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Beyond the obvious impact of domestic livestock grazing on temperate forest vegetation – A global review

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Abstract

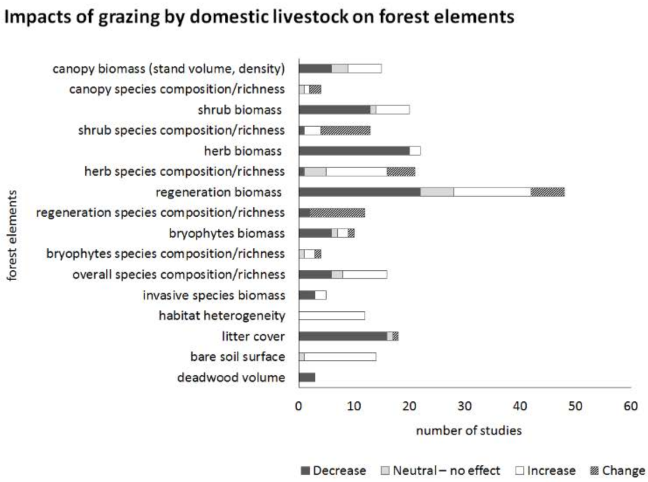
Large herbivores have a keystone role in many forest ecosystems. There is widespread recognition that undesirable changes may be caused by the complete removal of grazing-related disturbances, whereas there can be benefits from properly managed, targeted livestock grazing, both from a forest management and biodiversity perspectives. However, there are also many contradictory statements and results about forest grazing. We summarize the main scientific evidence and knowledge gaps on forest livestock grazing through a global review of the literature for the temperate region. We analysed 71 publications discussing the impact of livestock grazing on vegetation in forests. Grazing reduces vegetation biomass, but less obvious effects relevant to conservation include increased habitat diversity and increased regeneration of selected canopy tree species. Moreover, detailed guidance on how grazing should be carried out for conservation purposes is limited because the results are strongly context dependent. The direction and amplitude of effects can be influenced not only by forest type and stocking levels, but by foraging preferences of livestock, availability of alternative forage, grazing season and herder activity. We stress the need for well-planned real-world experiments and observations, and for more quantitative studies to foster evidence-based conservation management. Grazing differences between wild ungulates and livestock should be better studied, because the effects are often overlapping. We suggest widening the temporal and spatial scales of case studies and stress the need to create space and openness for interdisciplinary and participatory research and conservation approaches, initiating knowledge co-production on the benefits and dis-benefits of grazing in forests.

Keywords: biodiversity; conservation grazing; knowledge gaps; silvopastoral systems; targeted grazing; vegetation management

Highlights:

- Targeted livestock grazing can benefit both forest management and biodiversity.
- We reviewed 71 papers on the vegetation impact in temperate forests.
- Grazing can increase habitat diversity and regeneration of canopy tree species.
- Impacts are highly contextual but local factors are often not properly documented.
- Approaches and attitudes towards livestock forest grazing should be reconsidered.

Graphical abstract:



1. Introduction

Large herbivores, both wild and domestic, are keystone species in many forest ecosystems through their long-term and large-scale influence on ecological functioning. Herbivores influence the extent of forests through limiting or facilitating their spread on to open ground, their structure and openness, the composition of the tree, shrub and ground flora, with indirect effects then on the fauna (Adams, 1975; Rackham, 1980; Putman, 1996; Belsky and Blumenthal, 1997; Ramirez et al., 2018). Livestock grazing in European and Asian temperate forests has a long history, following the gradual displacement of wild herbivores and domestication (Buffum et al., 2009; Rotherham, 2013), but was introduced to North and South America, Australia and New Zealand a few centuries ago (Borman, 2005; Mazzini et al., 2018). This paper reviews what we know, and do not know, about livestock grazing in temperate forest systems, aiming to provide new insights that may help foster discussion, research and experimentation on and employment of this historical but often disputed practice.

There is an ongoing debate as to the extent to and manner in which grazing and browsing by large herbivores influenced the structure and dynamics of the natural forest (Vera, 2000; Mitchell, 2005) and in derived cultural landscapes (Rackham, 1980; Rotherham, 2013). Their impacts extend, however, from altering the composition and structure of the vegetation at a point to wider effects through altering nutrient cycles (Adams, 1975; Bernes et al., 2018) and ultimately the balance between grasslands and open and closed forests in the landscape (Rackham, 1980; Vera, 2000; Rotherham, 2013; Poschlod, 2015). Within the temperate region there are few large natural forests (Burrascano et al., 2013) that retain a full suite of large native herbivores. Even in parts of the world where wild herbivores still predominate, they may be joined or replaced by a variety of native and introduced livestock such as cattle, sheep and ponies (Putman, 1996; Tubbs, 1997; Vera, 2000; Bernes et al., 2018). Livestock may have different impacts to past and present wild herbivore populations because of differences in their physiology, diet, behaviour, numbers and management (Kingery and Graham, 1991; Walker et al., 2015; Bernes et al., 2018; Cromsigt et al., 2018). Lack of awareness of these differences has created tensions and some foresters have sought to reduce livestock grazing, leading to bans in some countries at some periods (Kardell, 2016; Nichiforel et al., 2018). More recently there has been increasing advocacy of livestock grazing, because there is more potential to control both density and season of grazing, in comparison with wild herbivores (Hester et al., 1996). Grazing has also been introduced as a component of 'rewilding' mainly in semi-open habitats, such as wood-pastures (Smit et al., 2015; Cromsigt et al., 2018).

Assessments of the impact that grazing in forests is complicated by a general shift from multiple-use to single-commodity forest uses in the last two centuries (Rotherham, 2013; Samojlik et al., 2016). Livestock and game management came to be seen as competitors to timber production (Graham et al., 2010; Kardell, 2016). Livestock grazing, seen from the commercial forestry point of view, became an undesirable practice that should be completely taken out of the forests (Dambach, 1944; Kardell, 2016; Bernes et al., 2018; Nichiforel et al., 2018). This attitude has been hardened by increases in stocking rates of domestic livestock, compounded by more recent increases in wild ungulates (Putman, 1996; Bernes et al., 2018). The removal of livestock as a response to such situations has led to the disappearance of complex and specific disturbance patterns that in turn have triggered new conservation and ecological issues (Mitchell and Kirby, 1990; Kirby et al., 1994; Cooper and McCann, 2011).

Attitudes towards forest grazing by livestock are however changing. There is renewed interest for multiple-use systems and traditional, often abandoned historical practices, including the combination of pasturing and forestry, shown by the increasing number of studies on wood-pastures (Hartel and Plieninger, 2014) and initiatives towards silvopastoral management (Mosquera-Losada et al., 2005). Traditional practices are seen as providing both economic and ecological benefits, but also promoted in recognition of the rights of local communities and people with traditional occupations (Díaz et al., 2015). The implications for cultural traditions and rights of local communities relying on livestock husbandry have however generally been underrepresented in this debate (Norbu, 2002; Buffum et al., 2009; Shakeri et al., 2012).

Alongside the world-wide acknowledged negative effects of overgrazing (Dambach, 1944; Mitchell and Kirby, 1990; Noack et al., 2010; Milios et al., 2014), properly managed livestock grazing is recognized for its potential silvicultural, agroforestry, conservation and overall vegetation management benefits (Adams, 1975; Kirby et al., 1994; Thomason, 1995; Humphrey and Patterson, 2000; Lamoot et al., 2005; Chauchard et al., 2006; Darabant et al., 2007; McEvoy and McAdam, 2008). Yet research on these potential benefits has been limited and mainly qualitative.

The impacts of large wild herbivores (Gill, 1992; Putman, 1996; Ramirez et al., 2018), or domestic and wild herbivores have mainly been discussed together (Mitchell and Kirby, 1990; Kirby et al., 1994; Bernes et al., 2018). To our knowledge, there are only early (Adams, 1975) or regional (Belsky and Blumenthal, 1997 – USA, the Interior West; Mazzini et al., 2018 – South America) reviews available on the vegetation impacts of livestock alone in temperate forests. We lack studies and understanding of the complex mechanisms (the impacts of different grazing regimes and interacting effects of grazing, trampling, manuring and forest history) that can give rise to different outcomes (Mitchell and Kirby, 1990; Kirby et al., 1994; Bernes et al., 2018; Mazzini et al., 2018). Such an understanding would help in planning and conducting targeted grazing for conservation management.

In this paper we review the impact of livestock grazing on vegetation in temperate forests at a global level. The reduction of vegetation biomass by grazing is well-known, so we focused on the less obvious effects and on the findings of comparative studies, i.e. not just grazing versus no grazing, but the effect of different levels of grazing. We identify knowledge gaps, and formulate recommendations for future research that could support the development of management plans harnessing the vegetation management, conservation and silvicultural potential of livestock forest grazing.

2. Methods

A literature search was conducted on 15 February 2017 in the Web of Science (WoS) database, using the query formula 'TOPIC: ((forest OR wood* OR grove OR stand OR acorn OR silvopast*) NEAR (graz* OR brows* OR pastur* OR herd* OR pannag*))', with no limit for time-span or language. The search yielded 9512 titles. The initial title screening reduced the list further down to 586, which were then checked for abstract, keywords and location, leaving 147 titles where the full text was downloaded for thorough analysis.

Papers were excluded at this stage if they focussed only on wild ungulates or considered habitats other than temperate forests, based on the vegetation, location and the geographic boundaries reported for the temperate forest biomes (Olson et al., 2001). Localization of study sites was performed using ArcGIS version 10.1 (ESRI, 2012). From the bibliographies of these papers, we selected further titles of potential interest for detailed scrutiny. In total 67 relevant publications were identified.

The search was repeated on 30 September 2018, yielding 10609 hits, refined to 644 by the initial screening. Once duplicates were removed, and secondary checking for abstract, keywords and location carried out, four new publications were added to the list. Thus, our analysis was based on 71 publications (57 from the WoS database and 14 from bibliography searches; Supporting information S1). Unless specified otherwise, under the term grazing we are referring to the entire complex process, including grazing, browsing, trampling, etc.

The selected studies covered almost 75 years of publication history, varied greatly in their methodology, with a heterogeneous mixture of study sites. Potentially critical information on the study conditions were often missing (see next section). Therefore, we felt it more useful to conduct a classic review instead of a meta-analysis, where there was a higher risk of losing ecological meaning or misinterpretation.

3. Results

3.1. Characteristics of the studies included

3.1.1. Study locations, habitat types and grazer species

The great majority of the studies in the final selection were from Europe (Fig. 1), particularly from the United Kingdom (17 studies), followed by North America. There were relatively few studies from regions where traditional livestock forest grazing is still widely practiced e.g. from the temperate forests of Asia (Buffum et al., 2009) and the non-Mediterranean Southern Europe (Papachristou and Platis, 2011).

