those of biodiversity conservation. Here, we focus on conflicts between livestock production and the conservation of wild herbivores, which have received little attention in the scientific literature. We identify four key socio-ecological challenges underlying such conflicts, which we illustrate using a range of case studies. We argue that addressing these challenges will require the implementation of co-management approaches that promote the participation of relevant stakeholders in processes of ecological monitoring, impact assessment, decision-making, and active knowledge sharing.

Highlights

Conflicts between the interests of livestock production and those of wild herbivore conservation are an increasing global challenge.

Addressing these conflicts is hindered by a poor understanding of key underlying social and ecological drivers.

In particular, there is a need to reconcile the real and perceived costs–benefits of livestock–wild herbivore interactions. This includes better understanding how these interactions vary across migration ranges and are influenced by trophic network structure.

In many cases, these conflicts are perpetuated by a disconnect between livestock husbandry practices and scientific research on sustainable management.

Addressing these conflicts will require the development of reliable protocols for impact assessment and the implementation of participatory processes that bring together relevant stakeholders.

Limited space for livestock and wild herbivores

The intensification and expansion of agricultural activities to feed an ever-growing human population is among the greatest threats to biodiversity globally [1,2]. With more than 10% of the global human population currently facing food insecurity [3] and an estimated 25% of wild species threatened with extinction as a result of anthropogenic drivers [4], conflicts between the interests of crop and livestock production (hereafter, both referred to as 'agriculture') and those of wildlife conservation are becoming globally widespread [5,6]. Such conservation conflicts pose a major threat to both human well-being and the health of natural ecosystems, emphasising an urgent need to develop and implement sustainable strategies aimed at fostering coexistence between agricultural activities and biodiversity conservation [4,7].

Livestock production currently accounts for up to 26% of the earth's terrestrial surface, representing almost 3.38 billion hectares under permanent meadows and pastures worldwide [8]. Today, global human biomass (ca. 0.06 Gt C) and livestock (ca. 0.1 Gt C) surpass wild land mammal biomass (ca. 0.003 Gt C) [9]. The increasing demand for meat and dairy products has resulted in an estimated ~150–450% rise in the numbers of animals produced globally. While this increase has been linked to an intensification and industrialisation of livestock production, extensive grazing systems still dominate the terrestrial landscape [10]. Such systems, which range from ranching to nomadic pastoralism, are associated with large, sometimes fenced, areas of land on which livestock are left to graze native vegetation. Their global expansion is recognised as a major driver of land-use change, with important implications for wildlife, whose access to wild spaces and resources continues to be impacted [1,4].

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An important consequence of the rise in biomass and space occupied by extensive grazing systems has been an increased level of interaction between livestock and wildlife. Although these interactions can be beneficial to both livestock production and wildlife conservation, they are most often considered and framed as negative [11,12]. This is reflected in an exponential increase in the number of studies on conflict and coexistence between agriculture and wildlife conservation in recent years [13]. Much of this work, however, has focused on livestock predation by wild carnivores (e.g., [14,15]) or crop consumption by wild herbivores [16]. In contrast, conflicts centred on interactions between wild and domestic herbivores have been largely overlooked [17], despite their important implications for both biodiversity conservation and human well-being.

Wild herbivores can potentially compete with livestock for resources, be vectors of diseases, and fall prey to large carnivores that may in turn be attracted to co-occurring livestock [18]. Such interactions often lead to social conflicts between the interests of different stakeholders about the extent to which wild herbivore populations should be managed or conserved [19,20]. These conflicts are often exacerbated by considerable amounts of uncertainty regarding the ecological, social, and economic aspects of herbivore–livestock interactions. For example, the extent to which wild herbivores and livestock compete for forage remains a matter of considerable debate [20,21] and the persecution of native herbivores to minimise competition is still widespread. Despite increased efforts to reconcile conservation and agricultural interests, real and perceived negative interactions between wild and domesticated herbivores continue to be an important driver of the on-going global decline of wild herbivores [22,23].

Here, we identify key challenges underlying conflicts between livestock production and wild herbivore conservation, using four contrasting case studies from South America, Europe, Asia, and Africa to highlight common themes. We put forward key concepts that tie together these different challenges and suggest holistic approaches to promoting coexistence.

