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REVIEW

Effects of large herbivores on fire regimes and wildfire mitigation

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Abstract

1. Abandonment of agricultural land is widespread in many parts of the world, leading to shrub and tree encroachment. The increase of flammable plant biomass, that is, fuel load, increases the risk and intensity of wildfires. Fuel reduction by herbivores is a promising management strategy to avoid fuel build-up and mitigate wildfires. However, their effectiveness in mitigating wildfire damage may depend on a range of factors, including herbivore type, population density and feeding patterns.
2. Here, we review the evidence on whether management with herbivores can reduce fuel load and mitigate wildfires, and if so, how to identify suitable management that can achieve fire mitigation objectives while providing other ecosystem services. We systematically reviewed studies that investigated links between herbivores, fire hazard, fire frequency and fire damage.
3. We found that, in general, herbivores reduce fuel load most effectively when they are mixed feeders, when grazing and browsing herbivores are combined and when herbivore food preferences match the local vegetation. In some cases, the combination of herbivory with other management strategies, such as mechanical clearing, is necessary to reduce wildfire damage.
4. *Synthesis and Applications*. We conclude that herbivores have the capacity to mitigate wildfire damage, and we provide guidance for grazing management for wildfire mitigation strategies. As areas undergoing land abandonment are particularly prone to wildfires, the maintenance or promotion of grazing by domestic or wild herbivores is a promising tool to reduce wildfire risk in a cost-effective way, while also providing other ecosystem services. Relevant land-use policies, including fire suppression policies, agricultural and forest(ry) policies could incentivise the use of herbivores for better wildfire prevention.

KEYWORDS

browsing, fire regimes, grazing, herbivory, pastoralism, rewilding

[Correction added on 14-September-2021, after first online publication: The figures have been moved from Supporting Information to the main text. Figures S6 and S7 have been renamed to Figures S1 and 5, respectively, Table S1 has been renamed to Table 1.]

1 | INTRODUCTION

In recent years, wildfires have been an increasing concern in many parts of the world. In 2017, for example, wildfires affected approximately 1 M ha of land in Europe (San-Miguel-Ayanz et al., 2019), with large impacts on nature (e.g. loss of native vegetation, expansion of invasive species, loss of essential habitat) and human property, lives and communities (IPBES, 2019). Of these areas, many contained threatened habitats and species of high conservation and cultural value. These wildfires have important economic costs estimated around €58 billion between 1998 and 2017 worldwide (EM-DAT, 2018). In addition, wildfires emit about 8 bn tons CO_2 per year globally (van der Werf et al.,l., 2017). Future climate change will likely increase drought conditions with severely hotter, drier weather and thereby increase fire events, also in high latitude regions that currently do not experience many wildfires (IPBES, 2019).

The increase of wildfire frequency and intensity (see Box 1) due to climate change is exacerbated by increased fuel build-up, driven by three main trends in land use change (Moreira et al., 2020). First, changing demographics with an ageing farming population and low attractiveness for new generations to continue traditional farming practices have caused large-scale land abandonment (Moreira et al., 2011). Second, socioeconomic and technological factors, as well as agricultural subsidies, drive the expansion of modern, more intensely managed farms, outcompeting more traditional land uses like pastoralism, while failing to avert land abandonment of less productive areas (Pe'er et al., 2020). Third, tree plantations and intensive forestry management create land-use change with agricultural areas being afforested. Resulting changes lead to landscape homogenisation, with large areas of a single land cover such as plantations, and shrubland replacing the traditional mosaic of cultural landscapes (Lasanta et al., 2018). A major concern is that these developments, alongside a lack of long-term fire prevention policies, contribute to an increase in fuel loads and thereby fire hazard (Moreira et al., 2020). Urgent questions to address to mitigate wildfire risk include which restoration and land management strategies can be employed to reduce high severity fires (Ockendon et al., 2018).

Here, we investigate to which extent, and how, herbivores can reduce fuel loads and thereby the frequency and severity of wildfires. Grazing and browsing ungulates (hereafter referred to as 'herbivores') typically reduce plant biomass and could mitigate fire risk. Effects of wild and domestic herbivores on their surroundings (and hence wildfires) may depend on specific management methods such as pastoralism, or species reintroductions, as well as their different diets and feeding behaviours (Gordon & Illius, 1989).

The aim of our systematic review is, first, to develop a conceptual framework on the various pathways by which herbivores affect wildfire frequency and intensity (see Figure 1). Earlier reviews on the role of different types of herbivory for the prevention of wildfires focused on only one type of herbivory (Lovreglio et al., 2014), pyric herbivory (i.e. the interaction of herbivores and fire; Fuhlendorf et al., 2009), a single grazing type only (i.e. rewilding: Johnson et al., 2018) or specifically on firebreaks (Valette et al., 1993). Our review expands upon these by assessing a broader range of herbivores and management systems, throughout the world, and by examining how these might mitigate fire hazard. While, in many ecosystems, wildfires are a natural phenomenon that can have positive effects on, for example, biodiversity, nutrient turnover and the maintenance of ecosystems (Bond & Keeley, 2005), in this work, we focus on how herbivores can be used to mitigate negative consequences of wildfires. We expect that herbivores can mitigate wildfires by reducing fuel loads, types, structure and moisture, depending on herbivore densities, feeding preferences, associated management, topographic conditions and climate (see Figure 1). Our review aims at identifying grazing management options that contribute to mitigating wildfires. We then discuss how policies can facilitate 'best management practices' for the use of grazing for wildfire mitigation.