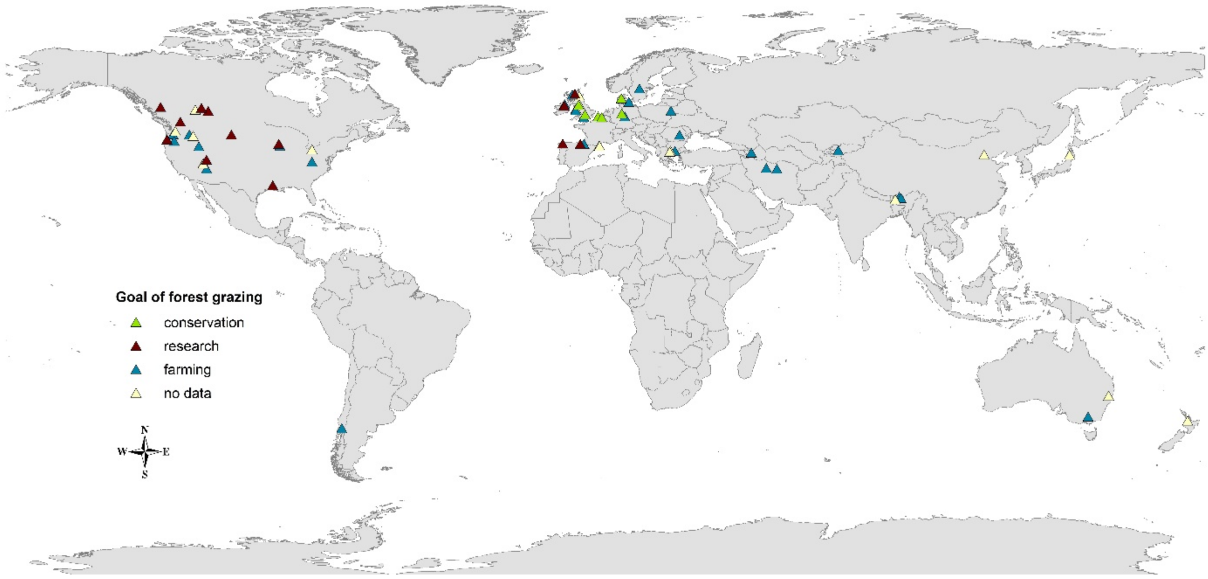


Fig. 1. Location of the studies considered in the review and the main goals of forest grazing (basemap source: ArcGIS.10.1.ESRI/ArcGIS_online world countries)

Around one third (28) of the studies were conducted in European broadleaf forests, followed by North American conifer forests (12), and North American (8) and Asian (7) broadleaf forests (Supporting information Fig. S1). The great majority (56) of the studies were conducted in natural/semi-natural forests, six in a combination of natural and plantation forests, eight in plantations and for one no data was provided regarding origin. This classification is based on the original authors' description, though we recognise that there may not always be a clear-cut distinction. The young plantations included areas that were previously managed as forest, but also new plantations on formerly open habitats such as pastureland.

The earliest publication dated from 1944, but over 60% of the reviewed papers were published after the year 2000, reflecting increased interest in this topic (Supporting information Fig. S2). General reviews referred to archive data and forest grazing history from the Medieval period onwards, but mostly the last 250 years (e.g. Mitchell and Kirby 1990; Thomason, 1995). However, the majority of the reviewed studies provided data from the mid-20th century onwards. It is interesting to highlight that the studied period was mentioned only in around 50% of the reviewed papers.

Over half the studies involved only one grazing animal species, with cattle being the most common. There was only one study (Van Uytvanck and Hoffmann, 2009) clearly stating that large wild herbivores were absent in the study area. In 23 studies wild ungulate presence was mentioned, but the authors claimed that they were in low numbers and the impact was negligible in comparison with livestock. There was only one study that clearly differentiated wild herbivore and cattle impact (Walker et al., 2015).

3.1.2. Study objectives and methodologies

Most studies focussed on the effects of livestock grazing on vegetation composition, tree regeneration and stand structure (Fig. 2). Only two studies discussing vegetation effects had 'observing livestock behaviour' as their main focus and only 12 included observations on animal behaviour. There was only one study that was based on interviewing stakeholders (Mayerfeld et al., 2016) and another one in which such interactions with locals were mentioned (Buffum et al., 2009).

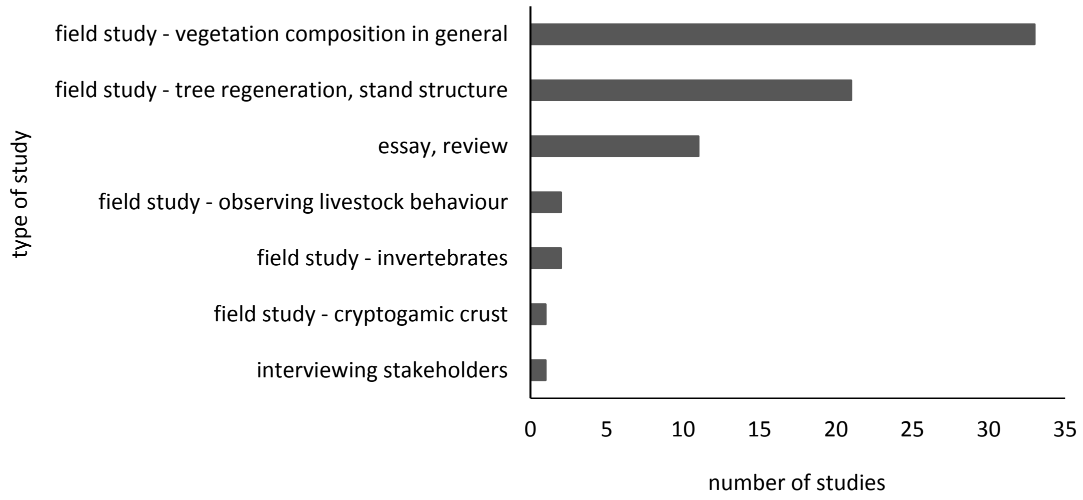


Fig. 2. The primary objectives and methodology of the studies considered in the review

3.1.3. Study design

Sixty-five percent of the 60 primary research papers, thus excluding the 11 essays and reviews, were based on the comparison of at least two grazing conditions, but most just compared grazing versus lack of grazing conditions (Fig. 3).

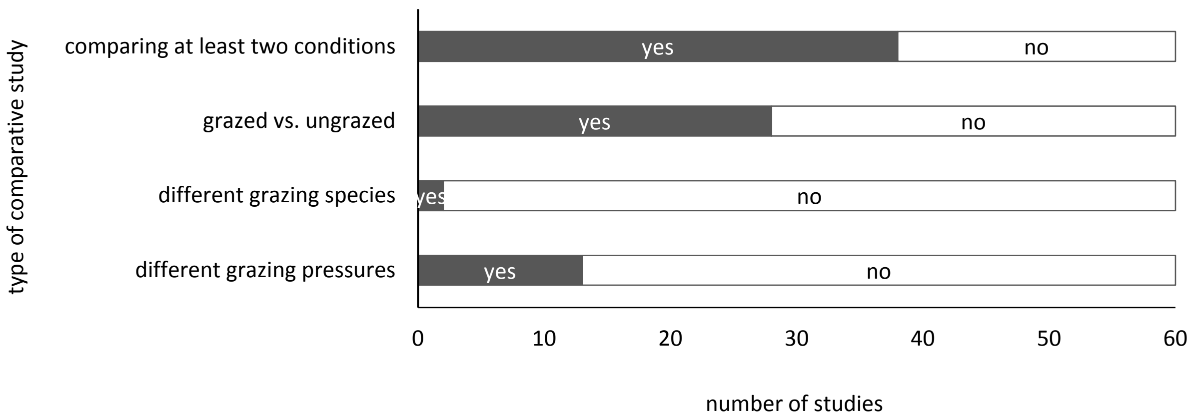


Fig. 3. The amount and type of comparative studies within the reviewed papers

There were only two studies comparing the vegetation impacts of at least two different grazer species, and only 13 compared different grazing pressures.
Information on previous land-use (including grazing) history and the situation preceding the study was lacking in about one third of the 60 research papers, while more than half lacked information on the stocking density (i.e. grazing pressure). More than one third of the studies did not provide information on seasonality of grazing and on the grazing method (Fig. 4). Among those that did, free-ranging was the most studied method of grazing, followed by fenced and exclosure studies, while there was only one study where animal movement was reportedly controlled by a herder (Zhang et al., 2009).

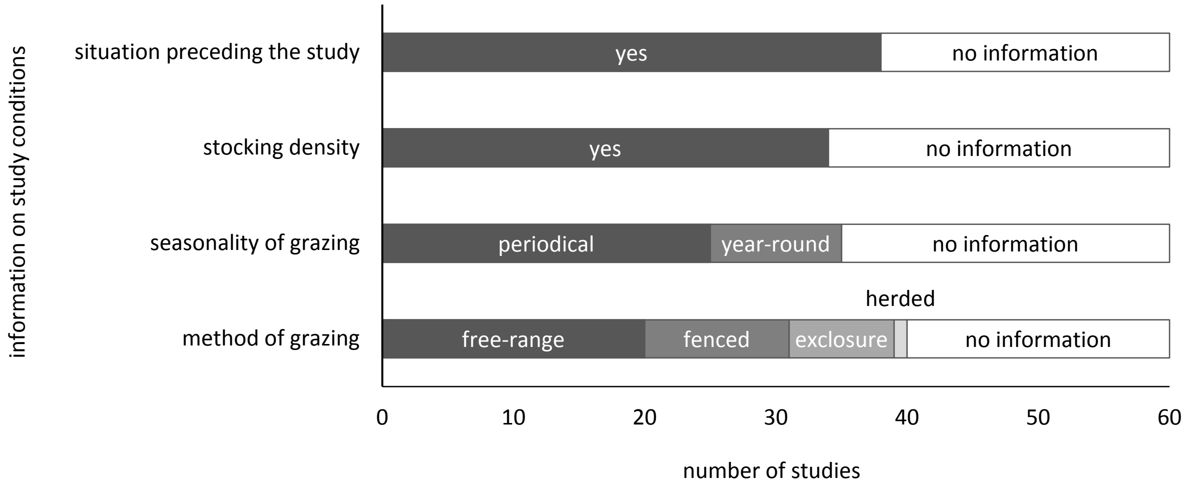


Fig. 4. Overview of the information provided and missing regarding the conditions of the analysed studies

3.2. Overview of the impacts of grazing on composition and richness of forest elements
Grazing affected forest elements in diverse ways, and the reported outcomes often differed among the reviewed studies (Fig. 5, Table 1, Table S1). There was a bias towards studies of the effects of grazing on the species composition of the herb layer (e.g. Darabant et al., 2007; Galleguillos et al., 2018). The most frequently reported outcome was that livestock grazing in forests decreases plant biomass, especially the regeneration and herb layer (e.g. Belsky and Blumenthal, 1997; Garin et al., 2000; McEvoy and McAdam, 2008). The opposite effect was also reported, though in fewer cases, especially for natural regeneration, but also for shrubs and bryophytes (e.g. Humphrey and Patterson, 2000; Galleguillos et al., 2018). Increase of invasive species biomass was reported by two studies (Smale et al., 2008; Galleguillos et al., 2018), while the opposite effect was reported by three studies (Chauchard et al., 2006; Mayerfeld et al., 2016; Mazzini et al., 2018).
Habitat heterogeneity, canopy species composition, invasive species or bryophytes were less studied (e.g. Thomason, 1995; Mayerfeld et al., 2016). Species composition changed in many studies (e.g. Dambach, 1944; Zhang et al., 2009), several studies assessing habitat heterogeneity reported an increase (e.g. Tubbs, 1997; Strandberg et al., 2005), referring to changed microsite attributes and seedling bank structure at plot or stand scale (e.g. Laskurain et al., 2013), or assessing forest dynamics and structure at landscape scale (Madany and West, 1983). Litter cover decreased, while the amount of bare soil increased in most cases (e.g. Mitchell & Kirby, 1990; Laskurain et al., 2013).