Quantifying the costs and benefits of livestock–wild herbivore interactions

Resource competition and disease transmission are the two primary negative impacts that wild herbivores and livestock can have on each other [12]. The implementation of management strategies aimed at mitigating these impacts is a major driver of conflict between proponents of wild herbivore conservation and the production of livestock [23,24]. A key challenge is the difficulty in obtaining reliable estimates of both the tangible and intangible costs and benefits of these interactions [25], including their objective translation into measures of economic and societal loss or gain for producers, as well as potential threats (or benefits) to populations of protected wildlife (Boxes 1 and 2). This is particularly the case in rangeland systems characterised by low human intervention, vast and often dry landscapes, and harsh climatic conditions [26], where interactions occurring between wildlife and livestock left to graze extensively remain poorly understood [27], hindering the implementation of reliable methods to quantify potential costs and benefits (Box 3).

Niche overlap between co-occurring wild and domestic herbivores is often considered a strong indicator of resource competition [28] (Boxes 1,3, and 4), yet evidence supporting this theory is mixed. Recent studies have shown that, under certain conditions, resource partitioning and even facilitation can arise in extensive grazing systems [29,30]. For instance, Kimuyu *et al*. [31] showed that rainfall and the composition of wild herbivore assemblages influenced the cost–benefit potential of livestock–wild herbivore interactions in a Kenyan savanna, with some mega-herbivores moderating the negative effect of livestock on meso-herbivores. Ranglack *et al*. [11] found that cattle faced greater competitive challenges from lagomorphs than from large wild herbivores, such as bison (*Bison bison*). Despite the more nuanced perspectives offered by such studies,

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Box 1. Guanaco management and sheep production in the Chilean Patagonia

Sheep (*Ovis aries*) farming is the primary agricultural livelihood in Patagonia [83], with a historical peak of 2.2 million heads in the 1950s [84]. The expansion of sheep farming activities into extensive steppe rangelands has led to increased interactions with the guanaco (*Lama guanicoe*), the largest native herbivore in the area. After experiencing steady declines across the region during the second half of the 20th century due to poaching and intense resource competition with domestic herbivores [85,86], guanaco populations have recently shown signs of recovery in Chilean Patagonia [87]. However, overgrazing combined with increased overlap between sheep farming activities and the distribution of guanacos, has rekindled a social conflict due to different stakeholder views on the potential for competition between the two species and the effectiveness of wildlife management. In particular, local producers are concerned that guanacos reduce forage availability and consume crops grown for sheep [33,88]. Despite high diet similarity and niche overlap, suggesting competition can occur [30,84,89], there is little evidence indicating that guanacos have a significant impact on sheep farming [30,89]. In 2000, the Chilean government authorised the implementation of a guanaco commercial harvest program that aimed to sustainably regulate guanaco population density, as well as contribute with new products for the local economy [90]. However, lack of consistent population and decision-making data has made it difficult to assess the potential success of the guanaco management plan, both from conflict-resolution and biodiversity perspectives [33]. In addition, the presence of guanacos is associated with the occurrence of natural predators such as pumas (*Puma concolor*), which locally are seen as a threat because they predate on sheep [91]. Overall, this case study demonstrates the value of collecting reliable evidence regarding levels of resource competition and interspecific interactions, lack of which undermines attempts at implementing wildlife control programs and improved husbandry practices (Figure 1).

the assumption of costly resource competition between wild and domestic herbivores remains widespread amongst livestock producers and conservationists [29], prompting these stakeholders to hold negative perceptions of livestock–wild herbivore interactions [32,33].

Wild herbivores and livestock may also exchange parasites and pathogens, which may represent risks for both [34] (Box 2). This is expected to occur more frequently as a result of rewilding processes linked to farmland abandonment and the natural recolonisation of wild herbivores [35]. However, due to complex epidemiological processes and interactions among species, quantifying the presence, cost, and impact of disease transmission on livestock productivity in extensive grazing systems remains a considerable challenge [36]. Although diseases may be transmitted in both directions, the role of wild herbivores as a source of pathogens for livestock is a major concern for producers, often driving the implementation of costly mitigation methods such as vaccination programs and extensive fencing [37]. As an example, the impact of tick-borne disease transmitted from wild herbivores to livestock could represent the greatest barrier to economic development in East Africa [34,38].