We first assess whether herbivores can mitigate fire risk. We then explore the pathways by which grazers affect fire risk, by assessing how grazers affect vegetation properties and thereby fuel loads (see Figure 1), and on how vegetation properties affect fire risk, depending on environmental conditions, and associated management. We then discuss management options that are most promising in providing wildfire mitigation, and discuss how policies can facilitate these.

2 | LITERATURE SEARCH

We systematically reviewed studies that assessed overall relationships between herbivory and wildfires, and papers that focused on

> **BOX 1 Definitions**
>
> *Fire hazard*: Preconditions of fires in terms of fuel characteristics, volume, type and location of vegetation (Hardy, 2005).
> *Fire risk*: Chance that a fire might start, as affected by the nature and incidence of causative agents (Hardy, 2005).
> *Fire frequency*: Number of times that fires occur within a defined area and time period. Fire frequency is a mathematical expression of fire occurrence or rate, such as the average time interval between successive fires or the number of fires in a given area within a specific period of time (Curt, 2018).
> *Fire intensity:* Rate of heat energy released by a fire, which is closely related to the amount of fuel available to burn. It is typically measured in terms of flame length or rate of spread (Rossi et al., 2018). Not all case studies we reviewed explicitly distinguish between fire intensity and fire severity. In those cases, we use the term fire intensity for simplicity.
> *Fire severity*: Effect of fire on the landscape or ecosystems, for example, in terms of organic matter loss or tree survival. Measures of the fire severity are often interpreted as proxies of fire intensity (Hardy, 2005).

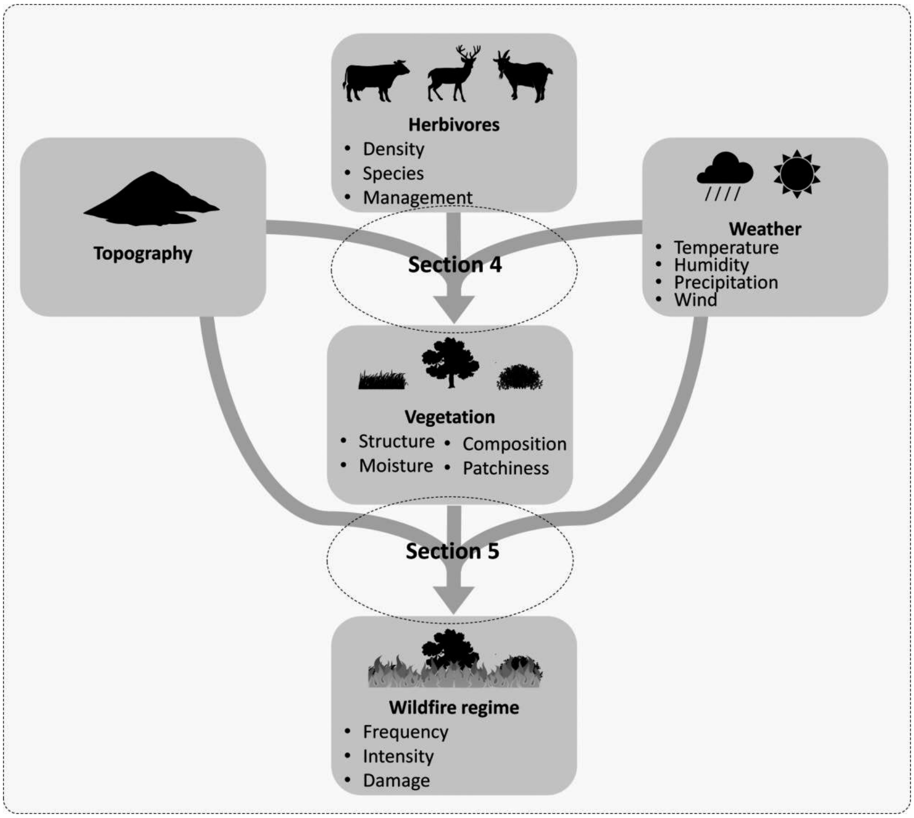

FIGURE 1 Effects of herbivores on wildfire frequency, intensity and damage depend on various factors, including grazing effects on the vegetation and thereby fuel load, as well as additional wildfire risk factors, such as local topographic and climatic conditions

specific pathways by which herbivores may affect wildfire risk (see Figure 1).

We performed a systematic literature search in January 2021 on Web of Science with keywords 'wildfire OR wild-fire OR fire-prevention OR fire-frequency OR fire-intensity OR fire-damage OR fire-risk OR fire-occurrence OR fire-hazard OR fuel-break OR fuel-load* OR fire-break) AND TS=(cattle OR grazin* OR herbivor* OR brows* OR graze* OR rewild* OR livestock OR cow* OR hors* OR sheep OR goat* OR bison OR donke* OR deer* OR chamoi* OR ibex OR reinde* OR moos* OR pastoral* OR ungulate*'. This search yielded 1,367 studies complemented by eight studies through cross-referencing. We scanned studies by title, abstract and full text. Of the 1,367 papers scanned, we included the 74 studies in our review that investigated the direct or indirect impact of large herbivore ungulates on wildfires.

An overview of the studies and PRISMA flowchart can be found as Figure S1.

