Grazing for wildfire prevention, ecosystem service provision, nature conservation and landscape management

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Grazing by large herbivores has the potential to provide multiple ecosystem services, depending on multiple factors. Through a range of interdisciplinary methods, including literature reviews, case studies, and semi-structured interviews, I seek to assess how grazing can contribute to sustainable landscape management, as well as how sustainable practices can be incentivised.

In chapter one, I focus on the role of grazing in wildfire prevention. Through a systematic literature review, I uncover new insights into the effectiveness of large herbivores in mitigating wildfires. I find that large herbivores can reduce wildfire frequency by promoting grass-dominated landscapes and reduce fire intensity by consuming vegetation and creating landscape features that reduce fuel loads. However, the effectiveness of large herbivores depends on the type of vegetation and diet preferences of the animals, and management practices associated with livestock grazing can also influence fire ignition.

In chapter two, I investigate the relationship between grazing management and ecosystem services through a literature review, focusing on synergies and trade-offs between them. I identify management practices that are beneficial to multiple ecosystem services as well as policy mechanisms that can incentivise them.

In the third chapter, I use case studies to investigate the role of domestic animals in rewilding projects. I describe how domestic and semi-wild herbivores can contribute to rewilding projects and make them more inclusive for rural and indigenous communities.

In the fourth chapter, I aim to identify the challenges faced by land users in performing sustainable grazing management through semi-structured interviews with 88 land users from eight case studies in Europe. I gain insights into land users' determinants of behaviour towards sustainable grazing practices using the Behaviour Change Wheel framework.

Overall I suggest that grazing can be a potential solution to the challenges of the Anthropocene, but only when done in the right way. I emphasize the importance of an interdisciplinary approach in grazing research and considering socio-ecological systems. I also highlight the potential of rewilding and semi-wild grazing systems especially in areas undergoing land abandonment. The results imply a shift in meat production and consumption and potential new pathways for human-livestock relations. Finally, agricultural policies such as the Common Agricultural Policy (CAP) can play a crucial role in incentivizing sustainable grazing management and should be improved to support extensive grazing and extensification.

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i.i.i European grazed landscapes can provide high biodiversity and supply various ecosystem services

i.i.i.i Grazing and grasslands in Europe

Grazing by large herbivores, whether they are wild or domestic, has been an important factor in shaping European landscapes. Both wild megafauna and domestic livestock play a crucial role in maintaining some key ecosystems and ecosystem services. However, not all grazing systems are able to provide ecosystem services in the same way, and under some conditions, grazing or grazers can also be environmentally harmful (Gerber et al., 2013; Garnett et al., 2017). It is clear that, whether the impact is positive or negative, it is a complex issue which is highly dependent on multiple factors. Since Europe is characterised by mostly highly anthropized landscapes, most of the large herbivores present in them are domestic. On the other hand, before the holocene, European landscapes have been shaped by wild herbivores. Important populations of megafauna herbivores impacted the ecosystems, also interacting with abiotic factors such as fires. Megafauna extinctions of the Pleistocene have profoundly changed landscapes that used to be populated by numerous large herbivores (Malhi et al., 2016). In the holocene, this has given way to changed ecosystems with more forested areas and less open landscapes (Svenning, 2002). During the last millenia, agriculture and rearing of domestic animals have shaped anthropized landscapes with fewer wild herbivores and altered fire regimes (Johnson et al., 2018). Thus most of today's grasslands in Europe are used for domestic animal grazing or mowed for haymaking (Pärtel et al. 2005). Grazing management is often conducted with food production as a priority rather than for nature conservation and is often detrimental to biodiversity and ecosystem services (Garnett et al., 2017). A key question is, therefore, what kinds of grazing systems can provide multiple ecosystem services, and how these can be implemented in a European context.

i.i.i.ii Types of grasslands in Europe

In Europe, land management that includes grazing by large herbivores is associated mainly with grasslands. On the one hand, permanent grasslands are defined by the European Union (Lesschen et al., 2014) as grasslands that have management continuity for more than 5 years. They can be natural, semi-natural or so-called "improved". Natural grasslands and semi-natural grasslands have vegetation developed under minimum human interference. They are grasslands that are composed of self-seeded herbaceous plants and shrubs (Lesschen et al. 2014). Semi-natural grasslands are usually associated with low intensity management and are present in different forms across Europe (Schils et al. 2022). They include for example floodplain meadows, upland and alpine hay meadows, limestone grasslands, lowland acid grassland and heathland, steppe grassland, Alpine and other montane rangelands, Mediterranean scrub/grassland mosaic such as Phrygana, Garrigue, Maquis, Dehesa and Matorral, boreal grasslands, etc. They are often considered High Nature Value farming areas. In some parts of Europe these semi-natural grasslands are common lands where different land users can let their livestock graze the land regardless of land ownership. These semi-natural grasslands are amongst the most species-rich habitats in Europe.

"Improved" grasslands are typically intensively managed, by sowing and the addition of fertilisers. They can be permanent grasslands, consisting of mostly perennial grass species, or temporary, sown with annual, biannual or perennial species of forage. Temporary improved grasslands are often integrated in crop rotations and are sown on arable land. Both permanent and temporary improved grasslands are usually used for livestock production for grazing or hay- and silage- making. Their level of management intensity varies in terms of fertiliser application, mowing frequency, sowing, soil disturbance, etc. (Lesschen et al. 2014).

i.i.i.iii Grazing for meat and dairy production

Grazing herbivores and especially ruminants are often reared for meat and dairy production. Human societies have evolved in close relationships with grazing animals, and animal rearing has played an important role in shaping European landscapes. Grazing of herbivores also contributes to maintaining traditional agricultural landscapes such as wood pastures (Plieninger et al., 2015). However, nowadays, meat and dairy production is largely based on intensive production systems, often linked to negative environmental impacts both locally and outside of the EU through telecoupled effects. Telecoupling refers to the interactions and feedbacks that occur between distant systems that are linked through flows of goods or other factors. In the context of livestock, telecoupling refers to the ways in which the production, consumption, and trade of livestock in one region can have far-reaching effects on social, economic, and environmental systems in other regions. These effects may include, for example, changes in land use for production of feed crops, water use, greenhouse gas emissions, biodiversity loss, and socio-economic inequalities in both the production and consumption regions (Hull & Liu, 2018; Laroche et al., 2020; Lenschow et al., 2015). High demand and consumption of meat and dairy products, as well as policy incentives supporting intensive production of these, put pressure on production systems and, with them, on landscapes and ecosystems. Notably, by now, only a small fraction of them are based on extensive, pasture-based animal products and very large farms with more intensive practices account for 71.4% of all the animals being reared in the EU (Eurostat, 2018). While herd numbers are declining in Europe, consumption of meat is still very high compared to other regions of the world (68 kg per capita, OECD/FAO 2021); and in parallel, much of European production is exported to other parts of the world. Around two thirds of croplands in Europe are used for animal fodder (Alexandratos and Bruinsma, 2012), and much of the feed consumed by animals in Europe is imported from outside Europe, with some crops being fed almost only to animals. For example, 80% of the soy grown globally is fed to livestock (Stoll-Kleeman and O'Riordanet, 2015). Multiple reports and studies have established that meat consumption especially in high income countries of the global North is unsustainable (Stoll-Kleemanand and O'Riordanet, 2015; Röös et al. 2017; van Zanten and Herrero, 2018), beyond planetary boundaries (Bowles et al., 2019) and not compatible with a fair food system (Willet et al., 2019). Thus, a key issue is to identify the types of grazing systems that can fit into sustainable and fair agricultural and food systems.

i.i.i.iv Grazing beyond meat production: other ecosystem services

Grazing animals are able to provide numerous ecosystem services beyond the provision of meat and dairy products, but this ability depends on multiple factors such as management intensity, grazing density, environmental and climatic factors, and more (Garnett et al., 2017). While trends of decreasing livestock numbers in Europe are projected to continue (Eurostat, 2018), there is also a need

to maintain important landscapes and habitats related to grazing, for example in high nature value areas (Kun et al., 2021; Oppermann et al., 2012).

While numerous studies have explored the linkages between livestock grazing and grazing intensity with biodiversity or plant biomass (Byrnes et al., 2018; Gao & Carmel, 2020; Herrero-Jauregui & Oesterheld, 2018; Mcsherry & Ritchie, 2013; Piipponen et al., 2022; Zhou et al., 2019), effects of other types of grazing systems' (e.g. rewilded systems) impact on ecosystem benefits are largely understudied. In this thesis, I focus on ecosystem services (and disservices) provided by grazers, be it domestic, semi-wild or wild animals. Land-use change related either to intensification or abandonment (see section i.i.ii.iii), including afforestation and conversion to cropland threatens some of the most valuable grasslands of the continent, including semi-natural grasslands and grazed forests systems (Kun et al. 2021). Protecting these grazing lands from either land abandonment, intensive management or land-use change towards for example afforestation or cropland requires extensive management with grazers, either domestic or wild. A first key issue that is guiding this thesis therefore lies in identifying **what type of grazing management, by domestic, wild or semi-wild animals, can provide multiple ecosystem services**.

i.i.i.v The rise of rewilding as landscape management

Rewilding is a form of nature restoration that has gained popularity in the past years (Carver et al., 2021; Lorimer et al., 2015; Root-Bernstein et al., 2018). The concept as well as first projects emerged in North America but has been gaining traction in Europe (Navarro and Pereira, 2012) amongst the research community and practitioners (Ceausu et al., 2015; Jepson, 2016). Rewilding aims at promoting the restoration of self-sustaining and complex ecosystems, with interlinked ecological processes that promote and support one another while reducing human intervention. One of the theoretical bases of rewilding is to return ecosystems to a "self-wiled" state with trophic complexity, dispersal and connectivity and stochastic disturbance regime (Perino et al., 2019).

i.i.ii Challenges for European grazed systems

Land management and agricultural practices are especially important in a context of multiple crises that characterises the Anthropocene. Indeed, it is particularly relevant to identify how multiple ecosystem services can be provided by grazing in this context. Here, I will explore sustainable pathways for grazing management in Europe. In particular, I will explore how large herbivores can contribute to the provisioning of ecosystem services and biodiversity and how it can be part of nature-based solutions to the challenges of the Anthropocene. I thereby expand the current state of knowledge on grazing and rewilding with large herbivores. While the livestock sector has been designated as one of the most significant contributors to the most pressing environmental issues (Garnett et al., 2017), such as greenhouse gas emissions (IPCC, 2021), land use changes, deforestation and land degradation (IPBES, 2016), grazing represents a key leverage in addressing these. In the light of the current existing climate and biodiversity crises, it is urgent and important to explore what kind of livestock and semi-wild grazers are desirable and sustainable. Here I delve into key ecosystem services that were the core of this thesis

i.i.ii.i Climate change and grazing

On the one hand, livestock is an important contributor to climate change through direct emissions from animals, as well as through driving land-use change related to animal rearing and land degradation from overgrazing (Gerber et al., 2013; Garnett et al. 2017). On the other hand, grasslands can act as carbon sinks and store large quantities of carbon, depending on management and land-use. Grazing can potentially contribute to carbon storage by stimulating plant growth and increasing belowground organic carbon matter contents. The potential of carbon sequestration is, however, limited in time. Domestic livestock systems with ruminants especially are an important contributor to the release of methane in the atmosphere and are driving large scale (often telecoupled) land use changes that are responsible for important release of CO2 in the atmosphere. Indeed, the livestock supply chain is contributing to about 14.5% of global anthropogenic emissions (Gerber et al. 2013). This includes emissions linked to multiple aspects of livestock production such as ruminant enteric fermentation, feed production effects, as well as livestock-induced land use change. When looking at a European context, large parts of cattle-induced emissions are linked to telecoupled effects in other parts of the world where feed is produced and imported (Fuchs et al., 2020).

i.i.ii.ii Emerging wildfires threat

While the role of grazers in providing ecosystem services such as milk and meat is largely acknowledged, their role in providing regulating and cultural ecosystem services is not much recognized. For instance, wildfire prevention through grazing in the Mediterranean Basin is an important regulating ecosystem service that is increasingly important in the light of climate change. Extreme weather events such as droughts, floods and fires are already causing important damage globally, and in Europe such events are projected to increase in frequency in the future (IPBES, 2019). The past decades have already witnessed a rise in extreme climatic events such as floods and wildfires (IPBES 2019). Fires are a natural disturbance in many ecosystems that are associated with recurrent large or low intensity grazing, but nowadays fire regimes are heavily influenced by anthropogenic drivers. However, climate change and some land-use change patterns are driving an increase in wildfire events and extent, causing damage to ecosystems and human infrastructure, and risking lives. Wildfires,which are uncontrolled fire in the vegetation of an area, are intimately intertwined with grazing issues since their intensity depends largely on the amount of vegetation or fuel available and grazed areas such as grasslands are much less likely to have fires turn into wildfires (Moreira et al., 2020). In Europe, there are concerns that decline in livestock numbers as well as pastoral practices have caused large scale shrub encroachment which increases the amount of fuel and thereby the risk of wildfire in case of ignition. Moreover, some activities linked explicitly to livestock rearing have given way to other activities that are more economically viable such as tree plantations, for example Eucalyptus tree plantations in the Mediterranean, that are generating much fuel and risks for large-scale fires.

Both plantation expansion and forest closure, and the lack of grazers (or even their exclusion) in both, are generating the conditions for fire ignition and rapid expansion. Under these circumstances, it is very important to facilitate landscapes that are resilient to climate change and that can even mitigate the effect of extreme weather events. Wildfires of exceptional intensity have impacted different areas of the world, including Europe, and these are largely due to climate and land use change patterns (Duane, 2021). With a growing concern for large wildfires as an emerging risk, and the urgency to find nature-based solutions to climate change, grazing with large herbivores can potentially play a

role in mitigating extreme weather events such as wildfires. However, to date **there has been no systematic review on the role that grazing by large herbivores could play in wildfire mitigation. Providing such a synthesis is a second key issue of this thesis.**

i.i.ii.iii Land use change

Another set of challenges for European landscape are the two main contrasting trends characterising the management of agricultural landscapes, namely intensification and abandonment. Agricultural and grassland intensification has been an important trend in Europe, especially in newer member states of the EU, facilitated by production-oriented systems and policies (Pe'er et al., 2020; Schils et al., 2022). More specifically, landscapes in Northwestern and much of central Europe are quite intensely used, with little expansion but either intense or intensifying grassland use (Schils et al., 2022); whereas processes of expansion and intensification are taking place primarily in new member states. Land-concentration is another relevant phenomenon, with less farmers owning or managing larger areas (Eurostat, 2018).

In parallel, due to multiple environmental, socio-economic and technological factors, large parts of the EU agricultural lands are being abandoned (Lasanta et al., 2017; Moreira et al., 2011; Maes et al., 2020). These farmland abandonment processes have multiple drivers, both social, economical and ecological. Environmental and ecological factors are important drivers of agricultural land abandonment, for example impoverished soils, remote areas, slopes or droughts (Ustaoglu & Collier, 2018). Large scale land abandonment also happened in Eastern Europe's post-soviet countries when after the collapse of the communist regimes, agricultural lands were returned to farmers but many had emigrated to cities in the meantime.

These land use change processes, in combination with the challenges of climate change and extreme climate events, pose the question of how grasslands should be managed to mitigate these risks and preserve land uses that provide high biodiversity and multiple ecosystem services. In the face of multiple crises, there is an urgent need to protect and restore grasslands and grazing systems. First, these need to be identified in a European context and explore the type of management that provides multiple ecosystem services. These processes shift the European landscape away from any known baseline, raising the question of what type of land use, and especially what type of grazing management should be prioritised to deal with sustainability challenges and crises. Hence, **a third goal of my thesis is to find out whether rewilding can represent an opportunity for land management provisioning multiple ecosystem services**, especially in areas that have undergone agricultural abandonment in grasslands. Also, multiple factors impact land management and land use change, and **a fourth key issue is to assess how policy influences and drives decision-making on land management at multiple levels**.

i.i.ii.iv Policy and land management

With around 40% of the surface of Europe being used for agriculture (including croplands used for livestock feed production) and around 14% being grasslands, how these areas are managed is extremely important for the sustainability of the European continent. Agriculture being an important driver of biodiversity decline and associated ecosystem services (Pe'er et al. 2022), agricultural policies

are a crucial leverage point to mitigate biodiversity loss. Indeed, it is estimated that around 76% of terrestrial biodiversity losses caused by agricultural activities in Europe are linked to livestock rearing (Leip et al. 2015). In the EU, several policies serve as important factors shaping landscapes and farmer decisions regarding on-the-ground practices. Among them, the Common Agricultural Policy (CAP) has been an important driver of land use change and changes in farming practices in EU member states (Van Zanten et al., 2014). Indeed, the CAP was originally created to incentivize and assist an increase in agricultural production through supporting prices and import and export subsidies. The CAP also supported development of agriculture towards increasing yield and production; and its main role remains to support farmers being farmers - mostly through income support mechanisms ("Direct Payments"; Lefebvre et al., 2015). Some instruments of the CAP have been incentivising intensification of agriculture and favouring fewer but larger farms. Production-based agricultural subsidies, such as coupled payments, incentivize increasingly intensively-used croplands and grasslands (Navarro & López-Bao 2019; Pe'er et al. 2020). Moreover, the CAP supports intensive use of non-organic fertilisers, herbicide and pesticide. In the more recent reforms of the CAP, however, measures have been introduced to limit the negative impact of agriculture on the environment (Pe'er et al., 2022), including cross-compliance, and voluntary measures such as agri-environmental climate measures (AECM). Other policies that are relevant to grazing are the nature directives, water framework and nitrate directive. Also, the EU Green Deal and its Farm-to-Fork strategy is aiming at making European food systems more sustainable and resilient.

Multiple instruments in the CAP can influence grazing management and therefore the ecosystem services provided by the grazing systems. A new period of the CAP covering the period 2023-2027 is providing new instruments affecting grasslands and grazing management. The new CAP has several components that can affect land users in different ways.

Firstly, Pillar I provides financial support to farmers based on the amount of land they own and the practices they implement, in the form of so-called Direct Payments. A newly installed instrument, named eco-schemes, requires Member States to reserve a minimum of 25% of their Pillar I budget for environmental and climate-related measures. Eco-schemes offer additional payments to farmers who adopt sustainable practices, such as organic farming or the reduction of fertiliser use, on top of the compulsory requirements set by cross compliance. Since 2023, the CAP has expanded the conditionality requirements that farmers must meet to receive direct payments, known as GAEC (Good Agricultural and Environmental Condition) standards. The GAEC requires for example farmers to maintain a minimum soil cover, limit soil erosion, and avoid excessive use of fertilisers and pesticides. The GAEC 1 and 9 are especially relevant to grassland conservation with the GAEC 1 addressing the issue of amongst others grasslands conversion and the GAEC 9 addressing the safeguarding of species and habitats in Natura 2000.

The Pillar II of the CAP provides funding for rural areas in order to support rural development, promote local economies, and protect the environment. The 2023-2027 CAP includes six policy objectives for rural development, such as enhancing the competitiveness of agriculture and promoting resource efficiency and climate action. The funding available under this pillar has increased for the 2023-2027 period, and Member States have more flexibility to tailor their rural development programs to local needs. Also, Member States are required to set aside a minimum of 25% of their Pillar II funds for Agri-environmental Climate Measures (AECM).

The CAP and its different instruments have the potential to impact positively or negatively the sustainability of land users' practices and the CAP post 2023 presents opportunities for encouraging sustainable farming. However, it is important to understand the potential uptake of CAP instruments and their application by member states as well as their consequences for different land users. Previous studies have found that the CAP was not encouraging sustainable practices and fostering biodiversity (Kindvall et al. 2021), but it is uncertain how land users are affected in their grazing management in different European contexts. One of the aims of this thesis is finding out how the CAP promotes or hinders sustainable grazing practices.

In the context of the crises and challenges described in the previous section, policy plays an important role in steering land use and land management practices. Indeed, having landscapes that are resilient to catastrophic weather events, as well as having the potential to mitigate climate change is desirable. There are multiple factors allowing and encouraging land users and farmers to engage in sustainable farming including for example economic incentives (Kabii and Horwitz, 2006), regulations (Koundouri et al., 2009), social context (Burton, 2004) and more. While there are previous studies exploring land use decision factors (Baumgart-Getz et al. 2012; Belknap and Saupe, 1988; Dwyer et al. 2007; Lynne et al., 1988), there are few looking specifically at motivations for different grazing-related management practices.

i.ii Thesis methods and outline

i.ii.i Literature reviews (chapters 1 & 2)

The first two chapters of my thesis are based on a literature review. The fields of sustainability and land management research are experiencing a rapid increase in knowledge production, yet knowledge and findings are fragmented and scattered across disciplines. Therefore, literature reviews as a research method is highly relevant, especially in interdisciplinary research. Literature reviews involve a systematic approach to gathering and analysing previous research, and represents a strong basis for synthesising knowledge (Baumeister & Leary, 1997; Snyder, 2019). By combining findings from various fields, the literature reviews I conducted are able to provide interesting and novel insights that require synthesising knowledge from several fields.

The first chapter is a systematic review that uses the PRISMA literature search framework (Moher et al., 2009) and seeks to synthesise the impacts of different types of grazing on wildfires. In the second chapter, instead of a systematic literature review, I prioritised using other reviews and meta-analyses, as the scope of my study was much broader (i.e. effects of grazing management on biodiversity and multiple ecosystem services), making an exhaustive, systematic literature review unfeasible. In cases where existing reviews left knowledge gaps, I supplemented these reviews with individual studies, which were identified through a more targeted search.

i.ii.ii Case studies (chapters 3 and 4)

The other two chapters of my thesis are based on case studies.

In chapter 3, I use four case studies to illustrate and inform how domestic livestock has been used more or less successfully in rewilding projects, in order to show how the approach of rewilding can exist in different contexts. It is a perspective article using multiple case studies to inform and generalise guidelines for the using of domestic livestock to maintain or restore key processes for rewilding. The third chapter is a conceptual study that characterises the relationship between livestock and rewilding and how domestic breeds of herbivores can fit into rewilding projects. Here, case studies were used for illustrating some key concepts in rewilding. Here I used a so-called descriptive case study approach, which is defined as "an empirical inquiry that investigates a contemporary phenomenon in depth and within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident" (Yin, 2009).The aim of the study is to provide a new proposition of how grazing by large domestic herbivores can fit into rewilding projects. Within this proposition emerges the concept of 'Rewilding Lite', that offers a nuanced definition of the application of the rewilding concept. While case studies in this chapter can provide an interesting qualitative overview of the different aspects of how domestic livestock fits in rewilding, the emergence of this research concept requires further and complementary research, addressed to some extent in chapter 4, regarding how to incentivise sustainable grazing practices, and facilitate management with semi-wild herbivores.

The final chapter is based on 88 interviews that were conducted within my PhD. The interviews were conducted within the project GrazeLife, an EU Life Preparatory project that aims at improving implementation possibilities of different grazing models – both by domestic and wild/semi-wild herbivores – to identify the most effective means to promote wildfire prevention, climate adaptation, the provision of multiple ecosystem services. The project also aimed at promoting landscape and nature conservation, and to minimise human-wildlife conflicts, by maintaining long-term stable and resilient ecosystems. The project provided case studies from partners from the Rewilding Europe network that are described in the following section (i.ii.ii.ii).

A particularity of these interviews is that they were conducted by project partners within the GrazeLife project and not by myself. The main reason for this approach is first and foremost a language barrier and the necessity for interviews to be conducted in the respondents native language. I however developed the interview guide and coordinated the interview process with project partners in the field. I designed the interview guide early in the project and from the start adhered to the epistemic principles of phenomenology by which the subjective lived experiences of respondents were inquired (Smith et al., 1999). The interviews were designed as semi-structured, open-ended interviews and test interviews were conducted early in the project and put through an iterative process after feedback from interviewers (Flick et al. 2014). These interviews provide insights into the land users experiences, practices and attitudes in regards to their land use practices. The interview guide was organised around several sections, the first part sought to apprehend the participants' background and the nature of their activities in relation to land management. The second part addressed the challenges of the land management and potential human-wildlife conflicts. The third part addressed their decision-making drivers in relation to grazing activities and how these were incentivised. A final part of the interview gathered more quantitative information about land practices to be able to compare the practices of the different land users. The interviews were transcribed and translated by project partners in the GrazeLife project. A sample of interview transcripts were double coded then organised by themes. (Smith et al., 1999). I analysed the results with the help of the Behaviour Change Wheel. The Behaviour Change Wheel (BCW) framework was originally designed for implementing behaviour change

interventions. It was developed on a synthesis of different behaviour change frameworks (Michie et al., 2011). The framework consists of three layers. The "COM-B" model, which describes the three essential components of behaviour: capability, opportunity, and motivation, which I used to analyse the decision-making drivers of land users in conducting sustainable practices. The second layer is the "intervention functions," which describe the types of interventions that can be used to change behaviour and the "policy categories," which describe the types of policies that can be used to support behaviour change interventions (Michie et al., 2011). The Behaviour Change Wheel provides a systematic approach for understanding and addressing the barriers to behaviour change which was very useful in providing a comprehensive overview of decision-making drivers as well as to be able to provide specific recommendations for policies.

i.ii.ii.i Case studies for chapter 3

Swedish Lapland

The first case study explores the initiative, launched in 2015 by Rewilding Europe, Rewilding Lapland, launched in 2015 by Rewilding Europe (since renamed Rewilding Sweden). This project encourages a new economy based on the cultural landscape of Saami and the Laponia region, that stretches over the north of Sweden and Norway. The area is populated by the First Nations Saami people and herding of semi-domesticated reindeer is an essential part of the landscapes. This case study was selected because it is one of the only rewilding projects in Europe that includes indigenous population and provides interesting insights in how rewilding can be combined with First Nation People's interests (Koninx, 2018; Rouet-Leduc & von Essen, 2019). It was also selected because of my previous research experience in the area that allowed me to gain a good understanding of the project through interviews with stakeholders (Rouet-Leduc & von Essen, 2019).

Coa Valley, Portugal (also used as a case study in chapter 4, where I coordinated stakeholder interviews for this region)

The Côa Valley is located in the North East of Portugal, in a rural area with a Mediterranean climate. The area has been undergoing land abandonment and rural depopulation in the past decades. The abandoned agricultural lands have often been used for afforestation for timber production or left abandoned and therefore with ecological succession processes. Both abandonment and afforestation create problematic landscapes with increased risk of wildfire because of abundance of fuel and homogenization of landscapes. In the Faia Brava reserve, semi-wild living horses and cattle are living in a rewilding reserve that was created on former agricultural land to recreate a mosaic landscape. This project aims at fuel management for fire prevention, but also more generally for landscape conservation and for contributing to ecotourism activities of the area (DeSilvey & Bartolini, 2019). This case study was selected since it illustrates the rewilding opportunities in post-agrarian landscapes due to land abandonment in the Mediterranean basin.

Knepp Estate, England

The Knepp Estate is one of the most famous examples of rewilding in Europe, stretching over 1,400 ha of former farmland, and home to numerous wild-living herbivores. The reserve focuses on creating a rewilding area that is not determined by the conservation of a specific species or habitat, but rather

by the restoration of natural processes and the use of large herbivores as keystone species to achieve this vision. In the area also practises of ecotourism activities are organised, as well as sales of premium meat products. This case study was selected since it provides an interesting and unique example of combining rewilding and agricultural practices (Overend & Lorimer, 2018).

Oostvaardersplassen, Netherlands

Oostvaardersplassen is one of the most famous, influential but controversial, rewilding projects in Europe and in the world. The reserve is about 6,000 ha of wetlands, grasslands with some trees and shrubs, surrounded by human dominated landscapes with limited no connectivity to other natural areas. Up until recently the reserve had a completely hands-off approach of managing the animals, with very high densities of cattle, horses and red deer living in the reserve. This case study was used in the study because it embodies a good example of a completely hands-off management approach to rewilding with large herbivores (Lorimer & Driessen, 2014).

i.ii.ii.ii Case studies of Project GrazeLIFE used in chapter 4

The Border Meuse (Netherlands/Belgium)

This case study is focused on a cross-border nature reserve that stretches along the Meuse river, at the border of Belgium and the Netherlands. Semi-wild living horses (Konik) and bovines (Galloway) are grazing there and managed by a collective of farmers from the area. It represents a good example of a nature reserve being managed with natural grazing of semi-wild grazers, and recreation and ecotourism activities are conducted in the area. It is also a good illustration of challenges that can be faced by nature managers and land users when conducting rewilding with large herbivores. The animals are living outside year-round in social herds without supplementary feeding and are rarely treated with deworming medicine and only in a targeted way when they are sick. This area was also a great display of the challenges that managers of nature reserves with semi-wild grazers are faced with when doing their management.

Rhodopes (Bulgaria)

The Eastern Rhodopes Mountains is situated in the South of Bulgaria, they are a low mountainous area with traditional mosaic landscapes of semi-open areas, shrublands and forests. Animal rearing is an important activity, and like in many other parts of Europe, the area is undergoing agricultural land abandonment. Traditional grazing activities include year-round low intensity grazing, sometimes with transhumance. Most of the participants interviewed in this area were practising some sort of pastoralism, very extensive grazing or semi-wild grazing practices. Participants interviewed in this area were also using traditional rustic breeds of grazers such as Rhodope Shorthorn cattle or Karakachan sheep. This case study is interesting inasmuch it presents the challenges and opportunities for land users practising grazing that could be defined as naturalistic or semi-wild, with animals living in social herds without fenced enclosure. These interviews allowed us to understand the challenges of practising natural grazing while complying with rules and regulations on nature conservation but also on criteria to obtain CAP subsidies. In a context where national policies encourage intensification, land users face challenges to combine their extensive practices with requirements for infrastructure and fencing, as well as veterinary and management regulations.

Galicia (Spain)

The Spanish case study is situated in the region of Galicia. Like in the other case study areas, the landscapes are characterised by a combination of land abandonment processes and development of afforestation activities, in this case often with Eucalyptus plantations. Otherwise, Galicia is reputed for the presence of wild living ponies that live in the mountain ranges and are brought down to villages annually for a highly cultural event, the *curros*. This case study included two different areas with on the one hand Serra do Xistral, a heathland with a combination of extensive cattle grazing and wild ponies grazing on communal land. On the other hand, Serra da Groba is an area characterised by heathland and afforested areas with mostly wild pony grazing combined with little extensive cattle grazing activities. The area has been affected frequently by wildfires in the past decades, and it is characterised by tension around land use between extensive cattle grazing, pony grazing, and afforestation.

Velebit Mountains/Lika Plains (Croatia)

This area, like the of the rural parts of Croatia, has undergone a lot of socio-economic changes after accession to independence in 1990. Rural depopulation, land abandonment and agrarian poverty characterise a lot of the area of the case study. Different types of land users are present in the landscapes. On the one hand, large cattle and dairy farms land users and some family farm owners are often more educated and easily access CAP subsidies. On the other hand, some farms are practising traditional grazing methods, often very extensive, that are more oriented towards subsistence agriculture and rarely access subsidies.

Danube Delta (Romania/Ukraine)

The Danube Delta area is mainly composed of the Danube Delta Biosphere reserve, established in 1998, including the Romanian and the Ukrainian side of the Delta, with other more traditional management outside the reserve. This case study includes different types of grazing management; extensive grazing with animals being stabled parts of the year and subsidised by agri-environmental schemes as well as semi-wild grazing, amongst other with cattle and feral horses (for example in the Letea forest). The case study is particularly interesting since it stretches over two different countries, including Ukraine which is not part of the EU. The Ukrainian side has more semi-wild grazing management while the Romanian side has more land users practising extensive grazing and having to comply with CAP and veterinary regulations.

Oder Delta (Germany/Poland)

The Oder Delta area is situated at the border of Germany and Poland. The area has witnessed a decline in livestock rearing activities in the past years. It has led to both abandonment and succession but also in some cases to changes to other land uses instead of extensive grazing, amongst other intensive crop cultivation. This area is also an interesting case as it presents another example of transborder comparison. Its geographic location as well, on a delta, represents an interesting example since there is a potential for rewetting former agricultural land, leading to changes in subsidies compensations for land users.