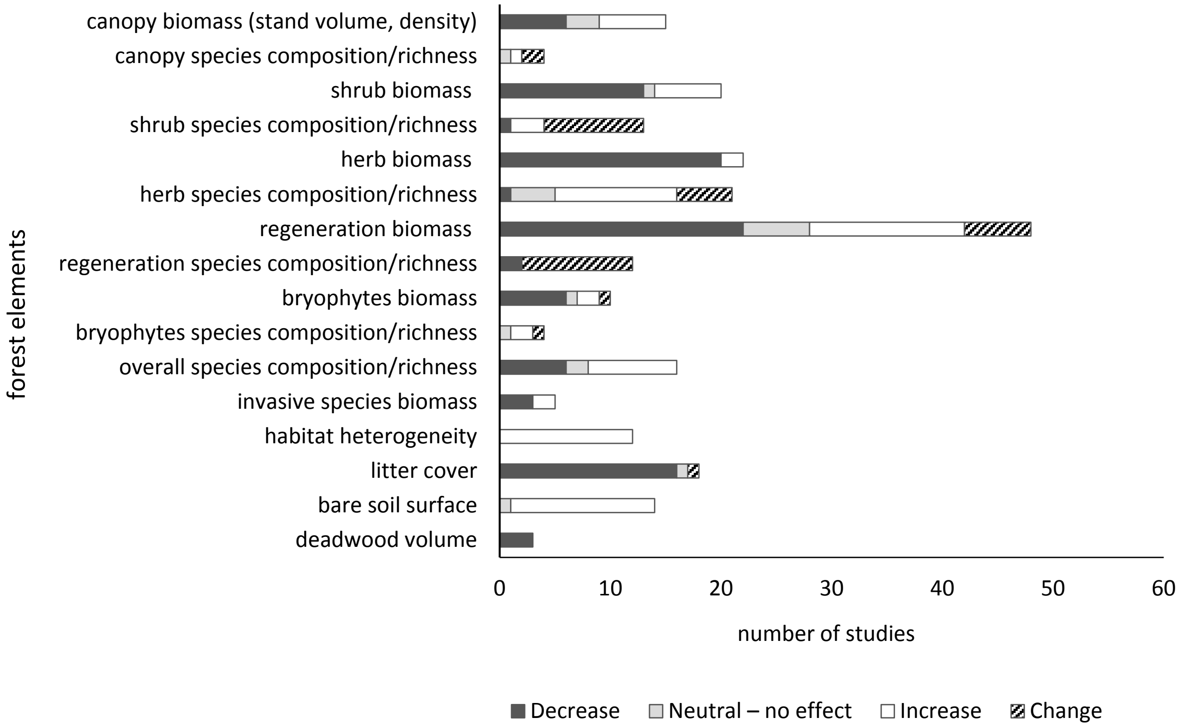


Fig. 5. Impacts of grazing by domestic livestock on forest elements

Table 1. Trends in livestock grazing effects at landscape scale and on various forest elements (increase: ↗; decrease/reduction: ↘; qualitative changes: X), and examples of the processes and mechanisms

Effects on	Trend	General pattern for processes and mechanisms	References
Landscape scale and overall vegetation			
Habitat heterogeneity and species richness	↗	Alteration of forest boundaries; modifying microsite attributes (e.g. amount of bare soil, litter). Grazing livestock can change the seedling bank structure, thus affect the dynamics and structure of forest remnants. Forest grazing can result in higher floristic diversity, create niches and spatial heterogeneity for several species. Cattle grazing can increase species richness, particularly in the herb layer, though these effects can take several years to be expressed.	Kirby et al., 1994; Tubbs, 1997; Strandberg et al., 2005; Vanbergen et al., 2006; McEvoy et al., 2006a; Laskurain et al., 2013
Species richness	↘	Introduction of invasive weeds or non-native species, and suppression of grazing intolerant palatable and forest specialist species. Plants in grazed sites can be sparser and less vigorous. Seedling establishment, sapling recruitment and functional diversity can be greater in un-grazed than in grazed forests.	Dambach, 1944; Norbu, 2002; Smale et al., 2008; Lindgren and Sullivan, 2012; Ford et al., 2018

Ruderal and thorny, unpalatable species	↗	Grazing tolerant species benefit from heavy grazing pressures, and introduction of species through zoochory. The understory of grazed forests can become dominated by unpalatable species, like the tall tussocky grass, *Molinia caerulea*.	McEvoy et al., 2006a; Smale et al., 2008; Cooper and McCann, 2011; Ford et al., 2018; Galleguillos et al., 2018
Canopy layer			
Shaping the appearance of understorey specimens	X	Eating tree leaves; pollarding of trees for leaf fodder in winter, when grasses and other edible herbage are not available. Browsed branches of *Ilex* sp. had reduced leaf size and increased spinescence. Browsing also reduced understory height, leading to suppressed adult individuals.	Putman et al., 1987; Kirby et al., 1994; Garin et al., 2000; Norbu, 2002
Canopy openness	↗	Preventing the development of dense understorey (i.e. regeneration of existing canopy species) and favouring a transition from canopies of tall, long-lived trees to short, ephemeral ones. Reversing successional processes and litter decomposition rates in oak forests by maintaining the forest in a species rich open stage.	Strandberg et al., 2005; Vanbergen et al., 2006; Konstantinidis et al., 2008; Smale et al., 2008
Stand density/volume	↗	Reducing the competitive herb layer, helping the development of dense *Pinus ponderosa* forests. Grazing improved site conditions for tree regeneration (inhibitor vegetation control), leading to increased height and DBH of regenerating trees in grazed stands.	Madany & West, 1983; Sharrow at al., 1992; Belsky and Blumenthal, 1997; Borman, 2005; Chauchard et al., 2006
Stand density and timber volume	↘	Increased openness can lead to reduced resilience of forest regeneration. Stand volume decreased exponentially with livestock density whereas biodiversity and forage cover showed a humped response function to livestock density.	Mitchell and Kirby, 1990; Noack et al., 2010
Timber volume	X	No differences between grazed and non-grazed woods in long term as regards growth rate or total ring width	Cutter et al., 1998
Shrub layer			
Shrub cover	↘	Grazing and trampling (mainly cattle) and browsing (mainly goat and sheep) can lead to reduced shrub volumes and cover. Cattle had an impact both by direct consumption and by opening initially closed scrub.	Sharrow et al., 1992; Kirby et al., 1994; Lamoot et al., 2005; Zhang et al., 2009; Lindgren & Sullivan, 2012; Mayerfeld et al., 2016
Outcompeting fast-growing shrub and tree species	↘	Grazing and trampling (mainly cattle) and browsing (mainly goat and sheep). Cattle can inhibit the regeneration of non-native pines, impacting scrub development, both by direct consumption and by opening initially closed scrub, favouring timber species (e.g. *Fagus* sp.) against outcompeting trees and shrub.	Nakashizuka & Numata, 1982; Lamoot et al., 2005; Chauchard et al., 2006; Darabant et al., 2007; Cooper & McCann, 2011
Non-native invasive species	↘	Goats can destroy and eliminate unwanted shrubs. Cattle can inhibit the regeneration of black pine, which is recruiting naturally in areas where cattle are excluded. Farmers and	Chauchard et al., 2006; Mayerfeld et al., 2016

		professionals acknowledged the potential of grazing in managing several invasive and opportunistic species (e.g. *Rhamnus cathartica*, *Zanthoxylum americanum*, *Acer negundo*).	
Abundance of light-demanding, poisonous, thorny and introduced shrubs	↗	Increased light conditions following the reduction of the coverage of the upper canopy, favouring light-demanding species, like *Crataegus* spp., *Malus sylvestris* and *Corylus avellana* in the understorey, and oak in the canopy layer. When it is a long-term disturbance factor, grazing can lead to the increase of abundance of non-palatable, spiny, or grazing resistant shrubs, such as *Juniperus oxycedrus* or *Quercus coccifera*.	Emborg et al., 2000; Konstantinidis et al., 2008; Smale, 2008; Cooper & McCann, 2011; Shakeri et al., 2012; Galleguillos et al., 2018
Rubus spp. cover	↘	Grazing and trampling disturb thickets. Large herbivore grazing reduces the cover and height of *Rubus* spp., while removal of grazing results in significantly higher *Rubus* cover than in grazed areas.	Fitzgerald et al., 1986; Latham & Blackstock, 1998; Garin et al. 2000; McEvoy et al., 2006a; Van Uytvanck & Hoffmann, 2009; Cooper & McCann, 2011; Shakeri et al., 2012
Herb layer			
Species richness and diversity	↗	Cattle grazing decreases the volume and slows the rate of competitive exclusion and increases herb richness and diversity in fertilized stands.	Lindgren and Sullivan, 2012
Grass cover, especially of grazing-adapted species	↗	Increasing light and reducing tall or competitive palatable species (e.g. *Hyacinthoides non-scripta*). In combination with active canopy management, cattle grazing can reduce shrub cover, favouring higher quality grass cover when forage production is a goal.	Kirby et al., 1994; McEvoy et al., 2006 a,b; Tasker & Bradstock, 2006; Lesica, 2009; Cooper & McCann, 2011; Galleguillos et al., 2018
Reduces the total biomass of the herb layer	↘	Grazing can decrease the competitive dominance of the herbaceous layer, significantly reducing sward biomass. Sheep can be very effective in removing grass phytomass.	Sharrow et al. 1992; Belsky and Blumenthal, 1997; Garin et al., 2000; McEvoy & McAdam, 2008; Papachristou & Platis, 2011
Abundance of palatable species decreases and abundance of unpalatable species increases	↘ ↗	Selective forage and diverse palatability of herb layer species (e.g. high forage value plants are often good winter forage, like *Hedera helix*). Grazing has a negative impact on the palatable *Hyacinthoides non-scripta*. The abundance and/or frequency of species highly preferred by cattle, like *Fagus orientalis* seedlings or *Vicia crocea* is reduced.	Madany & West, 1983; Kirby et al., 1994; Garin et al., 2000; Fraser et al., 2001; Van Uytvanck & Hoffmann, 2009; Shakeri et al., 2012
Light-demanding and ruderal, and less forest-specialist species	↗	Grazing changes species composition, leading to more species common in open pastures. Exclosure from grazing reduces the abundance of light-dependent ruderals and increases the abundance of shade-tolerant forest species, changes being greater under a more developed tree canopy.	Dambach, 1944; Garin et al., 2000; McEvoy et al., 2006; Smale et al., 2008; Cooper and McCann, 2011