Box 2. African buffalo conservation and livestock production in northern Botswana

Foot-and-mouth disease (FMD) is a viral disease that affects cloven-hoofed mammals, including both wild and domestic bovids. Across the African continent, the economic impact of FMD has been estimated at between 1 and 5 billion USD, including both production losses and vaccination costs [92]. The African buffalo (*Syncerus caffer*), a species listed as Near Threatened by the IUCN Red List, is considered to be the main wild host of the FMD virus [93], a status that has prompted intense management of the species in range countries reliant on livestock production for both national and international markets. In Botswana, management has involved the establishment of multiple cordon fences (so called 'buffalo fences') and disease-free zones, as well as costly vaccination programs for the subsidized production of industrialised beef [94]. Although these measures have significantly reduced the frequency of FMD transmission and outbreaks as a result of buffalo–cattle interactions, they have had a considerable impact on the migratory behaviour of other wild species, such as blue wildebeest (*Connochaetes taurinus*), red hartebeest (*Alcelaphus caama*), and zebra (*Equus quagga*). Furthermore, such measures have failed to address the concerns of local subsistence producers, for which the risk of FMD transmission from buffalo was found to be a significant factor explaining negative attitudes and perceptions of wildlife for 74% of households surveyed in the Okavango delta [95]. Despite the potential for FMD and its management to affect both wild and domestic herbivores, important knowledge gaps remain, including the frequency and direction of transmission, the host or carrier status of other herbivore species of conservation concern (e.g., the African elephant *Loxodonta africana*), and the contribution of international herbivore movements to disease dynamics [93–95]. Such uncertainties highlight the challenges of managing disease transmission between domestic and migratory wild herbivores (Figure 1).

Box 3. Wild herbivore conservation and cashmere goat production in Mongolia

Pastoralism remains the dominant form of land-use in Mongolia today, with half of the country being dependent on livestock production [96]. Mongolian rangelands are also particularly important for the conservation of large herbivores [e.g., Mongolian gazelle (*Procapra gutturosa*), black tailed gazelle (*Gazella subgutturosa*), Mongolian saiga antelope (*Saiga tatarica mongolica*)] as well as for several species of large protected carnivores [e.g., grey wolf (*Canis lupus*), Eurasian lynx (*Lynx lynx*), and snow leopards (*Panthera uncia*)] [97]. In recent decades, numbers of cashmere-producing goats have undergone a fivefold increase as herders have responded to strong international market demands for cashmere fibre [21]. Coupled with the impacts of a warming climate, this increase has resulted in overgrazed and degraded pastures that are less able to support both livestock and wildlife [21,98]. In this context, the potential for dietary overlap and competition between wild herbivores and livestock has presented significant challenges for rangeland management [99]. In addition, there are also concerns for large carnivores, such as wolves and snow leopards, which are at risk from reduced populations of wild prey and are being hunted for potential sporadic predation on livestock [21]. This case study illustrates how economic incentives from global markets can influence the transition from traditional livestock practices to more intensive forms of livestock production, thereby impacting rangeland ecosystems and exacerbating perceptions of resource competition between wild and domestic herbivores. In addition, it highlights the vulnerability of livestock to predation by internationally protected carnivores as a result of decreasing wild prey populations (Figure 1).

The migratory behaviour of wild herbivores

Migration is an essential life history trait for many wild species [39], yet it can pose unique challenges to the coexistence of wild herbivores and livestock production. These include the need to consider the influence of fenced agricultural land on wildlife movement, the existence of marked spatiotemporal dynamics in wild herbivore–livestock interactions, and the requirement for collaborative management efforts across administrative boundaries (Boxes 2 and 4).

Fencing represents a widely used method of separating the activity of livestock and that of wild herbivores. Extensive fences can be established around protected or agricultural areas in such a way that minimises the risk of resource competition or disease transmission [37]. Yet, fences can impose severe restrictions on the movement of wild herbivores, with important implications for conflicts between livestock production and wild herbivore conservation. These include disruptions to seasonal migrations [40], depletion of overgrazed local resources, and unintended increases of negative interactions with herbivores along alternative migratory pathways [41]. Whilst allowing fencing for livestock to proceed unregulated across migration paths would be contrary to the interests of conservation, preventing it from occurring may also be problematic