3 | OVERALL EFFECTS OF HERBIVORES ON WILDFIRE RISK

3.1 | Effects of herbivores on wildfire frequency

Of the 74 studies included in this review (see Figure 2), 21 directly assessed the effects of herbivores on fire frequency. [Correction added on 14-September-2021, after first online publication: Citation to Figure 2 has been added.] Thirteen studies (see Table 1) found that grazing reduces wildfire frequency. Most other studies found that grazing only reduces wildfire frequency in certain cases, depending on the time of the year, the management associated with grazing (Vacchiano et al., 2018) or the vegetation type (Starns et al., 2019). In some cases, herbivore presence creates the conditions for more frequent but lower intensity fires, therefore reducing the frequency of extreme wildfires. Although herbivore grazing can maintain grass-dominated ecosystems that favour low-intensity fires and reduce frequency (Kramer et al., 2003), intensive grazing can have the opposite effect by reducing the cover of grassy vegetation (Pausas & Keeley, 2014) and favouring recruitment of highly flammable woody vegetation (Bachelet et al., 2000).

Further evidence that herbivores can decrease wildfire frequency comes from research on species extirpation and introduction (Pausas & Keeley, 2014). Also, historical evidence of changes in fire frequencies shows that declines in pastoral management and rearing of livestock, especially in mediterranean regions (Kalabokidis et al., 2007; Torres-Manso et al., 2014), increased wildfire frequency. However, in some cases, grazing management practices are associated with increased fire ignitions and frequency (Cano-Crespo et al., 2015; Vacchiano et al., 2018; Zumbrunnen et al., 2012). Thus, the ability of herbivores to reduce fire frequency depended on season, intensity of grazing or landscape type (see Table 1).

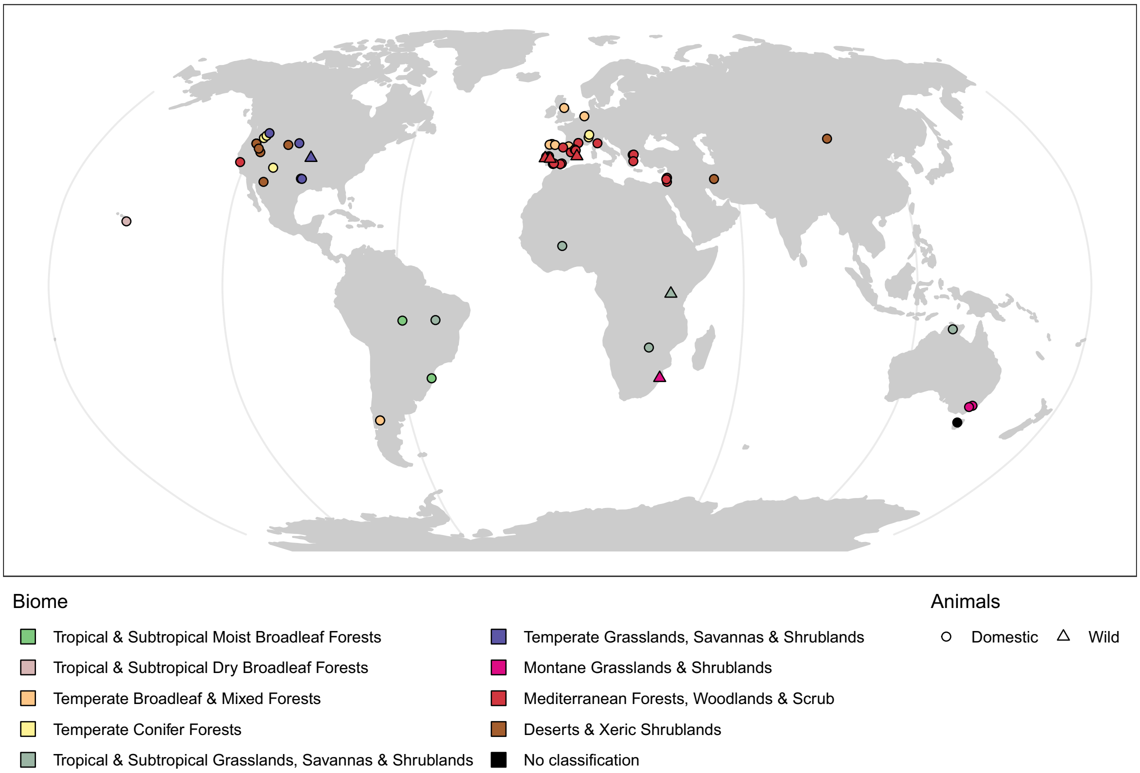

FIGURE 2 Locations of reviewed studies. The colour and shape indicates the type of biome where the study was conducted and if it focused on wild or domestic animals

Even if most evidence available is from Mediterranean systems, herbivores can also reduce wildfire frequency in other types of environment, for example, temperate or alpine environments (Kramer et al., 2003) or in tropical savannas (Smit & Archibald, 2018).

3.2 | Effects of herbivores on fire intensity or severity

Of 12 studies, seven reported that grazing reduced fire intensity and/or severity. Even light grazing and browsing could reduce fire intensity (Bachelet et al., 2000; Blackmore & Vitousek, 2000; Silva et al., 2019). Cattle grazing also reduced fire spread rate in shrub- and grass-dominated systems (Bruegger et al., 2016; Davies et al., 2016), especially when their resource utilisation was maximised with herding and supplement feeding. Through reducing fuel loads and height by consuming the vegetation and trampling, herbivores were able to reduce flame length as well (Probert et al., 2019; Savadogo et al., 2007), which reduces fireline intensity.