Abundance of ground-growing bryophytes	↗	Heavy grazing reduces the competition from vascular plants and accumulation of litter from vascular plant and trees.	Kirby et al., 1994; Thomason, 1995
Bare soil surface	↗	Trampling and uprooting removes dead and live plant materials from forest floor, leading to an increase in bare soil cover.	Mitchell & Kirby, 1990; Beymer and Klopatek, 1992; Vanbergen et al., 2006; Laskurain et al., 2013; Galleguillos et al., 2018
Deadwood	↘	Probably as an outcome of trampling, hooves shredding the woody debris, thus speeding up the rate of decomposition.	Latham and Blackstock, 1998; McEvoy et al., 2006a; Smale et al., 2008
Litter cover	↘	Trampling and grazing reduce the thickness of the herb and regeneration layer. In a less dense herb layer wind removes litter more easily. Grazed forests have lower litter depth and cover.	Dambach, 1944; Belsky and Blumenthal, 1997; Bromham et al., 1999; Latham & Blackstock, 1998; Humphrey and Patterson, 2000; Galleguillos et al., 2018
Non-native, species abundance	↗	Introducing forest grazing into regions where it was not traditionally practiced.	Smale et al., 2008; Galleguillos et al., 2018
Regeneration			
Regeneration survival rate	↘	Grazing and trampling causes injuries and plant deaths, keeps the regeneration plants at low height. In forests used for grazing *Quercus* had limited regeneration. As a result of grazing, sapling numbers are much lower than seedlings numbers.	Peterken and Tubbs, 1965; Adams, 1975; Hester et al., 1996; Chauchard et al., 2006; Buffum et al., 2009; Kaufmann et al., 2014; Milios et al., 2014; Mazzini et al., 2018
Seedling height and/or diameter	↘	Grazing or trampling of terminal buds/ leaders prevent growth. Intensive grazing keeps the regeneration plants at low height.	Kingery & Graham, 1991; Fraser et al., 2001; McEvoy et al., 2006b; Milios et al., 2014; Schulze et al., 2014; Rhodes et al., 2018;
Seedling survival and growth	↗	Removal of outcompeting vegetation creates niches for regeneration. Grazing reduces the competition between unwanted woody vegetation and young conifers. Sustained heavy grazing removes grass competition, permitting the seedling trees to grow.	Rummel, 1951; Nakashizuka and Numata, 1982; Mitchell and Kirby, 1990; Sharrow et al., 1992; Belsky and Blumenthal, 1997; Darabant et al., 2007; McEvoy & McAdam, 2008
Regeneration of light-demanding tree species	↗	Creating open niches by removing competitive vegetation. Grazing enhances the hoarding activities of small rodents, benefiting the early seed-dispersal fitness of *Quercus liaotungensis*.	Madany and West, 1983; McEvoy et al., 2006b; Zhang et al., 2009; Shakeri et al., 2012

3.3. Factors influencing the effects of grazing

Livestock preferences and the characteristics of the forest affected the outcomes (Fig. 6, Table S2). For example, Garin et al. (2000) showed that sheep selected larch plantations which reduced damage to high conservation value oak (*Quercus*) and beech (*Fagus*) forests. Cattle preferred uncut forest sites instead of harvested sites, thus damage levels were insufficient to alter deciduous regeneration in plantations (Kaufmann et al., 2014).

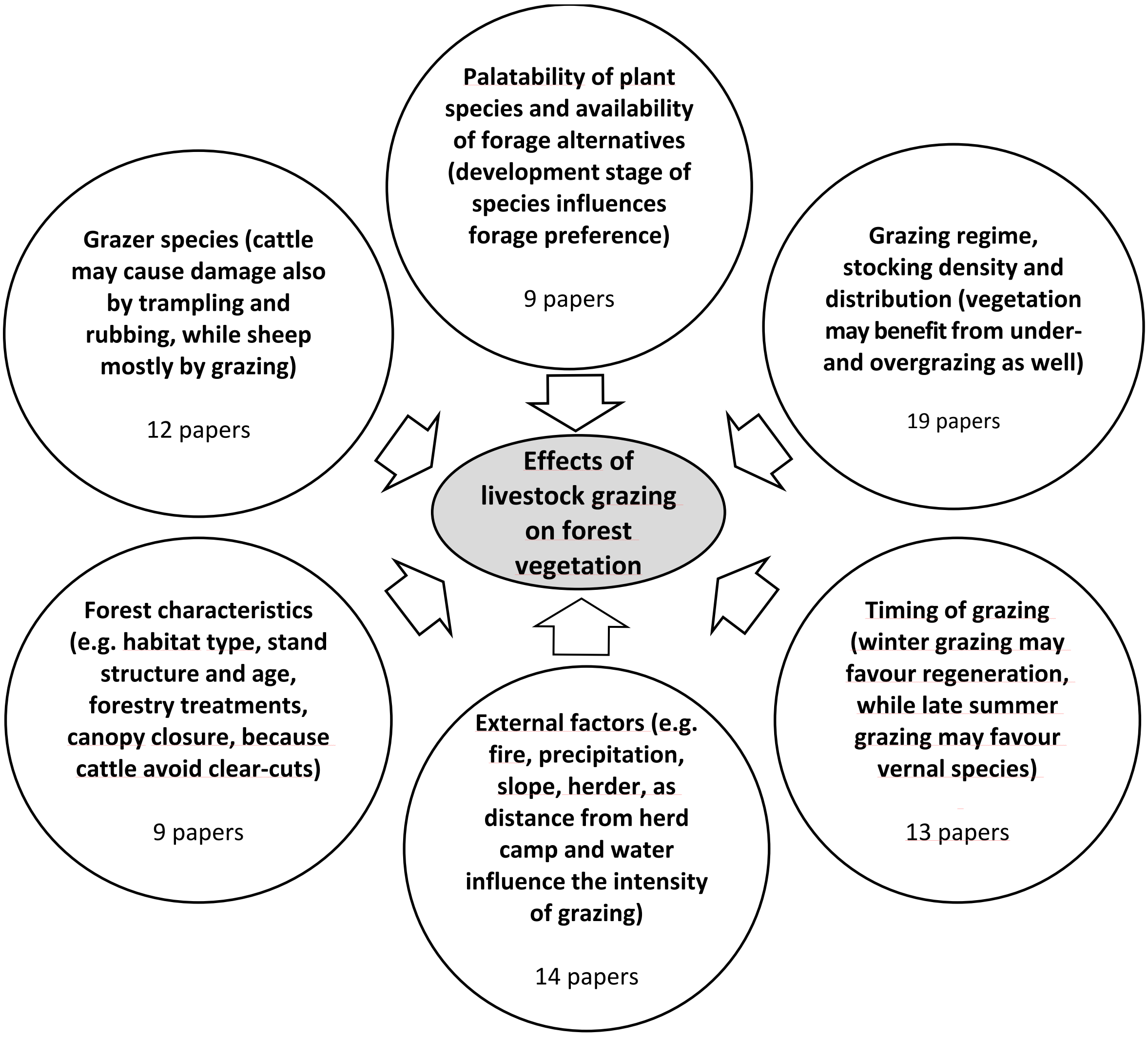


Fig. 6. The main biotic and abiotic factors that influence the effects of forest grazing by domestic livestock (with number of references stressing out each factor), based on the reviewed literature (see Table S2 for a complete list of references)

Seasonal variation in impacts were also observed. For example, snowberry (*Symphoricarpos* sp.) unpalatable in early season, became more acceptable later on, when alternative forage was unavailable (Fitzgerald et al., 1986). Cattle preferred the forest in spring and end of summer, and autumn (Mitchell and Rodgers, 1985; Lamoot et al., 2005; Papachristou and Platis, 2011), while goats preferred woody vegetation in spring (Papachristou & Platis, 2011; Mayerfeld et al., 2016). Grazing, particularly in winter, may benefit early seedling growth by reducing competition from the ground vegetation, but once the saplings start to grow above the height of the surrounding vegetation, they are vulnerable to winter browsing (Kirby et al., 1994). Grazing at the end of the growing season had little effect on tree growth, thus being recommended as a silvicultural tool for removing competitive grasses in plantations (McEvoy and McAdam, 2008). Besides the differences in palatability between species (Kirby et al., 1994; Garin et al., 2000; Darabant et al., 2007), grazing preference also changes over time (Fitzgerald et al., 1986). *Rubus* spp. were one of the palatable species most targeted by deliberate grazing, which was shown to be most effective in spring (Van Uytvanck and Hoffmann, 2009).

Stocking level and grazing regime are important but have unpredictable effects on grazing impact. Heavy grazing was beneficial for certain species and groups, like small-seeded trees such as birch, that need bare soil as potential regeneration sites (Kirby et al., 1994).

Few studies dealt with external factors such as the role and management activity of the herders, who often have a deep knowledge and responsibility for the management of their grazing lands (Norbu, 2002). For example, planting and managing fodder trees by herders can improve forage resources and enhance tree species diversity (Fraser et al, 2001; McEvoy & McAdam, 2008), influencing the stand structure and openness of forests (Norbu, 2002). Herding dogs also influence the effects of grazing on vegetation (Fraser et al., 2001). Livestock density decreased with distance from the herdsmen camp, influencing forage cover and plant diversity (Noack et al., 2010).

3.4. Recommendations for (re-)integrating livestock grazing and forest management

Forest grazing was recommended in some of the studies either as a silvicultural tool or for nature conservation purpose. The first category included cases of free-range grazing for the control of non-native species, i.e. black pine (*Pinus nigra*) in a mixed deciduous forest (Chauchard et al., 2006); for promoting the regeneration of conifers (Darabant et al., 2007); and the application of mob-stocking with sheep for grass control in plantations (McEvoy and McAdam, 2008). Grazing with livestock was considered an effective nature conservation tool, i.e. it helped to create or maintain the desired habitat and species mixtures, in mixed deciduous (e.g. Lamoot et al., 2005; Strandberg et al., 2005; Fortuny et al., 2014) and mixed conifer forests (Lindgren and Sullivan, 2012), and particularly in UK forest studies (e.g. Mitchell & Kirby, 1990; Kirby et al., 1994; McEvoy et al. 2006b). It was also recommended for maintaining open ground within conifer plantations that had been established on species-rich grasslands (Humphrey and Patterson, 2000).