Lithuania

Finally, the Lithuanian case study was a bit special in the way that it did not concern a specific area within the country like for the other cases, but has been focusing on the country as a whole and interviews were done with a sample of land users in different parts of the country. The general trend in the agricultural sector is that farm size is increasing while the number of animals is decreasing, the general trend being a decrease in grassland area. The land users that were interviewed practised extensive grazing, sometimes in addition to mowing. Like in many other of our case studies, the livestock sector faces challenges of rural depopulation, ageing of population and lack of workforce willing to work in these sectors.

These case studies offered insight into the land users challenges and incentives in practising sustainable management. They also shed light on how wild and semi-wild grazing can be interesting alternatives to provide the same type of ecosystem services as domestic herbivores.

i.ii.iii General approach and methodological considerations

My thesis is highly inter- and transdisciplinary in nature. Transdisciplinary research in collaboration with practitioners and non-governmental organisations allows for a focus on societally relevant issues and to identify real world solutions (Lawrence et al., 2022). In order to link land management practices with implementation at different levels, it was therefore relevant to take a transdisciplinary approach to these issues in order to have an understanding of the impact of multiple grazing systems on ecosystem services but also how to incentivize identified practices that provide ecosystem services. Sustainable grazing practices can and need to be encouraged at multiple levels to address the different decision-making drivers. Policies facilitating and incentivizing good practices are important, as well as policy uptake from land users/farmers/local governments. However, this approach is not devoid of challenges and it was a personal and academic challenge to navigate several disciplines that are far from each other. Successfully navigating interdisciplinary research has required methodological groundedness and epistemological agility to produce quality research (Haider et al., 2018). Traditionally, trans- and interdisciplinary research tended to be more grounded in a discipline and stepping outside of it for the requirements of specific research, while in the recent years, more and more research focuses on an interdisciplinary approach without necessarily developing the same strong disciplinary roots (Haider et al., 2018). Especially in sustainability science, where complex human–environment problems require an approach beyond disciplines, a trans- and interdisciplinary approach is particularly useful. In fact, this thesis could even be defined as “undisciplinary” research. The term Undisciplinary research was proposed to define “problem-based, integrative, interactive and emergent, reflexive and involving strong forms of collaboration and partnership.” (Haider et al., 2018; Robinson, 2008). This term seems to be very suitable for integrative research as used in this thesis.

i.ii.iv Research aims and questions

My research aim was to obtain an overview of how grazing management in Europe can contribute to multiple ecosystem services. I provide novel insights both on the different practices and management associated with grazing, as well as how these practices can be implemented and incentivised. The novelty especially lies in the inclusion of grazing systems beyond livestock systems, including rewilding systems and semi-wild grazing systems for comparison. Moreover, Using interview

data from land users in different contexts in Europe, I provide a comprehensive overview of land users' challenges and motivations regarding sustainable grazing practices. Using a transdisciplinary approach throughout my different chapters, I seek to provide insights that provide knowledge for filling gaps in this field as well as inform policy makers and practitioners. More specifically, my thesis is structured around four chapters that address the following questions:

i) Under which conditions, and by what mechanisms, can grazing mitigate wildfires?

ii) How does grazing contribute to multiple ecosystem services and what are the trade-offs and synergies between them?

iii) What could facilitate rewilding with large herbivores?

iv) What motivates land users to engage in sustainable grazing practices and what are the drivers and barriers, or challenges, in doing so?

The thesis combines literature reviews and interviews with land-users in eight case studies (described in Chapter 4) to generate a holistic and broad overview of how grazing systems can provide ecosystem services in a contrast-rich continent like Europe. In turn, I aim to improve our understanding of how large herbivores can impact wildfires in their ignition, intensity and frequency and the implications for policy making regarding fire prevention. Moreover, I explore how multiple ecosystem services have trade-offs and synergies in a European context. Finally, using the behaviour change wheel, I characterise what factors affect land users in their grazing management and how to incentivise good practices in different European contexts.

i.ii.v Thesis outline

In **research chapter 1**, to address the knowledge gap with regards to large herbivores' ability to mitigate wildfires and impact fire regimes and in turn, if grazing could be used as a fire mitigation strategy. In this chapter, I review the literature on grazing and wildfire prevention.

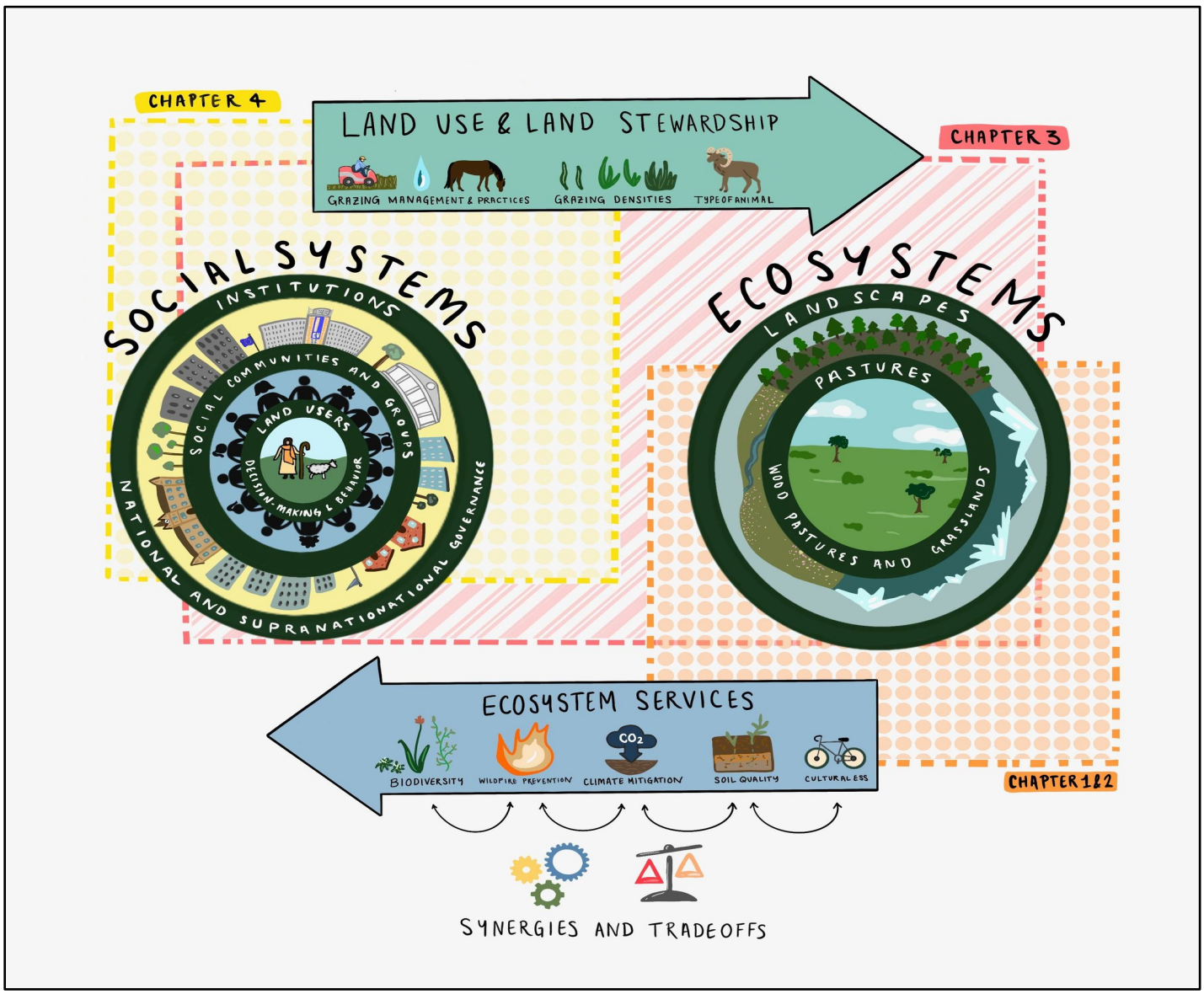
I explore different pathways by which grazing by large herbivores affects fire regimes. This chapter takes a global scope, and a systematic review approach, in order to provide a comprehensive overview of the different impacts large herbivores can have, and a global scope allows me in turn to make recommendations for Europe. My review suggests that large herbivores can impact fire frequency, amongst others by promoting and maintaining grass-dominated ecosystems. Furthermore, grazing can impact fire severity and intensity, mostly by affecting the amount and structure of fuel available for fire. Also the impact grazers can have on fuel depends on diet preferences of the animals as well as characteristics of the vegetation. I also show that the management practices associated with grazing can impact fire regimes in multiple ways, for example affecting the frequency of fire ignition. I conclude the chapter by discussing the possible implications of my findings in a context of growing wildfire threats and land abandonment, especially the possibility of using rewilding as an alternative to traditional livestock management in abandoned areas. I also provide policy recommendations that can facilitate good management for wildfire prevention.

In **research chapter 2** I expand the view toward a larger number of ecosystem services (and disservices) provided by different grazing systems, bringing the focus to a European context. Here the aim is to define what types, and levels, of grazing can be defined as "sustainable". In this chapter I focus specifically on habitat provisioning for biodiversity, climate change mitigation, soil quality, moderation of extreme events and cultural services. Although there are many more ecosystem services that are provided by grazed systems, I chose to focus on these five services because of their high importance for both local and global stakeholders and their complementarity with respect to each other. I explore ecosystem services synergies and tradeoffs arising from different grazing management characteristics and associated practices. I provide an overview of how different grazing management types deliver ecosystem services in different European bio-climatic conditions. I continue by discussing the management and policy implications of such findings, especially identifying which instruments of the Common Agricultural Policy can promote grazing systems that can deliver multiple ecosystem services.

In **research chapter 3**, using four case study examples in Europe where domestic livestock is used in grazing practice, I explore how rewilding can serve nature conservation aims by being adapted to local contexts and include domestic livestock. Reflecting on an approach of "rewilding lite", I provide examples of how semi-wild or domestic livestock can be used in rewilding projects, in a way that provides higher acceptability for rewilding and that is closer to traditional practices. I argue that using domestic or semi-domestic animals in rewilding projects can appear to be in opposition to some of the definitions of rewilding, as far as rewilding involves the restoration of self-willed ecosystems, but that using some lighter version of rewilding can allow to dedicate more land to rewilding and nature conservation. Also, using domestic rustic and hardy breeds can ensure that traditional livestock herders are involved in rewilding projects and that these contribute positively to the overall socio-economic context of rural areas. This approach of the concept of rewilding based more on a land-sharing approach to nature conservation also allows for indigenous animal husbandry practices to be part of rewilding efforts.

In **research chapter 4**, I build on the knowledge gained from the previous chapters, particularly on the practices that can be considered as sustainable grazing, to address the question of what motivates land users to engage in sustainable grazing practices and what are the drivers and barriers, or challenges, in doing so. This chapter is based on semi-structured interviews, conducted within the GrazeLife project with 88 land users in eight case studies (see section i.ii.ii.ii). Using this rich dataset I explore the factors that facilitate or hinder engagement in sustainable practices among land users. The case studies represent contrasting environmental and socio-economic contexts, allowing me to focus on land users practising very extensive grazing or managing semi-wild herbivores, amongst others in rewilding projects. I use the COM-B model ("capability, opportunity and motivation-behaviour") to identify key drivers and barriers of land users' sustainable grazing management decisions. I find that socio-economic factors such as land abandonment and rural exodus, especially in parts of South and Eastern Europe, impact land users' decisions. Furthermore, challenges linked to the environment are particularly important in remote areas. I also found economic aspects to be important in driving land-users decisions, especially fiscal measures of the Common Agricultural Policy. Finally, engagement in sustainable grazing practises often is motivated by wishes for nature conservation, intergenerational continuity and cohesion in the rural community. Identifying drivers of sustainable grazing management allows me to explore what type of policy can encourage or hinder sustainable practices

i.iii Graphical abstract



Graphical abstract of the thesis: representation of grazing systems as socio-ecological systems

1. Chapter One

This chapter was published as article: **Rouet-Leduc, J**., Pe'er, G., Moreira, F., Bonn, A., Helmer, W., Shahsavan Zadeh, S. A. A., Zizka, A., & van der Plas, F. (2021). Effects of large herbivores on fire regimes and wildfire mitigation. *Journal of Applied Ecology*, 58(12), 2690–2702.

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 1:1) 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 1:1). 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 1:1). 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.

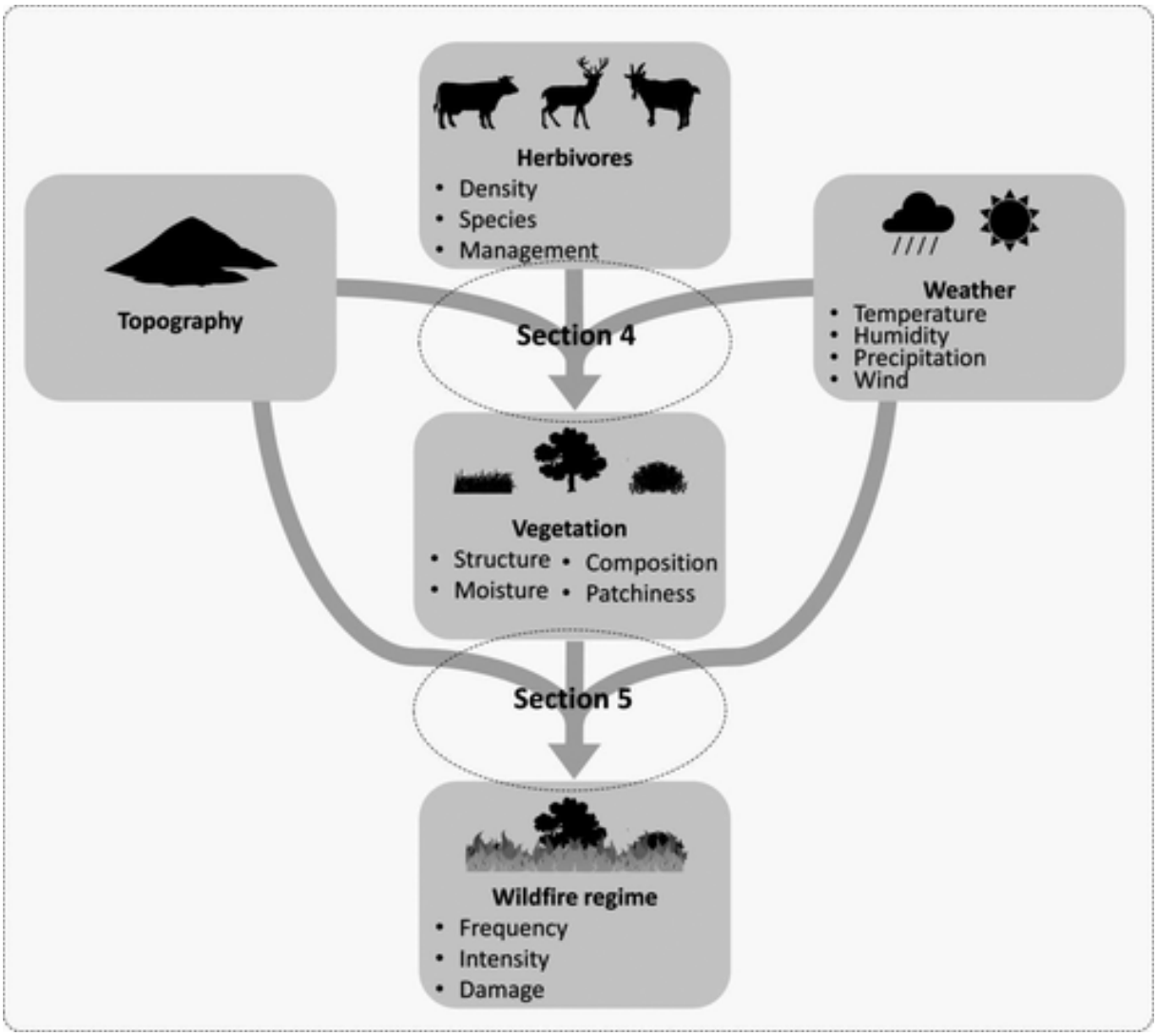


Figure 1:1 *- Effects of herbivores on wildfire frequency, intensity and damage depend on various factors, including grazing effects on the vegetation and thereby fuel load, as well as additional wildfire risk factors, such as local topographic and climatic conditions*

Box 1:1 - 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).

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 1:1), 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.

1.2 Literature search

We systematically reviewed studies that assessed overall relationships between herbivory and wildfires, and papers that focused on specific pathways by which herbivores may affect wildfire risk (see Figure 1:1).

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 S1.1.

1.3 Overall effects of herbivores on wildfire risks

1.3.1 Effects of herbivores on wildfire frequency

Of the 74 studies included in this review (see Figure 1:2), 21 directly assessed the effects of herbivores on fire frequency. [Correction added on 14-September-2021, after first online publication: Citation to Figure 1:2 has been added.] Thirteen studies (see Table 1:1) 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).

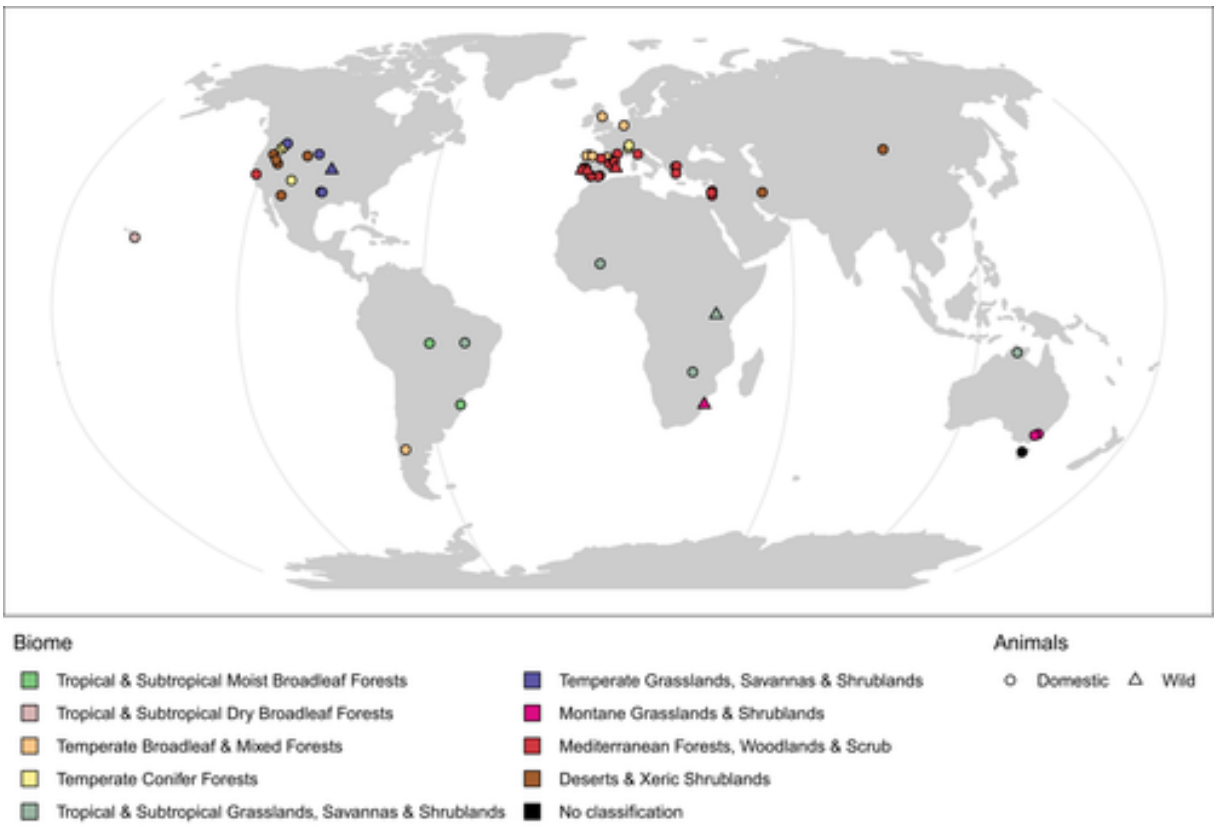


Figure 1:2 *- Locations of reviewed studies. The colour and shape indicates the type of biome where the study was conducted and if it focused on wild or domestic animals*

Table 1:1 - *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)

Main findings	Effect type	Reference
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)

Main findings	Effect type	Reference
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)
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)

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 1:1).

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).

1.3.2 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).

1.4 Effects of herbivores on fuel loads 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 1:3). Herbivores 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).

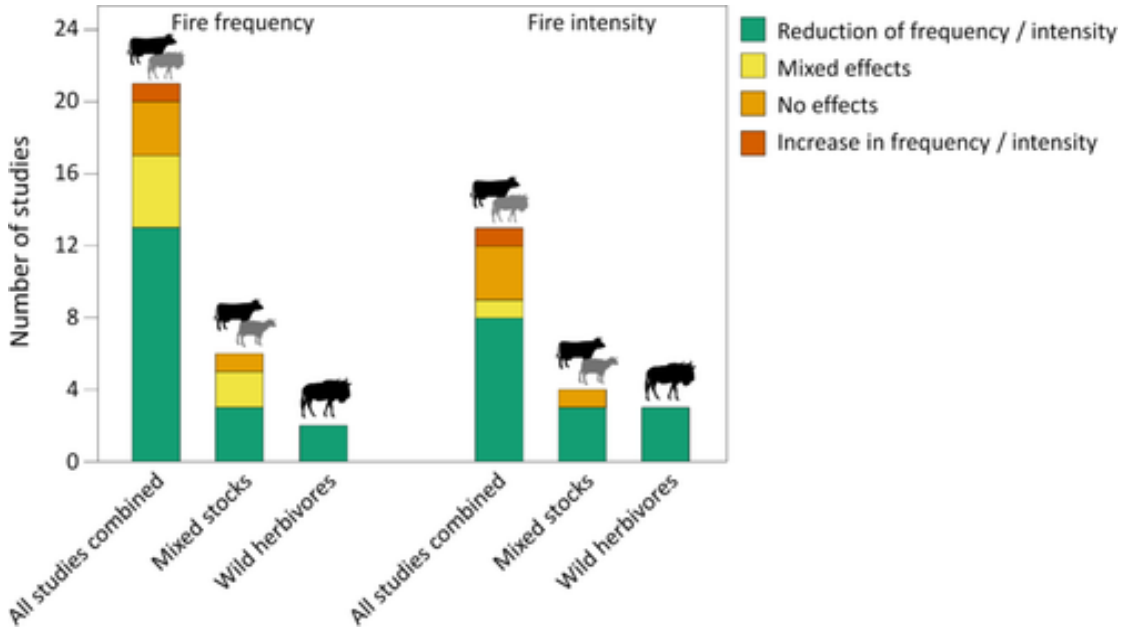


Figure 1:3 *- Effect of different herbivores on fire intensity/frequency reported in reviewed studies*

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 1:4). 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).

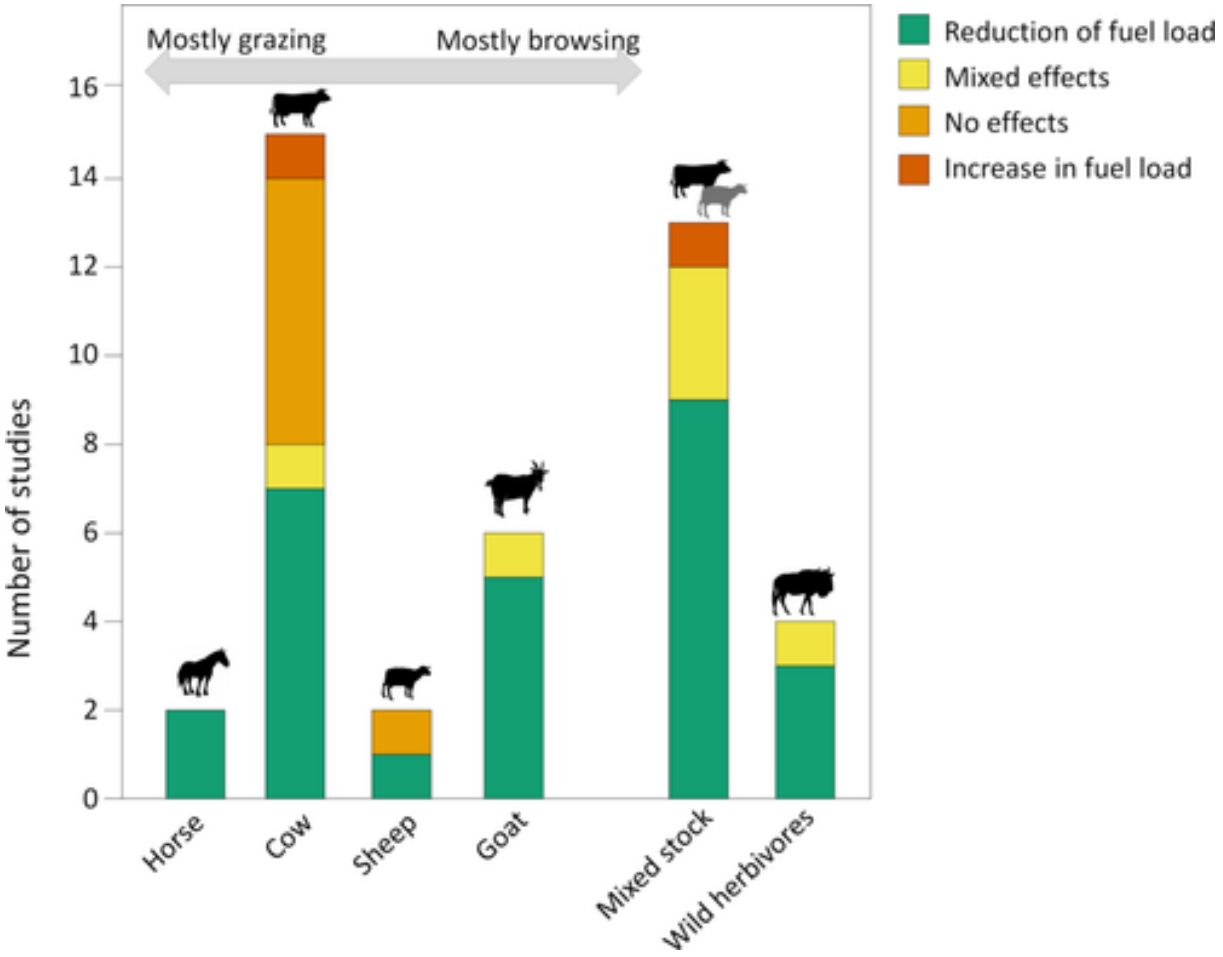


Figure 1:4 - *Effect of different herbivores on vegetation biomass reported in reviewed studies*

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 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.

1.5 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).

1.6 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).

1.7 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 1:5), 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).

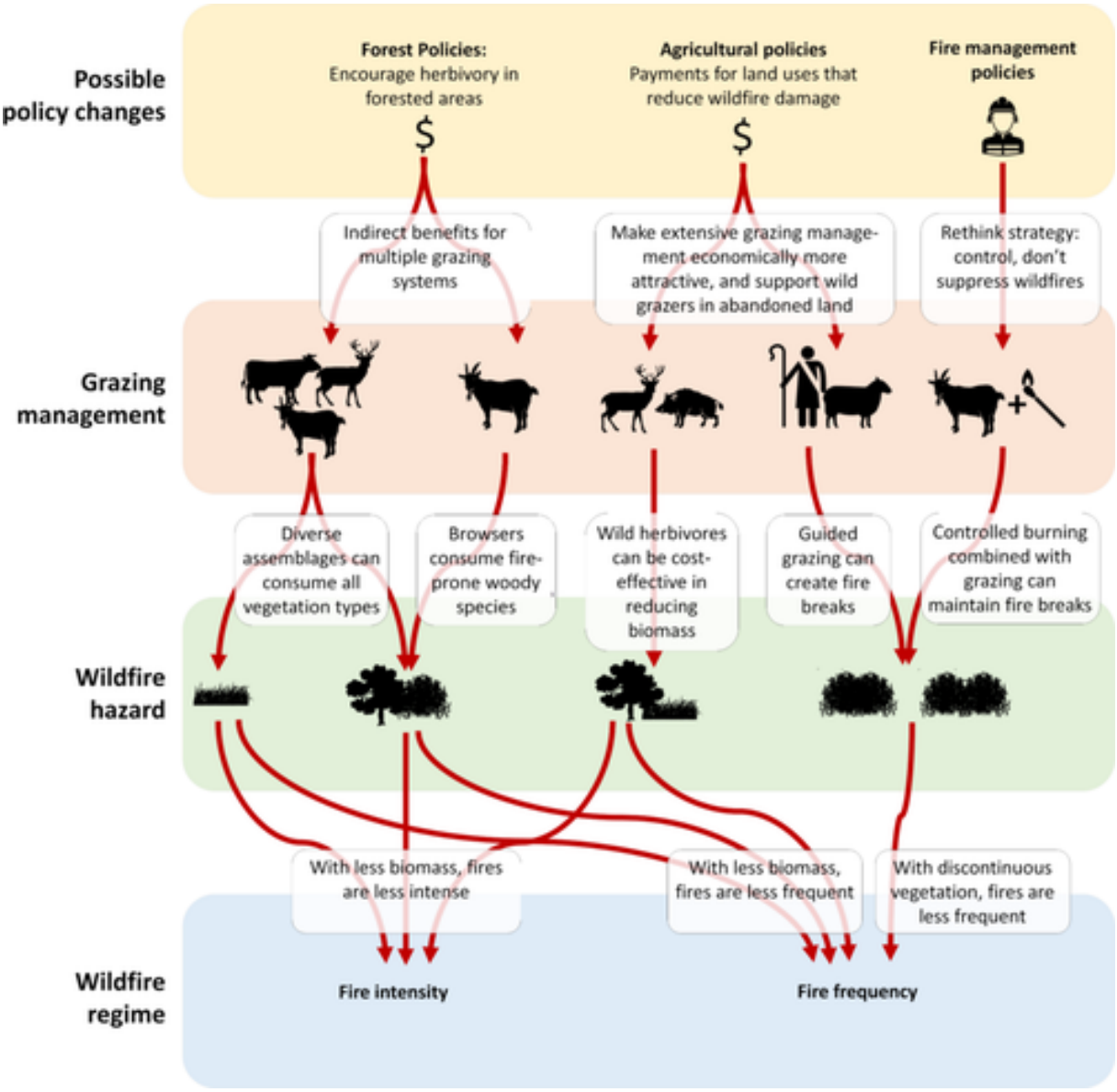


Figure 1:5 - *Possible (agricultural and fire) policy changes and their effects on wildfire frequency and intensity, through changes in herbivore management*

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 1:5). 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 1:5; 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 1:4). 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 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.

1.8 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 1:5).

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).

1.9 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 1:2).

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.

2. Chapter Two

This chapter is an article submitted as: **Rouet-Leduc, J**., Pe'er, G., Bakker, E. S., Bonn, A., Helmer, W., Moreira, F., van der Plas, F. Grazing and ecosystem service provisioning in European grasslands: synergies, trade-offs and win-win management. *Under review*

2.1 Introduction

Over a third of European agricultural land are grasslands and these are often used as pastures, especially permanent grasslands. There are differences across Europe, with fewer grasslands in areas that are less productive, such as in Northern Europe (Mosquera-Losada et al., 2019). Key grazed ecosystems include pastures, natural and semi-natural grasslands, and grassy shrublands. These grazed ecosystems supply multiple ecosystem services (Bengtsson et al. 2019), including provision of food, above- and belowground carbon storage (and hence climate change mitigation) (Conant et al. 2017), mitigation of extreme events, such as wildfires (Rouet-Leduc et al. 2021), and cultural services (Plieninger et al. 2019), such as recreation or sense of place, as well as biodiversity conservation benefits (Herrero-Jáuregui et al., 2018; Bardgett et al., 2021). However, both the supply and the demand of these services can vary widely. For example, while some grazed areas are biodiversity hotspots, hosting many threatened plant and animal species (Wilson et al., 2012), others have low biodiversity and very limited conservation value. Furthermore, while some grazed areas act as carbon sinks and harbor the world's largest belowground carbon stocks, others have only low and depleting carbon stocks (Zhou et al., 2017; Eze et al., 2018). With declining grazed areas and a high demand for multiple ecosystem services, a key question is how grazed areas can be managed in such a way ecosystem multifunctionality is maintained or restored, to maximize the range of ecosystem services provided.