Observational studies report an increase in fire intensity following historical extirpations of herbivores, especially in productive environments (Johnson et al., 2018), probably due to a change in disturbance regime caused by herbivores (Fuhlendorf et al., 2009). For example, the extinction of megafauna in North America at the end of the Pleistocene was followed by a shift from fire regimes with frequent, low fire intensity to high-intensity crown fires. Large wild herbivores were possibly able to maintain a high level of disturbance that contributed to grass-dominated, heterogeneous ecosystems with a higher frequency of low-intensity fires (Pausas & Keeley, 2014).

While grazing by herbivores was found to reduce the intensity and severity of wildfires in many cases, there were exceptions. Some studies found no effect of herbivores on fire intensity (Williams et al., 2006), or no difference between treatments with controlled burns and grazing versus only controlled burns (Diamond et al., 2009). Fire simulations in an Aleppo pine forest with different fuel treatments showed that herbivores alone were not sufficient to reduce fire intensity, and that it was only effective when combined with slash removal (Mitsopoulos & Dimitrakopoulos, 2017). Also, especially in forests, repeated, heavy grazing of herbaceous plants can increase woody vegetation, thus creating fuel ladders that can carry fires into the canopy (Endress et al., 2012; Williamson et al., 2014).

4 | EFFECTS OF HERBIVORES ON FUEL LOAD AND FIRE HAZARD

Herbivores have the potential to affect fuel load and, thereby, fire hazard. We found 45 studies assessing the effect of herbivores on fuel biomass. Most studies (n = 30) reported decrease in vegetation biomass (e.g. Bruegger et al., 2016; Tsiouvaras et al., 1989), while only one study reported increases (Endress et al., 2012). Thirteen studies found neutral (e.g. Blackhall et al., 2012; Travers et al., 2020) or mixed (Briggs et al., 2002) effects of herbivores on fire hazard, depending on context, type of vegetation or herbivore (see Figure 3). Herbivores

TABLE 1 Overview of studies explicitly assessing the effects of herbivores on wildfire frequency or intensity

Main findings	Effect type	Reference
Livestock grazing reduced fire frequency by reducing grass biomass and enhancing the expansion of woodland	Frequency, intensity	Bachelet et al. (2000)
Cattle grazing reduced fuel loads when herded. They reduced fire spread and reduced flame length	Intensity	Bruegger et al. (2016)
Spatial distribution of livestock activities was negatively related to wildfire frequency in a Mediterranean area	Frequency	Kalabokidis et al. (2007)
Herbivores reduced the frequency of small and large fires by reducing fuel loads and changing vegetation structure. Strength of effects were mediated by ignition frequencies and habitat type	Frequency	Kramer et al. (2003)
Following a regional shrub clearing plan coupled with livestock grazing in a Mediterranean environment, there is a decrease in fire frequency	Frequency	Lasanta et al. (2018)
Browsing reduced fine fuel load. In browsed plots, modelled wildfire rate of spread, flame length, probability of canopy fire and fireline intensity decreased	Intensity	Lecomte et al. (2019)
Grazing with controlled burning reduced fire intensity under moderate moisture but not dry conditions	Intensity	Mitsopoulos and Dimitrakopoulos (2017)
Analysis of temporal and regional drivers of fire ignition in Portugal shows that land abandonment, and land-use change from cultivated and grazed land explain an increase in forest fires	Frequency	Nunes (2012)
Review indicates that natural grazing by large herbivores maintains grass-dominated ecosystems that favour more frequent but lower intensity fires, while (intensive) livestock grazing can favour woody vegetation recruitment and leads to more intense fires	Frequency, intensity	Pausas and Keeley (2014)
Wildfire ignitions are likely in landscapes with large areas of low intensity grazing, and even more in areas with many small patches with higher grazing density	Frequency	Ruiz-Mirazo et al. (2012)
Low intensity goat grazing reduced fire intensity in a shrub-grassland habitat	Intensity	Silva et al. (2019)
Simulation study indicating that pyric herbivory consistently reduces fire frequency and intensity more strongly than prescribed fires only	Frequency, intensity	Starns et al. (2019)
No historical causal relationship between livestock grazing and fire incidence in Portugal. Extensive grazing can reduce fire risk but grazing management practices are also linked to higher ignition density	Frequency	Torres-Manso et al. (2014)
The density of grazing animals in an Alpine Valley had opposite effects on summer (positive correlation) and winter (negative) fires	Frequency	Vacchiano et al. (2018)
No evidence of cattle reducing fire severity in a *Eucalyptus* forest, since they hardly forage on flammable heathland and prefer the grassland	Intensity	Williamson et al. (2014)
Historical evidence in Alpine Switzerland shows that livestock density negatively relates to fire frequency during 1904–1955. However, during 1956–2006, fire frequency was lowest with intermediate livestock densities	Frequency	Zumbrunnen et al. (2012)
Cattle grazing reduced flame length and fire intensity in a dry ecosystem by reducing canopy height of grass grassy vegetation	Intensity	Blackmore and Vitousek (2000)
Targeted grazing with cattle led to a significant reduction in biomass of grassy vegetation. However, with simulation, flame length was similar in graze-burn and burn treatment	Intensity	Diamond et al. (2009)
In this experiment, fire intensity and frequency were linked to grazing. Fires were smaller in areas with high density of livestock enclosures and high wildebeest utilisation	Intensity	Probert et al. (2019)
In a savanna ecosystem, grazers reduced fuel loads and quality by consumption and trampling of vegetation. However, they did not affect fire spread	Intensity	Savadogo et al. (2007)
No effect of cattle grazing on fire occurrence or intensity in an Australian alpine environment	Frequency, intensity	Williams et al. (2006)
Greater occurrence of fires in shrubland than in other land uses in Mediterranean countries	Frequency	Bashari et al. (2016)