Box 4. Goose conservation and livestock production on Islay, Scotland

Between October and March, the Scottish island of Islay is home to over 50% of the global population of Greenland barnacle geese (a distinct flyway population of *Branta leucopsis*) [100], a number that has repeatedly exceeded 40 000 individuals in recent years [101,102]. Although, the species is currently listed as Least Concern by the International Union for Conservation of Nature (IUCN), it was legally protected under the 1979 EU Bird's Directive, and remains so, with only very limited culling permitted under certain conditions. The number of geese that winter on Islay is positively correlated with the availability of improved grassland specifically grown to feed livestock on the island, but also warming temperatures on breeding grounds in Greenland and hunting intensity on staging grounds in Iceland [101]. Geese damage improved grass through trampling and feeding, with large flocks often sighted on pastures during winter months. Overall, it has been estimated that the cost of damage caused to agriculture (including livestock production) on Islay stands at approximately £1.6 million per year [101,103]. One of the most contentious measures used to mitigate damage caused by geese was the adoption in 2000 of a culling programme, which, since 2014, has specifically aimed to decrease damage to pastures for livestock by 25–35% [103]. In spite of the existence of specific derogation options aimed at reducing agricultural damage, this cull is considered as unlawful by conservation organisations, who decry a lack of reliable assessments relating damage levels to goose abundance and behaviour. There is also little evidence regarding the relationship between the number of geese and livestock productivity, despite decreasing numbers of sheep on the island and the existence of strong negative perceptions of geese by farmers [101,103]. This case study highlights how access to evidence-based solutions to measure wild herbivore damage and the level of competition with livestock production could decrease conflicts between conservation and agricultural activities. In addition, there remains a crucial need for trans-boundary and flyway-based monitoring and management of hunting quotas, as legal hunting of Greenland barnacle geese in Iceland could interact with the cull implemented on Islay to influence the intensity of conflict through changes in goose population size (Figure 1).

from the point of view of livestock producers, thus highlighting the need for compromise and evidence-based spatial planning. Although permeable and semi-permeable fences have been suggested as alternative solutions [42], these approaches do not solve the potential for resource competition to occur with livestock along wildlife migratory routes. Such competition may occur repeatedly during the year and at unpredictable intensities depending on the species, movement patterns, number of individuals, and weather conditions [43].

The migratory behaviour of wild herbivores can result in an increased risk of competition with livestock at specific stages of migration where access to resources is required to build up energy reserves [44] (Box 4). This is the case in rangelands characterised by strong resource gradients, which not only drive the migration patterns of wild species, but also lead to spatial aggregation of wild and domestic herbivores at certain times of the year [45]. These aggregations can also be caused by the seasonal movement of livestock to resource-rich areas used by wild herbivores, such as high-altitude meadows or riparian areas (Boxes 2 and 4). Whilst such scenarios often lead to overgrazing and increased competition for limited resources, it is also important to recognise that traditional pastoralist practices that synchronise livestock movement along pasture gradients have been found to play a key role in strengthening the resilience of rangeland ecosystems [46]. Thus, although wild herbivore migration and movement patterns have been well studied [47,48], a better understanding for their interaction with the spatiotemporal patterns of resource use by domestic herbivores is needed. This is particularly important in the case of conflicts involving herbivores that migrate across multiple administrative boundaries [49]. Here, the difficulty lies in coordinating management efforts across socio-political realities that may differ in their legal obligations towards conservation and agriculture [50].

Traditional livestock husbandry practices in a changing world

Effective and evidence-based husbandry practices play a key role in minimising the impacts that co-occurring wildlife and livestock species might have on each other [19]. For example, the use of enclosure systems or the training of livestock-guarding dogs have played a significant role in reducing livestock predation by wild carnivores [51]. In comparison, research that synthesises the effectiveness of both modern and traditional husbandry practices in mitigating conflicts between wild and domestic herbivores remains scarce [52].

Many extensive livestock production systems rely on traditional husbandry practices (Boxes 1 and 3). While there is ample evidence that these practices can be beneficial to both food production and biodiversity conservation [53,54] they are vulnerable to deregulation by political and market forces seeking to increase production to satisfy growing national and international demands for livestock products [10]. The resulting tendency for unregulated grazing has had major impacts on natural ecosystems, leading to a greater risk of wild and domestic herbivores competing for limited forage [54,55]. This problem is exacerbated in protected areas that are located close to, or even encompass, traditional livestock grazing grounds. In these areas, conflicts can arise when livestock are effectively prevented from accessing valuable pastures, or when poor management results in unregulated use of the protected area by livestock [56]. Whilst the former extreme may be perceived negatively by livestock producers, the latter is problematic to conservation, highlighting the need for approaches that balance traditional uses and modern conservation objectives.