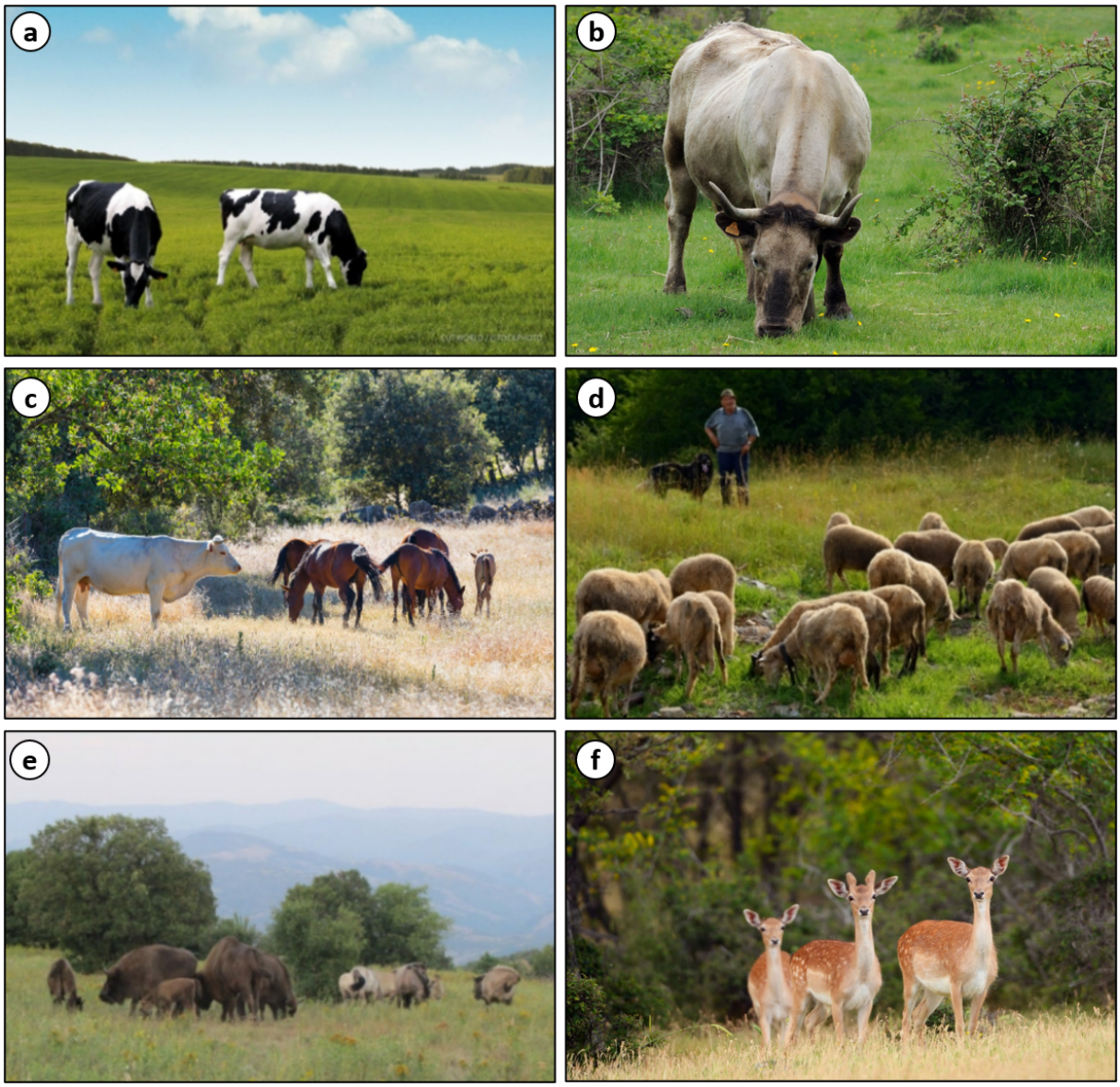


Figure 2:1 *- Grazing systems can vary in several components, including grazing intensity and herbivore diversity. A: Intensively grazed livestock systems require external fodder input, use of fertilizer and seeded pastures. B & C: In extensively grazed livestock systems, animals are mostly (but not always) raised on food that comes from natural or semi-natural grasslands (B: Photo by Staffan Widstrand). Mixed species are sometimes used in extensive livestock systems, for example cattle and horses (C: Photo by Juan Carlos Muñoz). D: In pastoral systems, herders move around herbivores in regular movements or semiannual transhumance depending on the landscape and vegetation availability (Photo by Staffan Widstrand). E: Rewilding with large herbivores such as semi-wild horses and bison sometimes creates heterogenous mosaic landscapes (Photo by Desislava Kostadinova). F: In wild systems, herbivores generally have little to no management from humans.*

Grazing management is widely variable. First, there are different grazing systems (Figure 2:1), varying from natural areas in which (semi-)wild herbivores are the dominant grazers, pastoral systems in which herders move livestock around across large areas, and conventional livestock systems. Second, grazed systems vary in their grazing intensity. While grazing intensity could be expressed in animal densities, or livestock units per area, in this study we define grazing intensity as a more relative

measure (i.e. grazing pressure in relation to plant biomass productivity), as this eases comparisons of grazing systems among regions differing in productivity. Grazing intensity can vary strongly in both natural and agricultural systems, although in natural systems, grazing intensity is rarely as high as in some livestock systems. For example, densities of wild grazers in Europe are rarely higher than 10,000 kg km^{-2} (Fløjgaard et al., 2021). In some cases, more extreme densities are found, e.g. up to 100 red deer per km^2 (Putman et al., 2011), equaling ~17,500 kg km^{-2}, but these densities are still 3 to 5 times lower than average livestock densities (52,000 kg km^{-2}) in European pastures (European Commission 2019). In the latter, such high densities are often only possible thanks to external fodder inputs, as biomass production within the grazed fields is not high enough to support such high densities. Third, grazed areas vary in the species and functional types of herbivores. Both natural areas and livestock systems can be grazed by a single herbivore species or mixed livestock systems with some natural areas harboring over 10 large herbivore species (Ripple et al., 2015). In addition, while some areas are grazed by herbivores that are 'strict grazers' that feed primarily on grass, others are grazed by mixed-feeders that also browse on woody species. Fourth, grazed areas vary strongly in their management practices. To maximize productivity, many intensive livestock systems use pastures that are regularly ploughed, fertilized and sown with only one or a few grassland plant species, while in some pastoral systems, grazers cause net nutrient export as they defecate in sheepfolds. For conservation purposes, some natural areas also have certain management activities to regulate herbivore densities, such as hunting to keep herbivore populations below certain thresholds (Putman et al. 2011).

These different components of grazing-associated management can vary largely independently from each other, and can all have important consequences for biodiversity, various ecosystem processes and the provisioning of ecosystem services. Importantly, management to promote one ecosystem service may not necessarily promote other services: both synergies and trade-offs have been observed (Nelson et al., 2008; Lavorel et al., 2011), and various studies demonstrate that these can be driven by management activities (Raudsepp-Hearne et al., 2011; Lavorel et al., 2011; van der Plas et al., 2019; Neyret et al., 2021). To identify optimal management, it is therefore key to understand these synergies and trade-offs in ecosystem service supply, and also to identify which services are prioritized by multiple stakeholder groups (Manning et al., 2018).

In addition, herbivores can strongly influence ecosystems beyond the areas where they graze. Some effects are direct, and manifest at landscape-level or regional scales. For example, the production of manure leads to atmospheric emission of ammonia and resulting nitrogen deposition in surrounding areas (Uwizeye et al., 2020). Other grazing-associated activities have global consequences. Prominent examples are methane emissions affecting the global climate (Rivera et al. 2021), and external feed inputs required by intensive (but sometimes also extensive) livestock systems that may be produced elsewhere in the world (IPCC 2021). A key question is therefore how positive, beyond-field impacts of grazing can be maximized, and disadvantages can be minimized.

Our study places a particular focus on Europe, where both pasture intensification and abandonment are widespread trends (Lasanta et al. 2017; Schils et al. 2022). Hence, our review focuses on studies that were specifically conducted in European countries, while also including reviews that provided a more general overview and included European studies as well as others. We focus on European studies in order to provide specific management and policy recommendations related to European grasslands, especially in the context of the Common Agricultural Policy (CAP). While earlier

reviews focused on the effects of grazing on biodiversity (e.g. Olff & Ritchie 2001; van Klink et al., 2015; Herrero & Jauregui 2018; Alkemade et al. 2013; Petz et al. 2014), or various single ecosystem services exist (e.g. Eze et al., 2018; Rouet-Leduc et al, 2021), or grazing in specific habitats (eg. salt marshes Davidson et al. 2017) the aim of our review is to gain insights beyond those earlier reviews, by synthesizing knowledge and identifying how different ecosystem services are associated with different grazed systems in a European context. In this paper we first (1) review the body of evidence on how different aspects of grazing activities, including grazing systems, grazing intensity, herbivore species composition, and associated management affect the supply of multiple ecosystem services, with a focus on habitat provisioning for biodiversity, climate change mitigation, soil quality, moderation of extreme events and cultural services. Although there are many more ecosystem services that are provided by grazed systems, we focus on these five services because of their i) high importance for both local and global stakeholders, ii) their complementarity with respect to each other, and iii) because we expect strong and direct links between these ecosystem services and grazing management. In some sections, we also discuss ecosystem services mostly indirectly affected by grazing: for example, in the soil quality section we also discuss water quality given the strong links between soil and water quality. We then examine (2) trade-offs and synergies between the supply of these services in grazed areas, and (3) we identify whether win-win scenarios exist whereby multiple services are maximized. As many of the effects of large herbivores can vary strongly, we aim to identify both generalities and context-dependencies and provide recommendations for management and policy based on our review.

2.2 Literature review: general methods

Our literature review focused on studies investigating effects of different grazing systems on biodiversity and four types of ecosystem services: mitigation of soil erosion, climate change mitigation, wildfire mitigation and cultural ecosystem services. While grazing systems are also important for food provision, we chose to focus on regulating and cultural ecosystem services. The main aim of our study was to synthesize understanding of effects of grazing on biodiversity and multiple ecosystem services, their co-supply and trade-offs. To do this, we first searched for literature where effects of grazing management on individual ecosystem services were assessed, and then used insights of these studies to infer how grazing management can cause trade-offs or synergies between multiple services. Given the very general scope of our study, we did not aim for an exhaustive literature overview, but instead we prioritized on obtaining reviews and meta-analyses on relationships between different components of grazing management, biodiversity and ecosystem services. In cases where existing reviews left knowledge gaps, we supplemented these reviews with case studies. Specifically, for the topics of biodiversity and soil carbon sequestration, we focused on reviews due to the abundance of literature, while complementing with individual studies to bring more specific evidence when needed, while for the others ecosystem services we took in consideration original studies and literature reviews because of the more limited amount of literature reviews available. We performed literature searches by combining keyword-based literature searches on Web of Science with cross-referencing. In our Web of Science search, we used grazing related keywords (graz* OR herbivore OR brows* OR the names of various common herbivore species [see the Supplement Materials for a complete overview]) in combination with keywords relating to the key themes of this study: 1) biodiversity, 2) climate change mitigation, 3) soil quality, 4) wildfire mitigation, or 5) cultural ecosystem services. We included studies conducted in Europe as well as global studies that included European regions or studies. As criteria for

inclusion, the articles has to focus on at least one of the nine components of grazing-management we studied in relation to different biodiversity or ecosystem service indicators: 1) grazing intensity, 2) grazer diversity, 3) presence of mixed (i.e. also feeding on woody species) grazers, 4) external fodder inputs, 5) ploughing of non-permanent grasslands, 6) fertilizer application, 7) application of deworming medication, 8) burning management or 9) hunting activities.

Regarding the grazing intensity, we define it as the grazing pressure (plant biomass eaten) in relation to plant biomass production. While these numbers are often not quantified in case studies, in practice this meant that we mostly relied on the expert interpretation of original authors of studies, that e.g. distinguished between 'light', 'intermediate' and 'heavy' grazing. External fodder inputs are often, but not always, related to grazing intensity: highly intensively grazed systems with high grazer densities typically require external fodder inputs (Garnett et al., 2017). However, the opposite is not always true: some extensively grazed systems still rely on external feed inputs. In our study we departed from the definition of extensive or intensive grazing given by the authors of the study, regardless of additional feeding since it was not always specified and highly context dependent. Altogether we included 81 studies in this review (see Table S2.1 & 2.2 for an overview of the literature used).

To find out whether overall relationships between the above listed 9 grazing management characteristics and biodiversity / ecosystem service indicators were positive, negative, neutral or more complex (e.g. where a service is provided at highest levels at intermediate grazing intensity), we i) created a table in which the findings of each reviewed study are summarized, and we then ii) synthesized for each combination of ecosystem service indicators and grazing management characteristics the overall relationships, and which reviewed studies these overall relationships are based on (Supplementary table S2.1 and S2.2; visualized in Figure 2:2). In some cases, too little information was available to draw general conclusions. Based on the overall relationships between grazing management characteristics and biodiversity / ecosystem service indicators, we also assessed the presence or absence of grazing management-induced trade-offs and synergies (Figure 2:3). We identified grazing management-induced synergies as cases where particular grazing management characteristics overall have similar (e.g. joint positive, or joint negative) effects on different biodiversity / ecosystem service indicators. For example, when the absence of fertilizer application is beneficial for both plant and soil quality, we concluded that it contributes to synergies between those services. In contrast, grazing-management driven trade-offs occur in cases where grazing management characteristics have opposite effects on different ecosystem services. For example, the overall effects of grazing intensity on soil quality (negative) and wildfire mitigation (positive) are in opposite directions, causing trade-offs.

2.3 Results

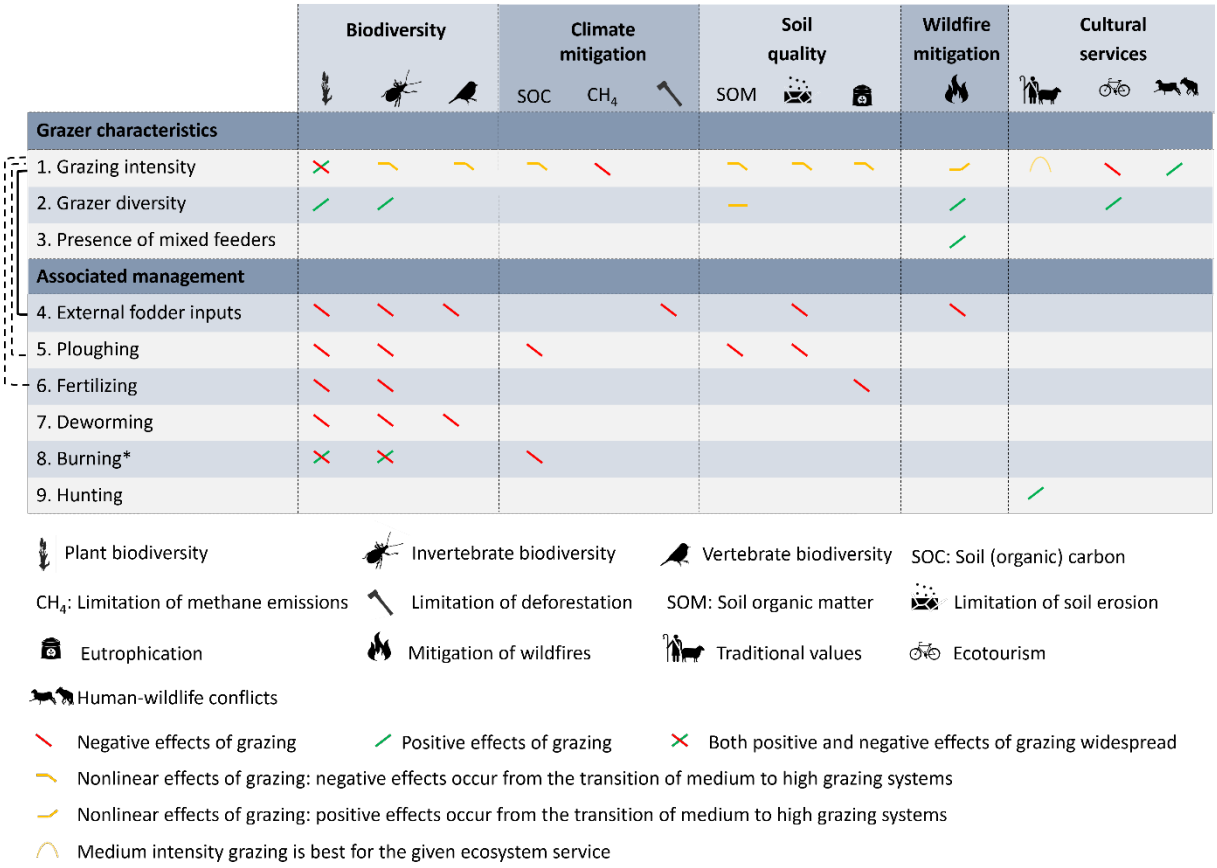


Figure 2:2 *- Effects of different grazing characteristics and management associated with herbivores on biodiversity and ecosystem services, based on our literature review (see Appendix A for original sources). Green lines indicate positive effects, red lines indicate negative effects. Yellow lines indicate more complex or nonlinear effects of grazing intensity on biodiversity and ecosystem services. Intensive grazing management is often, but not always, associated with ploughing or fertilization activities, hence the dashed lines connecting these management characteristics. *here we refer to burning as a practice to maintain and manage grasslands.*

2.3.1 Effects of grazing on biodiversity

There is a general consensus that effects of grazing *per se* on biodiversity are highly context dependent (Olff & Ritchie 1998; Gao & Carmel 2020; Figure 2:2. Whether grazing is, or is not, beneficial for biodiversity depends on i) grazing intensity, ii) type of herbivore, iii) management practices associated with grazing iv) effects beyond field level.

Overall, intensive grazing typically has negative effects on the biodiversity of plants (Olff & Ritchie 1998; Herrero-Jáuregui & Oesterheld 2018), insects (Takagi & Miyashita 2014; van Klink et al., 2015a; Figure 2:2) and other animal taxa (Foster et al., 2014; Figure 2:2). While direct comparisons between taxa are relatively rare, effects of intensive grazing on belowground biodiversity are often less negative than those on aboveground biodiversity (Allan et al., 2014; Le Provost et al., 2021). Grazed systems that hamper biodiversity are typically intensive livestock systems, where additional external inputs (e.g. fertilizers and additional feeding) allow high grazer densities compared to the ones found in

natural systems. One of the main drivers of these negative impacts is a strong reduction in vegetation biomass associated with intensive grazing (van Klink et al. 2015a). Various plant species cannot tolerate very intensive biomass removal (Olff & Ritchie 1998), especially not in unproductive environments where regrowth is slow, for example in more arid Mediterranean systems. As a consequence, intensive grazing has its most negative effects in areas with naturally low productivity (Proulx & Mazumber 1998; Bakker et al., 2006), including in areas found for example in Southern Europe. Indeed, in more arid areas, grazing tends to have a more negative impact on biodiversity (Maestre et al. 2022), than in mesic environments, for example in central and northern Europe (Milchunas et al. 1993). Strong reductions in vegetation biomass is also associated with a decline in many animal species that rely on structurally complex vegetation (Pöyry et al., 2006; van Klink et al., 2015a), and in their services, such as pollination and seed dispersal (van Klink et al., 2015a; Bakker et al. 2003). Furthermore, trampling by herbivores, and associated soil compaction can decrease plant biodiversity (Olff & Ritchie 1998). Negative effects of intensive grazing are often stronger for animals (such as insects and other arthropods) than for plants (van Klink et al., 2015a), due to a simplification of the vegetation structure (Bourn & Thomas 2002), disturbances caused by e.g. trampling (Beja et al., 2014; van Klink et al., 2015b) or due to unintentional consumption of arthropods by large herbivores (Gish et al., 2017). However, for some groups. e.g. birds, the effects of grazing are variable and species-specific, because some species benefit from short grazed swards whereas others prefer taller vegetation (Reino et al. 2018).

Compared to intensive forms of grazing, extensive grazing systems are generally better or less harmful for biodiversity (Foster et al., 2014; van Klink et al., 2015a; Herrero-Jáuregui & Oesterheld 2018; Figure 2:2). Many of the negative effects of grazing described above (e.g. too high biomass removal, disturbances, unintentional consumption) are more moderate when grazing intensity is lower. Furthermore, low intensity grazing can also have beneficial effects on biodiversity, through various mechanisms. First, extensive grazing can slow down the succession towards more species-poor shrub or tree dominated systems (Hobbs & Huenneke 1992; van Klink et al., 2015). This, however, depends on the type of animal, their feeding preferences, or if supplementary feeding is used. While this is also the case for intensive grazing, too much biomass removal is often associated with biodiversity losses, as described above. Second, grazers can promote habitat heterogeneity through selective foraging (Adler et al., 2001), thereby promoting biodiversity (Olff & Ritchie 1998; Joern & Laws 2012; Gao & Carmel 2020). This structural diversity can also promote the growth of flowering plants that are important for pollinating insects (Garrido et al 2019). Third, herbivores can create habitat features unique to grazed systems that offer opportunities for many specialist species, such as dung pellets, walking paths and wallows (Olff & Ritchie 1998; van Klink et al., 2015a). In addition, large herbivores disperse the seeds of many plant species (Doboszewski et al., 2017). Interestingly, positive effects of extensive grazing on plant and invertebrate biodiversity are especially large when multi-species herbivore stocks are used (Wang et al., 2019; Figure 2:2). While it is clear that extensive grazing is in most cases better for biodiversity than intensive grazing management, the comparison to ungrazed systems is less unequivocal. Meta-analyses show both positive and negative effects (compared to ungrazed situations) of extensive grazing on plant diversity are approximately equal (Herrero-Jáuregui & Oesterheld 2018; Figure 2:2). It is also important to note that effects of grazing on insect diversity are typically less beneficial, or more negative, than effects on plant diversity (van Klink et al., 2015). Thus, when assessing the potential benefits of extensive grazing for biodiversity, specific contexts, and multiple taxa need to be considered.

The majority of studies on extensively grazed systems and biodiversity focus on livestock or pastoral systems. Nevertheless, some studies focus on the effects of wild or semi-wild herbivores, and found that experimentally removing these grazers (e.g. through exclosures) sometimes causes a loss in biodiversity (Suominen and Olofsson, 2000; Wells et al., 2021), while in other cases it has more neutral (Keesing & Young 2014; van der Plas & Olff 2014) or even positive effects (Collins et al., 1998). An important question is whether the effects of wild herbivores on biodiversity differ from those of livestock, and whether different wild herbivore species have different effects on biodiversity. Various studies suggest that for biodiversity, grazing intensity matters more than the type of herbivores (e.g. livestock or wild herbivores) that are the dominant grazers in an area (Scimone et al., 2007; Ramos et al. 2021). However, as even those areas with the world's highest wild herbivore populations experience much lower grazing pressure than intensive livestock systems (Fløjgard et al., 2021), the negative effects on biodiversity associated with intensive livestock systems are rare in natural systems. Therefore, it is expected that biodiversity in areas that are currently undergoing land abandonment may benefit from active, trophic rewilding (e.g. Soulé & Noss 1998; Svenning et al., 2016; Gordon et al., 2021), although in some cases, biodiversity losses may also occur (Collins et al., 1998).

There are other management-related components of grazed systems that can also influence biodiversity. Some livestock systems (especially intensive livestock systems) occur in temporary grasslands, with the associated management activities (e.g. ploughing) resulting in lower biodiversity compared to permanent grasslands (Liu et al., 2016; Austrheim & Olsson 1999; Figure 2:2). Another management activity common to both extensive and intensive livestock systems is the application of medication, particularly deworming medication. This can result in lethal effects on non-target insects, as well as cascading negative effects on higher trophic levels, such as birds (Floate et al., 2005; Lumaret et al., 2012; Figure 2:2). In addition, in some parts of Europe, controlled burning is done to mitigate wildfires, but this can also influence plant biodiversity (Fuhlendorf et al., 2009; Figure 2:2).

Importantly, effects of grazing on biodiversity can sometimes occur beyond the fields where grazing activities occur, at telecoupled landscape, regional, or even global scales. Through the production of dung, herbivores cause atmospheric emission of ammonia, which can lead to nitrogen deposition in surrounding areas, with detrimental consequences for terrestrial plant and animal biodiversity (Bobbink et al., 2010), as well as freshwater fauna and flora due to run-off (O'Callaghan et al., 2019). Another major consequence of livestock systems, is that they often rely on fodder crop inputs, including grain and legumes. These products are often produced elsewhere, including in regions in other continents, and their telecoupled production is often associated with local declines in biodiversity due to habitat destruction and cropland management (Barlow et al., 2016; Song et al., 2021; IPBES 2019; Figure 2:2).

2.3.2 Effects of grazing on climate change and its mitigation

While approximately a third of all human-driven greenhouse gas emissions are associated with land-use and the livestock sector is responsible for nearly half of this share (Gerber et al., 2013), grasslands are also a considerable carbon sinks. We organize our results based on three main mechanisms by which grazers and management activities associated with grazing influence climate regulation: i) greenhouse gasses directly emitted by grazers, ii) telecoupled effects and land use change, and iii) effects on soil organic carbon (SOC) storage within grazed areas.

Large grazing mammals directly emit several greenhouse gasses. When digesting plant materials, large herbivores emit substantial amounts of methane, which constitutes to 4.3% of the EU's total greenhouse gas emissions (Eurostat 2017). These methane emissions are largely proportional to grazing intensity (Rivera et al. 2021), so that especially intensive livestock systems emit high amounts of methane. Since certain species (e.g. non ruminants like equids) and breeds of livestock emit lower levels of methane, there are some opportunities to reduce emissions through species and breed selection (EIP-AGRI 2017). To which extent wild grazers contribute to greenhouse gas emissions is uncertain (Smith et al., 2015), although given their total lower biomass densities (in Europe typically around 2500 kg km^{-2} for wild herbivores (Fløjgaard et al. 2021), with higher densities of wild herbivores up to ~17,500 kg km^{-2} (Putman et al. 2011), compared to average densities of 52,000 kg km^{-2} in European pastures (European Commission 2019), emissions by wild herbivores are likely to be substantially lower.

For example, densities of wild grazers in Europe are rarely higher than 10,000 kg km^{-2} (Fløjgaard et al., 2021)., In some cases, more extreme densities are found, e.g. up to 100 red deer per km2 (Putman et al. 2011), equaling ~17,500 kg km-2, but these these densities are still 3 to 5 times lower than average densities (52,000 kg km^{-2}) in European pastures (European Commission 2019).

Additionally to greenhouse gases directly emitted by grazers, emissions related to land-use change in relation to grazing occurs in several ways. Globally, livestock grazing often drive land degradation or deforestation processes, directly or indirectly (Garnett 2017). Consumption patterns of importing agricultural products from overseas to Europe, amongst others animal feed, drives land use change in other parts of the world through telecoupled effect with both deforestation and conversion of natural grasslands into croplands or intensively managed pastures (Cuypers et al. 2013). Around 70% of the world's deforestation is related to the production of livestock feed (Stoll-Kleemann & Schmidt 2017). Direct results of deforestation include the release of carbon from biomass into the atmosphere, as well as reductions of capture-potentials, thereby strongly contributing to climate change (IPCC 2019).

Third, grazers also influence climate mitigation through their effects on local carbon storage. Grassland soil carbon stocks are among the world's largest (Read et al., 2001; Crowther et al., 2019). Furthermore, grasslands often act as carbon sinks (Chang et al., 2015), although there is large variation among grazed areas in their ability to store carbon, depending both on different bioclimatic contexts and grassland management. Effects of grazing on soil carbon are complex to understand, and depend on 1) the inputs from e.g. plant biomass and litter production and 2) the loss through both respiratory processes and soil erosion (Swift et al., 1979). A direct effect of herbivory is the removal of plant biomass, and therefore one could also expect reductions in soil carbon. Furthermore, grazers can create patches of bare soil, soil compaction, thereby causing soil erosion and soil carbon loss. On the other hand, herbivores can potentially increase processes of sequestration when plants compensate for grazing-associated biomass losses through increased growth (Oesterheld & McNaughton 1991), which e.g. happens especially in cooler climates with systems dominated by perennial graminoids and forbs. However, in warmer and drier climates dominated by more annual species that may not be able to compensate for grazing-induced biomass losses, high grazing intensity can also have a negative impact on soil carbon storage (Maestre et al., 2022). In addition, grazers can prevent the loss of aboveground carbon to the atmosphere, by reducing wildfire frequency and intensity (Rouet-Leduc et

al. 2021). Grazing can also affect soil respiration (and related soil carbon loss). For example, soil compaction may slow down soil microbial activity and respiration, due to high moisture and low oxygen levels, thereby limiting soil carbon loss (McSherry, 2013). On the other hand, grazing can cause increased investment in plant root biomass, higher quality litter inputs (through transferring low quality litter into high quality dung), which may all increase the activity of soil life and hence soil respiration, thereby causing soil carbon loss (Zhou et al. 2019). Multiple meta-analyses and reviews indicate that net effects of intensive (livestock) grazing are that they generally reduce soil carbon stocks compared to ungrazed situations (Zhou et al., 2017; Conant et al., 2017; Byrnes et al., 2018; Eze et al., 2018; Lai et al. 2020). Only in situations of rotational grazing (i.e. grazing of short duration where parcels are grazed and rested sequentially), effects on soil carbon are more neutral or even positive (Byrnes et al., 2018; EIP-AGRI 2018). In contrast to intensive grazing, the net effects of extensive grazing on carbon storage may on average be neutral (Tanetztap & Coomes 2012; McSherry & Ritchie 2013; Byrnes et al., 2018), slightly negative (Eze et al., 2018) or even slightly positive (Zhou et al., 2017; Lai et al. 2020). However, it is important to emphasize that net effects of grazing on soil carbon storage vary across Europe. Increased grazing intensity increases soil carbon in grasslands with C4-dominated grasslands (in Europe most dominant in the Mediterranean), but decreases it in C3-dominated grasslands (McSherry, 2013). Furthermore, effects are more negative in (typically low-productivity) areas with sandy soils than in areas with other soil types (Lai et al. 2020), (e.g. in many parts of Scandinavia, Portugal and the Netherlands), and hot and dry areas (e.g the Mediterranean). Relatively little literature is available on wild and semi-wild herbivores and their impact on soil carbon (Cromsigt et al., 2018), while existing studies portray a mixed outcome. In the case of transhumant pastoralism with for example reindeer, some studies found that reindeer grazing reduced (Stark et al., 2010) or had no effect (Köster et al., 2013; Stark et al., 2010) on soil carbon. In contrast, Francini et al., (2014) found in two different sites that reindeer grazing increased soil organic matter (a strong indicator of soil carbon) compared to ungrazed control sites. High wild herbivore densities are associated with low aboveground biomass due to grazing activities, but these aboveground carbon losses are often compensated by increased storage belowground (Sandhage-Hofmann et al., 2021). A current view is therefore that positive effects of wild herbivores on carbon storage in natural ecosystems may be underestimated, as benefits may mostly manifest at long time-scales (Kristensen et al 2021). Besides direct effects of grazers, also other components of pasture management influence soil carbon stocks. For example, prescribed fires, as well as ploughing (of temporary grasslands) can cause decreases in soil carbon stocks (Girona-García et al., 2018; Haddaway et al., 2017).

2.3.3 Effects of grazing on soil quality

While soil quality is difficult to measure, indicators of soil quality include i) amount of organic matter (and carbon) content, ii) soil erosion, and iii) contamination with pollutants and nutrients (Bünemann et al., 2018). We organize this section according to these indicators.