(Continues)

TABLE 1 (Continued)

Main findings	Effect type	Reference
Accross the tropics, high livestock density generally correlates with lower fire frequency	Frequency	Bernardi et al. (2019)
Livestock density of sheep and goat was positively linked with fire frequency	Frequency	Colantoni et al. (2020)
Greater occurrence of fires in shrubland than in other land uses in Mediterranean countries	Frequency	Damianidis et al. (2020)
Fall and Spring grazing decreased fuel loads and increased fuel moisture, but spring grazing greater effect on fire spread and ignition	Frequency	Davies et al. (2017)
Historical evidence of impact of impact of livestock numbers on fire regimes	Frequency	Guiterman et al. (2019)
Livestock density is one of the variables that was found to influence fire occurrence. Positive relation with fire occurrence	Frequency	Oliveira et al. (2012)
Positive relation of cattle and goat with fire occurrence in Southwestern Europe. However, in Southeastern Europe goat density is negatively associated with fire occurrence	Frequency	Oliveira et al. (2014)
Presence of buffalo in savanna ecosystems contributes to patchy ecosystems and low intensity fires as well as less frequent	Frequency, intensity	Trauernicht et al. (2013)

also postponed the regrowth of flammable biomass after a fire event (e.g. Ne'eman et al., 1997) and created heterogeneity in the organisation of the fuel, as well as fuel moisture (Davies et al., 2015), thereby affecting fire regimes (Schoenbaum et al., 2018).

Most studies addressing the effects of herbivore species and intensities on fire hazard focused on cattle and pastoral systems. However, compared to cattle, we found that goats were more often effective in reducing vegetation biomass (five of six studies; see Figure 4). This is probably due to their capacity to browse on plant parts such as branches, young trees or tree bark that are unpalatable to many other species (Jauregui et al., 2009; Mancilla-Leytón & Vicente, 2012; Pareja et al., 2020; Valderrábano & Torrano, 2000). The effectiveness of goats can depend on the specific breed and size, due to foraging differences. For example, Celtiberic goats prefer heather plants and cause a higher reduction of shrub biomass than Cashmere goats that promote a better balance between woody and herbaceous plants (Celaya et al., 2010).

Mixed herbivore systems may lead to stronger reductions in fuel loads than single herbivore systems, especially in a mosaic landscape with high vegetation heterogeneity, and when different animals vary in dietary preferences (Gambiza et al., 2008; Waldram et al., 2008). This was especially the case in African savannas, where more diverse herbivore assemblages consume more plant biomass (van der Plas et al., 2016). Similarly, in savannas, multiple species of herbivores with different body sizes and eating habits interact and have the effect of creating more patchiness and smaller burnt areas. These systems usually have frequent, low-intensity fires (Savadogo et al., 2007; Waldram et al., 2008).

While herbivores are often effective in reducing vegetation biomass and therefore fire hazard, there are also studies reporting mixed (Bashan & Bar-Massada, 2017; Briggs et al., 2002; Travers et al., 2020) or nonsignificant effects (e.g. Calleja et al., 2019; Dittel et al., 2018). In addition to the type of herbivore, vegetation palatability is key in whether herbivores effectively reduce

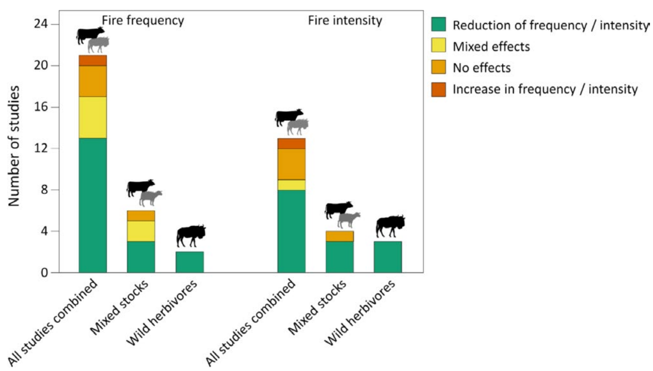

FIGURE 3 Effect of different herbivores on fire intensity/frequency reported in reviewed studies

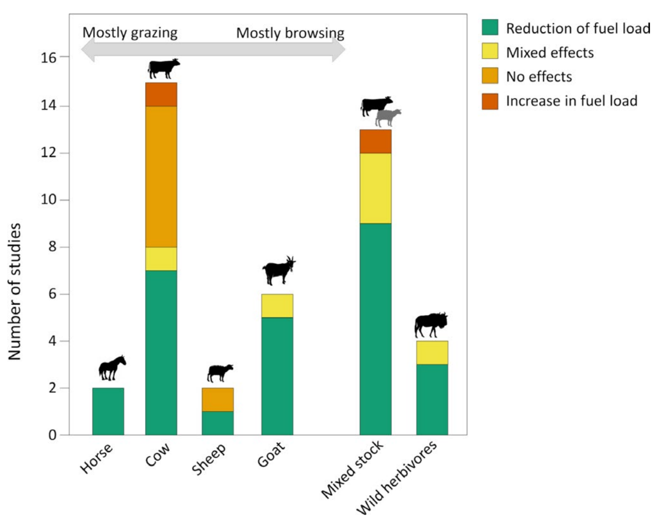

FIGURE 4 Effect of different herbivores on vegetation biomass reported in reviewed studies