The importance of valuing, integrating, and, when necessary, complementing traditional agricultural practices has been recognised as key to achieving international biodiversity targets [4,53,54]. This could be done, for example, by using the results of experimental work to inform and complement existing husbandry practices with the aim of making them both sustainable and culturally acceptable. For example, Riginos *et al*. [19] highlighted both positive and negative contributions of traditional pastoralist practices to biodiversity by analysing data from a long-term enclosure experiment, in particular showing that interspecific competition could be minimised by increasing habitat heterogeneity and by implementing mobile fencing systems that provide wildlife hotspots and restore grass for wild and domestic herbivores. Yet, such an approach relies on a two-way transfer of knowledge between science and local producers, which in practice is often lacking [54,57]. This is likely due to restricted access to scientific and evidence-based information that could be used to promote coexistence of livestock production and wild herbivore conservation. At the same time, even when such information is available, reluctance to change management practices to accommodate conservation interests can result from strong cultural traditions and the desire to maintain competitiveness in a modern market economy [58] (Box 2).

Livestock production within complex trophic networks

Interactions between wild and domestic herbivores occur within a trophic network in which species have the potential to affect each other directly and indirectly. Generally, wild herbivores are the natural prey of carnivore species, which may negatively affect co-occurring livestock (Box 3). Although the impacts of predation on livestock by carnivores is a well-documented conflict in conservation [15,51], the extent to which the occurrence of these impacts is mediated by wild herbivore prey remains unknown. Nelson *et al*. [59] put forward two mechanisms to describe this interaction. The prey tracking hypothesis states that carnivores are attracted to their wild prey but kill livestock as a by-product where both types of herbivore co-occur [59]. In contrast, the prey scarcity hypothesis proposes that carnivores switch to hunt livestock when wild prey are scarce [60]. Both hypotheses suggest a complex link between native predators, livestock, and wild herbivores, which has been overlooked in the livestock–wild herbivore conflict literature.

In parallel, predation by large carnivores can reduce populations of wild herbivores, controlling the risk of disease transmission and allowing vegetation growth that will benefit livestock [53,60]. The persecution of large carnivores for their real and perceived impacts on livestock production may inadvertently promote negative interactions between wild and domestic herbivores. Such predator–prey dynamics vary across study areas and are expected to influence social conflicts between proponents of wildlife conservation and livestock production.

Future steps towards coexistence

The occurrence of conflicts between the interests of livestock production and wild herbivore conservation is likely to increase in the future, due to the rising demand for livestock-derived products and the implementation of actions aimed at promoting the recovery of wild spaces and associated species beyond protected areas [25]. In this context, our review highlights major gaps in our understanding and ability to mitigate current and future conflicts. In particular, we emphasise that:

(1) the costs and benefits from livestock–wild herbivore interactions are difficult to evaluate, hindering the development and application of cost-effective mitigation;
(2) the large-scale movement of wild and domestic herbivores can influence the spatiotemporal patterns of interactions;
(3) there is a disconnect between the development of sustainable livestock husbandry practices and current scientific knowledge;
(4) livestock–wild herbivore conflicts occur within complex networks of interacting species, an understanding of which requires multi-species approaches.

As illustrated by our case studies, these challenges often co-occur across different socio-ecological contexts, although their relative importance may vary (Figure 1). Addressing these challenges will thus require the application of holistic, socio-ecological approaches able to identify