Extensive grazing can have a positive effect on soil quality, especially in temperate grasslands (Mayel et al., 2021) and particularly through increase in SOM and SOC (see previous section, on climate mitigation). Studies assessing whether more diverse grazing systems lead to higher SOM than areas grazed by a single herbivore did not detect meaningful differences (Rose et al., 2013). By contrast, most studies report that intensive grazing, and in some cases also extensive grazing, decreases soil organic matter and soil carbon, leading to soil erosion and less favorable conditions for nutrient cycling

and plant growth (Bünemann et al., 2018). As also discussed above, these effects are particularly negative in areas with sandy soils (e.g. in many parts of Scandinavia, Portugal and the Netherlands), as well as in relatively dry and hot areas (e.g. the Mediterranean) (Lai et al. 2020). Management activities associated with grazing, such as ploughing for reseeding - occurring frequently in temperate grasslands - can also drive losses in soil organic matter (Haddaway et al., 2017).

In some cases, grazing activities can also influence erosion. Some dramatic examples of soil erosion caused by highly intensive livestock grazing can be found in Mediterranean areas (Kéfi et al., 2007). Historical records also demonstrate soil degradation due to overgrazing also in high-latitude regions: for example, in Iceland, overgrazing contributed to soil erosion between the years ~1660 and 1960 (Greipsson 2012), and in some sandy areas of the Netherlands, historical overgrazing of nutrient-poor heathlands has caused local desertification and resulting sandstorms (Heidinga 2010). Common to all these cases is their occurrence in areas with relatively low soil moisture and plant productivity. Semi-arid and cold areas, as well as some very sandy areas and high-altitude areas have inherently low productivity, so that in some cases even moderate livestock densities can surpass carrying capacity, causing soil degradation, and as a result, desertification. Importantly, management activities associated to grazing, such as ploughing, can in some more cases also lead to soil erosion (Collins et al., 2021). Furthermore, the effects of intensive grazing on soil erosion are not limited to the field scale. The reliance of many (especially intensive livestock) systems on the production of fodder crops often leads to deforestation in other parts of the world, with associated soil erosion (Fearnside 2002).

Many livestock systems, especially those with high grazer densities (although in some cases also extensive livestock systems), are associated with high external inputs of fertilizers, and the production of manure, which can lead to an oversupply of soil nutrients (eutrophication) such as nitrogen at both the field and landscape level (Leip et al. 2015). This is especially critical in some parts of Northwestern Europe (e.g. Netherlands, Belgium, western Germany, Denmark), where current nitrogen deposition rates are strongly exceeding critical loads (Forsius et al. 2021) and where livestock densities are among the highest in Europe (Dumont et al. 2019). However, type and amount of fertilizer used influences the impact it has on soil quality and biodiversity: mineral fertilizers generally have a more negative impact than organic fertilizers on SOC (Allam et al. 2022), soil biodiversity (Bebber et al. 2022), and nutrient leaching (Wei et al., 2021). Oversupply of nutrients generally leads to nutrient leaching, causing a decline in groundwater and surface water quality (Hooda et al. 2000; Bilotta et al. 2007) - with negative consequences for human health and ecosystems. Other practices associated with intensive livestock grazing, such as application of insecticide products on animals also has negative impacts on water quality and aquatic ecosystems (Hooda et al. 2007).

2.3.4 Effects of grazing on wildfire mitigation

Grazers can impact wildfires through different mechanisms: i) by reducing vegetation biomass and creating fire and fuel breaks, they can reduce fuel loads (Starns et al., 2019); ii) management activities associated to animal rearing can influence wildfire ignitions and subsequent fire spread.

As vegetation is the primary fuel for wildfires, grazers can play an important role in influencing the frequency and intensity of wildfires. This may be particularly important in areas experiencing rural exodus, where traditionally grazed systems are being abandoned, leading to shrub encroachment

(Loepfe et al., 2010; Lasanta et al., 2018) and potentially to increased wildfire risk. Main characteristics of the vegetation that determine fuel load include biomass, horizontal vegetation structure (including the presence of short/bare patches that serve as fire breaks), and moisture content (Fares et al., 2017). Type of animal as well as grazing intensity are important factors impacting grazers' ability to reduce biomass and thereby mitigate wildfires (Rouet-Leduc et al., 2021). In some cases, even extensive grazing management can mitigate wildfire frequency and intensity through fuel reduction (Lasanta et al. 2018), but in cases when there is a lot of shrubby vegetation, extensive grazing alone is often not enough to reduce effectively fuel loads (Ruiz-Mirazo et al. 2018). Regarding the type of animal, animals that are mixed-feeders, such as goats, are especially effective in mitigating wildfires. (Mitsopoulos & Dimitrakopoulos, 2017; Lovreglio et al., 2014; Rouet-Leduc et al., 2021). This is mostly attributed to their diet, by feeding on both herbaceous and woody species that are often not palatable to other species. Also, grazing systems consisting of multiple herbivore species can be particularly effective in reducing the frequency and intensity of wildfires, as different herbivore species typically have different dietary preferences (Lovreglio et al., 2014). As a result, they can consume a larger range of plant species compared to single grazer species, thus reducing wildfire hazard. Nevertheless, while some studies supported the effectiveness of mixed stocks in reducing wildfire hazard (e.g. Ne'eman et al., 1997; Jauregui et al., 2009; Ruiz-Mirazo et al., 2011), others did not find clear evidence for this (Endress et al., 2012). Since mixed assemblages mostly occur in the wild, with lower densities compared to single-species livestock systems, it is hard to establish whether wild herbivores are more effective than domestic grazers to mitigate wildfires. While grazing reduces the intensity and severity of wildfires in many cases, it also depends on bioclimatic conditions (Krawchuk et al., 2009). Ecosystems with regular and high levels of precipitation, such as temperate climates in Northwestern Europe, rarely burn often even if their plant biomass is high. Hence, using grazers for limiting vegetation biomass is especially relevant for wildfire mitigation in areas with dry seasons, such as Mediterranean systems (Moreira et al., 2020). Also, especially in forest ecosystems, intensive livestock grazing can lead to the recruitment of woody species, thereby creating fuel ladders that carry fires into the canopy (Mitsopoulos & Dimitrakopoulos, 2017). In some cases cattle cannot avoid shrub encroachment due to their preference for non-woody plants (Calleja et al., 2019), making them less suitable for avoiding intense wildfires.

Management associated with grazing can also have an impact on wildfires. Several studies also identified specific forms of grazing management that reduce fuel loads and thereby the frequency and/or intensity of wildfires. First, guided grazing (sometimes combined with mechanical clearing) has been identified as a cost-effective method to remove biomass at strategic places, thereby creating fire breaks (Mitsopoulos & Dimitrakopoulos 2017; Lasanta et al., 2018). Second, if done with care, grazing can be combined with controlled burning to reduce fuel loads (Ruiz-Mirazo et al., 2012; Starns et al., 2019). It is important that this is done with care, as pastoral burning practices can turn into wildfires in certain conditions (Rouet-Leduc et al. 2021). Third, in regions undergoing land-abandonment, such as many parts of Eastern and Southern Europe, the use of wild or semi-wild grazers may reduce wildfire risk in a cost-effective way (Johnson et al., 2018). For example, adding salt licks or mineral blocks at strategic places, to generate areas of frequent visitation by animals, can help create fire breaks using wild or semi-wild animals (Velàmazan et al. 2018). Beyond direct impacts at the local level, grazing has also an indirect impact through fodder inputs, where associated deforestation can be accompanied by fires (slash and burn) or lead to increased occurrences of wildfires in fodder-producing areas elsewhere in the world (Nepstad et al., 2008).

2.3.5 Effects of grazing on cultural ecosystem services

Cultural ecosystem services are the non-material benefits people receive from nature, and include the aesthetic and spiritual appreciation of landscapes and their features, as well as provision of recreation opportunities (Milcu et al., 2013). Studies on cultural ecosystem services that relate to grazing focus mostly on either one of two types of cultural ecosystem services: i) the services associated with pastoral systems and extensive agriculture, and ii) cultural services associated with rewilding and wild grazers.

Multiple studies have reported that while intensive grazing provides more products like meat and dairy, extensive grazing systems provide a broad range of cultural ecosystem services (Morgan-Davies et al., 2008; Muenzel & Martino 2018). For example, low intensity grazing of semi-natural grasslands creates landscapes that are aesthetically pleasing due to the presence of wildflowers and the diversity of contrasting habitat types (Wehn et al., 2018). Furthermore, traditional agricultural areas receive many tourists for activities such as cycling and hiking (Van Berkel & Verburg 2014). Pastoral systems have been extensively explored in terms of the cultural ecosystem services they provide (Oteros-Rozas et al., 2014; Plieninger et al., 2015; Surová et al., 2018; Maldonado et al., 2019). Many of these studies focused on mediterranean pastoral systems and found that their features are associated with landscape aesthetics and traditional knowledge. For example, the silvopastoral systems of Montado or Dehesa in Portugal and Spain are associated with a strong cultural identity and landscape aesthetics are particularly important (Surová et al., 2018). Also in other regions, there is often a clear and strong attachment to the aesthetics of silvopastoral systems, with the presence of animals being highly valued both by farmers and non-farmers (Plieninger et al., 2015). Landscape features associated with transhumance like drove roads are also considered aesthetically pleasing (López-Santiago et al., 2014). Other types of traditional transhumant rearing of animals are also associated with strong cultural identity and aesthetic values, like reindeer herding in Northern Scandinavia (Koninx 2018; Rouet-Leduc & von Essen 2019). Reindeer herding and transhumance is associated with many traditions from the Sami indigenous populations, and reindeer is considered a charismatic animal that is characteristic of the landscapes of Sapmi. Abandonment of traditional activities causes a disconnect with these services (Raatikainen & Barron 2017; Martino & Muenzel 2018; Wehn et al., 2018). In most parts of Europe, some types of landscapes used for extensive grazing activities are associated with a high cultural value, such as the 'bocage' in French landscapes (Burel & Baudry, 1995). Also, (local) products that stem from traditional grazing systems (and associated livestock breeds) are often popular, and a central source of attraction for tourism as well as a source of income for land users (Genovese et al., 2017; Surová et al., 2018).

Cultural ecosystem services that relate to wild grazers, inter alia through rewilding with wild herbivores, can also bring multiple cultural ecosystem services. These include especially opportunities for recreation and ecotourism, as well as restoring aesthetic values in formerly abandoned landscapes (Navarro & Pereira 2012; Perino et al., 2019). On the other hand, rewilding can bring very different aesthetic qualities compared to managed landscapes, where natural processes can also bring some uncomfortable experiences, like rotting vegetation or carcasses (Prior & Brady 2017) - albeit potentially with positive effects for biodiversity (van Klink et al. 2020). Nevertheless, in a study looking at the valuation of different ecosystem services, van Berkel & Verburg (2014) found that rewilded agricultural land was rated more attractive than extensive farmland. In wild or rewilded systems, people can

encounter wild and often charismatic large herbivores, and the cultural value of wild grazers lies in the unpredictability of their behavior, and the uncertainty and unexpectedness (and hence excitement) of encountering them (Greaves, 2019). Presence of charismatic animals in an area can also be an incentive for touristic activities such as hiking and wildlife watching (Balčiauskas et al., 2017; Navarro & Pereira 2012; Berkel & Verburg 2014; Perino et al., 2019).

2.3.6 Synergies and Trade-offs of different grazing practices and ecosystem services

As different grazing systems have different effects on biodiversity and ecosystem services, it is important to illustrate overall effects and trade-offs, as summarized in Figu*re* 2:2. Most importantly, intensive livestock grazing is generally negatively associated with biodiversity and most ecosystem services, such as climate change mitigation, soil quality, and cultural ecosystem services, while it can support the prevention of wildfires. Low-intensity livestock grazing and pastoral systems are generally beneficial for cultural ecosystem services, while effects for biodiversity and soil carbon stocks are mixed (Byrnes et al. 2018; Conant et al. 2017; Bakker et al. 2006), with particularly large risks of negative effects in drylands (Maestre et al. 2022). In Eastern Europe and the Mediterranean Basin, low intensity grazing practices are associated with cultural landscapes of high cultural value that often provide multiple ecosystem services (Plieninger et al. 2015, 2019). Low grazing intensities in naturally wild or semi-wild grazing systems have context-dependent effects on biodiversity conservation, wildfire prevention, climate change mitigation and cultural ecosystem services across different bioclimatic regions (Suominen et al., 2000; Velamazán et al. 2018). Ungrazed grassland, including abandoned systems, are associated with increased wildfire risks and can be either beneficial or harmful for biodiversity and soil carbon storage, depending on context. Especially in more arid environments, grazing cessation can often be beneficial for both carbon storage and biodiversity (Gao et al. 2020; Eze et al.2018). Importantly, a greater diversity of grazers either in domestic livestock or wild grazers is generally beneficial for both biodiversity and most ecosystem services (Fraser et al. 2014).

While effects of grazing density and grazer species composition vary, the most striking negative impacts of grazing practices on biodiversity and multiple ecosystem services are related to intensive livestock grazing aiming to meat and dairy production (Figure 2:2). In particular, high inputs of external fodder, which increase monotonously with livestock intensity, require significant additional land use and drive land-use changes, including deforestation, with negative consequences for biodiversity, climate change mitigation, soil quality, wildfire mitigation and cultural services. Also ploughing for grassland reseeding, which mostly takes place in temperate grasslands (often associated with, but not essential to, intensive livestock systems), have negative effects on biodiversity, climate change mitigation and soil quality. Fertilization, especially the use of mineral fertilizers, which is also mostly associated with more intensive livestock systems, decreases biodiversity and negatively affects soil and water quality. Deworming medicine, which are used in many livestock systems, negatively affects biodiversity, especially when used systematically for preventive purposes.

What emerges from these insights is that extensive grazing management can in some cases benefit biodiversity and multiple ecosystem services, thus generating synergies, while in other cases, it generates trade-offs when different ecosystem services respond in opposing ways to grazing management (Figure 2:3). Such trade-offs and synergies can occur among different ecosystem

services, but also among different indicators of the same ecosystem service. In most cases, different indicators of the same ecosystem service (e.g. soil carbon storage, limitation of methane emissions and limitation of deforestation, which all contribute to climate change mitigation) show synergies (Figure 2:3), as they are promoted by the same management activities (low grazing intensity and a lack of external fodder crop inputs in this case; Figure 2:2). On the other hand, while intermediate levels of grazing intensity can benefit plant biodiversity, invertebrate and vertebrate biodiversity are often optimized at somewhat lower grazer intensities (Figure 2:2).

In some cases, either synergies or trade-offs can arise between the same set of ecosystem service indicators, depending on grazing management activities. For example, trade-offs between animal and plant biodiversity can emerge due to choices on the intensity of grazing management, but avoiding external fodder crop inputs, fertilization, and ploughing activities will have benefits for both plant and animal biodiversity. This may explain why some previous studies found synergies between the biodiversity of different taxa in grazed areas (Manning et al., 2015), while others found trade-offs (Kruess & Tscharntke 2002; Pöyry et al., 2006).

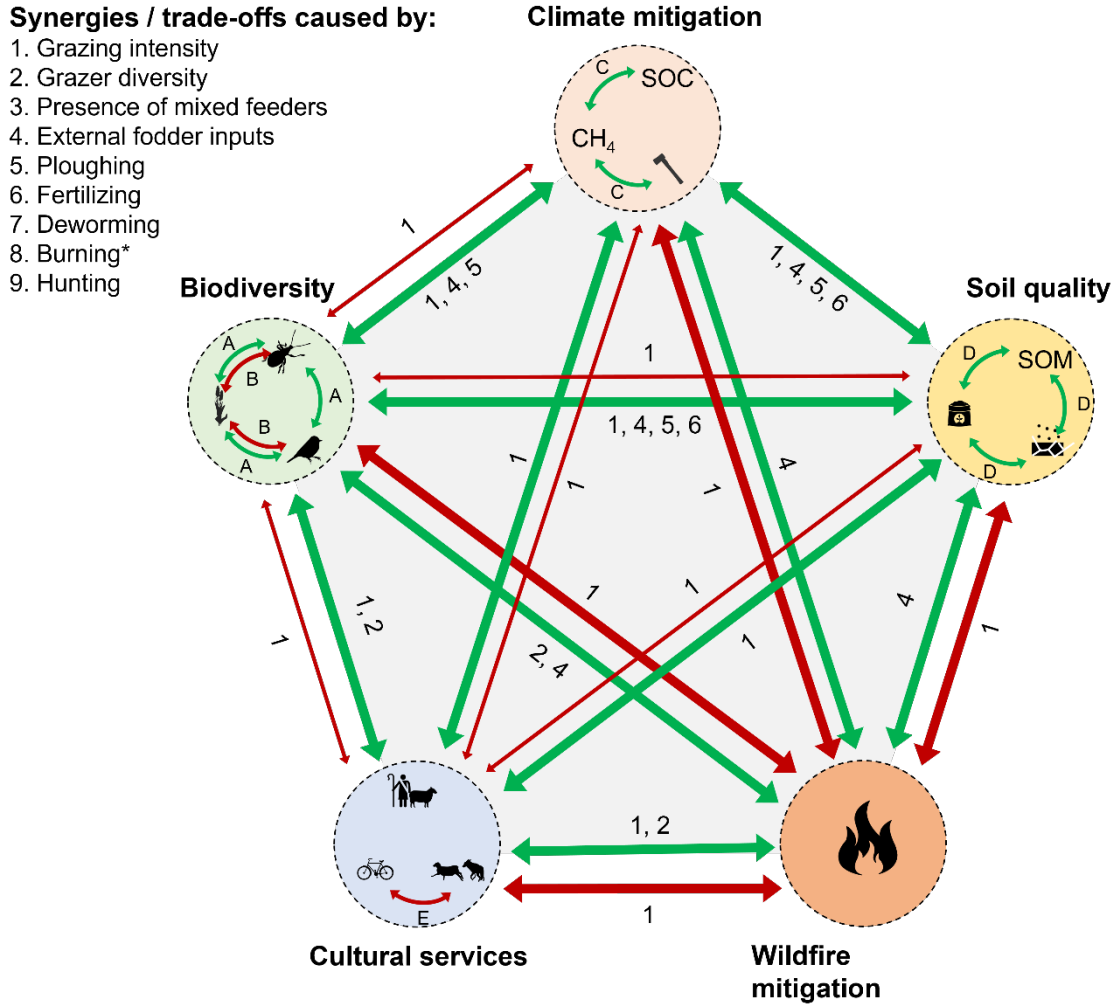


Figure 2:3 *- Trade-offs and synergies between biodiversity and multiple ecosystem services, and the grazing management characteristics contributing to them. Green arrows indicate synergies, while red arrows indicate trade-offs. Trade-offs and synergies are derived from Figure 2:2, with synergies indicating ecosystem services responding qualitatively similar to grazing management, and trade-offs*

indicating services that respond in opposing ways to grazing management. The width of the arrow indicates the expected strength of the trade-off / synergy. Arrows are present both between different indicators of the same ecosystem service, and among ecosystem services. Note that our review only identified effects of deworming, burning and hunting on single ecosystem services (Figure 2:2), hence we cannot draw any conclusions regarding the extent by which they contribute to trade-offs or synergies. Letters (A-F) indicate the grazing characteristics causing the associated trade-offs / synergies between indicators of the same ecosystem services, while numbers indicate the grazing characteristics causing synergies and trade-offs between different ecosystem services, following results presented in Figure 2:2. A: Grazing management lacking external fodder inputs, ploughing, deworming or fertilization activities promotes multiple components of biodiversity. B: Decreasing grazing intensity can increase local animal biodiversity, while it can decrease local plant biodiversity. C: Low intensity grazing (usually associated with no/few external fodder crop inputs) promotes multiple components of climate change mitigation. D: Low intensity grazing (usually associated with no/few external fodder crop inputs) promotes multiple components of soil quality. E: Low grazing intensity is associated with high value for ecotourism, but can be associated with human-wildlife conflicts in rewilding contexts.

Our review also suggests that synergies between all assessed ecosystem services can be promoted by some forms of extensive grassland management. The transition of temporal, heavily grazed systems towards more extensive, permanent pastures will in most cases reach the largest number of benefits, namely promote biodiversity, climate change mitigation, soil quality and cultural services. While local effects on wildfire mitigation might be negative, avoiding fodder crop production (often associated with deforestation) can avoid wildfires in other areas. As a result, at local and regional scales, one might often expect positive associations between biodiversity, soil carbon storage, soil quality, and carbon storage, but negative associations with wildfires. In line with this, several previous studies have found synergies between biodiversity and carbon storage (e.g. Lavorel et al., 2011; Fan et al., 2019; Clec'h Solen et al., 2019), biodiversity and erosion prevention (Fan et al., 2019), biodiversity and cultural services (Clec'h Solen et al., 2019; Neyret et al., 2021), carbon storage and erosion prevention (Petz et al., 2014), climate regulation and soil quality (Hanisch et al., 2020), and between carbon storage and recreation (Clec'h Solen et al., 2019), often in grazed ecosystems. However, in other contexts, trade-offs among these services can occur (Anderson et al., 2009; van der Plas et al., 2019). For example, Anderson et al. (2009) found negative relationships between biodiversity and soil carbon storage across large spatial extents, although this was likely mostly driven by geographic variation, rather than by field management. Such trade-offs between plant biodiversity and carbon storage can also occur in relatively productive systems in Northern Europe, where soil carbon storage is maximized at low levels of grazing intensity, while plant biodiversity is maximized at relatively higher levels of grazing intensity (Lienin & Kleyer 2012). In line with expectations based on Figure 2:3, several studies have suggested that changes in grazing management can cause trade-offs between wildfire mitigation and biodiversity, carbon storage and soil erosion at local spatial scales (van der Zanden et al., 2017; Lecomte et al., 2019). However, in some parts of Europe, like in the northwest, these trade-offs are hardly relevant, given the generally very low risk of wildfires. Where these trade-offs do matter (like in the Mediterranean, where wildfire risk is high), they can be minimized when grazing intensity is sufficiently high to avoid fuel buildup, but at the same time sufficiently moderate to also promote biodiversity and carbon storage (Rouet-Leduc et al., 2021; Kristensen et al., 2021).

2.3.7 Recommendations: optimizing ecosystem multifunctionality in grazed systems

With a view toward maximizing the potential benefits that can be achieved from grazing, promoting ecosystem multifunctionality (at different scales) should be a key objective (Mastrangelo et al., 2014; Manning et al., 2018). Our review indicates that in most cases, this can be achieved by reducing grazing intensity to benefit biodiversity, climate change mitigation, soil quality and cultural ecosystem services. Given that negative effects of intensive grazing on biodiversity, and services such as climate mitigation, are even greater in (semi-) arid regions than in more mesic conditions (Maestre et al. 2022), benefits of maintaining low intensity grazing may be greatest in Mediterranean regions. On the other hand, these are also regions with increased risk of wildfires, so that measures mitigating wildfire risk (e.g. targeted grazing to create firebreaks) still need to be taken (Moreira et al., 2020). In central and Northern Europe, issues associated with overfertilization (reducing soil quality and biodiversity) could also be mitigated by reducing grazing and management intensity and the use of fertilizers. The benefits go beyond the field level, as avoiding intensive livestock management reduces downstream nutrient flows, and allows reducing external fodder crop inputs, with associated telecoupled effects such as deforestation. While optimal grazing intensity for plant biodiversity and wildfire mitigation may be slightly higher than for most other services, these services could be optimized by using mixed grazing stocks or promoting diverse wild herbivore communities, rather than using a single grazer species (Wang et al., 2019). Furthermore, some intensive livestock systems receive (artificial) fertilizers, which typically reduces both plant- and animal-diversity (Parfitt et al., 2010; Figure 2:2). Another management activity common to both extensive and intensive livestock systems is the application of medication, particularly deworming medication. This can result in lethal effects on non-target insects, suppress seed germination of several plant species, as well as cascading negative effects on higher trophic levels, such as birds (Floate et al., 2005; Lumaret et al., 2012; de Souza & Guimarães, 2022; Figure 2:2). In addition, in some parts of Europe, controlled burning is done to mitigate wildfires, but this can also influence plant and insect biodiversity (Fuhlendorf et al., 2009; Joern & Laws, 2012; Figure 2:2).

While the above management recommendations may often promote multifunctional grasslands, there is likely no single 'one-fits-it-all' management plan that promotes all ecosystem services of interest. Rather, multifunctionality should optimally be balanced at the landscape level, by managing different fields in different ways, so that they complement each other in the services they provide (van der Plas et al., 2019; Neyret et al., 2021). For example, diversified landscapes can consist of a combination of lightly grazed patches (maximizing animal biodiversity, soil quality and carbon storage), some patches that are more heavily grazed (maximizing plant biodiversity, and mitigating wildfire risk), as well as some patches with only very low grazing intensity, in which encroaching shrubs can provide habitat for the (many) species requiring structured vegetation for shelter or food. Such mosaic landscapes may of course consist of various land-cover and land-use types, including grasslands, croplands, forests and plantations. Such landscapes often characterize High Nature and cultural Value farmlands, known for their value in terms of biodiversity and multiple ecosystem services (Plieninger et al. 2019). These landscapes are present in different bio-climatic regions and are often characterized by their heterogeneity combining grazed and ungrazed areas while providing multiple ecosystem services including cultural ecosystem services (Moreno et al. 2017).

Areas that have undergone land abandonment, such as large areas of the Mediterranean Region and Eastern European countries, require grazers as an important ecosystem engineer (Perino et al. 2019), but they can benefit from more hands-off approaches, such as rewilding with large herbivores. This type of management can also be cost effective, for instance for wildfire prevention, especially in remote areas that otherwise may be prone to wildfires (Navarro & Pereira 2012; Fuhlendorf et al., 2019; Rouet-Leduc et al. 2021).

Multiple types of policies have an impact on grazing management (Table 2:1), but agricultural policies are especially relevant, as they provide both the financial means and the regulatory framework for land users involved with grazing areas, and accordingly affect how they manage them. From a policy perspective, the most dominant policy instrument in the EU is the Common Agricultural Policy (CAP), which - with circa 55 billion Euros a year - includes several instruments affecting, or even directly determining, grazing management in Europe. Payments for organic farming and for farmers within protected areas (Natura 2000), as well as some types of Agri-Environment-Climate-Measures (AECM) specifically prescribe management criteria for environmentally-sustainable grazing. Starting in 2023, Eco-schemes is another new instrument which can support farmers in achieving ambitious environmental targets, also for grasslands and grazed areas (Pe'er et al. 2022). However, a much larger proportion of the CAP's budget is taken by other instruments, much of which affecting farmers involved in grazing - both positively and negatively. Among Direct Payments (73% of CAP's budget), 'coupled payments' (i.e. those that are coupled with production) are strongly associated with intensification of animal production and can be considered a harmful subsidy (Alliance Environment 2019). In consequence, there is much room for improving the CAP's environmental performance (Pe'er et al. 2019, 2020, 2022; Scown et al. 2020), also to support sustainable grazing and the people engaged in it. This can be achieved by reducing CAP subsidies for intensive grazing in sensitive areas, enhancing CAP support for extensive farming (and farmers) through AECM and Eco-schemes, phasing out coupled payments (Pe'er et al. 2020), and performing an in-depth evaluation of Direct Payments for their impacts on livestock and grazed systems. Additional relevant policy instruments are the Birds and Habitats' Directives, determining management criteria for grasslands especially in protected areas. EU strategies, especially the Green Deal and Farm to Fork Strategies, are highly relevant as well (Table 2:1). Specifically, grazing extensification is central to achieve the Green Deal's goals of reducing net greenhouse gas emissions by 55%, reducing the use of antibiotics by 50% and fertilizers by 20%, as well as expanding the land share of organic farming to 25%, all by 2030 (European Commission, 2019). These targets tightly link with the goals of reducing nutrient runoff and water pollution, in accordance with the Nitrate Directive and Water Framework Directive (European Commission, 2010), and are rightly reflected in the restoration law and Sustainable Use Regulation (SUR) proposed by the European Commission (EC 2022, EP2022).

Extensification can release land from intensive production, both directly and indirectly - but should be achieved without generating undesirable pressures elsewhere (Fuchs et al. 2020). This requires solutions both at the production and the demand sides. Particularly, reducing the overall demand for meat and dairy products can be achieved through a transition towards more plant-based diets. Reducing meat consumption and switching to plant-based diets would significantly reduce greenhouse gas emissions (Stoll-Kleemann & Schmidt 2017), land-use pressure and imported deforestation (Rajão et al. 2020; Bager et al. 2021). To support such transitions, there is a need for better labels for sustainably-produced animal-based products (in accordance with the Green Deal). The EU should also

invest more in campaigning for healthier and more balanced (plant-based) diets. In the long-term, however, a coherent food policy (or at least a policy framework) needs to be established to address both production and demand-side challenges. Regarding the telecoupled effect of livestock and other products inducing land use change and deforestation in other parts of the world, the EU has taken significant steps in haltering commodity-driven deforestation outside of the EU in the context of the Green Deal by approving a new regulation aiming at preventing deforestation and forest degradation in selected supply chains of the EU, amongst other for products from cattle (European Council, 2022).

Table 2:1 *- Key European targets of relevance to grazing. Legend: CAP = Common Agricultural Policy; AECM = Agri-Environment-and-Climate Measures; EnC = Enhanced Conditionality (formerly Cross Compliance); npINV = non-productive Investment Measures; ANC = Areas facing Natural Constraints; GHG = Green house gases*

EU targets to 2030 relevant to grazing lands	**How does can grazing management contribute to the target?**	**Relevant policy instrument(s) in the grazing context**
Reduce **GHG** emissions (-55%)	Reduction of herd size, reducing N-fertilizer use	CAP (AECM; npINV)
High diversity landscapes features 10% of UAA	Extensification, rotational practices, protection and restoration of mosaic (HNV) landscapes	CAP EnC (4% on arable land), Eco-schemes and/or AECM for expansion to 10% (especially on grasslands); Restoration through npINV; ANC (when well targeted)
Reduction of **nutrient** losses by 50%, Fertilizer use -20%	Reducing N-fertilizer use	Nitrate Directive, Water-Framework Directive; implementation through the CAP: EnC; Eco-Schemes
Expanding the area under **organic farming** to 25%	Extensification of grassland management	CAP - Organic certification requirements in the EU covers a range of aspects of extensive grazing (by domestic animals). Extensification: npINV
Animal welfare goals	Extensive, year-round, pasture-based grazing is considered good for animal welfare	CAP AECM, npINV
Protection of 30% of EU land	Extensive grazing is essential to maintain sensitive habitats, particularly grasslands and scrubland (avoid scrub encroachment or succession to closed forests)	Habitats and Birds Directives, implementation and funding through national legislation, additional (limited) funding through CAP
Significant areas of degraded and carbon-rich ecosystems are restored. **Habitats and species** show no deterioration in conservation trends and status; and at least 30% reach favorable conservation status or at least show a positive trend.	Extensification is essential in many grassland habitats, especially to reduce nutrient loads and fertilizers. Extensive grazing is essential in many grassland and scrubland habitats to maintain or restore them to good conditions, and avoid succession or, bush- or fern-encroachment. Grazing in forests and wood pastures is essential to open them or maintain them open.	Habitats and Birds Directive, Biodiversity Strategy, Restoration law

Restoring natural functions of ground and surface **water**: "reduce pollution from excess nutrients"	Extensification can reduce all these pressures. High-intensity grazing generates pollution through dung, fertilizers and soil erosion (e.g. through trampling).	Water-Framework Directive, implementation primarily through CAP, a plan to release "a zero pollution action plan for air, water and soil".
Reduce the use of **antimicrobials** in agriculture by 50%	Reducing the size of herds, and extensification reduces risks of contaminations. Using antibiotics only in a targeted way rather than as a preventive measure	CAP AECM

2.4 Outlook

While provision of food production is often the main goal of grassland management, grazing management provides many additional benefits as well as disbenefits for biodiversity and ecosystem services. In our review we specify the impacts on ecosystem services and how they are mediated via grazing density and grazer species composition. While this review focused on the effects of grazing on environmental ecosystem services, it is clear that food production is often the main goal of grassland management and it often drives the management decisions regarding more than provision of other ecosystem services. Importantly, associated management practices to support dairy and/or meat production, such as external fodder production and fertilizer input have the largest negative impacts and endanger goals for biodiversity conservation and climate change. While at the field scale, intensively grazed systems contribute more to dairy and/or meat production than extensively grazed systems, due to external fodder inputs, net effects on global food production, climate change mitigation and biodiversity can be highly detrimental. In contrast, less productive grazing systems with mixed grazer communities and lower grazer densities can contribute to biodiversity and multiple ecosystem services, and are overall more sustainable. These can be achieved through e.g. High nature value farming, that allows for both food and other ecosystem service supply. Ideally, grazing management should contribute to environmental as well as economical sustainability at multiple scales. We hope our review contributes to advancing our understanding on how grazing management can contribute to a more sustainable world.