Recommendations for future management varied among studies (Supporting information Table S3) and highlighted the importance of appropriate stocking levels and grazer species (Kirby et al., 1994; Fraser et al., 2001; Papachristou & Platis, 2011), controlled, rotational or periodical grazing (Hester et al., 1996; McEvoy et al, 2006; Van Uytvanck & Hoffmann, 2009) and flexibility in relation with herbage production and other site characteristics (Mitchell and Kirby, 1990; Thomason, 1995; Pollock et al., 2005; Galleguillos et al., 2018). Several articles stressed the importance of controlling overgrazing (Nakashizuka and Numata, 1982; Mitchell & Kirby, 1990) and ensuring that the preferred woody species can grow to heights beyond the reach of animals (Papachristou and Platis, 2011; Kaufmann et al., 2014).

Complete exclusion of grazing might be likely to lead to dramatic changes in the structure and composition of forests (Kirby et al., 1994), including possible shifts in vegetation towards non-native species (Chauchard et al., 2006; Cooper and McCann, 2011). It was recommended only in situations of severe grazing (Dambach, 1944; Milios et al., 2014), in highly fragmented eucalypt forest remnants (Bromham et al., 1999) and in situations where livestock grazing was not part of the traditional forest management, as reported from a New Zealand conifer forest (Smale et al., 2008). Two other papers considered that closed canopy, high quality timber (commercial) forests should not be grazed, but acknowledged the potential for silvopastoral systems (Noack et al., 2010; Mayerfeld et al., 2016).

4. Discussion

Livestock grazing in temperate forests continues to be a major issue for managers and conservationists alike. Its complexity (Fitzgerald et al., 1986; Pollock et al., 2005; Kaufmann et al., 2013), diverse, large-scale and long-lasting influence can make it difficult, however, to generalise with respect its various potential uses in vegetation management (Kirby et al. 1994; Bernes et al., 2018).

The interpretation of the reviewed papers was often hampered by inadequate description of the study conditions. About one third of the research papers did not provide information about the land-use history and/or the situation preceding the study, and more than half lacked data about stocking density (i.e. grazing pressure). Studies lacking information on seasonality accounted for 42%. The issue of seasonality of grazing may also bias results because grazing is often done in early spring or winter, but the vegetation is assessed during the growing season. Apart from the differences in palatability between species (Kirby et al., 1994; Garin et al., 2000; Darabant et al., 2007), grazing preference also changes over time, together with changes in the availability of forage alternatives and the character of species (e.g. taste, forage value, proportion of leaves; Fitzgerald et al., 1986; Jones et al. 2011).

4.1. The complexity of impacts on vegetation

Forest grazing is a kind of inhibitor disturbance, with seemingly obvious effects, though often generating apparently independent processes. Forest grazing acts on plants through removing/damaging them directly and favouring certain species by selectively removing its competitors (Nakashizuka and Numata, 1982; Belsky and Blumenthal, 1997; Borman, 2005; Darabant et al., 2007) and though changing the physical environment (particularly light and nutrient regimes), which together also then change the competitive balance between species (Dambach, 1944; Garin et al., 2000; McEvoy et al., 2006b; Smale et al., 2008). Most studies reported the obvious and expected effects, including the reduction of vegetation biomass or increase in the grass cover, especially of grazing-adapted species (Kirby et al., 1994; Galleguillos et al., 2018; Fig. 2; Table 1), at the expense of shade-tolerant and forest specialist species in the herb layer or increase in the abundance of light-demanding and ruderal species (Dambach, 1944; Smale et al., 2008; Cooper and McCann, 2011).

Diversity of various species groups and features has been reported as both increasing and decreasing, but some of this difference might be due to methodological and/or scale bias. Most studies focus on stand/plot level effects for a short period of time, despite the fact that some effects (e.g. increase of floristic and structural diversity) can take several years to be expressed (see Table 1 for more mechanisms). At the plot or stand scale, habitat heterogeneity might decrease through the loss of litter (Belsky and Blumenthal, 1997; Bromham et al., 1999; Galleguillos et al., 2018), reduced understorey cover etc. (Strandberg et al., 2005; Vanbergen et al., 2006). However, at the landscape scale, if other areas are less grazed, heterogeneity might increase because there would now be mixture of high and low litter cover, open and closed understoreys etc. Grazing and trampling increases the amount of bare soil surface, compacting soils and influencing water infiltration rates, but also facilitates the burial of seeds and acorns, thus benefiting seedling establishment (Linhart and Whelan, 1980; Vanbergen et al. 2006; Laskurain et al. 2013). Livestock grazing can contribute to a decrease in the amount of deadwood, most probably through trampling (Latham and Blackstock, 1998; McEvoy et al., 2006a), change the character of forests, by inducing its development into dense monospecific stands, like the case of *Pinus ponderosa* forests (Belsky and Blumenthal, 1997), or benefit the early seed-dispersal of oak by facilitating acorn dispersal by small rodents (Zhang et al., 2009).

The significance of any impacts is affected by the landscape and historical context of the site, but these are often confounded. For example, slopes influence the vegetation composition as well as the movement and impact of livestock (Fortuny et al., 2014; Galleguillos et al., 2018). The presence or absence of forage alternatives, accessibility, distance from water and camp sites also influence the outcomes of grazing (Pollock et al., 2005; McEvoy and McAdam, 2008; Kaufmann et al., 2013). Landscape and historical factors may also affect the quality and quantity of the available forage at any time and hence interact with seasonality of grazing effects (Kirby et al., 1994; Garin et al., 2000; Darabant et al., 2007; Van Uytvanck & Hoffmann, 2009).

4.2. Revisiting what we expect from the forest and from grazing?

Livestock grazing in forests has a long history, but in the last two centuries societal perceptions were that separation of grazing and forestry was a more efficient way of organising farm and forest production (Noack et al., 2010; Kardell, 2016; Nichiforel et al., 2018). This went alongside a change in people's vision of what a forest should be like and in the nature of preferred forest products, focussing more on timber (Ciesielski and Stereńczak, 2018). However, both forests and societal perceptions have continued to change (Kirby and Watkins, 2015; Rois-Díaz et al., 2018), which brings us to the need for re-evaluating and reconsidering livestock grazing in forests.

What was seen as 'damage' to the forest, for example preventing regeneration, keeping stands open, is now often seen as potential cost-effective tool for vegetation management (Fraser et al., 2001; Chauchard et al., 2006; McEvoy & McAdam, 2008) that contributes to the maintenance and enhancement of biodiversity (Kirby et al., 1994; Pollock et al., 2005; Fortuny et al., 2014). Forest grazing can contribute to the survival of cultural traditions and the well-being of local communities involved in animal husbandry, without greatly affecting timber production (Norbu, 2002; Darabant et al., 2007; Buffum et al., 2009), therefore providing higher income from the same area of land (Kingery and Graham, 1991).

Tensions between worldviews and interests still exist. On the one hand, maintaining high abundance of a culturally keystone species, like the Bluebell (*Hyacinthoides non-scripta*) in the UK, might be seen as more beneficial than increasing botanical diversity through grazing (McEvoy et al., 2006a); livestock grazing in forests was viewed negatively by urban visitors in Colorado (Wallace et al., 1996). Nevertheless, in most cases nature conservation and promoting traditional forest grazing are mutually supportive, often because the species and assemblages we value have developed as part of this cultural landscape management (Poschlod, 2015).

4.3. Improving the research and practice of livestock grazing in forests

We propose the following recommendations to be considered in the planning of an improved research and management as response to the demands for more solid evidences:

- Future research needs to move on from simple comparisons of grazing vs. non-grazing situations (Kirby et al., 1994; Hester et al., 1996), to comparative, controlled and quantitative studies (Pollock et al., 2005; Noack et al., 2010; Mazzini et al., 2018; Fig. 3).
- Livestock behaviour should be better understood, and different activities, like grazing, browsing, trampling, dunging, rubbing against the trees should be separated when considering livestock effects (Mitchell & Rodgers, 1985; Kirby et al., 1994; McEvoy & McAdam, 2008; Popp and Scheibe, 2014).
- More use should be made of traditional ecological and land management knowledge held by traditional herders who are controlling the grazing activity on a daily basis (Fraser et al., 2001; Norbu, 2002; Zhang et al., 2009). Local herders and farmers could enhance the success of forest grazing activities by preventing damage (for example by taking the livestock out of the forest, since when the animals are satiated with the forage, or if it becomes limited, they start to harm the trees (McEvoy and McAdam, 2008).
- There should be full documentation of the study conditions as the situation preceding the study, site characteristics, description of timing, intensity, duration, type of grazing, use of additional fodder, etc. provide essential information for our understanding and interpretation of the outcomes, thus allowing the formulation of management recommendations (Borman, 2005; Pollock et al., 2005; Bernes et al. 2018). To improve management recommendations, and assess the results, defining stocking density is important, though impacts are determined by more than just animal numbers (Pollock et al., 2005).
- The negative view of forest grazing is partly the outcome of a mix up of the impacts of increased wild ungulate populations and livestock grazing (Kingery and Graham, 1991). Therefore, the impacts of wild and domestic grazers need to be properly separated, because (i) grazing and movement of livestock and wild ungulates can be different, thus having different effects on forest vegetation (Walker et al., 2015; Bernes et al., 2018; Cromsigt et al., 2018); and (ii) livestock are much easier to control (Hester et al. 1996; Fraser et al., 2001).
- Other activities taking place in the same area (e.g. forestry management) need to be assessed alongside the grazing impacts because there are likely to be interactions (Kaufmann et al., 2014).

- The reviewed studies varied greatly in the employed grazing method, therefore it is not possible, and, most of all, not desirable to single out one method (i.e. length and season of grazing, stock density, type and breed of livestock). Experiments are needed to find the best management practices in individual forests using livestock, including novel forest ecosystems (e.g. plantations, new agroforestry systems), at both site and landscape scale. These might then be built into a decision support system such as the Woodland Grazing Toolbox (Scottish Forestry, https://scotland.forestry.gov.uk/woodland-grazing-toolbox).

4.4. A future for livestock forest grazing in conservation and silviculture management

Our review has established a range of potential benefits from maintaining existing forest grazing and for its careful reintroduction.