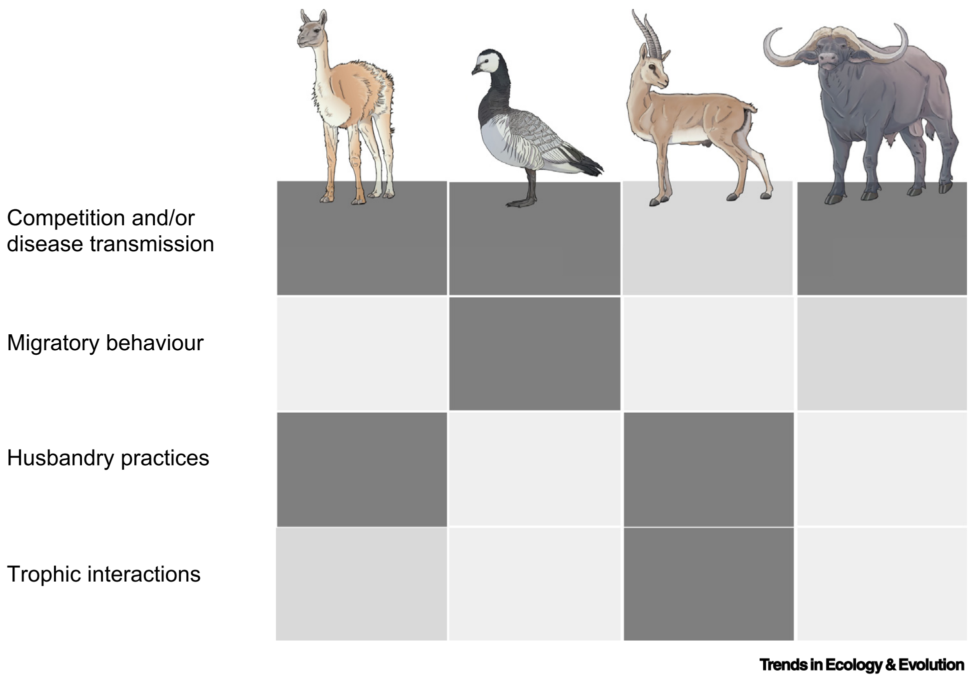

Figure 1. Relative importance of all challenges presented in this study for each of four case studies: guanaco (*Lama guanicoe*) conservation and sheep production in the Chilean Patagonia (Box 1); Greenland barnacle goose (*Branta leucopsis*) conservation and livestock production in Scotland (Box 4); wild herbivore conservation and the production of cashmere goats in Mongolia (Box 3); and African buffalo (*Syncerus caffer*) conservation and livestock production in northern Botswana (Box 2). Dark grey, light grey, and ivory white colours represent qualitatively assessed high, medium, and low relative importance, respectively. Illustrations by ©Pen&Paper (https://en.penandpaper-sci.com/).

different drivers and provide cost-effective pathways leading to sustainable solutions. We highlight three key components that need to be incorporated into future socio-ecological approaches aimed at fostering coexistence.

Co-design of cost–benefit monitoring and impact evaluation programs

Uncertainty relating to the costs and benefits associated with the interaction between domestic and wild herbivores is a major barrier to effective mitigation of conservation conflicts. While recent technical advances can contribute towards reducing this uncertainty, for example, by enabling close monitoring and quantification of livestock productivity [38] or reliable assessment of dietary niche overlap [61], the use of sophisticated approaches are often not available to, nor a priority for, most livestock producers. In many cases, it will also be necessary to look beyond traditional ecological and economic indicators of loss and gain, to acknowledging the intangible costs and benefits resulting from the interaction between livestock and wild herbivores [25].

Most importantly, approaches aimed at reducing uncertainty relating to the costs and benefits of livestock–wild herbivore interactions must integrate knowledge from a diverse range of stakeholders. Costs and benefits may not only be perceived differently by different stakeholders, but also accrue in different ways depending on the interests at stake. Costs may be particularly significant to producers or subsidizing bodies, whilst proponents of wild herbivore conservation may be more sensitive to benefits. Moreover, quantification of costs and benefits is typically derived from scientific research, with little involvement of livestock producers or pastoralist communities [18]. Recent studies have shown that this lack of involvement can create a disconnect between research-based knowledge and stakeholder perceptions, which has consequences for the targeting and effectiveness of mitigation strategies [11,62], but also leads to the misuse or rejection of relevant knowledge by different groups [63].

Engaging livestock producers and conservation practitioners in the co-generation of knowledge relating to livestock–wild herbivore interactions [64] could help address some of the challenges highlighted in this review [65]. In particular, co-participation in monitoring and knowledge exchange could ensure better alignment of real and perceived impacts of wild herbivores on livestock production, thereby minimising uncertainty and distrust between stakeholders [66]. Integrating scientific research on wildlife migration and local knowledge regarding pasture availability at different times of the year could help identify 'hotspots' of potential costs and benefits between wild and domesticated herbivores, thereby helping to design effective monitoring programs. Molnár *et al*. [67] recently showed that traditional herd management practices in central Europe resulted in significant conservation benefits, including avoidance of overgrazing and removal of invasive plant species. They advocate that stronger links between the scientific and traditional herding communities could enable better monitoring of the costs and benefits of rangeland use by both livestock and wild herbivores.

Co-management through active knowledge transfer and sharing

Co-management goes beyond the co-generation of knowledge by actively engaging stakeholders in decisions relating to how a conflict should be managed [68,69]. This process is particularly reliant on the active transfer and sharing of knowledge amongst stakeholders, lack of which is often a strong driver of conflicts [70,71]. We argue that active knowledge transfer is key to the development and strengthening of cooperative relationships amongst stakeholder groups.