3. Chapter Three

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3.1 Introduction

Across the globe, there is a growing recognition of the importance of wild landscapes for human wellbeing and the preservation of biodiversity and scenic values. In the USA this is driven by the wilderness agenda, whereas in parts of Europe it is because of the abandonment of pastoral systems of production as people move to the cities. Perhaps counterintuitively there is significant politics surrounding these areas where population densities are very low (Monbiot, 2014). This is because without deliberate intervention, landscapes may change in ways that are not desired by the public (e.g., forest encroachment in the French Alps; MacDonald et al., 2000). To avoid this scenario, managers need to decide when and how to intervene—even if the previous system of land management is no longer feasible. It is these contexts in which the connection between society and nature will play out. Thinking, imagining and acting will be key, because just doing nothing and letting nature take its course could lead to perverse outcomes (e.g., wildfires, loss of rare ecological assemblages such as grasslands), that will change the political agenda and humanity's relationships with nature. Now is the time to move beyond landscapes as simply a by-product of our production systems to deliberative *thoughtscapes*, and ultimately *actionscapes* before it is too late (portended by the recent fires in Australia and the western USA).

Nowhere on Earth is truly wild, human influence extends across the globe from the tallest mountains to the bottom of the deepest oceans (Goudie, 2018). These influences can be direct (e.g., land-use change, fishery harvest) and indirect (e.g., greenhouse gas emissions, pollution into rivers and coasts) (Rockström et al., 2009). Since the Pleistocene, humans have had negative impacts on ecosystems (over 75% of the land surface being significantly altered by human activity and over 85% of wetland area lost), and on species (with ~25% of species threatened with extinction) (IPBES, 2019). This is likely to get worse as human populations grow and the global consumption of goods increases, both in developed countries and in emerging economies. It is commonly perceived that there is a conflict between human needs, for example, food production to meet the increasing demands (which is expected to grow by over 70% in the next 30 years) of the human population that is growing in size and wealth, and nature conservation (Gordon et al., 2017). The argument is that nature must be protected from the negative impacts of intensive agricultural production; so-called “land sparing” (Fischer et al., 2008). The extreme example of this is “rewilding”, defined as “the reorganisation of biota and ecosystem processes to set an identified social–ecological system on a preferred trajectory, leading to the self-sustaining provision of ecosystem services with minimal ongoing management” (Pettorelli et al., 2018). It should be noted that rewilding is, in effect, a sub-set of restoration of ecosystems based upon the idea that restoration is “the process of assisting the recovery of an ecosystem that has been damaged, degraded or destroyed”, Society for Ecological Restoration International Science and Policy Working Group (2004). Following its introduction in the academic literature in the late 1990s, rewilding has gained significant momentum in recent years (average just over 3 publications per year in the 2000s to around 80 publications per year in 2018 and 2019; Figure 3:1; see also Svenning et al., 2016; Pettorelli et al., 2019). This reflects the growing concern about the impacts of humans on natural systems, particularly as related to their wilderness [as in the case of the US Wilderness Act (1964)], the conservation of biodiversity (Johns, 2019), and a concern that current approaches are not effective (Butchart et al., 2010; Tittensor et al., 2014; WWF, 2016; IPBES, 2019). This in turn often sees humans as separated from wilderness areas e.g., “an area of land untrammelled by man, where man is a visitor who does not remain” [Section 2(c) of the US Wilderness

Act (1964)] or "A wilderness is an area governed by natural processes. …. without intrusive or extractive human activity" (Wild Europe Initiative, 2013).

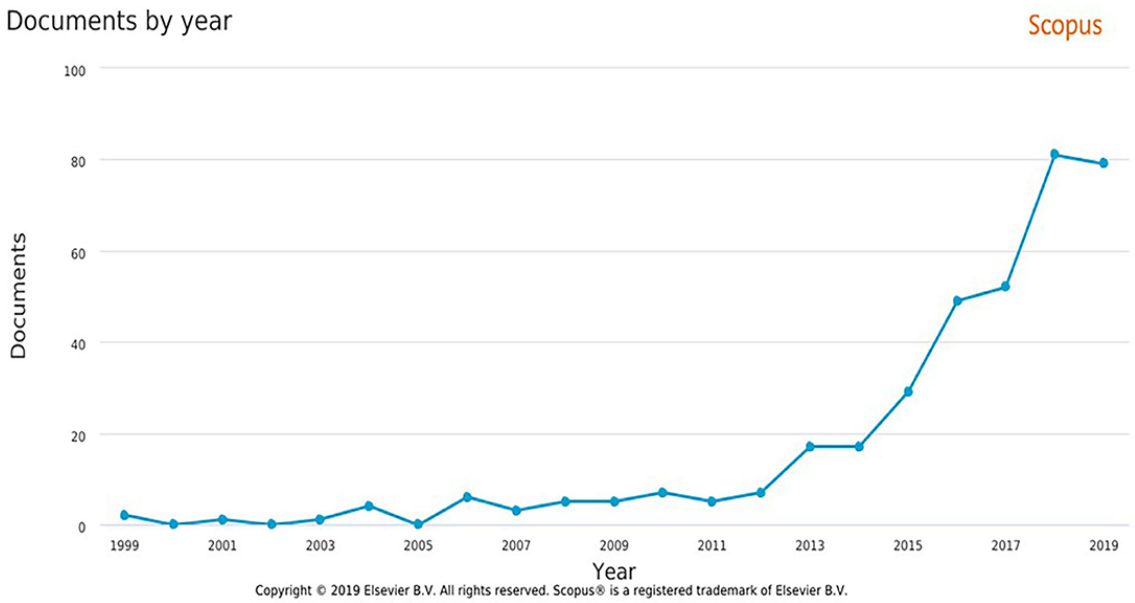

Figure 3:1 *- Number of articles listed in Scopus that mention "rewilding" or "re-wilding." The search led to 370 papers.*

Though there have been attempts by academic ecologists to define and steer rewilding as a concept (e.g., Pettorelli et al., 2019), its undoubted intuitive resonance with non-academics (Monbiot, 2014) means it is destined to be a panchestron (all things to all people). We expect its definition will continue to develop as an emergent property as different kinds of rewilding emerge (rewilding is, after all, about "self-willed" processes where rewilding is possible). We believe this flourishing diversity of definitions should be embraced because we see several major concerns with adopting an overly purist approach to rewilding, i.e.:

(1) there are few places in the world where "pure" rewilding is possible – most have some form of social or ecological constraint (Fuller et al., 2017; Ward, 2019);

(2) humans have been part of wild landscapes for millennia, and the separation of humans from ecological systems runs counter to the broader view of socio-ecological systems in many other areas of academic and practical endeavour (Ostrom, 2009; Perino et al., 2019);

(3) the extinction of many keystone species (ecosystem engineers) from continents across the globe means that the restoration of functionally important native species is not possible in many cases (Sandom et al., 2014a,b; Richmond et al., 2016); and,

(4) it is not necessary to "de-domesticate" congeners of extinct wild species to achieve the outcomes we want where we have hardy domestic breeds that most likely have ecologically equivalent, or near identical, impacts if kept in wild/semi-wild conditions. These breeds can fulfil ecological functions that reinstate processes representative of wilded systems.

For these reasons we see the potential benefits of including species of domestic (e.g., cattle, goats, sheep, horses/ponies, pigs) and semi-domestic (e.g., reindeer) livestock in the toolkit of managers responsible for rewilding. Unlike many proposed functional "niche substitutes" where rewilding involves evolutionarily distinct species to replace lost processes [(e.g., African lions (*Panthera leo*) to replace predation by sabre-toothed cat (*Smilodon* spp.) in North America; Donlan, 2005; Lundgren et al., 2020)], many domesticated species are the same species, or closely related, to the species that have been lost from the landscape (Lundgren et al., 2020). Logically, this means that the domestics' ecological function will be very similar to their wild ancestors/relatives, the key differences likely related to impacts of husbandry on social structure, mate choice by humans (selection), constraints on spatial movements, aggression, and body size (Clutton-Brock, 1989). However, it is not clear that these would significantly influence the ecological function if domestic animals were maintained "as-wild". Indeed, the Chillingham cattle in Northumberland (United Kingdom), that are thought to be derived from domesticated animals, have been maintained as-wild for at least 700 years, and live "probably close to the natural state" (p. 215) (Hall, 1989). The cattle display many wild behaviours, and rarely exhibit some behaviours associated with husbanded cattle (Hall, 1989). This raises questions about whether de-domestication (the process of turning domestic breeds into wild, self-sustaining animals; Gamborg et al., 2010) is systematically necessary to achieve rewilding goals if existing hardy livestock breeds are permitted to live as wild animals. If not, the use of hardy breeds which are less aggressive [noting there concerns that auroch (*Bos primigenius*) may be "too dangerous"; Stokstad, 2015] and have production value, might encourage livestock keepers to develop systems that deliver on rewilding principles. This would of course require a re-evaluation of the characteristics of rewilding and/or rewilded landscapes, changes in policy/regulation, financial mechanisms (e.g., subsidies), and changes in attitudes, particularly amongst some environmentalists and conservationists.

It is worth noting that, as compared to rewilding in the academic literature (with over 370 articles and reviews) the inclusion of AND "livestock" in our search turned up only 21 articles and reviews since 1980, with seven appearing in 2019 (Supplementary Material 1). These include publications on the relationship between livestock and predators/scavengers (Arrondo et al., 2019), and advocacy for multifunctional landscapes based upon extensive livestock production for economic, conservation and carbon storage outcomes (Hall, 2018). However, to date there has been no clear articulation of the potential for including livestock within the rewilding agenda. In fact, it is generally declared that livestock are not part of the equation for rewilding unless, of course they have been used to 'reconstruct' wild progenitors of domestic species (e.g., Heck cattle; Heck, 1951; Stokstad, 2015). Obviously, the role that livestock might play in rewilding will be context-specific, but it is by no means unique to only certain specificities (e.g., in the heavily transformed landscapes of Europe). For this reason, we will set out the stall for:

(1) the fact that, no matter how large, rewilded landscapes cannot be isolated from human activity, and therefore, management will be required even if it is to achieve 'an area governed by natural processes";

(2) that livestock should be included in the toolbox of such management actions;

(3) that livestock can provide an economic return for such management actions; and,

(4) in the long-term rewilding needs to be seen within a broader socio-ecological system, where external influences will shape the future of wild landscapes.

3.2 The Broader Theory of Rewilding and Potential Role for Livestock

Since the concept of rewilding was first published in the late 90s (Soule and Noss, 1998), with a focus on the "three Cs" (i.e., carnivores, corridors, and core areas), several variants of its definition have been proposed (Jørgensen, 2015), ranging from passive approaches on abandoned land (Navarro and Pereira, 2012) to the reintroduction of functional equivalents of the extinct megafauna of the Pleistocene (Donlan et al., 2006). While seemingly different, these approaches converge on the concept at the core of rewilding, which is the restoration of self- sustaining and complex ecosystems, with interlinked ecological processes that promote and support one another while minimising or gradually reducing human intervention. Recently, the ecological theory supporting rewilding allowed the formulation of a framework focusing on three ecological processes that interact with one another, and that should be restored to return an ecosystem to a wilder and self-sustainable state (Perino et al., 2019): (1) stochastic disturbances; (2) dispersal; and (3) trophic complexity. In the following sub-sections, we discuss the three ecological processes core to rewilding, the potential limits to their restoration, and the role that domestic species can play in the process.

3.2.1 Stochastic Disturbance Regimes

Disturbances that are natural in frequency and intensity promote spatial and temporal heterogeneity of habitats and the complexity of their structure (Turner, 1998; Kulakowski et al., 2017; Perino et al., 2019). Typical disturbances are, for instance, those created by large herbivores through their foraging, defecation and trampling (Navarro et al., 2015; Ripple et al., 2015). Fire regimes are also critical disturbances for the creation and maintenance of ecosystems (Bowman et al., 2009), and these are directly influenced by the grazing and browsing pressure (van Langevelde et al., 2019).

One of the most pervasive effect of human activities in a landscape, in addition to land- use change, is the alteration of the natural disturbance regimes: natural fires are suppressed (Archibald et al., 2013), and the stochastic disturbance by wild herbivores is replaced by long term deterministic disturbance by livestock and agronomic fertiliser application (Navarro et al., 2015; Perino et al., 2019). These anthropogenic landscapes have characteristic plant and animal assemblages that reflect the fact that herbivory has created and maintained assemblages that rely directly or indirectly on disturbance, historically by now extinct large herbivore species but now mainly by domestic livestock (Gordon et al., 2017; Bond, 2019). These modified ecosystems, and the economic, social, and cultural activities that depend upon them, are at risk once those livelihoods are abandoned (Cava et al., 2018; Van Meerbeek et al., 2019). Depending on the land-use legacy and the naturalness of the broader landscape, the abandoned land is vulnerable to significant degradation until the natural disturbance regimes are restored. Restoring natural disturbance regimes is, therefore, key in rewilding management (Torres et al., 2018) including to increase the resilience of the ecosystems to current and projected climate change (e.g., Kulakowski et al., 2017).

Domestic and semi-domestic livestock species can play an important role in the restoration of stochastic disturbance regimes, particularly in areas where wild large herbivore species are absent, as is often the case in areas with long-term and large-scale human pressure (Sandom et al., 2014a; Svenning et al., 2016). Until natural fire regimes have been restored, grazing by livestock could also limit the accumulation of fuel and thus lower the risk of wild and intense fires with risks to natural and human capital (Davison, 1996; Bruegger et al., 2016).

3.2.1.1 Dispersal and Connectivity

Dispersal is essential for the viability of wild populations, to increase access to ephemeral resources, facilitate recovery from disturbances, as well as to reduce inbreeding (Moseby et al., 2018; Perino et al., 2019). Dispersal by large herbivores also facilitates a range of ecological processes including pollination and seed dispersal (Corlett, 2013; Dirzo et al., 2014; Rey Benayas and Bullock, 2015). Where wild large herbivores have been lost from the landscape, it is important to ensure that the use of domestic livestock reproduces the movement patterns, large and small scale in space and time, of those wild species (García-Fernández et al., 2019). This can include active herding the ensures that ecological processes are restored or maintained. Nonetheless, land-use change and the fragmentation of landscapes, including due to linear infrastructure, greatly affect the size and integrity of habitats, thereby affecting the ability of individuals to disperse (Berger-Tal and Saltz, 2019).

Rewilding projects consider the restoration of the connectivity between patches of habitats, for instance by establishing corridors and making linear infrastructure more permeable and less lethal (Root-Bernstein et al., 2017; Torres et al., 2018; Perino et al., 2019). The restoration of dispersal can also be directly embedded within the human-dominated landscape, for instance by adding natural elements such as woodland islets in agricultural fields (Merckx and Pereira, 2015; Rey Benayas and Bullock, 2015). Furthermore, free-ranging livestock can play a role as seed dispersers (Bruun and Fritzbøger, 2002; Couvreur et al., 2004) and their trampling, as well as dung deposition, has been shown to contribute to germination, although with seldom discrimination between native and non-native species (Faust et al., 2011; Hogan and Phillips, 2011). Whether the ecological processes are restored by wild, semi-wild, or domesticated species, the ability of herbivores to disperse has implication for the viability (and welfare) of the populations, and their ecological role in the system Root-Bernstein et al., 2017; see Case study of Oostvaardersplassen below).

3.2.2 Trophic Complexity

Ecological theory supports the role of trophic complexity and trophic interactions in maintaining ecosystems, for instance *via* the regulation of populations sizes and distributions through processes such as predation and competition, as well as its impact on other processes such as disturbance and dispersal (Perino et al., 2019). The consequences of the degradation of trophic complexity is being increasingly witnessed and understood globally (Estes et al., 2011; Dirzo et al., 2014), particularly with the loss of large carnivores and large herbivores from ecosystems (Ripple et al., 2014, 2015).

An approach to rewilding illustrates the importance of trophic complexity i.e., “trophic rewilding” which places an emphasis on the reinforcement of populations, or on the reintroduction of missing species, particularly large carnivores and large herbivores (Svenning et al., 2016). However, in several

cases, the restoration of complex trophic networks will not be possible because some species have gone regionally or globally extinct (Svenning et al., 2016; Fernández et al., 2017). Even when keystone species are only regionally extinct, public acceptance of their reintroduction might be low, e.g., European bison (*Bison bonasus*) (Decker et al., 2010; Klich et al., 2018), often due to a phenomenon known as the 'shifting baseline' syndrome, whereby the human expectation of what are 'good' or 'natural' environmental conditions is determined by the current experience rather than a historic diversity that is not present in living memory (Pauly, 1995; Manning et al., 2006; Papworth et al., 2009; Clavero, 2014). The case studies as presented below fall on a gradient from greater human intervention in the case of reindeer herding through to much lighter management input in the case of OVP and Knepp. This demonstrates how the approach we are presenting can be applied in different rewilding contexts.

In the case of the restoration of trophic complexity specifically, the potential of livestock is still limited. For instance, the extent to which livestock can be considered as a replacement for wild herbivores will depend not only on their functional role in herbivory and fire suppression but also on people's acceptance of depredation by wild predators on those domestic or semi-domestic populations (Bautista et al., 2019). However, we know a huge amount about the interaction between livestock and a broad range of natural ecosystems and this knowledge can be used in replacing extinct species disturbance regimes (Gordon et al., 2004).

3.2.3 Interacting Processes

The three ecological processes discussed above do not act in isolation and their interactions should be considered for rewilding. For instance, the natural recolonization or reintroduction of large herbivores, or the use of livestock as functional proxies for wild species, without control by natural predators could alter the natural disturbance regime within the landscape and lead to detrimental grazing impacts. The restoration of the spatial and temporal variability of the trophic interactions is also important to take into consideration in rewilding projects, for instance with the restoration of a "landscape of fear" (Manning et al., 2009; Suraci et al., 2016), and its impact on the spatial distribution of nutrient deposition and grazing pressure. The landscapes to be rewilded must also be sufficiently large, or connected, to allow the movement of predators and prey species. Predation, by stochastically distributing carcasses in the landscape, also plays an indirect role in both the size of populations of detritivores and plant growth *via* nutrient depositions (van Klink et al., 2020). While large carnivores are not yet part of the ecosystem, managers of rewilding areas should consider how to replicate these trophic interactions artificially (ICMO, 2006).

Ultimately, restoration is a societal vision for interactions between humans and nature, and the choice of given interventions and their likely outcomes. In the case of rewilding, approaches and outcomes can vary greatly depending on the historical baseline considered and the intensity of the action that one is willing to apply (Fernández et al., 2017). This explains why the interventions considered to date can range from letting wild species recolonize recently abandoned farmland (Navarro and Pereira, 2012), to the reintroduction of elephants (e.g., *Elephas maximus*) as proxies for the ecological role that mammoths (*Mammuthus* spp.) played in the landscapes of the Pleistocene (Donlan et al., 2006). This broad spectrum of interventions for rewilding also means that there is room to shift from considering that the role of livestock exclusively for food production and the maintenance

of cultural landscapes, towards including their functional role into strategies for the short- or medium-term creation of self- sustaining and wild ecosystems.

3.3 General Case Studies

Given the emphasis in rewilding is on restoring natural ecological processes, rather than species *per se* there is no logical reasons against using domestic animals or niche substitutes if they provide ecosystem functions, achieve the desired ecosystem state, and provide the same ecosystem services. This may be particularly important in the early stages of a rewilding project. However, using domestic livestock for rewilding has implications for both the nature managers and for the animals themselves; in the upcoming section we will outline four case studies, and discuss how they have used, more or less successfully, domestic animals for projects associated to rewilding. These examples inform and generalise guidelines for the use of domestic animals to restore or retain key ecological processes for rewilding. Here domesticated animals are meant as animals that are tame, have their reproduction controlled by humans and are dependent upon humans for their survival (Drenthen and Keulartz, 2014), and semi-domesticated are meant as animals who still need some human intervention for their survival, but have some autonomy in their movements. However, there is a continuum between wildness and domesticity that depends on the amount of human intervention and care given to the animals, but also on the adaptability of the animals to their environment (Keulartz, 2010). Hence, we advocate for the inclusion of domestic animals in the toolkit of rewilding projects and for the increased deliberative intervention of managers in cases where scale, type of animal or social context do not leave room for a large scale, hands-off rewilding approach.

3.3.1 Reindeer Engineer in Swedish Lapland

Our first case study explores the initiative, launched in 2015 by Rewilding Europe, Rewilding Lapland (since renamed Rewilding Sweden). It is a unique project to encourage a new economy based on the cultural landscape of Saami and the Laponia region, that stretches over the north of Sweden and Norway. The area is populated by the First Nations Saami people and herding of semi-domesticated reindeer (*Rangifer tarandus*) is an essential part of their culture and has shaped the landscapes for generations. Reindeer herds wander freely in unfenced areas between foraging in the tundra during the snow free season and spend the winter in the boreal coniferous forest where they feed on lichen, thereby limiting the need for supplementary feeding. Comparably to other indigenous populations elsewhere in the world, the relationship of the Saami people with the Swedish State is complex and there is a long history of State repression of cultural activities (Lantto and Mörkenstam, 2008). Today, tensions are mostly with the forestry sector, representing a powerful industry that intensively manages forest plantations in Laponia. The region also includes the Laponia World Heritage area, which comprises large areas of old growth forest and stands as a symbol of co-management of natural resources between the Saami and the Swedish State (Reimerson, 2016).

The Rewilding Sweden project seeks to create an economy based on the unique socio- ecological system that includes Saami culture, wildlife, and free flowing rivers (Koninx, 2018). Reindeer and reindeer herding are an essential part of this nature-culture landscape, influencing landscapes through their grazing and trampling. In turn reindeer are connected to the semi- nomadic herders who engage in transhumance with the reindeer herds (Rouet-Leduc and von Essen, 2019). Reindeer are an

important source of income for reindeer herders, in terms of meat products but also products derived from the reindeer skin, antlers, etc. as well as tourism activities related to reindeer (Koninx, 2018). The path followed by Rewilding Europe (2020) generally is a bottom-up, network-based approach putting Saami knowledge and cultural relationship with nature at the heart of the vision for the new economy, with reindeer being the most important keystone species of the area because of their disproportionately large impact of the ecosystems compared to their abundance (Paine, 1966; Power et al., 1996). The Rewilding Sweden project promotes a network of nature conservation actions, with a focus on reindeer herding and river catchments, valuing pre-existing human-modified systems using semi- domestic reindeer. In this context, rewilding with predators or wild herbivores could create great disruption in the reindeer herding activities, since predator presence creates a major issue for herders (Sandström et al., 2009), and other wild herbivores are likely to compete with the reindeer for limited forage resources. Recognising reindeer as the keystone species of the area, despite it not being a truly wild animal, allows for a "relevant and minimally respectful compromise" to be made as the animal is at the heart of Saami livelihood and tradition (Rouet-Leduc and von Essen, 2019).

In Rewilding Sweden, approval from local, and especially Saami, communities is especially crucial; therefore, synergising the interests of reindeer herders and other issues of nature conservation allows for the creation of a long-term, large-scale project that has a social licence to operate. In contrast with the intensive forestry activities that occupy major areas of Swedish Laponia region, the project's approach is based on common interests in preserving wild areas (Widmark, 2009), since reindeer herding, like rewilding projects, depends on restoration or protection of wild nature, in this case old-growth forest.

3.3.2 Livestock Fire Brigade and Free Running Horses in the Côa Valley, Portugal

The Faia Brava reserve in Portugal, illustrates how the use of domestic livestock and human management is necessary, either as a transition period towards future "self-willed" wild nature, or because of other limitations that requiring cognisance of animal welfare, human-animal relations, or legislation.

In recent years, the Mediterranean region of Europe has seen a rise in the abandonment of farmland and traditional land management practises. This transition has led to shrub encroachment, increased fuel load (because domestic herbivores are no longer removing biomass and populations of wild herbivores are still relatively low), increasing the risk of wildfires (Moreira et al., 2011). This land abandonment process takes place on former traditional landscapes such as the Montado/Dehesa silvopastoral systems in Portugal and Spain that combine silvicultural activities, usually of cork oaks (*Quercus suber*), with agriculture and extensive grazing (Oteros-Rozas et al., 2014; Godinho et al., 2016). In the North East of Portugal, the Côa Valley is a textbook example of the rural exodus leaving large swathes of disused agricultural areas. The Portuguese Non-Governmental Organization Associação Transumância e Natureza (ATN), together with the support of the European organization Rewilding Europe, has established a reserve on former agricultural land, Faia Brava. The area was previously used for olive (*Olea europaea*), cork (*Quercus suber*), and almond (*Prunus dulcis*) groves, as well as extensive herding of goats and sheep (DeSilvey and Bartolini, 2019). The reserve, created in the 2000's, is now home to semi-wild Garrano horses (*Equus ferus caballus*) and cattle (*Bos taurus*) herds.

For several reasons, Faia Brava illustrates well the use of domestic animals and the human intervention in rewilded landscapes. The size (about 850 ha), as well as the nature of the reserve being situated in a highly anthropogenised landscape with a strong cultural value, calls for multiple human interventions to maintain the reserve and the animals that are present in it, creating a natural and cultural landscape of co-habitation and co-production (DeSilvey and Bartolini, 2019). As well as being limited in size, the reserve is surrounded by land that is still used for agriculture and pastoral activities. Therefore, a completely hands-off approach is not possible, and some level of management of the animals is necessary, to avoid human-animal conflicts and to meet requirements for animal welfare. The horses and cattle, therefore, receive supplementary feeding, especially in the years with harsh conditions, and have access to artificial water points in the reserve. Also, due to the near absence of predators in the area, managers of the reserve mimic predation and maintain populations of animals at a level they judge to be in accordance with carrying capacity of the area. In theory, the number of animals could be regulated bottom-up by the amount of food available, similarly to the initial management practises at Oostvaardersplassen, but the need for public acceptance requires human intervention in regulating populations of animals, to avoid public outrage in the absence of regulation by predators. Excess cattle are sold for meat while horses are sold as pets.

The management of the horses and cattle in the reserve is made easier by the relative tameness of the animals. Rewilding Europe aims at having a “self-sufficient wild bovine grazer” in multiple places, including Faia Brava, as part of their Tauros program but in this long transition phase, the cattle are still managed. The “back-breeding” process used in the Tauros project, selects traditional local breeds like the Maronesas and Sayaguesas cattle, and seeks to eventually bring back a functional relative of the extinct auroch (Goderie et al., 2016; Rewilding Europe, 2020), although we would assert that this is not necessary given that hardy domestic breeds are available.

In Faia Brava, as with all rewilding projects, social context must be taken into consideration, in terms of social preference as well as nature's contribution to people's lives and livelihoods in the form of ecosystem services (Perino et al., 2019). The successful annexation of the reserve was dependent on good relations with both regional authorities and local inhabitants. The use of semi-wild animals made their management easier but the continuous existence of traditional herding of cattle and sheep (*Ovis aries*) in the area made the relationships with herders a challenging cooperation (Pellis, 2019). In these post-agrarian landscapes (Lorimer and Driessen, 2016), transition is a lengthy process and requires cooperation across the traditional agricultural and rewilding sectors.

An important aspect that characterises this project is the will to involve and include the local community in deriving benefits from the reserve. This creates nature-based economic activities, as an alternative to land abandonment (with its associated reduced economic opportunities), as well as encouraging social acceptance of the rewilding project. Rewilding Europe and ATN have been actively collaborating with the local community, especially the local shepherds and the inhabitants of the neighbouring village of Cidadelhe (Pellis, 2019). The Faia Brava reserve is already home to ecotourism activities, based on wildlife viewing and other nature-based activities related to the area. Rewilding Europe is also emphasising the nature-culture aspects of these enterprises by combining the allure of the rewilding project with the broader benefits of the location in the Côa Valley, which is listed as a UNESCO World Heritage Site, for its Prehistoric rock art depicting large herbivores (UNESCO, Rewilding

Europe). More generally, managers of rewilding projects are aware of potential tensions that their vision of future landscapes can spark in traditional agrarian landscapes, where the culturally-based assumptions for how landscapes should be managed do not necessarily match with rewilding projects. Reconciling different management paradigms is a challenge which justifies, in the Faia Brava case, the use of semi-wild (or semi-domestic animals), that are similar to the domestic animals present in the area and are, therefore, more familiar and acceptable to the people living in the area. This case study, therefore, shows that, because of the strong cultural aspects and the omnipresence of traditional agrarian activities and cultures, rewilding must happen within a socially acceptable operating space that identifies and respects societal norms (Corlett, 2016; Perino et al., 2019).

3.3.3 Ecotourism and Sustainable Meat at Knepp Estate, England

The Knepp Estate in England is one of the most famous examples of rewilding in Europe, stretching over 1,400 ha of former farmland, and home to numerous wild-living herbivores, such as longhorn cattle, Dartmoor horses, red (*Cervus elaphus*) and fallow deer (*Dama dama*) and Tamworth pigs (Tree, 2018). While it is using some domestic species, the vision for the Knepp Wildland project is to create a rewilding area, that is not determined by the conservation of a specific species or habitat, but rather by the restoration of natural processes and the use of large herbivores as keystone species to achieve this vision. In just two decades, since the Knepp Wildland project began, the estate has seen a remarkable restoration of biodiversity, including rare species like the purple emperor butterfly (*Apatura iris*) and the peregrine falcon (*Falco peregrinus*).

The Knepp Wildland project started as a rewilding experiment on impoverished farmland and is now seen as an example of successful land management, and also a good case of nature-based economy. Indeed, the Estate is both an important place for ecotourism with its relative closeness to London, and it also produces around 75 tonnes of “wild” organic meat per year. The Knepp Wildland project started in 2001 and aims at creating a rewilding area with naturalistic grazing acting as a model for rewilding agricultural land in the UK (Overend and Lorimer, 2018). Considering the size of the Knepp Wildland, and the fact that there are no predators of large herbivores in the area, animal numbers must be controlled artificially. The domestic breeds such as longhorn cattle and Tamworth pigs are culled for the meat market, while deer are culled by stalking. Additional management is required by regulations, meaning that all the animals, except for the deer, must be registered, taken care of, and slaughtered in accordance with national legislation. The livestock, even though feral are managed so as not to pose a threat to humans and are not “too” wild (Rotherham and Handley, 2011) to keep public support for the project. Knepp Wildland has developed a broad range of activities based on rewilding that provides an alternative income to using the land for agriculture purposes. For example, the Estate sells sustainable premium meat from the longhorn cattle, the Tamworth pigs, as well as different types of venison from the deer. It focuses on the meat products being “wild range meat”, and the fact that the meat comes from ancient breeds and that the animals have lived and fed in a “wild” environment is a selling point. Also, the Estate offers numerous opportunities for recreation, such as wildlife watching and safari-like excursions.

The Knepp Wildland project is an excellent illustration of how domestic breeds of livestock can be included in the toolkit of nature managers in rewilding projects. As keystone species the animals perform specific roles in shaping the landscape, providing multiple ecosystem services including

habitat for biodiversity, while also giving an economic return in the form of premium wild meat and ecotourism. However, in other circumstances there may be social and ethical issues associated with the harvesting of animals in rewilding projects (as has been discussed for wildlife species, see Thulin and Röcklinsberg, 2020).