fuel loads (Valette et al., 1993). For example, cattle were unable to reduce shrub biomass in a Mediterranean area in Spain since very few shrub species are palatable for cattle (Calleja et al., 2019). While, at high densities, cows consume a higher proportion of shrubs, this can be detrimental to their health (Teruel-Coll et al., 2019). In other cases, grazing does not alter the amount of fuel but rather its composition, reducing the herbaceous layer and increasing tree regeneration (Briggs et al., 2002; Zimmerman & Neuenschwander, 1984). The ability of herbivores to reduce fuel loads also depends on the season (Davies et al., 2016) and associated management, such as controlled burning (Bashan & Bar-Massada, 2017) or mechanical clearing (e.g. Etienne et al., 1995). Thus, the effectiveness of herbivores on fuel loads is affected by several factors, including external factors such as the season or animals' diet preferences.

5 | EFFECTS OF VEGETATION CHARACTERISTICS ON FIRE REGIMES

The amount and type of vegetation strongly influence fire regimes, while there are also feedbacks whereby fires have short- and long-term effects on plant communities and vegetation structure (Pausas & Keeley, 2009). Low fuel loads often limit fire frequency and spread, while environments with high fuel loads provide a greater fire hazard (McLauchlan et al., 2020). Importantly, the effects of fuel loads on fire regimes are modulated by climatic conditions and sources of ignition (Krawchuk et al., 2009, see also below). Ecosystems with high and regular levels of precipitation, such as temperate systems or evergreen rainforest, do not burn often even if their plant biomass is high. Similarly, if other environmental conditions that promote burning such as wind or drought are lacking, wildfires are unlikely to occur, even with high vegetation biomass. Hence, limiting vegetation biomass is especially relevant for wildfire mitigation in areas with dry seasons, such as Mediterranean systems, savannas or dry woodlands (Moreira et al., 2020).

Other vegetation characteristics also drive flammability. Spatial distribution of vegetation in landscapes affects fuel continuity and therefore fire spread (McLauchlan et al., 2020). Thus, when herbivores either create heterogeneity in vegetation structure, including (almost) bare patches, due to feeding preferences, or when managers stimulate herbivores to graze at specific sites, wildfires spread can be limited even if other parts of the landscape still have high vegetation biomass. Furthermore, moisture content of vegetation, which often responds to grazing, impacts flammability (Fares et al., 2017) as higher fuel moisture will lower ignitability as well as decrease the rate of spread of fires (Davies et al., 2015, 2017).

6 | EFFECTS OF GRAZING-ASSOCIATED MANAGEMENT ON WILDFIRES

Generally, within rural areas, both livestock densities and fire frequency increase with human activity (Ruiz-Mirazo et al., 2012). Thus, while herbivores have the potential to decrease wildfire frequency through efficient fuel management, increases can occur if grazing management is associated with fire use by land managers (Eloy et al., 2019; Probert et al., 2019). In mediterranean regions, winter wildfires are almost always of anthropogenic origin (Ruiz-Mirazo et al., 2012), mostly by arson or controlled fires that escaped. Pastoral burnings are a common practice to clear shrubs and favour palatable species for livestock (Cano-Crespo et al., 2015; Ruiz-Mirazo & Robles, 2012). In alpine environments, fire ignitions typically peak at the end of winter and beginning of spring when much of the pastoral burning occurs. As this is done prior to livestock introduction, there is a positive correlation between density of animals and fire frequency in the summer, and a negative correlation in winter (Vacchiano et al., 2018). The same occurs in tropical forests and other ecosystems where livestock rearing is a key driver of conversion of forest to grasslands, often by using prescribed fires (Bernardi et al. 2019).

Herbivore management may also directly be employed to reduce the frequency and intensity of wildfires. For example, targeted grazing is often specifically implemented with the purpose of creating and maintaining firebreaks (Papanastasis, 1986; Valette et al., 1993). Also, grazing combined with controlled winter fires can contribute to promoting specific types of vegetation (Eloy et al., 2019) or creating a palatable herbaceous undercover that can be maintained by strict grazers (Thavaud et al., 2009).

7 | IMPLICATIONS FOR MANAGEMENT

The impact of herbivores on wildfires is largely determined by the type of associated management. Building on our review, the following recommendations for management emerge.

Firstly, we recommend extensive or targeted intensive grazing as a cost-effective method to reduce wildfire risks (see Figure 5), especially in ecosystems with high fire risk, such as mediterranean or savanna systems. Payments for ecosystem services can be cost-effective incentives for shepherds to enact management most beneficial for fire prevention (Ruiz-Mirazo & Robles, 2012). Often, using herbivores is more cost-effective to reduce fuel biomass than mechanical removal (Varela et al., 2018). Grazing also complements mechanical clearing of biomass or controlled burning (Lasanta et al., 2018; Mitsopoulos & Dimitrakopoulos, 2017; Valette et al., 1993), especially when the land has been partly abandoned (García-Ruiz et al., 2020). It can increase the efficiency of mechanical actions and decrease the frequency by which such interventions are necessary. Targeted grazing can also be used to create strategic firebreaks for mitigating the impact of wildfires—for example, using temporary fences to promote high densities of herbivores for a short time (Bashan & Bar-Massada, 2017) and to improve fire suppression efforts. While intensive grazing may be even more effective than extensive grazing in reducing local fuel loads, it tends to decrease biodiversity and other ecosystem services, such as soil organic carbon content, soil erosion, pollination services etc. (Mcsherry &

Ritchie, 2013; van Klink et al., 2015). Also, in intensive grazing systems, supplementary food is usually necessary to meet animals' nutrition needs, in cases, supplementary feed such as soy leads to telecoupled effects (Boerema et al., 2016).