For conflicts centred on wild herbivore–livestock interactions, information transfer and sharing could allow husbandry practices to benefit from relevant scientific results, thus bridging the knowledge-action gap [13,71]. At the same time, active knowledge sharing could promote the integration of local knowledge and traditional practices in the design of sustainable management strategies [34]. For example, Ali *et al*. [72] recently evaluated socially acceptable conservation strategies for the critically endangered hirola antelope (*Beatragus hunteri*) among local communities in eastern Kenya, with the aim of informing livestock management and promoting long-term rangeland restoration. More generally, local and indigenous knowledge, as well as traditional methods of managing natural resources have been increasingly recognised as vital to sustainability and conflict management [73,74]. Local knowledge could also be relevant to the characterisation of trophic networks or the identification of multispecies impacts based on the experience of indigenous communities [4,75,76]. Indeed, negative livestock–wild herbivore interactions are rarely attributable to only one species and conflict mitigation stands to gain from consideration of trophic interactions identified by local stakeholders.

Active knowledge transfer and sharing is vital to the co-management of herbivore species whose range or migration patterns span multiple countries [77]. For example, following the successful implementation of a range-wide management plan for the Svalbard pink-footed goose (*Anser brachyrhynchus*) in Europe [78], the African-Eurasian Migratory Waterbird Agreement is currently drawing up a plan for a coordinated Europe-wide management of barnacle goose populations (Box 4). This management plan aims to foster knowledge exchange and dialogue among all stakeholders, including scientists, local producers, local non-governmental organisations, and governmental organisations, to facilitate future decision-making regarding conservation actions and farmland management.

Application of holistic socio-ecological frameworks

Conservation conflicts, such as those occurring between livestock production and wild herbivore conservation, pose complex socio-ecological challenges requiring interdisciplinary solutions [70]. In recent years, a number of socio-ecological frameworks have been developed to support the management and conservation of biodiversity in the presence of divergent stakeholder objectives. Such frameworks have, however, rarely been applied to manage conflicts between the interests of wild herbivore conservation and livestock production. In Figure 2, we demonstrate how the challenges and issues described in this review could be mapped onto two of these frameworks: the socio-ecological framework for ecosystem disservices and services (SEEDS) [62] and management strategy evaluation (MSE) [79]. The former is a conceptual framework that enables integration of competing perspectives on wildlife management under different socio-ecological contexts. SEEDS recognises the need to explicitly acknowledge the costs (i.e., disservices) and benefits (i.e., services) associated with the presence of wildlife, including how these vary across different stakeholder groups. The implementation of the SEEDS is guided through a series of steps that seek to characterise the structure, needs, and interactive processes pertaining to a given socio-ecological system and its different components, with the aim of promoting participation, co-management, and sustainability. This framework would be particularly relevant to wild herbivore–livestock conflicts through its ability to integrate knowledge on costs and benefits across stakeholders.

Modelling approaches can play an important role in testing and predicting socio-ecological responses to different management approaches, which would not otherwise be possible in real life. The MSE framework enables the evaluation of management decisions and goals put forward by a set of stakeholders. For example, Mapstone *et al*. [80] successfully used the MSE framework with fisheries to combine stakeholder views on multiple management objectives with community