3.3.4 Oostvaardersplassen: The "Wild Experiment"

Oostvaardersplassen (OVP), in South Flevoland in the Netherlands, is one of the most famous, influential but controversial, rewilding projects in the world (Lorimer and Driessen, 2014a). It was established on a reclaimed polder, originally intended for industrial development, but due to economic downturn in the early 1970s, was instead turned into a nature reserve (Vera, 2009; Lorimer and Driessen, 2014b). The reserve is about 6,000 ha of wetlands, grasslands with some trees and shrubs, surrounded by human dominated landscapes (intensive agriculture, urban fabric) with no connectivity to other (semi-)natural areas. This means that populations of large herbivores are not only not top-down regulated, but they can also not disperse. The site has become a very important habitat for birds, with over 78 species recorded (Schwartz, 2019). Species such as spoonbill (*Platalea leucorodia*), bittern (*Botaurus stellarus*), marsh harrier (*Circus aeruginosus*) and bearded tits (*Panuris biarmicus*), all previously rare in the Netherlands, established there (Vera, 2009). Also, bird species that were completely extinct as breeding species in the Netherlands established including the graylag goose (*Anser anser*), great white egret (*Ardea alba*) and white-tailed eagle (*Haliaeetus albicilla*) (Vera, 2009). Over 30,000 greylag geese over-winter there and influence the ecosystem through their grazing (Vera, 2009).

To avoid willow (*Salix cinereal*) encroachment onto grasslands two large de- domesticated forms of herbivore species were introduced in the mid-1980s, i.e., Heck cattle (*Bos taurus*) and konik horses (*Equus ferus caballus*). Red deer were introduced in the 1990s. These introductions were also underpinned by an alternative theory of past forest dynamics in which it was argued that ancient forests were more open than previously assumed, because of herbivore grazing and browsing (Vera, 2000). Critically, the herbivores were to be "unmanaged" and live as wild (i.e., free mate choice, social structuring) with population numbers being determined by food availability in the winter (Vera, 2009). As such, there were "no targets, no models and no explicit action plan" (Lorimer and Driessen, 2014b, p.48), which was a major divergence from mainstream conservation practise and regulation. The fact that the land was reclaimed from below sea-level, perhaps provided greater flexibility in thinking and experimentation with the focus on nature and natural processes ("new wilderness"—Schwartz, 2019), rather than the more traditional guided conservation management pathway towards a past or pre-determined state. Critically, the reserve is surrounded by human dominated landscapes (intensive agriculture, urban fabric) with no connectivity to other semi-natural areas.

From the initial introduction of founders (32 Heck cattle, 18 Konik horses and 40 red deer), the populations grew to over 5000 individuals, and the philosophy meant there were no prescribed targets (Schwartz, 2019). This meant that animals would die of starvation in tough winters (though rangers would proactively cull animals that were suffering), and carrion would provide food for predators including white-tailed eagle (Vera, 2009; Schwartz, 2019). This approach was controversial and challenged in court but was permitted to continue with some recommended changes (Vera, 2009; Theunissen, 2019). Though a review in 2006 noted that "the public preference for avoiding OVP

management policies that involve the routine culling of substantial numbers of healthy animals" (ICMO, 2006, p. 7), indicating divergence in community views on the management principles. However, during a harsh winter in 2017 over 3,000 (~60% of the population) animals were euthanized or died of starvation. There were public protests, and people illegally threw bales of hay over the fence surrounding the reserve (Schwartz, 2019). The provincial authority of Flevoland reviewed the management of the large herbivores (van Geel et al., 2018) and changed the management regime to set target populations sizes (210 Heck cattle, 550 Konik horses and 500 red deer). The populations were to be managed through active control and relocation to other projects. There was also a stipulation that each individual herbivore should be sighted three times a week, its condition assessed, and veterinary attention provided if needed (Schwartz, 2019). The changes effectively ended the "self-willed" management of the herbivore population. There was perhaps, a missed opportunity, following the earlier review of management in 2006 by independent large herbivore experts at a time when public opinion appeared to have supported the novel management regime, but issues were emerging (ICMO, 2006). They outlined a range of alternative management scenarios: (1) no intervention (2) proactive culling or removal (3) reactive culling (4) contraception. They recommended proactive culling or removal to minimise starvation and winter mortality *but* suggested these could be designed to mimic natural processes by (i) simulating the impact of natural predation and episodic mortality; (ii) removal of a fixed level of annual recruitment – but that range could be varied according to ecological carrying capacity; and (iii) removal of a variable numbers of animals each year based on body condition (ICMO, 2006). This recommendation allowed for a more nuanced, naturalistic management regime than eventuated in van Geel et al., 2018, when public opinion appeared more fixed against the original principles. This outcome serves as an important reminder of the need to consider the interaction of the society and ecology when defining management goals for rewilding (while at the same time recognising that all outcomes cannot be predicted at the outset).

There are many lessons from the Oostvaardersplassen "wild experiment"—these are not just ecological, but also social, philosophical and theoretical. Although it has been criticised as a "failure" by some (e.g., Theunissen, 2019), given it was largely experimental, and the outcomes of the novel approaches were not known *a priori*, it is perhaps unfair to apply measures of success retrospectively. While it may have failed by some perspectives, it has allowed the exploration of the principles of rewilding, and the relationship between this process and the public (i.e., social licence), and arguably helped to propel the broader rewilding movement to where it is today—on the cusp of becoming mainstream (Bakker and Svenning, 2018; Pettorelli et al., 2018, 2019).

Oostvaardersplassen raises important questions about the definition of rewilding, or rather whether there should be accommodation of different types of rewilding. At its core is a debate about human intervention—how much, when and what? Some of the criticism of Oostvaardersplassen has been that the area was too small and there was no natural predation (Schwartz, 2019) —though noting that Vera (2009) argued that evidence from Africa suggested bottom-up processes (i.e., food availability) would naturally drive the majority of mortality, and, therefore, overwinter deaths were to be expected. Therefore, in order to maximise the level of "self-willed" properties and processes, should human intervention be considered (can it be avoided?) in some parts of the ecosystem? —at least in the establishment stages? At the same time, it is likely that rewilding projects will want to avoid succumbing to the previous constraints (Butchart et al., 2010; WWF, 2016; IPBES, 2019; indeed many of the cumulative failures, e.g., at a global scale) of more mainstream "command and control" resource

management (*sensu* Holling and Meffe, 1996). In short, and perhaps counterintuitively, is deliberative, measured, targeted intervention the price that must be paid to have rewilding at a broadscale?

The introduction of population targets at Oostvaardersplassen in 2018 raises some interesting research questions and highlights an opportunity. Firstly, is it necessary to have to intervene in herbivore populations, as a price for having "rewilded" populations and ecosystems? How can evidence-based offtake targets be derived based on assumed bottom-up and top-down (predation) pressure? How do managers mimic natural mortality to maintain the ecological and evolutionary processes that are desired? The ICMO (2006) provided some valuable suggestions of how this might be achievable. The Heck cattle and Konik horses of Oostvaardersplassen had been under bottom-up selective pressure since the mid-1980s, but how will the culling towards the new targets change selection pressure across the population? Secondly, the combination of annually determined harvest levels, but the continuation of otherwise "wild" life history of the large herbivores, potentially opens the possibility of an integrated rewilding-farming model that markets the meat of the harvested animals, as in the case of the Knepp Wildland project above. Such products could be branded as supporting the rewilding of these extensive ecosystems and all of the co-benefits seen at Oostvaardersplassen [though we are not advocating this for Oostvaardersplassen, rather the concept, noting that using culled animals for human consumption was floated in the ICMO (2006) review]. The benefits of such a model are that the potential for financial feedback means more farmers could consider this as an alternative model for their land management, and, therefore, more land could operate under rewilding principles. In essence, this could be a Knepp+ or Faia Brava+ model in which feral livestock and wild herbivore species live as wild for their full life history (i.e., "self-willed"), but are monitored to meet societal expectations for their welfare and harvested to manage population size and to fund rewilding activities that would otherwise not take place.

3.4 Conclusions

Rewilding, as a conservation practise, is regularly criticised for being the subject of internal disagreement regarding its definition (Lorimer and Driessen, 2014a; Jørgensen, 2015; von Essen and Allen, 2015). The idea of using domestic animals in rewilding projects can appear to be in opposition to some of the core definitions of rewilding, inasmuch as the term of rewilding involves restoration of "self-willed" nature or the "autonomy of the more than human world" (Jørgensen, 2015; Prior and Ward, 2016). We argue, however, that a lighter version of rewilding, *rewilding lite* if you will (Carver, 2014), allows for the use of livestock in support of these broad objectives. To re-emphasise, this is not restoration dressed up in sheep's clothing but still has at its heart the core outcomes of rewilding but through a different mechanism of reinstating lost processes.

It is still early days for the rewilding agenda within conservation science and practise. However, there are large areas of historic research that can be brought to bear in support of the outcomes that are the philosophical underpinnings of the approach (e.g., conservation/ecological sciences, agricultural research, community-based conservation). From this, key lessons can be applied in the new context of rewilding. Firstly, there must be clear statements of the objectives for any rewilding project, and a plan (preferably based upon a theory of change) to get to the outcome. Just 'letting nature take its course' is not likely to be enough in many situations and can be a derogation of the duty of those responsible for the project. Not doing anything is a management decision in itself and must

be assessed in the same way as interventionist options. In the early stages of a rewilding project, it is likely that the management interventions will be required, and the manager is best served by having a broad range of options in the toolkit. These should include the opportunity to use livestock to remove vegetation (native and invasive) and change vegetation structure in support the improvements of biodiversity or the provision of ecosystem services on the site. Secondly, attempts to de- domesticate livestock to create facsimiles of ancient breeds may not be necessary if the goal is to facilitate ecological process for rewilding. The desire to create an animal that looks like a lost species, such as an auroch (Stokstad, 2015; Goderie et al., 2016), should not be conflated with the goal of finding an animal that returns lost processes. The reconstruction of the facsimile of extinct species is fraught with challenges and may lead to animals that are more needy than their constituent ancient breeds [e.g., Heck cattle appeared to be susceptible to competition from other grazers which impacted the cattle's condition; ICMO (2006)]. Indeed, there is a circularity in the logic of the process of de-extinction given that creating such a species depends on existing hardy breeds as founders—which raises the question why not just use the hardy breeds? Selective breeding to create facsimiles also assumes humans can pick traits through selection that confer adaptive advantage in the wild better than does natural selection. For example, an unintended consequence of the new management regime at Oostvaardersplassen may be ceasing natural selection and de-coupling of animals from the ecosystem—because natural selection of cattle, horses and deer has, largely, been replaced with human selection (the antithesis of rewilding). It may instead be more effective to use existing hardy breeds bred by humans for many generations to thrive in regional conditions, or to establish a rewilding project with a mix of livestock breeds and let selection evolve a locally adapted wild breed. Having said that, the new suit of gene editing techniques may help offer an alternative route to bringing back extinct species in the future (Richmond et al., 2016). Thirdly, except in exceptional circumstances, rewilding projects do not sit in isolation from the broader socio-economic system of the region, country, or continent (even though the approach appears to be setting nature in juxtaposition to humanity). There is, of course, the real risk that rewilding becomes tarred with the same brush as the 19th- and 20th-century approach called fortress conservation that attempted to isolate nature from people's impact by removing indigenous communities and only allowing access to the elites (Dowie, 2009). As such, from even before the inception of the rewilding project, mechanisms need to be in place to ensure that the broader community is on board with the project and ideally is invested in the project. Particularly, traditional livestock keepers (i.e., pastoralists, herders and farmers) could have an important role to play in broad-scale rewilding rather than being opposed to it. This is for instance the approach taken by Rewilding Europe when designing and establishing a rewilding project together with local populations (Helmer et al., 2015). Finally, linked to the third point, but separate from it, in its purest form rewilding posits people as external to the restoration of ecological processes. First Nations people have been engaged in the management of ecosystems for generations, and the keeping of livestock, both domestic and semi-domestic for millennia; First Nations people should, therefore, be encouraged to initiate rewilding projects and be central to the development of project across the continents of the planet. This socio-ecological systems approach should, in our view, be foundational to rewilding philosophy and practise.

The case studies outlined above represent points on a rewilding continuum for the role that semi-domestic, domestic livestock could play in rewilding projects (Figure 3:2). In the case of the semi-domestic reindeer herds of the Saami First Nations people in northern Scandinavia (Rewilding Sweden), the transition to support rewilding objectives requires very little change to the management

regimes. For Knepp and Faia Brava the removal of inputs through, energy, labour, and fertiliser/irrigation were key to meeting the objectives, however, clarity is required on what ecological process states are the intended outcomes of the rewilding project. If these entail removal of vegetation, or the maintenance/creation of open areas within potentially wooded/forested landscapes, then grazing is an effective way of achieving this over large areas. If there are constraints (management, social, economic, environmental, regulatory, welfare) to the use of wild herbivore species then domestic livestock species are a potential option. When livestock species are used, be they semi-domestic or domestic, there will be a requirement for intervention in most situations (the same is the case for wild species where predators are not present in the system). These interventions will depend upon the local circumstances but are likely to include aspects of livestock husbandry required to meet environmental, biosecurity, legal and welfare objectives. The Oostvaardersplassen example, demonstrates the need for such measures to be put in place early so that public support for the rewilding project is not compromised.

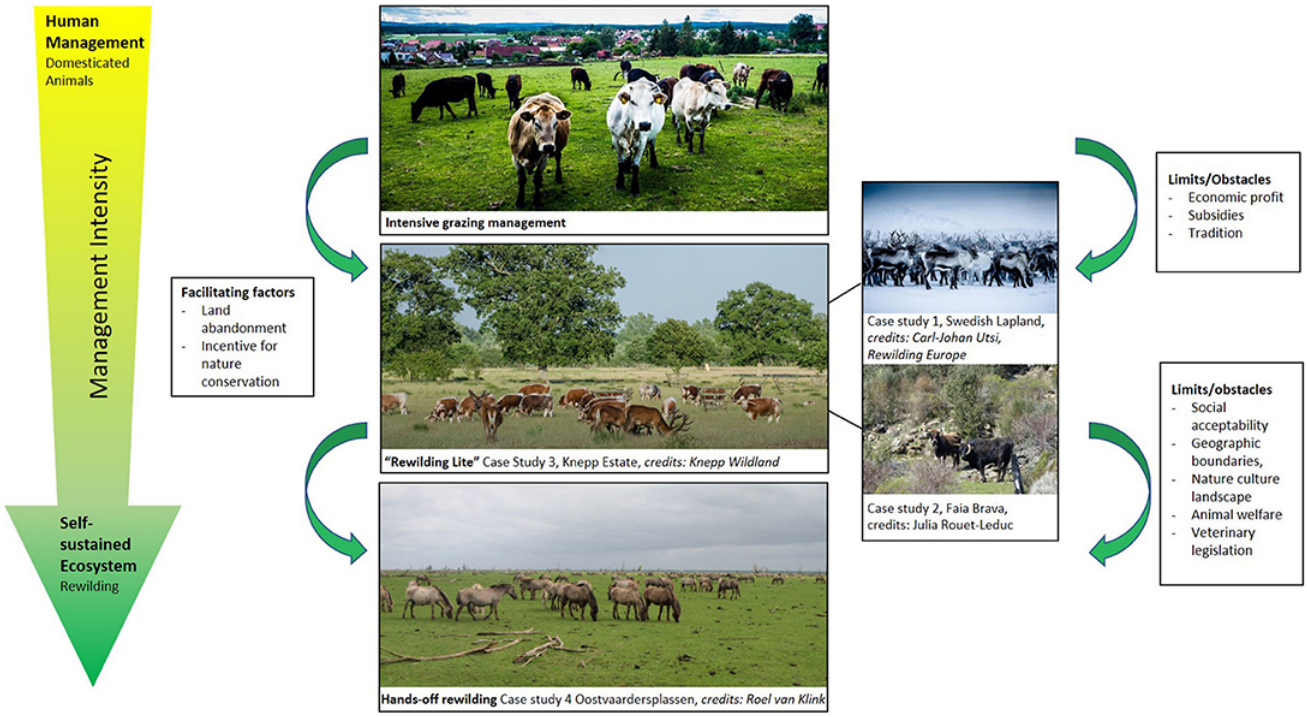

Figure 3:2 *- Schematic representation of how different types of land managements with large herbivores are facilitated or hindered by different factors. Our case studies are all situated within the second type of land management, that is rewilding with domestic animals. The top panel represents traditional rearing of animals with high management intensity, and the bottom panel represents "hands-off" rewilding (i.e. "rewilding max") with minimal human intervention, in this case Oostvaardersplassen.*

In some cases (as exemplified by Knepp Wildlands) money can be generated from harvesting livestock products, but it should be noted that this would be counter to the original principles of rewilding if this were the primary reason for the husbandry activities. So, the offtake of products needs to be a byproduct of delivering the rewilding outcomes. The degree to which livestock are managed will vary depending upon circumstances, however, the introduction of a safe operating space (c.f., Rockström et al., 2009) could be incorporated into the rewilding principles. In this paradigm managers can be hands-off whilst the system fluctuates within a set of predefined boundary conditions

(though these will be broader than those in traditional agriculture and conservation), be they structural or process-based; however, interventions will be brought to bear when the system is at risk of moving beyond those boundaries (see also Corlett, 2019). In effect, this is what happened in the case of Oostvaardersplassen, however, it was not formally incorporated into a management plan until after the project had run into severe public relations problems. The safe operating space will, therefore, incorporate a component of the socially acceptable operating environment (social licence to operate) as defined by the community of engagement with the rewilding project. Obviously, there will be ecological and evolutionary consequences of this approach, that will play out in the wild and livestock species within the system.

In conclusion, we see the potential benefits of including species of domestic and semi-domestic livestock in the toolkit of managers responsible for rewilding. This will require a re-conceptualisation of the characteristics of rewilding and/or rewilded landscapes, along with release from some of the policy/regulation constraints imposed on feral/free-living livestock (Hall et al., 2005), and changes in attitudes, across all sectors engaged in this thought-provoking and forward-looking approach to the engagement between nature and people.

4. Chapter Four

Rouet-Leduc, J., van der Plas, F., Bonn, A., Helmer, W., Marselle, M. R., von Essen, E., Pe'er, G. Sustainable grazing: land users' motivations, incentives and challenges. *Under review*

4.1 Introduction

In recent decades, two main, opposite trends have characterised the management of grasslands in the European Union (EU): intensification and land abandonment. First, intensification of grassland management is driven by economic pressures and also by support through the EU's Common Agricultural Policy (CAP) (Navarro & López-Bao 2019; Pe'er *et al.* 2020). Second, socioeconomic factors have led to the abandonment of many grasslands that were traditionally used as pastures or meadows (Moreira *et al.* 2011). This abandonment trend is expected to continue (Perpiña Castillo *et al.* 2018). Grassland intensification, on the other hand, is largely considered environmentally detrimental (Humbert et al., 2021; Manning et al., 2015; Rouet-Leduc et al. 2021). It typically has negative effects on plant biodiversity (Olff & Ritchie 1998; Koerner *et al.* 2018) and insect biodiversity (Takagi & Miyashita 2014; van Klink *et al.* 2015a).

In contrast, land abandonment presents a more complex picture as a strategy for the countryside, by generating both benefits, such as restoration through extensive grazing and rewilding opportunities with wild grazers and risks, such as succession driving away grassland species (Moreira *et al.* 2011). Nevertheless, a consensus appears to be that extensive grazing, whether domestic, semi-wild, or wild, is central for maintaining provision of multiple ecosystem services on the countryside. Indeed, in addition to providing meat and dairy products, it has the potential to maintain habitat for biodiversity (Olff & Ritchie 1998; van Klink et al. 2015), reduce wildfire risks and impacts (Rouet-Leduc et al. 2021), and provide numerous cultural ecosystem services for people (Plieninger et al., 2015). However, this presupposes that such grazing is done in an environmentally sustainable way; for example through very low intensity grazing practices or minimal use of parasiticide medicine (Floate et al., 2005; Verdú et al., 2018). It also presupposes that land users are equally equipped, willing, and cognizant of requirements to make the shift to extensive grazing and to manage it in a sustainable way. The latter includes farmers adopting good management of their large herbivores, which are known to create heterogeneity in the landscape (Fuhlendorf et al., 2006; González-Hernández et al., 2020) and increased biodiversity.

What drives decisions to adopt such strategies, and to endorse extensive grazing more broadly? Previous studies looking at land users' behaviours in agricultural practices found that land-owner decisions to enact more sustainable behaviour were influenced by contextual factors such as financial resources (Kabii and Horwitz, 2006), social environment (Burton 2004), physical capacity, and infrastructure (Belknap and Saupe, 1988; Dwyer et al. 2007) and environmental and biogeographical conditions (Wilson and Hart, 2001). Equally, psychological capacity, which comprises knowledge, access to information and education (McDowell and Sparks 1989, Wilson 1997), may also determine one's ability to perform sustainable grazing management. Finally, beliefs and attitudes are additional important drivers of behaviours and decision-making (Lynne et al., 1988; Baumgart-Getz et al. 2012). We lack, however, a comprehensive understanding and systematic evaluation of which of these different factors are most important in driving or hampering land users' engagement in environmentally sustainable grazing management. It is also important to note that competing understandings of sustainability may separate not just farmers and managers, but individual farmers.

With this point of departure in mind, we seek to apply and ameliorate The Behaviour Change Wheel (BCW; Michie et al., 2011; 2014) in the context of land users decision-making. The BCW provides a

structured approach to designing behaviour change interventions and strategies. The model has three layers; the 'behaviour system' or COM-B model (Capability, Opportunity, Motivation, Behaviour), the 'intervention functions', and the 'policy categories'. The BCW can be used to help 1) identify key barriers or facilitators to the target behaviour via the 'behavioural system', 2) consider potential intervention functions to target these barriers or facilitators, and 3) determine the most appropriate policy areas in which to apply these interventions. In this study, based on interviews with farmers and other land users, we use the COM-B model of the framework to understand their perceptions, motivations, opportunities, and challenges. Policy interventions are then addressed in the discussion. According to the COM-B model, behaviours are influenced by (i) physical and psychological capability, (ii) physical and social opportunity, and (iii) reflective and automatic motivation.

Physical capability involves having the physical skill, strength or stamina to engage in a behaviour (Michie et al, 2011). Psychological capability is the knowledge and/or psychological skills, strength or stamina to engage in the necessary thought processes for the target behaviour (e.g. memory, comprehension, attention, reasoning) (Michie et al, 2011, 2014). In our study, we also include the access to others' physical capability - human resources and qualified labour force to conduct farming activities. We define psychological capability as the mental skills it takes to conduct different types of management as well as to gain knowledge and understand best practices and rules in place (Michie et al., 2011; West et al., 2020). Opportunity, in the COM-B model, refers to aspects of the physical and social environment that enable or hinder the target behaviour (Michie et al., 2011, 2014). Physical opportunity refers to opportunities provided by the environment, such as time, location and resource, including geographic and physical boundaries that enable or hinder land users' practices in relation to grazing, accessibility of their areas, environmental challenges, or land use conflicts. Social environment in this study includes the social and cultural norms that influence the way land users conduct their management. Motivation is defined as the mental processes that encourage or inhibit behaviour (Michie et al., 2011, 2014). Reflective motivation includes conscious processes such as plans, intentions, and evaluations automatic motivation is the unconscious processes involving emotions and impulses (Michie et al., 2011, 2014; West et al., 2020).

Importantly, capability, opportunity, and motivation do not work in isolation, but interact to influence behaviour (Figure 4:1). So far, the COM-B has mostly been used for topics related to public health (Alexander et al., 2014; Bentley et al., 2019), and has only recently received attention in nature conservation and land-management contexts (e.g. pollination, Marselle et al. 2021; pest management, Kropf et al., 2020). We apply the COM-B model in this study because engagement in sustainable land management involves complex interaction of all features relevant to the COM-B model: cognitive processes, material constraints and opportunities (in the landscape), and interpersonal relations and social norms in relation to ideas of proper conduct, continuity in the cultural landscape (Prokopy et al, 2019). Together, these enable an informed discussion about also broader change processes and values among farmers in relation to the landscape. The COM-B model of the the Behaviour Change Wheel is in this way not used purely instrumentally to map quantitatively the motivations of farmers, but as a vehicle for discussion. With this, we aim to answer three key questions. First, what factors affect land users to engage in sustainable grazing practices? And secondly, what are the drivers and barriers, or challenges, in doing so? Thirdly, what are the main intervention functions and policy types that can facilitate these practices?

4.2 Methods

4.2.1 Interviews

Semi-structured interviews with 88 land users were conducted as part of the EU project GrazeLIFE, which has eight case study areas across Europe (Figure 4:1). In each of the 8 areas, between 7 and 14 interviews were held with local stakeholders (land users and local experts), covering a range of grazing models. For this study, we focus on land users and managers that self-identified as engaged with extensive, or 'sustainable' grazing models (Rouet-Leduc et al. in review) as a sole practice or alongside others (including more intensive practices). This is primarily because we were interested in the motivation of people already engaging with such practices, rather than on the question of transition towards such practices. Some participants with more general knowledge, so-called local experts, were also interviewed, such as veterinarians, policy advisors, administrators and members of NGOs. Participants in the interviews were recruited through stakeholder workshops and provided informed consents prior to participating in the interviews.

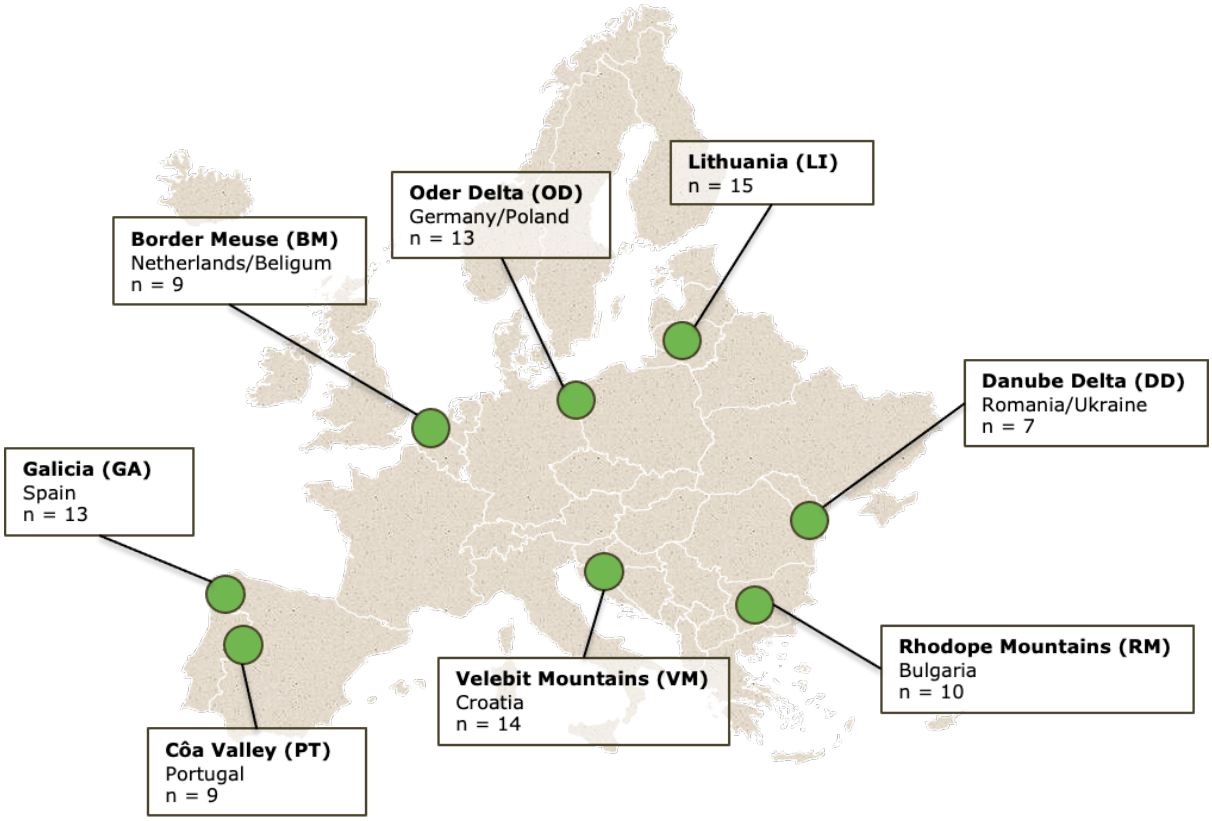

Figure 4:1 *- Overview of the case study areas, abbreviation and number of participants.*

4.2.1.1 Development of interview guide

The interview guide is based on key questions that emerged from project GRAZELIFE and previous literature, including both a set of questions and guidelines to the interviewers. The guide was tested with a pilot set of 11 stakeholders in 3 countries. Based on this, we revised the interview guide to improve clarity (See Supplementary Material 1). All interviews were conducted by local partners in each case study. To ensure consistency, all interviewers received guidelines and one person conducted

all semi-structured interviews within a case study region. This also facilitated trust with respondents and familiarization with the area. Interviews were in the local languages, face to face with participants between 2019 and the beginning of 2021. All interviews were recorded, transcribed, and translated to English.

4.2.1.2 Analysis

Interpretative Phenomenology Analysis (IPA) was used to analyse the interviews (Smith et al., 1999). Our analysis was guided by the themes that reflect land users' perception and action in relation to their land management. A sample of interview transcripts were coded independently by two different researchers (redacted for anonymity) using MaxQDA. Following this step, themes were grouped together into main themes and subthemes (Smith et al., 1999), then linked to the six aspects of the COM-B model in order to identify the different drivers of land users' sustainable grazing behaviours. As the interviews proceeded in an open-ended way both in execution and first-tier analysis, the COM-B model was only applied in the analytical stage. In other words, it did not predetermine our initial reading of the interviews.

4.3 Findings from interviews: Determinants of sustainable grazing decisions

Participants' answers provided us with information on different decision making factors influencing them in their management. Using the COM-B model, namely capability, opportunity and motivation, we refer first to the *external* conditions that surround these land users: demographic, infrastructural and economic opportunities and constraints on the countryside. Second, we refer to *internal* conditions. These include, for example, the individual farmers' ability and skills (Michie, van Stralen, & West, 2011), but also collective resources that farmers draw on for coping and innovating in rural communities. The latter may be seen as a cultural storehouse of knowledge and strategies.

4.3.1 Physical capability: the impact of the 'rural exodus'

Participants mentioned challenges in conducting grazing activities linked to the lack of human resources and infrastructure. These reflections were often said with a degree of despair, as they linked to broader processes of a rural exodus that now characterises most post-industrial countries. Among the farmers interviewed, a recurring refrain was that younger generations leave the areas for greener (urban) pastures:

"There is no people who can work, I can create jobs but there is no people." (RM_4_LU)

Furthermore, participants often expressed that their chosen land use stemmed from a long family tradition, but that new generations are rarely interested in continuing this type of activity. For the few youths that would consider this, there simply did not exist as many traditional farms associated with extensive grazing anymore, giving way to larger farmers such as in the Oder Delta. This may have further pushed youth away. The term of 'abandon' was used to describe the emigration of these young generations, contrasting them with older 'stayers', as in:

"Only old generation practises grazing, young generation largely abandon the area." (DD_2_LU)

While such stayers were credited for their loyalty to the landscape, their physical prowess as farmers could not compete with those of young people. Simply, able young bodies were needed to invigorate the workforce, as much labour was manual. However, some farmers suggested that it was the physical nature of this job on the farm that deterred new recruits and contributed to youth leaving for more comfortable jobs, as in:

"The next generation does not want to farm, because it is too hard, too much work. They usually leave abroad and choose easier career options." (LI_1_LU)

Indeed, activities such as herding animals and having animals grazing far away from the farm requires substantial labour compared to when animals are kept in a barn (Bernués et al., 2005). It was curious to note, however, that in some places, farmers pointed to the importance of the increased mechanisation and automatization of the work associated with farming. One said:

"The decline of agriculture and forestry does (nearly) not lead to land abandonment, it leads only to raised efficiency and productivity, resulting in the reduction of jobs." (OD_3_LU)

Hence, the farmer implied to us that manual labour was also being phased out by technology. But his critical take suggested that rather than make the work less strenuous, it led to a reduction of jobs available. The job situation on the countryside appears to be fundamentally linked to farming, such that when fewer jobs on the farm are available, there may be a decline in other jobs on the countryside as well to support this industry. Indeed, the fact that the grazing areas are remote and lack infrastructure was argued to make it challenging to develop other activities such as tourism and to find employees to work in these kinds of activities.