- Livestock grazing can be used to control or encourage the spread of forest to create landscape-scale vegetation mosaics which have been shown to have high cultural and biodiversity values (Humphrey & Patterson, 2000; McEvoy et al., 2006b; Mayerfeld et al., 2016; Galleguilos et al., 2018).
- Within woodland it may be used to favour desired vegetation structures and compositions for conservation and forestry reasons (Kirby et al., 1994; Darabant et al., 2007; Kaufmann et al., 2013; Fortuny et al., 2014).
- It has also found value as a silvicultural tool for supressing competitive herbaceous and woody species in plantations (Sharrow et al., 1992; McEvoy and McAdam, 2008), and in controlling invasive woody species (Chauchard et al., 2006; Mayerfeld et al., 2016).
- It can have an important role in fire mitigation, reducing the flammability of forests through reducing the combustible load of the forest understorey (McEvoy et al., 2006b, Varela et al., 2018), representing a potential management tool in the context of increasing incidence of extreme forest fires as an outcome of climate change.
- Forest grazing may also generate income for farmers through the sale of animals or meat, thus helping to support local livelihoods and communities (Kingery and Graham, 1991; Norbu, 2002, Rois-Díaz et al., 2018).

To enable us to fulfil the above potential more needs to be done to develop community-based research and knowledge co-production involving different stakeholder groups, such as foresters, herders, conservationists and stock owners (Wallace et al., 1996; Norbu, 2002; Mayerfeld et al., 2016). Researchers need to understand the social environment where forest grazing is taking place. There is the knowledge held by the international scientific community, as reflected by the methodology of our literature search, but also much practical knowledge is available in the grey literature (e.g. Humphrey et al., 1998; Mayle, 1999), which, with few exceptions (e.g. Bernes et al., 2018) is often overlooked by the scientific community. Also often overlooked is the traditional ecological knowledge that may not even make it into the grey literature. We must create space and openness for interdisciplinary and participatory approaches, to improve mutual learning and understanding between the various knowledge holders for developing effective conservation management methods.

The focus of research and conservation needs to be extended towards larger temporal and spatial scales, and shifted in the direction of more community-, evidence-based approaches in order to promote resilience of socio-ecological production forest landscapes. Grazing can be conducted in various ways, with just as numerous effects on vegetation, not all of which will be obvious from short term studies. Nonetheless, experiments are needed to provide the basis for harnessing the potential of livestock grazing in forests to deliver silvicultural and conservation benefits. At the same time we need to recover and learn from the historical meanings of forest grazing, and the effects of different types and regimes (such as pannage, free-range, herded, or mob-stocking, recognising the complex role of traditional herders and other people who manage grazing. We should reconsider our perception of forests and approaches and attitudes towards livestock in the forest, recognising traditional and local knowledge and reconnecting local people to their environment and natural resources (Norbu, 2002; Hartel and Plieninger, 2014).

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Supporting information

Supporting information 1 – List of the 71 titles considered in the review

Supporting information 2 – **Fig. S1.** Location of the studies considered in the review and the major forest categories where these studies have been conducted

Supporting information 3 – **Fig. S2.** The cumulative number of the 71 publications included in the review, addressing the issue of domestic livestock grazing in temperate forests

Supporting information 4 – **Table S1.** Impacts of livestock grazing on forest elements

Supporting information 5 – **Table S2.** The main biotic and abiotic factors that influence the effects of livestock grazing in forests

Supporting information 6 – **Table S3.** Practical recommendations for the management of livestock grazing in temperate forests

Supporting information S1

List of the 71 titles considered in the review

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Supporting information 2

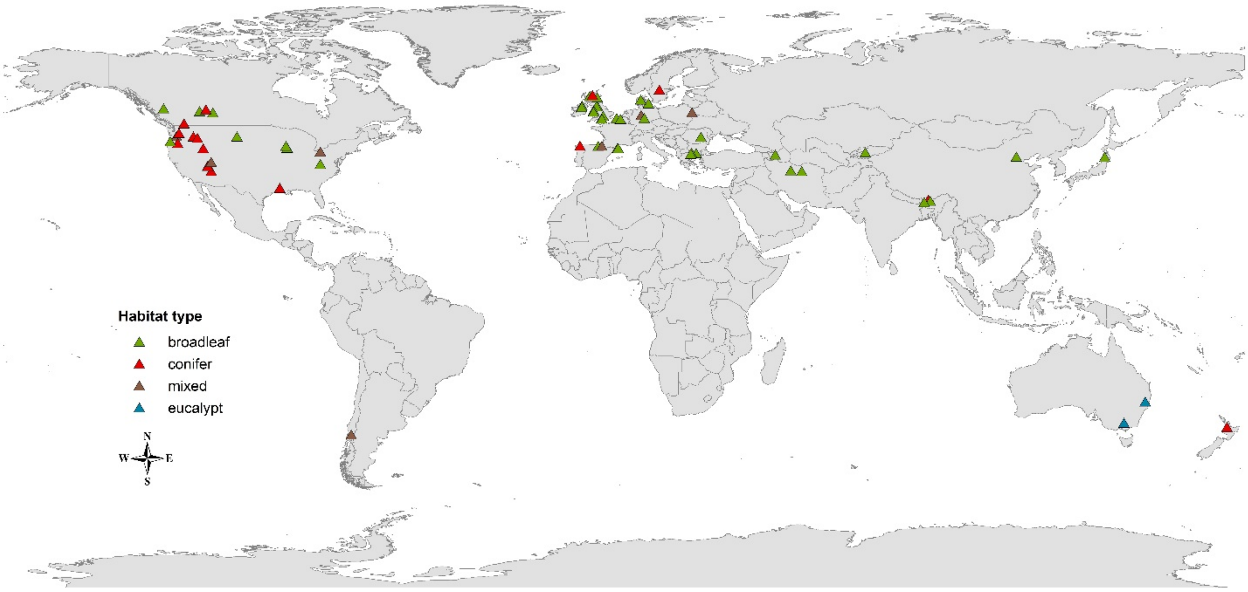

Fig. S1. Location of the studies considered in the review and the major forest types where these studies have been conducted (basemap source: ArcGIS.10.1.ESRI/ArcGIS_online world countries)

Supporting information 3

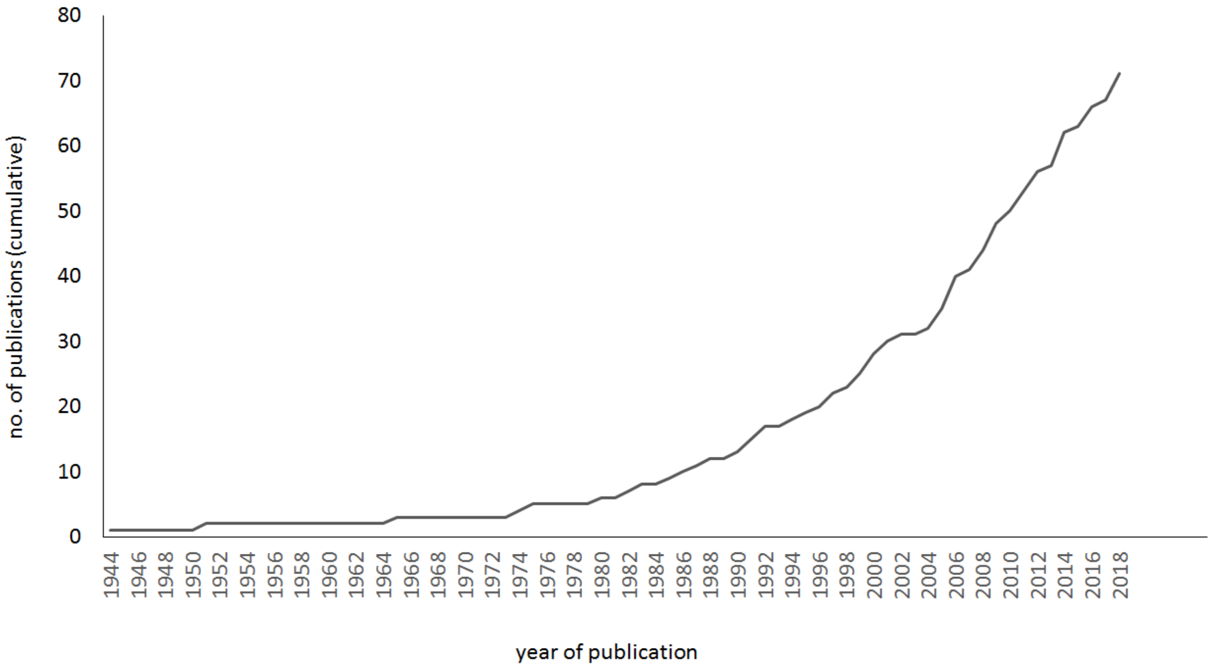

Fig. S2. The cumulative number of the 71 publications included in the review, addressing the issue of domestic livestock grazing in temperate forests

Supporting information 4

Table S1. Impacts of livestock grazing on forest elements. 'Change' marks situations when the direction of the trend was unclear

Impacts of livestock grazing on forest elements	References
Canopy biomass (stand volume, density)	
Decrease	Mitchell & Kirby, 1990; Vanbergen et al., 2006; Buffum et al., 2009; Noack et al., 2010; Lindgren & Sullivan, 2012; Milios et al., 2014
Neutral – no effect	Cutter et al., 1998; Lindgren & Sullivan, 2012 Galleguillos et al., 2018
Increase	Madany & West, 1983; Steven et al., 1992; Belsky & Blumenthal, 1997; Bromham et al., 1999; Borman, 2004; Ford et al., 2018
Change	
Canopy species composition/richness	
Decrease	
Neutral – no effect	Garin et al., 2000
Increase	Ford et al., 2018
Change	Madany & West, 1983; Belsky & Blumenthal, 1997
Shrub biomass	
Decrease	Tubbs, 1977; Nakashizuka & Numata, 1982; Mitchell & Kirby, 1990; Sharrow et al., 1992; Kirby et al., 1994; Bromham et al., 1999; Borman, 2004; Lamoot et al., 2005; Chauchard et al., 2006; Darabant et al., 2007; Cooper & McCann, 2011; Lindgren & Sullivan, 2012; Mayerfeld et al., 2016
Neutral – no effect	Lamoot et al., 2005
Increase	Linhart & Whelan, 1980; Emborg et al., 2000; Konstantinidis et al., 2008; Noack et al., 2010; Samojlik et al., 2016; Galleguillos et al., 2018
Change	
Shrub species composition/richness	
Decrease	Lindgren & Sullivan, 2012
Neutral – no effect	
Increase	Linhart & Whelan, 1980; Emborg et al., 2000; Samojlik et al., 2016
Change	Adams, 1975; Fitzgerald et al., 1986; Kirby et al., 1994; Garin et al., 2000; Konstantinidis et al., 2008; Smale et al., 2008; Noack et al., 2010; Papachristou & Platis, 2011; Shakeri et al., 2012