Second, management aiming to reduce wildfire risk should also make conscious choices on the herbivores type to use so that the vegetation is compatible with their feeding habits (see Figure 5). If grazers would be preferable in grassland environments, mixed feeders such as goats are most effective in shrub- and grass-dominated systems (Lovreglio et al., 2014). In shrub-dominated systems, we advise in favour of using mixed feeders, and against using only strict grazers such as cattle that consume mostly grass, and therefore could facilitate shrub recruitment (Valderrábano & Torrano, 2000; Williamson et al., 2014).

Third, burning combined with grazing is an effective management option to clear shrubland and thereby reduce fuel loads (see Figure 5; Starns et al., 2019). However, this practice, when uncontrolled, is responsible for many wildfire ignitions (Cano-Crespo et al., 2015; Ruiz-Mirazo et al., 2012).

Fourth, in regions with strong land abandonment (Jones & Fleskens, 2016; Loepfe et al., 2010), as well as in wilderness areas, we recommend the use of wild and semi-wild herbivores for reducing wildfire risk (see Figure 4). In places vulnerable to wildfires, encouraging populations of native wild herbivores (e.g. through reduced hunting) or introducing wild-living herbivores can avoid costs related to infrastructure and to rearing domestic animals. Also, because of social acceptability of most herbivores (Varela et al., 2014), they can easily be used at the interface between urban and rural areas to reduce fuel loads (Brunson & Shindler, 2004)—with potential side benefits of promoting ecotourism in such regions (Oteros-Rozas et al., 2014). Providing water supply points and mineral supplements in strategic places can be used to guide wild and semi-wild herbivores to specific areas for the purpose of fire risk mitigation (Velamazán et al., 2018). While wild and semi-wild herbivores can be effective tools for wildfire prevention (Johnson et al., 2018; Kramer et al., 2003; Pausas & Keeley, 2014; Velamazán et al., 2018), there are challenges that need to be addressed for successful implementation. Impacts of herbivores at local and landscape level need to be taken in consideration (Gordon & Hester, 2004), since too high grazing densities may reduce the provision of other ecosystem services, such as the maintenance of soil fertility (Mcsherry & Ritchie, 2013), and habitat for other species (van Klink et al., 2015). In addition, it is

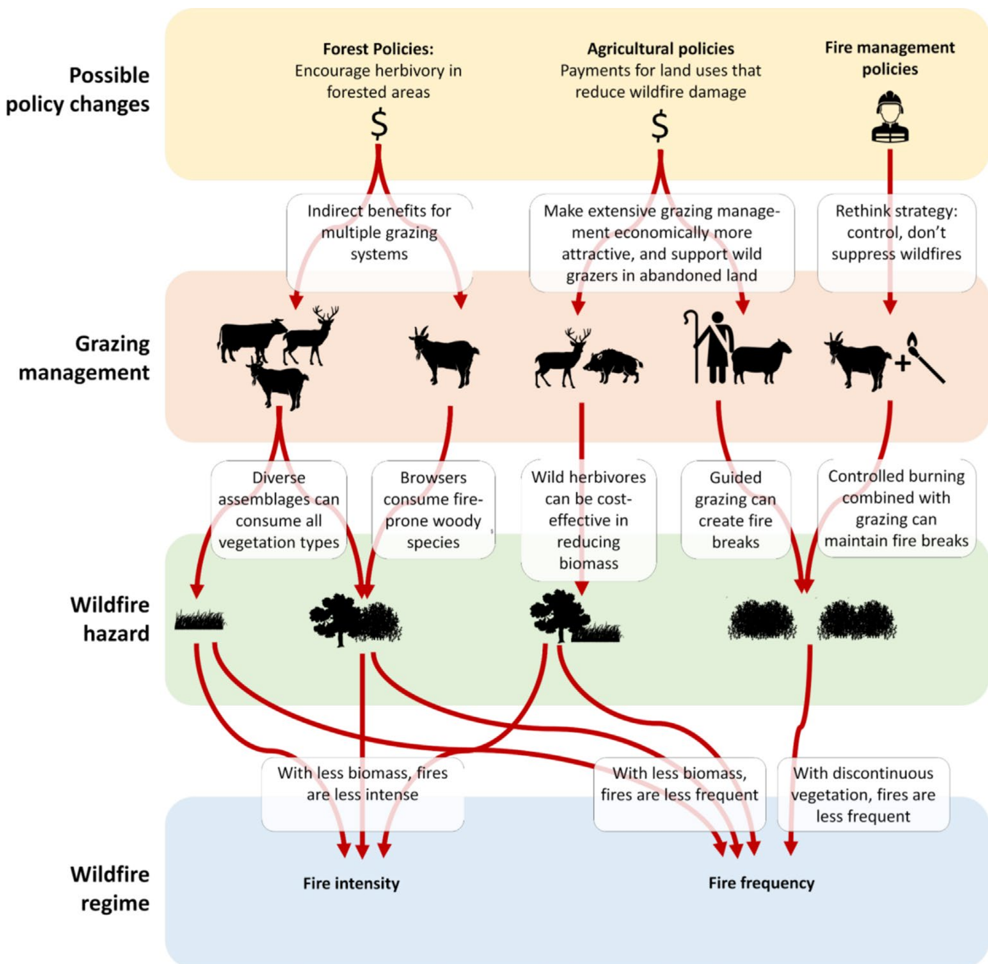

FIGURE 5 Possible (agricultural and fire) policy changes and their effects on wildfire frequency and intensity, through changes in herbivore management

also important to note that wildfires are natural phenomena in many ecosystems, that can have positive effects on, for example, biodiversity and ecosystem processes (Bond & Keeley, 2005). Therefore, complete avoidance of wildfires should not always be the goal. From that perspective, wild herbivore populations, which generally do not have extremely high densities, may be ideal for avoiding highly damaging wildfires, while still allowing natural pyrological processes.