4.3.2 Psychological capability: access to knowledge and understanding of administrative rules influences how land users conduct their management

Psychological capability refers to having the psychological skills and access to knowledge to perform a certain behaviour (Michie, van Stralen, & West, 2011). Lack of knowledge and access to support and education is a challenge that some land users stated they are facing. In some cases, land users expressed "isolation" and difficulty in accessing knowledge about the conditions and parameters under which they can access subsidies, especially from the EU Common Agricultural Policy (CAP):

"Farmers are still very vulnerable, lacking financial education, living an isolated life, lacking communication." (LI_8_LU)

Such isolation, we surmised from this farmer, was both physical and cultural. Moreover, the isolation theme painted a picture of increased polarization between countryside residents and bureaucrats in cities. The applicability of knowledge from remote experts was questioned on the farm:

"veterinary inspectors should get proper training about beef cattle, to learn that they are stronger than dairy cows, that they can graze throughout winter and that the animal welfare does not suffer from this." (LI_5_LU)

They mentioned valuable knowledge was lacking amongst professionals associated with the industry, which could hinder land users from implementing what they perceived as good practices rooted in experiential, situated knowledge. Amongst other things, farmers mentioned that veterinary inspectors and their practices were not necessarily compatible with some practices associated with sustainable grazing, such as refraining from systematic deworming, or having animals outside all year round.

Lastly, keeping with isolation of different knowledge systems, several farmers spoke about their own deficiencies in navigating the 'system'. Concretely, this referred to lacking 'bureaucracy literacy' which exacerbated in some cases land users' disadvantage in relation to adopting some practices. This was particularly the case with the Cross Compliance and Agri-Environment-Climate Measures of the CAP that require substantial administrative work. Indeed, one outright said:

"If I would have known that this bureaucracy would be so much, I maybe would not have started this all." (OD_2_LU)

In this way, lack of knowledge and understanding of policies and regulations is seen to be actively limiting the ability for land users to get support in the form of subsidies.

4.3.3 Physical opportunity

4.3.3.1 Land use conflict and human-wildlife co-existence

Physical opportunity relates to the external factors afforded by the environment that support the target behaviour or makes it possible, such as time, resources, locations, cues or physical 'affordance' (Michie et al., 2011). When it comes to land management, it can e.g. relate to the landscape and geographical limits, the remoteness, resource scarceness or conflicts with other land uses. Since the eight case study areas have very different topographical contexts, the environmental opportunities and challenges that land users face vary. Nonetheless, a recurrent theme across case studies was the challenge pertaining to remoteness, such as challenges linked to water scarcity, drought, and accessibility. These environmental conditions influence the type of land use available to land users, and areas that are more remote and difficult to access often appear more suitable for semi-wild grazing practices or rewilding opportunities.

Participants recurrently mentioned that challenges could arise from tensions with neighbouring land users - such as pollution through intensive farming nearby - and thereby influence their own land management decisions. They felt their efforts to manage their land sustainably were in vain in light of neighbouring land uses impacting their activities, for example when conducting organic farming or semi-wild grazing next to conventional farms:

"There should be more control over the surrounding farms especially for the use of herbicides, fungicides and pesticides. When you farm organically but the nearby farms pollute the environment, then your motivation becomes low." (LI_2_LU)

Tensions around land-use are even more present in systems of commons where semi-wild animals are co-existing with other types of land management, tensions can arise around land use that challenges land management with semi-wild grazing animals roaming freely the land:

"There are conflicts between semi-wild pony grazing and land owners (Common Lands) that dedicate the land to afforestation leaving the ponies without good grazing areas. The problem is worse in the case of eucalyptus which dries out the land. The commoners also fence some areas where pines are regenerating and don't allow ponies and cattle to use that land." (GA_7_LU)

4.3.3.2 Policies, regulations, and economic support for sustainable grazing

An obvious structuring context for land users was the legislative framework that surrounds them at any given moment, regardless of their type of management. The CAP was most frequently mentioned by participants as having a central impact on management decisions and practices. In particular, the requirements set by the Habitats' and Birds' Directives are often implemented through the CAP, i.e., through Cross Compliance, since it applies to agricultural areas in which grazing management is usually conducted. Participants mentioned that this aspect of the CAP was a strong driver of their management decisions as it provides guidelines and criteria as to how animals, and relevant habitats, need to be managed; land owners do what is necessary to comply with the CAP directives.

Even if economic support stemming from the CAP subsidies often represented a significant source of income for participants, they reported that economic considerations are important regardless of the type of land management they conduct. Lack of economic support especially for small farms, particularly as direct payments, which are calculated based on farmed area, lead to an increase in CAP support with farm size. This generates a benefit for larger land owners and, indirectly, an incentive for land concentration processes where 'big' land-owners and farmers are taking over land from 'small' land-owners or farmers.

"*large farms (…) hog up the entire land available for grazing of communities*". (DD_1_LU).

This has a particular impact on commons, i.e. land managed by, or used by, communities since several types of land uses can co-exist on the same land. When economic support from the CAP is not possible - either due to not fitting the CAP land management criteria or size requirements - participants mentioned seeking other forms of economic support to facilitate their sustainable grazing land management, such as national funds for nature protection or private foundations, for example when conducting rewilding activities. Participants in rewilding areas felt that CAP subsidies would even hinder them from conducting good management and therefore focused on other types of financing.

"[we] can't get any subsidies. Subsidies can lead to a wrong kind of management of nature areas because it is driven by just 1 species or 1 area type (N2000), which sometimes doesn't fit the area" […]

By not applying for CAP support, we have the freedom to really see what suits the local ecosystem". (BM_1_LU)

4.3.4 Social opportunities

Just as a supportive economic context influences how land users conduct their management, social context is also very important. In several of the areas where interviews were conducted, tradition and heritage remain strong drivers of behaviour. For example, in Galicia, semi-wild pony grazing and extensive cattle systems are part of very old traditions and participants emphasised that they were not doing it for financial incentives but because of their passion, or because of links to a strong sense of belonging and pride for cultural heritage:

"The main reason for the maintenance of this system is that people related with it love the ponies, they "have a fever", and this tradition runs very deep in their hearts." (GA_5_LU)

Cultural and family traditions related to animal rearing were found to be particularly present in our case studies in Southern and Eastern Europe, and are strong drivers of decision making, but engagement in grazing activities is slowing down and participants witness increasing rural exodus and depopulation of traditional agricultural areas, these traditional extensive systems are often not economically profitable and young generations may be forced to seek work in other sectors or geographical areas:

"It is [a] family tradition, I have worked with animals since I was a child, I have a desire to work with animals. My grandparents were livestock breeders, but my uncle and I started not too long ago. If there is no possibility to breed animals we have to leave [the] area, to search for work abroad" (RM_3_LU)

Abandonment of traditionally managed rural landscapes seemed unavoidable according to participants and they believed this phenomenon was going to continue with the lack of interest of younger generations for this kind of activities.

4.3.5 Motivation

In most areas, and especially for participants that conducted grazing activities for the primary goal of nature conservation, reflective motivation was one of the main drivers of decision-making. Reflective motivation refers to the reflective conscious brain processes involving plans, intentions, beliefs and evaluations (Michie et al., 2011). The intrinsic care for nature and biodiversity and the will to perpetuate a management deemed "good" for ecosystem services, sometimes despite financial constraints, reportedly drove a lot of land users, especially those practicing semi-wild grazing:

"It's about passion. We invested so much -emotionally and financially- you just don't switch. You want to have a connection with your work. You also don't have the money to change." (BM_8_LU)

This vision of intrinsic value of nature as a motivation for practising nature-friendly management was even more present for managers practising semi-wild grazing. Indeed, in rewilding projects, the main priority is often the ecosystem services provided by specific large herbivores. Our interviews also

indicated that often land users were torn between their motivation to take care of nature and the sometimes conflicting need to be economically sustainable.

However, land users' motivation was not only stemming from reflective thought processes but also from habits and automatic motivation of doing what has always been done around them. Automatic motivation refers to automatic (or unconscious) brain processes, such as emotions and impulses that arise from associative learning and/or innate dispositions (Michie et al., 2011). Land users feel driven to do what they are doing because they have always done it, often because their family used to do it, or because it is the only type of management they know how to do. Often they choose to sustain a certain type of management to maintain a heritage and a family tradition:

"I had horses all my life… I remember all my past generations with horses: my grandfather, my great grandfather, my great-great-grandfather, everyone" (GA_5_LU)

Motivation as a decision-making factor was more important in land users that practised rewilding with grazers or some traditional very extensive or semi-wild grazing practises that were not necessarily economically sustainable but anchored in a long family or community tradition.

4.4 Discussion

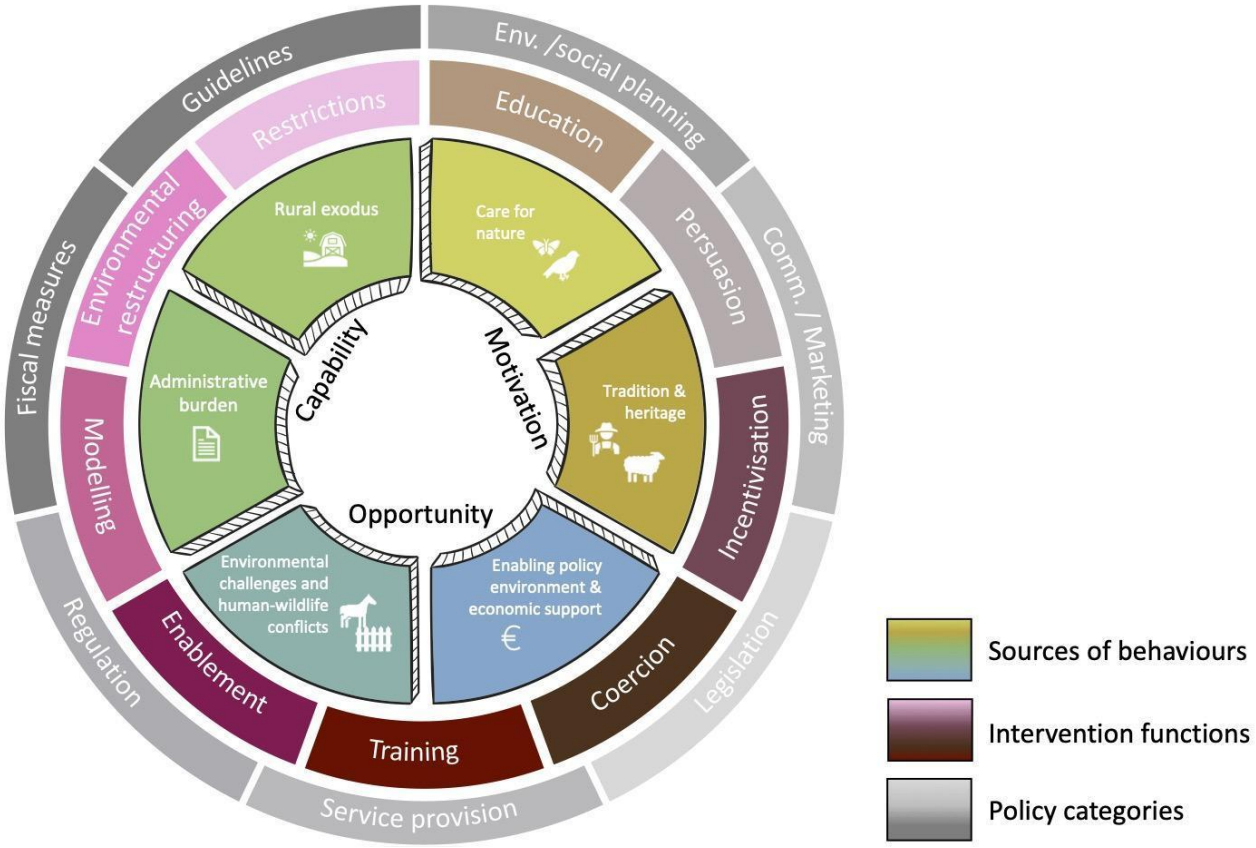

Figure 4:2 *The Behaviour Change Wheel (BCW)(adapted from Michie et al 2011) showing at the core the capabilities, opportunities, and motivations source of land users' behaviour, based on our interviews. The outer layers highlight the way behaviours can be influenced by 9 intervention functions and how these interventions are supported by policy instrument categories (outer part of the wheel), as discussed in 4.1*

The countryside is in flux all over Europe. New technologies enter, and demographics previously relied upon to invigorate the workforce, exit. At the same time, new policy plans for how to best utilise their land are imposed on land users, who cling to the idea of continuity and custom to guide many of their choices in management. Against this, the adoption of what the EU and the CAP considers to be sustainable extensive grazing practices may be fraught with obstacles. Rather than reproduce unhelpful narratives of backward farmers and how to best educate them, however, we sought to uncover deeper layers of motivation among land users involved in this practice. We interviewed 88 land users and experts across European regions with the aim of determining not only why they adopted certain practices, but why they did not and how they viewed their feasibility with the changing conditions of the countryside. This provided insight into land users' negotiations of policies to suit their own lands, which in turn revealed their norms on landscape, labour, the role of the countryside, expert knowledge, and animal welfare. Using the COM-B model served as a way to illustrate and disentangle farmers' thoughts, in the form of motivation categories.

Physical and social opportunity was in our study the most dominant component in participants' responses, indicating a mix of contextual factors affecting their land management behaviour. These contextual factors dictate what land users can do, due to for example access to resources, remoteness or conflicts with other land uses in the area. The broader socioeconomic context, including a supporting social and policy environment, are also important (Dessart et al. 2019; Läpple and Kelley, 2015). The most frequently mentioned driver among our farmers was the policy map of opportunities and barriers, with the EU's Common Agricultural Policy (CAP) as the dominant factor influencing land owners grazing management. The CAP offers finances to engage in farming, and regulations guiding what types of farming and management can be supported (and by which instrument). However, the CAP also comes along with a range of limitations. Land owners in our study perceived the CAP as containing out-of-touch requirements or guidance, excessive administrative barriers and sanctions, as well as disproportionately high financial support for what they deemed to be less sustainable practices. This points to understandings of sustainability in this context as somewhat heterogeneous, or at least not uniformly shared between farmers and experts.

With regards to physical and psychological capabilities, awareness and knowledge were found to be critical drivers of land users' decision making. This is in agreement with previous studies looking at motivation and behaviour change in farmers (Macgregor and Warren, 2006; Llewellyn, 2007). We found that especially the lack of qualified workforce, understood as physically strong, and people willing to take over traditional animal rearing practices, hinder the continuation of such activities (Ustaoglu et al. 2018). This is often exacerbated by the continuing trend where young generations do not share the traditional values of their parents, and do not want to continue extensive grazing practices that have persisted for multiple generations. Among farmers we interviewed, many indicated an inherent sense of duty of performing what they perceived to be good management for nature, while also being driven to perpetuate the traditional management that had been performed in their family. That young generations did not share this duty was lamented by some.

A common challenge for most land users is of financial nature (Kabii and Horwitz, 2006): engagement in extensive grazing offers a lower income compared to more intensive practices, making such practices less competitive or potentially even economically unviable, unless supported by subsidies such as from the CAP. These challenges highlight the tradeoff between what is ecologically and/or culturally valuable and what is economically viable - and accordingly, the challenge of reaching sustainability in the broader sense - i.e. economic, social and environmental sustainability. Moreover, it highlights the tradeoff among these dimensions, but also points at some solutions - such as enhancement of public acceptance and economical support (through e.g. increased subsidies) of traditional practices as cultural assets.

4.4.1 Intervention functions to support sustainable grazing, and associated policies

Given our findings, we can identify, using the BCW model, a wide range of possible interventions that would influence land manager's behaviours (Table 4:1), of which three key types are enablement, environmental restructuring and restrictions (Michie et al. 2011). First, enablement interventions aim at increasing means and decreasing barriers to desirable behaviours; it is thus a straightforward

approach. Examples in our study include providing funding for land users engaging in good practices through e.g. fiscal measures.

This may be understood as a top-down incentive-based approach. Second, environmental restructuring involves changing the environmental and social context to favour sustainable practices – in effect, a bottom-up approach. In our study, it includes for example land management interventions that aim at preserving or restoring semi-natural pastures, wood pastures, or grazed heathlands (Sutherland et al. 2019), or interventions that facilitate the societal context for sustainable grazing practices, for example nudging land users into conducting sustainable practices (Sutherland et al. 2019; Marselle et al. 2021). Third and finally, restrictions are rules to limit unsustainable behaviours. In our case, it could be for example restricting the number of animals allowed per ha, or restricting the access to some veterinary medicine products that have a negative impact on biodiversity (Floate et al., 2005). However, prohibitions need to carefully follow countryside norms, and be openly discussed with land-users as to their reasoning and implications. The notion of already substantial bureaucracy also coming with a suite of proscriptions is not likely to elicit compliance from farmers who already feel aggrieved.

Table 4:1*: Possible behavioural intervention types and supporting policy options based on our COM-B analysis based on Michie et. al (2011)*

Source of behaviour	Behavioural intervention functions	Type of policy instruments
Psychological Capability, Reflective Motivation	**Education** Increasing farmer and community education to support sustainable choices	Communication, Marketing, Guidelines, Regulation, Legislation Service provision
Reflective and Automatic motivation	**Persuasion** Using communication to stimulate action, e.g., communicating on advantages to conducting sustainable grazing	Communication/Marketing, Guidelines, Regulations, Service provision
Reflective and Automatic motivation	**Incentivisation** Developing subsidies systems encouraging sustainable practices	Communication/ marketing, guidelines, fiscal regulation, legislation service provision
Reflective and Automatic motivation	**Coercion** Creating an expectation of cost when 'bad' management is conducted	Communication/ marketing, guidelines, fiscal regulation, legislation service provision
Physical and psychological capability	**Training** Providing opportunities to learn new skills related to sustainable grazing	Communication/ marketing, guidelines, fiscal regulation, legislation service provision
Physical and social opportunity	**Restriction** Using rules to reduce the opportunity to engage in unsustainable grazing practices	Guidelines, regulation, legislation service provision

Automatic motivation, Physical and social opportunity	**Environmental restructuring** Changing the social and environmental context to favour sustainable practices	Guidelines, fiscal regulation, legislation service provision, Environmental/ social planning
Automatic motivation	**Modelling** Valorizing land users that are conducting 'best practices'	Communication/ marketing, service provision
Physical and psychological capability Physical opportunity	**Enablement** Increasing means/reducing barriers to increase capability or opportunity for land users to conduct sustainable practices	Guidelines, fiscal regulation, legislation, Environmental/ social planning, service provision

The above mentioned categories of enablement, environmental restructuring and restrictions may be said to correspond to interventions relevant insofar as they address predominant factors influencing behaviours in our study: social and physical opportunity (see Table 4:1). In what follows, we combine land users' own suggestions relayed to us in the interviews with those of previous policy analyses (Pe'er et al. 2020, 2021, 2022). In so doing, we highlight four types of policy instruments , i.e. i) regulation & legislation, ii) fiscal measures, iii) environmental & social planning and iv) service provisioning, that can support the above interventions outlined, in order to help motivated land users, and to motivate the transition of others, toward sustainable grazing (Table 4:1).

Regulation and legislation can address multiple behavioural intervention functions (see Table 4:1). From our interviews, two key regulations in particular that could impact land users' practises and that could encourage more sustainable practises by removing barriers to practising sustainable grazing. First, land-users called for and would benefit from increased flexibility to the ear marking (CAP Regulation no 1760/2000) and microchipping obligations, which are currently difficult to carry out in extensive grazing schemes given that semi-wild grazers, especially in less accessible landscapes, are hard to locate, control and mark within the strict required timeframe that are currently applicable. Second, 'organic' may sound appealing to consumers, but to producers, it involves added paperwork to the point of deterring from adopting these practices. Therefore, reducing the regulation burden of organic farming could be a way to incentivise sustainable practices and make them less cumbersome (Sahm et al. 2013).

Fiscal measures serve two intervention functions that we have identified to be relevant to our study, namely environmental restructuring and enablement. They contribute to creating a better societal context for good practices among land users and provide behavioural support. The CAP was the most frequently mentioned policy affecting land users engaged in grazing practices, shaping their type of practice and management decisions top-down. Participants pointed at the value of CAP payments, across various instruments, for maintaining the grazing model that they are implementing, thus demonstrating the necessity and usefulness of such payments. At the same time, participants pointed at a much-needed improvement in coherence amongst CAP instruments to encourage sustainable grazing practises, especially through Agri-Environmental Climate Measures (AECM), Eco-schemes, and payments for Areas facing Nature Constraints (ANCs) - while concomitantly reducing support for intensive grazing. With the latter being economically more competitive, equal support leads to an unequal opportunity favouring intensification (Scown et al. 2020).

On this basis, it may be instructive for decision-makers to enhance investments of Member States in AECM to support sustainable (extensive) grazing systems, as they are effective when well implemented (Batáry et al. 2015). Member states should maximise their AECM budget and ensure that AECM are supplemented effectively by Eco-schemes to expand the supported area (and number of supported farmers) to improve habitat quality. It may furthermore be advantageous to maximise the budget for those AECM options that allow high *flexibility* in implementation, as this allows motivated farmers to utilise their situated knowledge for selecting optimal management and adapting to local conditions and changing weather (Reed et al. 2014). Importantly, flexibility permits farmers to also retain a degree of autonomy at a time when outside expert advice or policy may feel clunky in its one-size-fits-all approach. Flexibility is a theme that arguably also extends to the self-reporting by land owners. At present, the system around receiving compensation for predator attacks, and particularly to access prevention measures, was held as rigid and confusing, not adapted to the local realities of farmers involved in extensive grazing.

Extensive grazing by large herbivores is, as noted, a hallmark of the rewilding movement. Getting farmers onboard with rewilding and other semi-wild grazing practices, given its frequently contested nature, requires a delicate approach (Lorimer et al. 2015; Perino et al. 2019). Rewilding must not mean the absence of humans, infrastructure and support as far as grazers are concerned. Farmers already identified remoteness of resources and water accessibility to support such schemes are obstacles. Hence, in order to rewild, insofar as one wishes to get onboard with this branding of extensive grazing, requires both environmental restructuring and enablement. In practice, this will involve creating a more active countryside that can support multiple income streams, including ecotourism practices around wild and semi-wild grazing systems. Ecotourism could additionally contribute to environmental education and public awareness regarding semi-wild grazing systems and the value of rewilding. Moreover, ecotourism practices could allow for complementary income streams for land users or direct sales of products stemming from semi-wild grazing animals. This is especially relevant in areas that have undergone land abandonment. In these areas, the building of infrastructure relevant to ecotourism, but also anticipating and facilitating conflict resolution around rewilding (Pellis et al. 2019; Lorimer et al. 2015), are ways forward to reinvigorate the countryside and to promote extensive grazing. For such ecotourism to thrive, grazer species need to be selected for their function in the ecosystem, robustness and also charisma and potential for interesting ecotourism practises.

Environmental restructuring, a bottom-up approach, involves addressing landscape features (Pe'er et al. 2022). This is especially important in systems that rely on commons. Adopting a landscape design approach may allow a better understanding and planning of ecosystem services provision from grazing systems. Examples of ecosystem services that may benefit from landscape-scale planning are wildfire mitigation (Rouet-Leduc et al. 2021), enhancing habitat connectivity, and generating a larger-scale green infrastructure to secure habitat provisioning for macrofauna which requires both sufficient habitats and connectivity between them (Perino et al. 2019). Moreover, collaboration between different land users can improve not only ecological conditions but also social cohesion and engagement on good practices (Westerink et al. 2019). It can be noted that ideas of building from the ground up to shape the sorts of landscape practices and species distributions one desires, is an established approach in the countryside all across Europe (Hell, 1996).

4.5 Conclusions and outlook

Transitions to and continuation of sustainable extensive grazing practises depend on the capability, opportunity and motivations of land users. In this study, we leveraged the behaviour change wheel to deconstruct such capabilities and motivations among farmers across Europe. We situated our study in the policy context of the EU's Common Agricultural Policy, the cultural context of a rural exodus, and in an analytical context that understood land users as responsive to both top-down and bottom-up approaches to promote extensive grazing. At the same time, our behaviour change wheel illustrated that farmers are also part of social networks on the countryside that share norms about labour, farmer-animal relationships, and opinions about the place of veterinary expertise. Through our interviews across 8 case study sites, our study was able to provide a broad, yet systematic overview of the motivational landscape of present-day land users. As part of this, we identified challenges that were similar across different areas such as the difficulty related to controlling animals, administrative burdens or accommodating veterinary rules imposed by outside experts. Oppositely, we identified some regional characteristics. For example, challenges linked to rural depopulation and land abandonment were especially prevalent in Southern and Eastern Europe, while it was not the case in Northern Europe. With decision-making drivers being highly context-specific, it would be relevant to enrich this study with even more case studies from different places in Europe. Our findings also allowed us to identify the most relevant intervention functions for facilitating sustainable practices, as well as policy types. Using the behaviour change wheel helped to identify relevant intervention functions and policy categories and it is clear that when it comes to facilitating sustainable grazing practices, it is important to combine different intervention functions and types of policies in order to influence the different sources of behaviour.

5. Discussion

In this thesis I investigated in detail how grazing can, when done in the right way, be part of a solution to the multiple crises and challenges we are facing in the Anthropocene. The ecosystem services framework allowed me to present and put into perspective the contribution of different grazing systems to people and to society. Secondly, by focusing on the drivers of land user's decision making, I investigated key factors influencing land users who wish to practise sustainable grazing. This helped me identify which type of interventions and policy types can facilitate behavioural change towards more sustainable (grazing) practices.

Here I explore, more in depth, the context, the relevance of this research as well as overarching results and contributions to science. In the next chapter I then offer an outlook of the broad implications of my research as well as discussing remaining knowledge gaps.

5.1 Importance of the scientific, social and political context of the research

This thesis was developed within the EU Life Preparatory project GrazeLife, and the studies that compose it emerged from the knowledge gaps that were identified jointly with the European Commission. These knowledge gaps were specifically related to the question which grazing models have the most beneficial impact on EU targets regarding biodiversity, climate adaptation, reducing human-wildlife conflicts and reducing fire hazards, as well as what policies promote or hamper the implementation of these grazing models. The framework of the project and the network associated with it, allowed for processes of knowledge co-creation between academia, policy making institutions (the European Commission) and the non-governmental organisation sector, embodied in Rewilding Europe. Collaborative knowledge generation by academia working alongside other stakeholders has the potential to increase research impact (Greenhalgh et al., 2016). The emergence of the research topics in this thesis stemmed from knowledge gaps identified by the European Commission in the ability of different types of grazing systems to provide ecosystem services. Through discussions and interactions with policy-makers of the European Commission in the context of the project, I was able to identify research topics that would lead to policy-relevant research. Moreover, the case studies used in chapter 4 were chosen through the Grazelife project to create a comprehensive overview of land users in different parts of Europe with different socio-economic contexts and land use processes at play. I believe that the process of knowledge co-creation with policy makers and civil society through the NGO sector contributed to identify important knowledge gaps in the field and could lead to the publication of a publication with great societal relevance.

5.2 Societal relevance of the thesis

My research in this thesis provided concrete findings on relevant grazing management at the landscape level, and information for land managers and policymakers. It emerged from the need to address challenges of the anthropocene and emerging threats related to land use change, climate change, and extreme weather events. Current trends of land use change call for more sustainable land

management in the face of multiple crises.Using interviews and case studies allowed me to provide a nuanced picture of how grazing can contribute to multiple ecosystem services in different contexts. By integrating findings from natural sciences (ecology) on how grazing can contribute to multiple ecosystem services, with social sciences perspectives to explore the actual needs and challenges of land users that are seeking to conduct sustainable grazing, I developed relevant and actionable research results. This research comes at a time of growing concern about emerging threats related to climate change and extreme climate events; but also great concerns about the so-called rural exodus and rapid decline in the viability of rural populations (Lasanta et al., 2017). It also has great relevance in the current debate about agriculture extensification and the role of livestock farming in our societies (Ihle et al., 2017; McGregor and Houston, 2018), as well as the need for diet shifts towards more plant-based diets in high income countries. Therefore, the thesis stands at the core of the emerging and rapidly-developing field of sustainability sciences (Bettencourt & Kaur, 2011).

5.3 Policy relevance of grazing research

This research emerged from the interest of policymakers to identify decision-making drivers and challenges for land users to conduct environmentally-sustainable practices. Therefore this research project was associated with, and contributed to the development of reports stemming from the findings of the project (Pe'er et al. 2021; Rewilding Europe, 2021). Policy-relevant research on grazing is especially important in the context of sustainable development. Land use decisions on grazing systems impact the availability of natural resources, the health and quality of ecosystems, and the livelihoods of people who depend on them. My research has provided insights into the potential impacts of different land use decisions, to help policymakers design more effective policies that can promote sustainable land use practices with grazing. Most specifically, in chapter 2 I provided a detailed overview of the different instruments of the CAP that influence grazing practices; and in chapter 4, based on findings from the interviews, I was able to identify several types of policy instruments that are especially relevant in influencing decision making factors in land users practising grazing. These included legislation and regulation, fiscal measures, environmental and social planning.

5.4 The value of transdisciplinary research

To fit the complexity of the issues I explored in this thesis, transdisciplinary research was an essential approach to use. Indeed, transdisciplinary research involving collaboration with practitioners and non-governmental organisations is effective in addressing societal issues and developing policy-relevant and impactful research (Lawrence et al. 2022). Moreover, it is perhaps the only way to synthesise the needs of people and ecosystems, as well as to identify and address barriers and tradeoffs that may prohibit transformations. Specifically, given the need to link land management practices to implementation at various levels, adopting a transdisciplinary approach was crucial for understanding the impact of multiple grazing systems on ecosystem services and identifying ways to encourage and incentivise the relevant people to engage in sustainable grazing practices that can enhance ecosystem services. Ultimately, incentivising such practices requires action at multiple levels, starting with identifying what practices are optimal from an ecological perspective, through ensuring that policies take the right approach to incentivize such practices, to the stage where these are indeed adopted by land users, farmers, and local governments being some of the most critical actors in implementation.

5.5 Contribution of the research

5.5.1 Contribution of chapter 1: large herbivores and wildfire mitigation

In the first chapter, I chose to focus on grazing for wildfire prevention, as it represents a relatively under-studied ecosystem service compared with others (Moreira et al. 2011). I identified wildfires and wildfire prevention as a particularly important issue for Europe in the process of knowledge co-creation with policy makers and the NGO Rewilding Europe. Fire is intricately connected with issues of land use change in Europe as there are potential reinforcing feedback loops of climate change on wildfires. Climate change affects the frequency and severity of extreme weather leading to the ignition and spread of wildfires. It also leads to longer wildfire seasons where the fire season may begin earlier and end later (Mubashir et al., 2021).

Using a systematic literature review, I could provide novel insights on the role of large herbivores in mitigating wildfires, and was able to evaluate their potential role in dealing with increased wildfire risk in Europe and globally. I found that in a lot of cases large herbivores are able to reduce wildfire frequency, amongst others by promoting grass-dominated landscapes that favour low intensity fires and reduce their frequency. Furthermore, I also found that large herbivores could have an effect in reducing fire intensity and/or severity, even at low grazing intensities. By consuming vegetation and creating features in the landscapes, herbivores are able to reduce fuel loads and thereby fire hazard. However, their effectiveness depends largely on the type of vegetation and the diet preferences of the animals. Therefore mixed feeders or flocks with animals with different and complementary dietary preferences may be more effective in reducing fuel loads. Finally, management practices associated with livestock grazing have an impact on wildfire by influencing fire ignition, for example pastoral burning for pasture renewal. By compiling this evidence, I was able to provide management and policy recommendations on how large herbivores can contribute to fire mitigation. In particular, I discuss how grazing by large herbivores can be used for mitigating wildfires in a way that can contribute to multiple ecosystem services and can potentially be cost-efficient compared to other fuel management methods. Considering these findings, using semi-wild herbivores can be a relevant way of managing landscapes in areas that have undergone, or are undergoing, land abandonment and are subject to shrub encroachment or forest-closure. Indeed, when considering different wildfire prevention measures and fuel management methods, multiple aspects have to be considered, such as acceptability by the public (Varela et al. 2014), especially in peri-urban areas. Moreover, other ecosystem services also have to be taken in consideration with wildfire prevention methods since some fuel management methods can have very negative impacts on for example biodiversity for example through overgrazing causing excessive disturbances and soil erosion (Etienne & Rigolot, 2001, see also chapter 2 of this thesis).