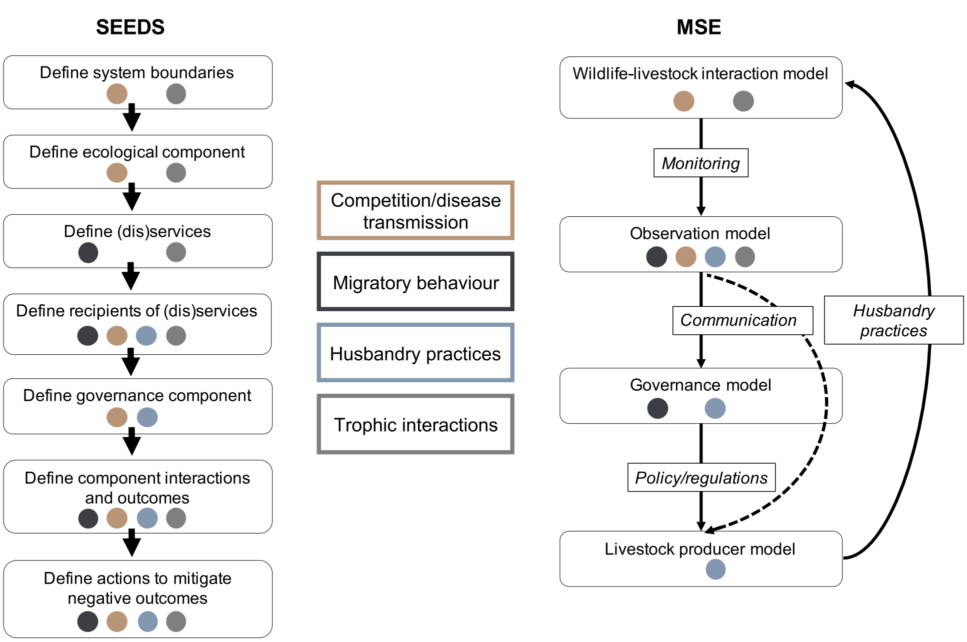

Figure 2. Schematic mapping of the challenges related to mitigating livestock–wild herbivore conflicts onto the socio-ecological framework for ecosystem disservices and services (SEEDS) and management strategy evaluation (MSE).

models of harvested fish populations in search of sustainable management compromises. Duthie *et al*. [81] and Cusack *et al*. [82] developed a game-theoretic version of the MSE framework that balances multiple objectives relating to wildlife population targets and agricultural production. Within the context of wild–herbivore livestock conflicts, such an approach could help evaluate the consequences of different wildlife protection and livestock husbandry strategies to reconcile conservation and food production objectives, promoting transparency and compromise among the groups involved.

Concluding remarks and future perspectives

In this review, we highlight the importance of addressing conflicts that occur between the interests of livestock production and the conservation of wild herbivores. We identify four key challenges that in our view constitute important barriers to fostering coexistence. In order to tackle these issues, future research should adopt mixed approaches to investigate both the ecological and social aspects of such conflicts (see Outstanding questions). In particular, we argue that closer cooperation and knowledge transfer between scientists, livestock producers, pastoralists, and conservation practitioners is needed to promote co-management and ensure the sustainability of mitigation strategies. Such cooperation could be promoted through grant programs that enable long-term interdisciplinary partnerships, the creation of multi-stakeholder management committees, and incentives to carry out research in multi-use landscapes as opposed to protected areas. From a research perspective, this serves as an excellent motivation to better understand, incorporate, and address the needs of different stakeholders. Not only would this help incorporate multiple stakeholders in processes of co-design, co-implementation, and co-management, but it would also enable targeted and reliable data to be collected in a way that can objectively characterise the cost and benefits of livestock–wild herbivore interactions. Such inclusive and participatory approaches, supported by state-of-the-art socioecological modelling, will help integrate traditional and scientific knowledge, thus bridging the gap between science and practice.

Outstanding questions

To what extent do real and perceived cost-benefits of livestock–wild herbivore interactions differ and what are the drivers of observed differences?

How variable can livestock–wild herbivore interactions be across species' migratory ranges and how does this variation influence conflict intensity?

What characteristics of traditional and contemporary livestock husbandry make them more vulnerable to conflict with wild herbivore conservation?

How does livestock production influence the structure of trophic networks? Can ecological information on wild species interactions be used to inform sustainable husbandry practices?

Acknowledgements

R.P. was funded by the ANID ACT19027 Anillo Project from the Pontificia Universidad Católica de Valparaíso (Chile), and by the Newton Fund, Researcher Links Biodiversity Grant from the British Council (UK). J.C. was granted internal funding from the Universidad Mayor (Chile). N.B., R.P., J.C., and J.M. were funded by the European Research Council under the European Union's H2020/ERC grant agreement 679651 (ConFooBio). P.A, J.E.M., J.T., and E.C.I. were funded by the Agencia Española de Cooperación Internacional (A/3895/05, A/9875/07, A/016431/08, A/024945/09), the Centro de Estudios para América Latina UAM-Banco de Santander (CEAL-AL/2015-19), the Servicio Agrícola y Ganadero, Chile (Ref. 446026103) and Comunidad de Madrid (Remedinal TE-CM, P2018/EMT-4338). E.C.I. was funded by a FPU PhD grant from the Spanish Minister of Education (AP2010-0330) and a FONDECYT postdoctoral grant N° 3190160 (CONICYT-Chile). P.C., S.R., and C.M. were funded by the FONDECYT 1171039 grant. C.M. acknowledges CONICYT Becas Chile 72140205 grant.

Declaration of interests

No interests are declared.

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