8 | IMPLICATIONS FOR POLICY

Several types of policies have an impact on fires and fire prevention with herbivores. One is fire management policy per se, in which herbivores should be considered as a fuel management tool. Secondly, agricultural and forestry policies deal with livestock and in some cases the management of semi-wild herbivores.

In many parts of the world, including Europe (Montiel-Molina, 2013; Moreira et al., 2020), North America (Kalies & Yocom Kent, 2016; Starns et al., 2019) and Africa (Alvarado et al., 2018; Butz, 2009), management policies are often oriented towards fire suppression rather than prevention (Montiel-Molina, 2013). Fire risk management often deals with prescribed fires and other disturbances, as well as to actions to maintain larger scale heterogeneity—and thereby reducing fire extent and impacts. This requires landscape-oriented planning. There is strong evidence that policies favouring full fire suppression lead to long-term accumulation of fuel and, consequently, broader and more intense fires (Moreira et al., 2020; Tedim et al., 2016). Furthermore, it is important to keep in mind that fires are an integral process in many ecosystems, that can support biodiversity, regulate nutrient flows and maintain certain ecosystem types (Bond & Keeley, 2005), so that full fire suppression is also not desirable from an ecological perspective. Fire policies should therefore adopt a mosaic approach that supports using herbivores as a cost-effective way to reduce fuel loads, in combination with prescribed fires (see Figure 5).

Agricultural and forestry policies can also play a central role in prevention of wildfire, since they shape landscapes, affect the amount of fuel available and can set management regulations that affect ignitions. With a large proportion of Earth's terrestrial area covered by farmland and forestry areas, agricultural and forest(ry) policies can be used much more effectively to address wildfires through these two aspects. First, policies can regulate and promote herbivory in forest and forestry areas. Traditionally, herbivores are often excluded to avoid damages to forests, while they could in turn reduce accumulation of fuel loads and consequently higher fire risks. Second, agri-environmental subsidies could be used to support extensive grazing and low-input farming systems, as well as other practices that can reduce fire risks while promoting other ecosystem services—such as pastoralism or targeted grazing (i.e. high-intensity, short-term grazing in risk zones). Such practices are often economically unviable or unattractive, and are under-funded in terms of agricultural subsidies. Acknowledging and better supporting extensive grazing as means of reducing fire risk in sensitive regions may thus generate a range of benefits including the protection of traditions and cultural values, as well as the conservation of biodiversity (e.g. where abandonment is a common problem, or as an alternative to intensive grazing). In areas that have already undergone land abandonment, policies could encourage recovery of wild animal populations, including reintroducing wild or semi-wild herbivores (San Miguel-Ayanz et al., 2010), to reduce fire risk in a cost-effective way. Payment for ecosystem services provision schemes including fuel management through herbivores for fire prevention can be used to incentivise practices that are beneficial for reducing fire damage through reducing fuel loads and creating fuel breaks (Pe'er et al., 2021).

Jointly with other policy instruments, it is important to incentivise silvopastoral systems that maintain landscapes that are resilient to fire while providing multiple other ecosystem services (Oteros-Rozas et al., 2014). Wood pastures, where grazing and browsing occur together with scattered trees and shrubs, provide biodiverse and attractive landscapes with natural firebreaks (Garrido et al., 2020), and should be supported by policies (Plieninger et al., 2015).

9 | CONCLUSIONS AND FUTURE CHALLENGES

Herbivores have the potential to reduce wildfire risk by reducing fuel loads and changing vegetation structure and moisture. They are most effective when their diets match the vegetation present, and it is likely that multiple species varying in their diets are also beneficial. Considering that many domestic herbivores are grazers, the potential of wild herbivores for this purpose, particularly in a context of land abandonment and rewilding, can be an interesting option to be considered.

While there is available literature on multiple types of ecosystems (Mediterranean systems, savannas, rangelands etc.), some parts of the world are underrepresented considering the prevalence of fire in these systems, especially in countries of the global South (see Figure 2).

Overall, policies and management promoting management with herbivores, especially in areas undergoing land abandonment, can provide nature-based solutions to reduce the frequency and intensity of wildfires and to enhance associated biodiversity and ecosystem services in a changing world.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

AUTHORS' CONTRIBUTIONS

J.R.-L., G.P., F.M. and F.v.d.P. designed the study; J.R.-L. reviewed the literature with help from SAASZ; J.R.-L., A.Z. and F.v.d.P. analysed the data and J.R.-L. wrote the first version of the manuscript; all authors contributed to writing and reviewing the manuscript.

DATA AVAILABILITY STATEMENT

Data available from the Dryad Digital Repository https://doi.org/10.5061/dryad.79cnp5hw1 (Rouet-Leduc et al., 2021).

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