Herb biomass	
Decrease	Linhart & Whelan, 1980; Fitzgerald et al., 1986; Sharrow et al., 1989; Sharrow et al., 1992; Kirby et al., 1994; Thomason 1995; Belsky & Blumenthal 1997; Tubbs 1997; Latham & Blackstock 1998; Bromham et al. 1999; Garin et al. 2000; Humphrey & Patterson 2000; Fraser et al. 2001; Borman 2004; McEvoy et al. 2006a; Van Uytvanck & Hoffmann 2009; Zhang et al. 2009; Papachristou & Platis 2011; Lindgren & Sullivan 2012; Shakeri et al. 2012
Neutral – no effect	
Increase	Vanbergen et al. 2006; Galleguillos et al. 2018
Change	
Herb species composition/richness	
Decrease	Smale et al. 2008
Neutral – no effect	Beymer & Klopatek, 1992; Epple 2001; Fortuny et al. 2014; Ford et al. 2018
Increase	Madany & West 1983; Kirby et al. 1994; Bromham et al. 1999; Humphrey & Patterson 2000; McEvoy et al. 2006a; Tasker & Bradstock 2006; Vanbergen et al. 2006; Lesica 2009; Cooper & McCann 2011; Shakeri et al. 2012; Galleguillos et al. 2018
Change	Pearson & Whitaker 1974; Kirby et al. 1994; Latham & Blackstock 1998; Noack et al. 2010; Kaufmann et al. 2013
Regeneration biomass	
Decrease	Peterken & Tubbs 1965; Adams 1975; Linhart & Whelan 1980; Fitzgerald et al. 1986; Kirby et al. 1994; Hester et al. 1996; Latham & Blackstock 1998; Garin et al. 2000; Fraser et al. 2001; Chauchard et al. 2006; McEvoy et al. 2006b; Buffum et al. 2009; Papachristou & Platis 2011; Kaufmann et al. 2014; Milios et al. 2014; Schulze et al. 2014; Kardell 2016; Mayerfeld et al. 2016; Samojlik et al. 2016; Ford et al. 2018; Mazzini et al. 2018; Rhodes et al. 2018
Neutral – no effect	Rummel 1951; Kingery & Graham 1991; Cutter et al. 1998; Pollock et al. 2005; Darabant et al. 2007; Buffum et al. 2009
Increase	Nakashizuka & Numata 1982; Madany & West 1983; Sharrow et al. 1989; Mitchell & Kirby 1990; Sharrow et al. 1992; Belsky & Blumenthal 1997; Darabant et al. 2007; Zhang et al. 2009

Change	Morgan 1991; Thomason 1995; McEvoy & McAdam 2008; Lesica 2009; Shakeri et al. 2012; Laskurain et al. 2013
Regeneration species composition/richness	
Decrease	Latham & Blackstock 1998; Ford et al. 2018
Neutral – no effect	
Increase	
Change	Linhart & Whelan 1980; Fitzgerald et al. 1986; Morgan 1991; Hester et al. 1996; Garin et al. 2000; Fraser et al. 2001; Zhang et al. 2009; Shakeri et al. 2012; Laskurain et al. 2013; Kaufmann et al. 2014
Bryophytes biomass	
Decrease	Latham & Blackstock 1998; Strandberg et al. 2005; Vanbergen et al. 2006; Darabant et al. 2007; Smale et al. 2008; Laskurain et al. 2013
Neutral – no effect	McEvoy et al. 2006a
Increase	Mitchell & Kirby 1990; Kirby et al. 1994
Change	Thomason 1995
Bryophytes species composition/richness	
Decrease	
Neutral – no effect	Beymer & Klopatek 1992
Increase	Kirby et al. 1994; Humphrey & Patterson 2000
Change	Thomason 1995
Overall species composition/richness	
Decrease	Dambach 1944; Norbu 2002; McEvoy et al. 2006a; Smale et al. 2008; Lindgren & Sullivan 2012; Ford et al. 2018
Neutral – no effect	Walker et al. 2015; Galleguillos et al. 2018
Increase	Beymer & Klopatek 1992; Strandberg et al. 2005; McEvoy et al. 2006a; Vanbergen et al. 2006; Noack et al. 2010; Cooper & McCann 2011; Fortuny et al. 2017; Galleguillos et al. 2018
Change	
Invasive species biomass	
Decrease	Chauchard et al. 2006; Mayerfeld et al. 2016; Mazzini et al, 2018
Neutral – no effect	
Increase	Smale et al. 2008; Galleguillos et al. 2018
Change	
Habitat heterogeneity	
Decrease	
Neutral – no effect	

Increase	Madany & West, 1983; Mitchell & Kirby, 1990; Kirby et al., 1994; Hester et al., 1996; Tubbs, 1997; McEvoy et al., 2006a; Vanbergen et al., 2006; Van Uytvanck & Hoffmann, 2009; Zhang et al., 2009Lindgren & Sullivan, 2012; Laskurain et al., 2013; Fortuny et al., 2014
Change	
Litter cover	
Decrease	Dambach 1944; Adams 1975; Linhart & Whelan 1980; Mitchell & Kirby 1990; Belsky & Blumenthal 1997; Latham & Blackstock 1998; Bromham et al. 1999; Humphrey & Patterson 2000; Epple 2001; Strandberg et al. 2005; McEvoy et al. 2006a; Vanbergen et al. 2006; Smale et al. 2008; Shakeri et al. 2012; Laskurain et al. 2013; Galleguillos et al. 2018
Neutral – no effect	Beymer & Klopatek 1992
Increase	
Change	Darabant et al. 2007
Bare soil surface	
Decrease	
Neutral – no effect	Humphrey & Patterson 2000
Increase	Mitchell & Kirby 1990; Beymer & Klopatek 1992; Kirby et al. 1994; Belsky & Blumenthal 1997; Latham & Blackstock 1998; Bromham et al. 1999; McEvoy et al. 2006a; Vanbergen et al. 2006; Smale et al. 2008; Zhang et al. 2009; Shakeri et al. 2012; Laskurain et al. 2013; Galleguillos et al. 2018
Change	

Deadwood volume	
Decrease	Latham & Blackstock 1998; McEvoy et al. 2006a; Smale et al. 2008
Neutral – no effect	
Increase	
Change	

Supporting information 5

Table S2. The main biotic and abiotic factors that influence the effects of livestock grazing in forests

Effects depend on	Example quotations	References
Palatability of plant species and availability of forage alternatives (development stage of species influences forage preference)	*Rose and raspberry were highly preferred as young shoots in the first year. Raspberry continued to be favoured in the second year as it produced new tender shoots from underground rhizomes.* (Fitzgerald et al., 1986) *The combination of decreased meadow and aspen understory vegetation quantity and nutritional quality lead to increased utilization on aspen suckers, particularly mid- to late-growing season.* (Jones et al., 2011)	Adams, 1975; Belsky & Blumenthal, 1997; Fitzgerald et al., 1986; Fraser et al., 2001; Garin et al., 2000; Jones et al., 2011; Konstantinidis et al., 2008; Shakeri et al., 2012; Smale et al., 2008
Grazer species, breed type, livestock age and level of forest adaptation (cattle may cause damage also by trampling and rubbing, while sheep mostly by grazing)	*Sheep breeds with strong herding instincts (Rambouillet, Corriedale) are easier to control on forest sites. With good shepherding, breeds which graze in more dispersed patterns, such as Suffolk, can be used effectively. The emphasis should be on the quality of shepherding effort, rather than simply on the breed. Mature dry ewes are the most suitable animals for a grazing flock.* (Fraser et al., 2001)	Pearson & Whitaker, 1974; Adams, 1975; Putman et al., 1987; Mitchell & Kirby, 1990; Tubbs, 1997; Fraser et al., 2001; Lamoot et al., 2005; Walker et al., 2005; Papachristou & Platis, 2011; Shakeri et al., 2012; Popp & Sheibe, 2014; Rhodes et al., 2018
Grazing regime, stocking density and distribution (vegetation can benefit from under- and overgrazing as well)	*Damage to regenerating stems in 2008 was also greater under high intensity (9.3%) than low intensity (5.0%) cattle grazing, with high cattle stocking rates leading to 4.3% […] more total damage and 3.6% […] more browsed saplings.* (Kaufmann et al., 2014). *Frequent mob stocking events of 24 h or thereabouts may provide the desired results whilst potentially reducing damage incurred to saplings.* (McEvoy & McAdam, 2008)	Rummel, 1951; Peterken & Tubbs, 1965; Pearson & Whitaker, 1974; Adams, 1975; Linhart & Whelan, 1980; Mitchell & Kirby, 1990; Kirby et al., 1994; Thomason, 1995; Hester et al., 1996; Belsky & Blumenthal, 1997; McEvoy et al., 2006b; McEvoy & McAdam, 2008; Buffum et al., 2009; Laskurain et al., 2013; Kaufmann et al., 2014; Milios et al., 2014; Samojlik et al., 2016; Galleguillos et al., 2018; Rhodes et al., 2018

Forest characteristics (e.g. habitat type, stand structure and age, forestry treatments, canopy closure - cattle avoid clear-cuts)	*The influence of cattle grazing on plant community abundance and diversity may be directly affected by forest enhancement treatments of repeated fertilization.* (Lindgren & Sullivan, 2012). *Uncut forests were preferred by cattle […] partially harvested areas and burned brush piles were neither preferred nor avoided.* (Kaufmann et al., 2013)	Adams, 1975; Belsky & Blumenthal, 1997; Garin et al., 2000; Pollock et al., 2005; Papachristou & Platis, 2011; Lindgren & Sullivan, 2012; Shakeri et al., 2012; Kaufmann et al., 2013; Popp & Sheibe, 2014
Timing of grazing (winter grazing may favour regeneration, while late summer grazing may favour vernal species)	*Preference for aspen at commencement of grazing was lower early in the season than late. As early grazing proceeded and alternative species were removed, aspen became more acceptable.* (Fitzgerald et al., 1986) *A grazing regime following the end of the growing season appears to have little effect on tree growth, despite more damage occurring to trees at this time.* (McEvoy and McAdam 2008)	Fitzgerald et al., 1986; Putman et al., 1987; Sharrow et al., 1992; Hester et al., 1996; Belsky & Blumenthal, 1997; Garin et al., 2000; Fraser et al., 2001; Lamoot et al., 2005; McEvoy et al., 2006a; McEvoy & McAdam, 2008; Van Uytvanck & Hoffmann, 2009; Jones et al., 2011; Kaufmann et al., 2014
External factors (e.g. fire, precipitation, slope, herder, distance from herd camp and water availability influence the intensity of grazing)	*The function has a maximum at a distance of about 100 m from herdsmen camps […]. Thus, plant diversity can also be expressed as a function of the distance to herdsmen camps.* (Noack et al., 2010) *Annual variation in precipitation and biomass production must be accounted for in grazing strategies, with attention paid to low herbaceous vegetation production years.* (Jones et al., 2011)	Dambach, 1944; Pearson & Whitaker, 1974; Adams, 1975; Madany & West, 1983; Thomason, 1995; Belsky & Blumenthal, 1997; Tasker & Bradstock, 2006; Van Uytvanck & Hoffmann, 2009; Noack et al., 2010; Jones et al., 2011; Kaufmann et al., 2013; Fortuny et al., 2014; Walker et al., 2015; Rhodes et al., 2018

Supporting information 6

Table S3. Practical recommendations for management of livestock grazing in temperate forests

Overall recommendation **Major habitat types** **Benefits (B) / Disadvantages (D)**	**Management recommendations**	**Habitat type (country)**	**Reference**
1. Some kind of management			
Broadleaf, Europe			
B: Considerable potential in vegetation management **D:** –	Reduction, but not complete exclusion	Ancient seminatural woodland (UK)	Kirby et al., 1994
B: Reduces the patch sizes of monospecific stands (*Rubus*, *Pteridium*) and encourages an increase in botanical diversity **D:** –	Light grazing in late summer	Broadleaf woodlands (oak, ash, beech) (Ireland)	McEvoy et al., 2006a
B: Eliminates bramble thus favouring rare species **D:** Reduce or prevent regeneration because seedlings are killed by grazing and the soil is compacted	Controlled, light grazing by sheep in winter and early spring	Oak dominated woodland (UK)	Linhart & Whelan, 1980
B: Control the growth of grasses, bilberry and bramble, to allow some regeneration of trees and shrubs in canopy gaps **D:** Seedlings are eaten, if the stocking rate is too high	Flexibility of stocking and grazing periods, dictated by grass growth, tree regeneration and weather conditions	Oak woodland (UK)	Thomason, 1995
B: Create niches for seedling establishment and the reduction in the height of competing field layer vegetation **D:** May be limiting natural woodland regeneration	Consider herbage production. The involvement and support of farmers and land owners is essential	Upland semi-natural woods (UK)	Mitchell & Kirby, 1990
B: Can be grazed sustainably within woodlands for landscape or biodiversity purposes **D:** Overgrazing and damage could happen	Reference to site characteristics is crucial. Importance of controlled experiments	Upland birch (*Betula*) woodlands (UK)	Pollock et al., 2005
B: Higher proportion of the seedlings are reaching sapling height in winter-grazed plots	Winter grazing is less detrimental than summer grazing	*Betula pubescens*, *Quercus petraea* and *Corylus*	Hester et al., 1996

D: Saplings will have the potential to attain canopy height only at the lowest grazing intensities		*avellana* with *Sorbus aucuparia* and *Fraxinus excelsior* (UK)	
B: Reducing competitive grasses in plantations without causing significant damage to the trees **D:** Damage to the lateral branches of oak and ash. Smaller annual increase in oak canopy diameter	A grazing regime following the end of the growing season appears to have little effect on tree growth, despite more damage occurring to trees at this time. Frequent mob-stocking is recommended over longer grazing periods; thus, livestock should be removed from the plantation before quality forage becomes limited	*Quercus* and *Fraxinus excelsior* plantation established on former pastureland (UK)	McEvoy & McAdam, 2008
B: Decrease cover of *Rubus* **D: –**	Moderate, rotational grazing. Providing temporal time gaps in grazing may prevent excessive grazing and trampling damage. Best forage quality for *Rubus* is reached in late spring	Alno-Padion, Carpinion forest (Belgium)	Van Uytvanck & Hoffmann, 2009
B: Good as a nature conservation management **D**: –	Combination of cattle and ponies	*Populus tremula*, *P. canadensis*, *P. canescens*, *Ulmus minor* and *Alnus glutinosa* forest (Belgium)	Lamoot et al., 2005
B: Cattle greatly reduce the regeneration of non-native black pine **D:** –	Lower ungulate densities are sufficient to eliminate almost all tree regeneration	Mixed beech–oak–maple forest with non-native black pine (France)	Chauchard et al., 2006

B: Control oak shoots in degraded oak forests to be converted into conifer forests **D:** –	Consider the type, breed, and class of livestock. Forest trees should have heights beyond the reach of animals	Oak woodland converted to conifer forest (Greece)	Papachristou & Platis, 2011; Samojlik et al., 2016
Broadleaf, mixed and conifer in N. Am			
B: Compatibility of cattle grazing and sustainable forest management **D:** –	No grazing should occur in May-June. Grazing should be allowed only when saplings are above 1.5 m height	Young *Populus tremuloides*, *P. balsamifera* and *Betula papyrifera* forest with secondary *Picea glauca* (Canada, Alberta)	Kaufmann et al., 2014
The effects of cattle grazing on plants cannot be generalized as beneficial or detrimental, as the response is undoubtedly a function of grazing intensity and nutrient status of the ecosystem	Strategies for conservation of plant diversity should include a diversity of forest enhancement treatments, including grazing	Lodgepole pine, douglas fir. *Picea engelmannii* × *P. glauca* and *Abies lasiocarpa* (Canada, British Columbia)	Lindgren & Sullivan, 2012
B: Sheep grazing for vegetation control, a cost-effective tool **D:** Potential for crop tree damage	Optimum flock size and appropriate timing – importance of herding	*Pinus contorta* and *Picea glauca* x *sitchensis* (Canada, British Columbia and Alberta)	Fraser et al., 2001
B: – **D:** Overgrazing of aspen in case of no forage alternatives	Rotational grazing strategies and attention paid to low herbaceous vegetation production years	Mixed conifer (*Pinus, Abies*) forest with aspen, *Populus tremuloides* (USA, California)	Jones et al., 2011
B: More area for feeding the animals, shade and shelter from heat and wind, suppression of noxious species such as *Rosa multiflora*. Reduced shrub cover for improved recreation. Natural distribution of manure, animal exercise. Keeping property taxes lower **D:** Damage to seedlings and saplings of desirable timber species. Less growth of herbaceous plants. Higher densities of undesirable species. Extra effort to maintain fences and difficulties in dividing the woodlots	Separating the top of the hills and valleys, as cattle prefer to graze on less steep slopes. Rotating into the most shaded paddocks at the hottest times. Actively managing canopy conditions to promote adequate light penetration for forages. Build exclosures around young trees	*Prunus serotina, Acer negundo, Ulmus rubra, Quercus alba, Fraxinus americana* (USA, Wisconsin)	Galleguillos et al., 2018

into paddocks for rotational grazing, and erosion along cattle trails			
B: Higher income from the same area, if it used also as a grazing area **D:** Damage to seedlings	Restricting grazing during the first months after planting	*Pinus ponderosa* plantation (USA, Idaho)	Kingery & Graham, 1991
B: – **D:** Combined big game and livestock severely reduces regeneration	Careful consideration of limiting, but not necessarily eliminating, large ungulate utilization	Mixed aspen-conifer forest (USA, Utah)	Walker et al., 2015
B: – **D:** Ungulate population size of any species or combination of species at sufficient density can cause aspen regeneration failure	Cattle, mule deer, and elk differ in their preference for aspen. Aspen at lower elevation are more susceptible to ungulate herbivory. Identify important thresholds for aspen recruitment	Mixed aspen-conifer forest *Populus tremuloides*, *Abies lasiocarpa, Abiesconcolor* (USA, Utah)	Rhodes et al., 2018
No differences between grazed and non-grazed woods in long term as regards growth rate or total ring width	Continuing the 30 years practice of regulating number per acre in accordance with the forage production	Young *Pinus elliottii* var. *elliottii* plantation (USA, Lousiana)	Cutter et al., 1998
Broadleaf and conifer in Asia			
B: Income for local communities **D:** Unregulated grazing results in reduction of density and change in species composition of broadleaf forest stands	Integrating grazing function as part of forest management practices	Broadleaf forest managed for industrial timber production (Bhutan)	Norbu, 2002
B: Beneficial effects of competition control	To be controlled to promote regeneration after logging in conifer forests	Mixed conifer forest (Bhutan)	Darabant et al., 2007
B: Grazing is good for the *Fagus* seedlings and decreases bamboo competition **D:** Grazing is necessary, but overgrazing could be dangerous	Control against overgrazing	Beech forest (Japan)	Nakashizuka & Numata, 1982

2. Complete exclusion			
B: Severely grazed woodland can become rejuvenated within a reasonably short time after protection is provided **D**: –	Encouraging farmers to exclude livestock from their woodlots	Beech-sugar maple woodland (USA, Ohio)	Dambach, 1944
B: – **D:** Intense grazing keeps the regeneration plants in low height	Grazing must be excluded from the area	Lowland forest *Q. pubescens* – *Q. frainetto* (Greece)	Milios et al., 2014
B: – **D:** Introduced pasture grasses were generally the sole component of the ground vegetation of grazed woodland	Limiting disturbance, assisting owners to fence woodland remnants, could benefit conservation in fragmented landscapes	Eucalyptus remnant woodlands (Australia)	Bromham et al., 1999
B: Good for the economy, but nothing more **D:** From a nature conservation perspective grazing is a harmful land-use type in this region	Grazing was not part of the traditional management and it is not beneficial for the studied forest sites	Conifer forest (New Zealand)	Smale et al., 2008
3. Arguments against complete exclusion			
D: Exclusion produces dramatic changes in the structure and composition of the woods	Need for specific conservation objectives and long-term plans. Control the land next to the wood as well	Ancient seminatural woodland (UK)	Kirby et al., 1994
B: Initially beneficial to the ecological condition of the woodland sites, allowing graze-sensitive, shade-tolerant woodland species to recover from grazing and trampling **D:** Grazing exclusion leads to loss of species of grassland habitats	Caution with exclusion (shifts in vegetation). The development of founder populations of non-native species associated with recovery from heavy grazing disturbance, should be the focus of conservation action	Lowland wet oakwood (UK)	Cooper & McCann, 2011
B: Cattle greatly reduce the regeneration of non-native black pine **D:** Non-native black pines are recruiting naturally where cattle were excluded	Cattle grazing is needed to prevent black pine recruitment	Mixed beech–oak–maple forest with non-native black pine (France)	Chauchard et al., 2006

4. Suggesting shift of management – acknowledging the potential of silvopastoral systems			
B: Shade, management of brush, and savanna restoration **D:** Damage of young trees, seedlings	Closed canopy, high quality woods should not be grazed and more discussion and research is needed on what types of woodlands might be suitable for silvopasture	Broadleaf (USA, Wisconsin)	Mayerfeld et al., 2016
B: Important for the rural community **D:** Detrimental for timber production	The production of timber and livestock is incompatible. If the aim is biodiversity conservation, then wood pasture management should be considered	*Fagus sylvatica* forest (Iran, Azerbaijan)	Noack et al., 2010