In this first chapter, I expanded on previous reviews (Valette et al., 1993; Fuhlendorf et al., 2009; Lovreglio et al., 2014; Johnson et al., 2018); and covered a broader range of grazing systems and types of animals. My study was also novel in the fact that it was looking at studies with various methods in order to provide a comprehensive overview of all the mechanisms by which herbivores can impact fire

regimes. Thereby I was able to examine a much broader range of management and policy recommendations related to wildfire prevention and grazing.

5.5.2 Contribution of chapter 2: grazing and multiple ecosystem services, trade-offs and synergies in a European context

In chapter 2 I expanded from fire to multiple ecosystem services. Chapter 2 emerged from the need to get an overview of ecosystem services and their grazing management-driven trade offs in a European context. It is relevant to look beyond a single ecosystem service in order to identify management that provides multiple ecosystem services with as few trade-offs as possible. Because doing a systematic review for all ecosystem services would be an exercise that is far beyond the scope of a PhD project (as identified in an initial literature search), I prioritised obtaining reviews and meta-analyses on relationships between different components of grazing management, biodiversity and ecosystem services. In cases where existing reviews left knowledge gaps, I supplemented these reviews with case studies. Specifically, for the topics of biodiversity and soil carbon sequestration, I focused on reviews due to the abundance of literature, while complementing with individual studies to bring more specific evidence when needed, while for the others ecosystem services I took in consideration original studies and literature reviews because of the more limited amount of literature reviews available. While the first chapter had a global scope, I chose here to focus on Europe in order to be able to delve into the complexities of the interactions and trade offs among ecosystem services, as well as to harvest and develop the most specific management and policy recommendations. Indeed, after reviewing what type of management provides the most ecosystem services, I discussed what policy instruments can contribute to supporting good grazing practices in a European context. Some of the most interesting results were that, beyond the known fact that extensive grazing performs generally better than intensive ones and contributes to multiple ecosystem services, a greater diversity of grazers, whether domestic livestock or wild grazers, is generally beneficial for both biodiversity and ecosystem services. Moreover, low-intensity grazing, whether pastoral, semi-wild or wild systems can be beneficial, particularly in Eastern Europe and the Mediterranean Basin while diminishing grazing pressure is particularly beneficial in arid environments. Moreover, management practices associated with intensive livestock systems are often detrimental to these ecosystem services, such as systematic application of deworming medicine or ploughing and reseeding pastures. High densities of herbivores can be beneficial for wildfire prevention but only when the type of animal matches the vegetation present. For instance, even at high densities, strict grazers such as cows would not be able to consume most of the woody vegetation, and hence mixed herds (including mixed-feeders such as goats or wild herbivores such as deer) may be important where bush encroachment is a problem. Regarding cultural ecosystem services, both grazing in traditional extensive systems and rewilding with herbivores could provide opportunities for recreation and aesthetic value, but in a different way since they create very different landscapes, and with potentially trade-offs between the different aesthetics. Identifying what could be considered as environmentally sustainable grazing (i.e. that can provide multiple ecosystem services), I explain how trade-offs between the different ecosystem services can complicate best management decisions. I could then provide management recommendations as well as classifying how different types of grazing can relate to different European policies.

In the second chapter I also explored how grazing can contribute to different ecosystem services and what are the synergies and trade offs between different ecosystem services. The aim was to

identify what type of grazing management should be incentivised by policymakers. In a context of land use changes in Europe and the important impact of telecoupling in other parts of the world by livestock systems, identifying what type of grazing provides multiple ecosystem services is relevant. Throughout this chapter I provide a new perspective on how grasslands could be managed through sustainable grazing in Europe. This is a progress from previous reviews as others have focused on a global scope (Petz et al. 2014), or focused on specific types of grazing lands (Maestre et al. 2022; Plieninger et al. 2019). Finally, this chapter identifies what kind of management can provide multiple ecosystem services at the same time; and which policies can facilitate this management in a European context.

5.5.3 Contribution of chapter 3: domestic livestock and rewilding

My third chapter, where I contributed as a last author, addressed an important issue in rewilding research, namely the role of domestic animals in rewilding projects. Building on the contribution of different grazers to different aspects of ecosystem functionality - as explored in the second chapter - here I described how domestic versus semi-wild herbivores can contribute to rewilding projects and in turn make these projects more inclusive also to rural communities. Using case studies, I characterised different types of rewilding projects based on their level of management. I used several examples of rewilding projects to illustrate the role of domestic livestock in different rewilding projects. These case studies were used to examine how domestic or semi-wild herbivores were used more or less successfully in rewilding projects, in order to be able to formulate recommendations. This chapter contributed to the field of rewilding research in defining how domestic animals can fit into rewilding projects and contribute to multiple ecosystem services provision. The question of the type animals and their role in rewilding is a long standing question in rewilding (Bruce et al., 2022; Lorimer & Driessen, 2013; Thulin & Röcklinsberg, 2020). This paper contributes to nuancing the definition of rewilding in its different applications.

Particular novelty of this chapter is the proposal to expand the perception of rewilding so that it can be viewed along a spectrum of naturalness, human modification, and management. At one end of the spectrum are "true" wilderness areas, while at the other end would be activities such as wildlife-friendly farming or agricultural rewilding which combines restoration of ecological processes with some degree of agricultural production (Corson et al., 2022; Vogt, 2021). Introducing more flexibility in the concept of rewilding could, however, create confusion and limit its usefulness (Carver et al. 2021). To address this challenge, it is important to be clear about the type of rewilding being discussed and the goals it is intended to achieve. This could help address some of the scientific and societal conflicts in philosophies around rewilding (Jørgensen, 2015; Pettorelli et al., 2018). Also, different types of projects on the rewilding “spectrum” embody different values of nature and expectations about animal welfare. Depending on the type of animals involved, and the intensity of management, it leads to different outcomes on the “rewilding spectrum”.

Areas undergoing agricultural abandonment, such as large areas in remote parts of the Mediterranean region, are good examples of where rewilding with domestic and semi-wild herbivores could be highly relevant. While the animals can contribute to multiple ecosystem services, and especially fire prevention (as in the case study of Faia Brava), their management is made easier by the fact that they are, to some extent, domesticated. Moreover, this aspect also makes it easier to mitigate potential human-wildlife conflicts in the area where pastoral activities and traditional animal rearing

is still performed. However, as we see in this chapter, using domestic or partly domestic animals for rewilding has ethical implications of taking care of them and protecting them from unnecessary suffering. The case study of the Oostvaardersplassen in the Netherlands illustrates how a rewilding experiment that started in the 1970's paved the way to multiple other rewilding projects and raised several key ethical questions regarding the management of animals used in rewilding projects. The controversial events that led to a change in management of Oostvaardersplassen, where over 60% of the introduced cattle, horses and deer died of starvation during a harsh winter in 2017-2018, raises the question of the level of human intervention that is necessary for the rewilding projects to maintain a social licence to operate and for the individual animals to be treated ethically as involuntary participants in rewilding projects. The degree to which animals should be managed is highly context-dependent. I argued in this chapter that the introduction of a safe operating space should be incorporated into the rewilding principles. There, management of rewilding projects can be hands-off whilst the system fluctuates within a set of predefined boundary conditions, while interventions should happen when the system is at risk of moving beyond those boundaries. This safe operating space should also incorporate a component of the socially acceptable operating environment (social licence to operate) as defined by the stakeholders and community engaged with the rewilding project as the project is initiated and evolving.

5.5.4 Contribution of chapter 4: drivers of decision making for sustainable grazing

In chapter 4, I sought to identify, through interviews with land users, what challenges they face in performing sustainable grazing management. In addition, I explored the factors of decision-making for their management practices, and thereby their behaviour. Using semi-structured interviews with 88 land users performed by project partners in 8 case studies in Europe, I got insights into what drives land users to conduct some specific types of management. I conducted a phenomenological analysis in order to get an overview of the land users' experience rather than objective, factual content, which seemed more relevant to identify their experiences of their management and experienced challenges and incentives (Flick et al., 2004).

By using the behaviour change wheel (Michie et al. 2011), I identified and analysed the different behavioural determinants among land users who are adopting sustainable grazing practices. While previous studies have explored motivation and behaviour determinants in farmers (Belknap and Saupe, 1988; Dwyer et al. 2007; Kabii and Horwitz, 2006; Wilson and Hart, 2001, Wilson, 1997), my study is novel in looking at a broad range of land users, across a range of bioclimatic and socio-economic regions, who define themselves as practising any form of sustainable grazing management. This goes beyond just livestock grazing, as it includes managers of rewilding areas as well as land users using semi-wild grazers. Moreover, the broad geographical range of my case-study sites offers a picture of the contrasting challenges faced by land users in different parts of Europe. I found that many land users interviewed struggled with maintaining an activity related to grazing, especially due to lack of labour from rural depopulation and lack of economic incentives. However, traditional grazing management has a very strong cultural and traditional value that land users wanted to perpetuate in spite of challenges. Moreover, I found that some regulations and policies were hindering some practices associated with semi-wild grazing and being a challenge for land users. Indeed some

veterinary obligations as well as geographical constraints were challenging for land users when conducting management they perceived as sustainable.

After having identified the main determinants of behaviours in land users, I could, using the structure of the behaviour change wheel, identify the type of policy instruments that could enable more sustainable practices in land users. The behaviour change wheel allowed me to provide a structured and integrative overview of the factors that impact farmers decision-making drivers for conducting sustainable practices. Considering that land users' motivation is based on multiple different factors beyond economic drivers, these insights can help to enable more effective and realistic policies. Agricultural policies should take into account other drivers of behaviours beyond financial incentives and especially allowing for adaptation to local contexts. Different intervention functions play a part in encouraging sustainable practices and hindering unsustainable practices. Enablement, for example through providing subsidies for agri-environmental measures can increase means and decrease barriers to desirable behaviours through legislation and fiscal measures. In our case studies, that could include flexibility on veterinary rules that are challenging to land users practising very extensive and semi-wild grazing, such as ear-tagging at birth. It could also be reducing support to intensive grazing practices such as in eco-schemes for standard grasslands management which do not currently include any limit on livestock density and can favour very intensive grazing systems. Environmental restructuring that involves changes in the environmental and social contexts can also be a way to drive land users towards sustainable behaviours. In our case, it includes for example land management interventions to preserve or restore semi-natural pastures, wood pastures, or grazed heathlands.

Our findings provided novel insights on land users and what drives their decision making on sustainable grazing. Thanks to a broad sample of land users that conduct grazing management I could get insights on what drives land users to conduct sustainable practices. My results support the notion that land users conducting their management have multiple drivers. Like previous studies, I found that knowledge and awareness were extremely important (Llewellyn, 2007; Macgregor and Warren, 2006). The knowledge system and access to information is also dependent on a supportive social environment (Dessart et al. 2019; Läpple and Kelley, 2015) and a system of shared values. Limitations and opportunities afforded by the physical environment were also found to be particularly important. Since the interviews were often conducted in areas that had environmental challenges of remoteness and access to resources, I found the physical opportunities to be a very important aspect of land users decision making drivers. Finally I also found that motivation and an inherent sense of duty of performing what they perceived to be good management for nature was decisive for land users' management choices. What I found confirms previous study from Mills et al. (2018) that environmental motivation was greater than financial when performing unsubsidised activities, and that a lot of land users' sustainable behaviours are driven by intrinsic motivation to do the management they believe is good management.

5.5.5 Interdisciplinary approach to grazing research, grazing areas as socio-ecological systems

With my thesis, I showed that grazing management can provide multiple ecosystem services and contribute to sustainable land management under certain conditions. My interdisciplinary approach allowed me to explore grazing systems as socio-ecological systems. I investigated multiple actors,

ecological components, interactions, and processes that shape grazed areas, including the social, economic, cultural, and political attributes of the people and communities within and around grazing areas.

Traditionally, grazing research often focuses solely on ecological aspects of grazing management, but has put less focus on the associated management components including needs and goals of land users and land owners. Furthermore, most previous studies focus less on concerns of land users, pastoralists, and rewilding managers in the case of rewilding with grazers, who face financial, labour and environmental challenges. Consecutively, the social sciences have provided in-depth knowledge on land use related to grazing, but have sometimes failed to link social, cultural, political, and ecological factors to ecological outcomes (Brunson 2012).

Grassland and grazing areas management cannot succeed if researchers and managers do not consider their impacts on economic, political, cultural, and social well-being. My thesis proposes a completely interdisciplinary approach to grazing research that links different elements of socio-ecological systems taking in consideration both the ecological aspect as well as the human dimension of grazing management. Social processes that sustain or degrade ecosystems occur at multiple scales and affect in turn the provision of ecosystem services. To improve the sustainability of grazing areas, managers and policymakers need not only ecological data but also a clear understanding of when, where, and how resources are used, who uses them, and how and why use varies over time and across the landscape. My thesis provides novelty in grazing research in exploring multiple aspects of grazing management, and combining findings from ecological and social sciences in order to provide insights on grazing systems as socio-ecological systems.

5.6 Limitations

5.6.1 The framework of ecosystem services

This research project has been developed around the concept of ecosystem services. This concept was useful in the context of my research but is not devoid of issues. Indeed, the concept of ecosystem services, while being useful, has limitations and pitfalls.

Firstly, the concept of ecosystem services has been criticised for its highly anthropocentric approach where nature's value lies in the value of resources that can be used for human benefit. The concept fails to capture the intrinsic value of nature, which is independent of its usefulness to humans and focuses on an instrumental relationship to nature (Arias-Arévalo et al., 2017). However, while recognizing the intrinsic value of nature and ecosystems, using the ecosystem services frameworks allows for presenting policy relevant research and to guide decisions about environmental management (Martín-López and Montes 2015). In using the framework as a useful tool to assess and compare different types of grazing systems, I still emphasise the importance of value pluralism and coexisting valuation systems for nature and ecosystems. Especially when exploring issues related to rewilding (chapter 3 especially), since one of the guiding principles of rewilding and how it came into existence is recognizing the intrinsic value of species and ecosystems that departs from an ecocentric rather than anthropocentric vision (Carver et al., 2021).

Other limitations of the concept of ecosystem services have been considered to oversimplify the complex relationships between humans and the natural environment. By reducing nature to a set of services, the concept ignores the complex social, cultural, and political factors that shape the ways in which humans interact with ecosystems. It is also less inclusive than the concept of Nature's Contributions to People (NCP). The NCP framework proposes a broader inclusiveness of multiple knowledge and cultural systems (Ellis et al., 2019). While acknowledging the limitations of the framework, I found it to be a useful tool for understanding the complex relationships between humans and the natural environment. It provides a language for articulating the benefits that ecosystems, in our case grazing systems, can provide to humans, and the ways in which these benefits are distributed across different groups and regions. It highlights the importance of valuing, managing and protecting ecosystems, with taking into consideration multiple values of ecosystems in decision-making processes at all levels of society.

5.6.2 Limitations to rewilding research

One of the aims of this thesis was to compare domestic grazing of livestock with wild and rewilding systems in order to draw conclusions on their respective contributions to ecosystem services. However, the extent of the literature on domestic grazing compared to the literature on wild and semi-wild systems was a challenging limitation. Even if it is possible to draw conclusions on semi-wild systems from the available literature, I could witness how important it is that more research is conducted on semi-wild grazing systems. When looking at the role of large herbivores in wildfire mitigation, my findings suggest that grazing of large herbivores is a relevant way of preventing and mitigating wildfires. However, in the light of land abandonment trends in many parts of Europe, it is likely, but insufficiently proven, that in some cases it could most cost-effectively be conducted by semi-wild herbivores. One main challenge has therefore been to do comparative research between rewilding and other land-uses with grazing, both because of the limited literature, but also as this type of research needs to be done at landscape-scale (which is logistically extremely challenging) to get comprehensive information on the multiple impacts it has beyond field level. Additionally, another challenge lies in the difficulty in measuring the success of rewilding efforts. Many rewilding projects take years or even decades to show measurable results, making it challenging to evaluate their effectiveness in a shorter time span (Torres et al., 2018; Segar et al., 2022). Rewilding success needs to be evaluated in the light of multiple aspects, including societal benefits through provision of multiple ecosystem services and aspects of social and economic sustainability through their socio-economic contribution to local population and society at large.

5.6.3 The challenge of addressing different socioecological and administrative scales

Another limitation, which reflects a much broader issue in socio-ecological research, is the issue of scales - and particularly, the scale of grazing research in my case. Ecological knowledge mostly stems from empirical data coming from a local plot (e.g. for vegetation monitoring), data from specific pastures, or focal landscapes; animals move at different scales depending on whether they are domesticated or wild; farmer decisions are taken at the borders of their ownership; while policy and its implementation occurs at the national, subnational or supra-national levels. Both for the aspects of socio-ecological research on the ecosystem services provided by grazing and for the policy aspect of

grazing management being impacted at multiple levels. These different scales of operation can lead to mismatches in the scales of challenges and solutions (Henle et al. 2014).

Farmers and land users can play distinctive roles as producers, landowners, and citizens, and their decisions on landscape management are influenced by these roles. While producers affect the landscape through land-use decisions and farming practices, land ownership is also subjected to numerous regulations, and farmers as citizens participate in community life and collective actions. The CAP also influences farmers' landscape and land-use management decisions at farm or field level, as seen in chapter 4.

Secondly, the landscape scale could be defined as an area with a coherent landscape character above the farm or field level, and its structure is defined in terms of composition and configuration. Decision-making at the farm level affects the landscape structure at a larger scale, and management decisions at the farm level can be inadequate because it does not account for the spatial scale of some ecological processes (Lefebvre et al., 2015).

Finally, the relationships between the grazing areas, the landscapes and the national and supra-national level are also very relevant. Landscapes offer benefits that extend beyond their local territory and they are impacted by policy and decision levels at national and supra-national level (Van Zanten et al., 2014). Policies and especially the CAP impact management practices of grazing areas through different factors such as agri-environmental regulations and European directives. Compliance with these regulations affects the structure and composition of the landscape, which in turn impacts the provision of multiple ecosystem services. Policies can also affect the demand for ecosystem services, such as rural tourism and certification of regional products, they can therefore alter the demand for provisioning and cultural services. Also, payments for ecosystem services schemes developed at EU level (for example for wildfire prevention services) can influence management practices and ecosystem services provision at landscape and farm/field level (Van Zanten et al., 2014).

Articulating these different scales within this thesis has been challenging, since linking the management on farm/field level with the ecosystem they provide are often relevant on landscape level and beyond. It is especially the case for chapter 1, where I investigated amongst others impact of large herbivores on fuel loads, and drew conclusions on their ability to mitigate wildfires, which are phenomena that occur on a much larger scale than a specific field or experiment (chapter 1). Therefore, to review the evidence for ecosystem services provided by different types of grazing, I also needed to generalise findings from particular studies to broader ecosystems. (chapter 1 and 2). In order to address these challenges related to scale in grazing research, we need larger-scale empirical grazing experiments, with long term monitoring. The case studies of the GrazeLife project were useful in addressing this challenge since there is no “one size fits all” grazing management that can provide multiple ecosystem services. Having 8 case studies across Europe I could see what issues are specific to an area and which ones are shared by all. However, the complexity of the issue of context dependency would likely require even more case studies.

5.6.4 Practical limitations

A single PhD is always limited by the capacities of a single person, and in this particular case, additional barriers were posed by COVID-19 restrictions during planned field work time. An initial plan for this thesis was to perform own interviews and engage in direct interactions with land-users in Europe. However, COVID-19 regulations and recommendations hindered these plans. Moreover, linguistic barriers made it impossible for me to conduct interviews in the countries selected in the project, since to get data of good quality, it was clear that interviews should optimally be conducted in the language of the land users. In consequence, many of the potentials of direct interviews with land-users, such as to learn about psychological elements that guide their decisions or to explore alternative scenarios for improvement, remain untapped and beyond the scope of this thesis.

6. Outlook

6.1 Future research needs

In order to achieve sustainable management of grazing in landscapes, several research gaps are still to be addressed that are beyond the scope of this thesis. While I established (in chapter 2), that the sustainability of grazing was highly context-dependent and that there was not a single model of good grazing management that could fit everywhere, it is clear that the dominant forms of livestock grazing are too intensive for most ecosystem services. The question then is *how much* lower grazer densities need to be. Identifying an order of magnitude for grazing densities and associated management in different climatic contexts would be highly valuable to get an estimation of the type of management that could contribute to sustainability in different areas. Being able to quantify the impact of different grazing densities on key ecosystem services such as biodiversity in different ecosystems and regions of Europe would be highly useful to inform especially agricultural policies.

This evaluation of grazing densities and types of grazing systems could moreover be a helpful indication of the amount of animal products that could be produced with such management and hence what would be, from an environmental sustainability point of view, 'optimal' meat and dairy production and consumption. This way, science could deliver important guidance toward the formulation of policy- and social-targets.

Also, when considering the consumption side of these sustainable grazing systems, identifying what societal transformations would be involved in a societal pathway with sustainable grazing is a relevant direction requiring much more research.

6.2 Pathways for sustainable grazing

All chapters of my thesis point out that land management with large herbivores, and the impact they have on multiple ecosystem services, needs to be put into a broader sustainability context. Regarding grazing by domestic herbivores, having shown, especially in chapter 2, the need to extensify the grazing management currently practised in many parts of Europe, this poses the question of the consequences on the consumption side. Namely, animal production is tightly linked to consumer demands and behaviour with respect to livestock products (e.g. dairy, meat). In this thesis I mostly focused, when looking at livestock, at the production side; although some aspects of the value chain came up at chapter 4, where land-users expressed the need for market opportunities and demands for their products, e.g. through direct marketing. Yet if the recommendation is to extensify livestock practices and reduce herd numbers, this can have consequences on the provision of animal based products such as meat and dairy, and therefore present the risk of relocating the issue associated with overgrazing to other parts of the world (Fuchs et al. 2020) - unless changes occur also at the demand side. Therefore, a shift in grazing practices to extensification of domestic livestock requires changes in consumption behaviours.

The issue of meat consumption is intricately linked to the topic of grazing management, and changes in landscape management regarding grazing can only be accompanied by changes in production and consumption patterns. In Europe, the average meat consumption per capita is 69.8 kg per year (European Commission, 2021). In current trajectories of meat consumption, with a current rapid increase in eastern Asia and an anticipated similar trend in sub saharan Africa in the longer-term, pressures on Earth's resources and GHG are predicted to significantly increase. Despite a scientific consensus for a need to reduce the consumption of meat, especially in high income countries (and among high-income individuals), few policies have been implemented on the European level to reduce consumption (Poore and Nemecek, 2018), and some are even promoting this consumption. There are several reasons for the continuing trends in meat consumption in spite of the evidence for the need to reduce: reluctance to change diets, cultural and social importance of meat and animal products (Milford et al. 2019), and influence of agri-food lobbies (Orset and Monnier, 2020). In light of my findings, questions arise regarding how extensive grazing management should be in a European context to maximise multiple ecosystem services. Another question is therefore to identify how production and consumption patterns would be impacted by a reduction in herd numbers and shifts in grazing models which relates to the concept of "less but better meat" (Resare Sahlin and Trewern, 2022).

A question remains whether a desirable pathway for grazing and livestock would be to focus on multiple ecosystem services provision alongside provision of meat and dairy. Focusing on very extensive grazing practices and including rewilding in agricultural systems could provide opportunities for addressing the challenges of biodiversity loss. Indeed, choosing a non-dualistic approach between agriculture and rewilding and rather focus on bringing sustainable practices to domestic livestock systems that could be embodied in the concepts of "rewilding lite" (chapter 3, Gordon et al., 2021) or agricultural rewilding (Corson et al. 2022). There, using rustic and hardy breeds of livestock in systems that include rewilding principles, can provide multiple ecosystem services and some of the advantages of rewilded systems such as restoring ecological processes, with animal production as a co-benefit rather than as a main goal. Agricultural rewilding (Corson et al., 2022; Thomas, 2021; Vogt, 2021) or rewilding 'lite' seeks to bring back a certain degree of wildness to the meticulous and systematic organisation that has characterised agricultural and even livestock systems (Gordon, Javier Pérez-Barbería, et al., 2021; Gordon, Manning et al., 2021) and it goes against the processes of simplification, standardisation, and intensification of agriculture and seeks to prioritise other ecosystem services than only food production. When it comes to livestock systems, a rise in what is called 'regenerative agriculture' has grown more and more popular where cattle is presented as a nature-based solution contributing to landscape management and carbon sequestration. A key research need lies in identifying to what extent these practices that are qualified as sustainable actually contribute to ecosystem services provision.

However, this proposed pathway for land management with grazing combining domestic grazing and rewilding while providing opportunities, also has potential risks in its approach. Indeed, the concept of rewilding lite, or agricultural rewilding with cattle presents the risk of giving a social licence to consume more meat products through a "green rebranding" of livestock (Cusworth et al. 2022) figuring meat eating as a form of planetary stewardship through the services that large herbivores provide in the landscape. This vision of combining domestic livestock and rewilding would fit in a proposition of caring and conscious form of consumption and offers an alternative to other

propositions of intensification of animal systems through science and technology to meet the ever growing demand for animal products, as well as propositions of vegan futures without animal rearing (McGregor and Houston, 2017; Cusworth et al., 2022). Striving towards this proposition however requires a more elaborate understanding of what "less but better meat" can look like, in defining how much is less and what is better meat to contribute to a sustainable future and for grazing to be contributing to multiple ecosystem services beyond animal products (Resare Sahlin and Trewern, 2022). Additionally this proposition also requires exploring how consumers' behaviour change in consuming animal products would change in response to a shift to more sustainable grazing models and therefore less meat and dairy products. A shift to basing the amount of animal products consumed on the provision of other ecosystem services while considering animal products as a co-product or even by-product of sustainable grazing systems would create important societal shifts that would require further research, as well as the implied changed human-livestock relationships.

7. Conclusion

In this thesis, I investigated the capacity of different grazing systems to provide multiple ecosystem services. I provide important and novel insights on domestic systems and grazing in the context of rewilding. The literature reviews conducted as the first part of my PhD (Chapters 1 and 2) provided an overview of how grazing can contribute to wildfire prevention and several other ecosystem services, as well as exploring their complex trade offs and synergies. The second part of my PhD used case studies, first to explore and illustrate potentials with regards to rewilding (chapter 3), and secondly, to gain in-depth understanding of land user motivations, needs and challenges. Thereby I could broaden our understanding of the challenges and incentives that drive land users to conduct sustainable practices (chapter 4). The phenomenological approach of the interviews with case studies participants brought to light new insights on land users' motivation and drive to conduct sustainable grazing, and allowed me to provide relevant management and policy recommendations.

Firstly, grazing by large herbivores can help prevent wildfires, or at least reduce their risks and extents, through different mechanisms. I found that large herbivores can reduce wildfire frequency and intensity by promoting grass-dominated landscapes, reducing fuel loads, and influencing fire ignition. Management and policy recommendations are provided on using grazing by large herbivores for wildfire prevention in a way that also benefits multiple ecosystem services and is cost-efficient. The study provides a comprehensive overview of the mechanisms by which herbivores can impact fire regimes, and suggests that using semi-wild herbivores can be a relevant way of managing landscapes in areas that have undergone or are undergoing land abandonment and shrub encroachment. Rewilding with large herbivores can also be one of the means, and an economically viable alternative especially for marginal lands. Importantly, herbivore density should be adapted to the context to avoid trade-offs with other ecosystem services, and their diet preferences taken in consideration in regards to the existing vegetation.

Secondly, grazing management practices can provide multiple ecosystem services in a European context, however with some trade-offs and synergies between different ecosystem services. By reviewing the literature on the contribution of grazing and multiple ecosystem services, several recommendations arise. First, I recommend that extensive grazing should be prioritised over intensive grazing, to provide multiple ecosystem services in a European context. This is because in many cases high grazing densities are detrimental to ecosystem services such as biodiversity, climate change mitigation, and carbon storage. Maintaining low intensity grazing is especially important in Mediterranean regions that are more vulnerable to wildfires. Also, reducing grazing and management intensity and the use of fertilisers can help mitigate issues associated with overfertilization and nutrient leaking, affecting soil, water and human health for instance in Northwestern Europe. Promoting diverse herbivore communities with complementary diets, and avoiding the currently-broad use of deworming medication to minimise negative effects on biodiversity and ecosystems, are two additionally important means to reduce environmental pressures of grazing and untap the positive potentials of grazers to deliver ecosystem services. Since the Common Agricultural Policy (CAP) is the dominant policy instrument in the EU that affects grazing management through various instruments, there is a need to improve its environmental performance to support sustainable grazing. This includes reducing or phasing out harmful subsidies such as coupled direct payments (serving as a core subsidy

for intensive grazing), enhancing support for extensive farming, and evaluating the impacts of direct payments as a whole. Other relevant policy instruments include the Birds and Habitats' Directives, and EU strategies like the Green Deal and Farm to Fork Strategies, which aim to achieve various environmental goals related to grazing extensification, reducing nutrient runoff, and water pollution.

Including domestic animals in rewilding projects can be an effective way to deliver multiple ecosystem services provided by rewilding while also being more easily adapted to local contexts and making it more inclusive to local communities (chapter 3) and fitting in some cases more easily into agricultural policies.

Beyond the need to improve the CAP and its instrument, understanding land users decision-making drivers for sustainable grazing is crucial. The interviews (chapter 4) revealed a wide range of decision-making factors that affect sustainable grazing practices, with some being common across different regions and others being specific to certain contexts. Beyond the well-known financial and administrative barriers, that could indeed be confirmed through the interviews, my findings emphasised the importance of physical and social opportunity, having access to resources and a supportive social environment, as well as an intrinsic motivation to do good management. These results highlighted non-economic components of decision-making, that translate into more novel recommendations - such as direct marketing and ecotouristic opportunities or strengthening social cohesion of land users.

In light of my findings, I could formulate several general recommendations stemming from all my chapters. I recommend easing the obligations applied to domestic livestock in case of a very extensive and semi-wild system, to provide more flexibility for land users and incentivise these kinds of practices. Secondly, I recommend the use of livestock or semi-wild herbivores in conservation and nature projects with the goal of generating ecosystem services, and be close to traditional pastoral practices. I recommend the use of semi-wild herbivores in abandoned marginal agricultural areas where traditional rural practices are disappearing, as an alternative to provide livelihood for rural populations and as an opportunity for providing multiple ecosystem services.

My thesis clearly reveals three main knowledge gaps that can guide further research. Considering the highly context dependent effect of grazing on multiple ecosystem services and that there is no “one size fits all '' grazing management, large scale empirical grazing experiments, with much broader monitoring and over a longer time period could contribute to bringing even more context relevant findings to light. Moreover, my thesis identified knowledge regarding the impact of rewilding and semi-wild grazing on ecosystem services, since most of the literature is based on grazing experiments in livestock systems. Further research is needed to identify how rewilding systems contribute differently to multiple ecosystem services. Finally, having identified decision-making drivers in land users to practise sustainable grazing and potential policy and management interventions to incentivise them, more research would be needed on the impact of the new CAP 2023-27 implementation on land users practices and the consequences for ecosystem provision of grazing systems.

Finally, I find it important to highlight that in spite of the potential ability for grazing systems to provide multiple ecosystem services, most livestock systems today are decoupled from grazing lands and are currently a leading threat to biodiversity and climate change. Extensive and sustainable grazing

models can therefore only go hand in hand with profound changes in both production and consumption patterns, with a shift toward sustainable plant-based diets.

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Summary

Grazing by large herbivores, whether wild or domestic, has shaped European landscapes and plays a crucial role in maintaining key ecosystems and providing their ecosystem services. Grazing systems, especially the rearing of domestic animals, are taking a key part in shaping Europe's highly-antropised ecosystems but are also important culturally. Most grazed areas in Europe today are part of meat and dairy production systems and do not prioritise provision of other ecosystem services beyond food. Moreover, land use change is a significant challenge for European landscapes, and it can have a range of impacts on biodiversity, ecosystem services, and climate change. At present, intensification of agriculture, which involves increasing production efficiency and yields through the use of chemical fertilisers, pesticides, and intensive grazing practices, has been especially pronounced in newer member states of the European Union, encouraged by production-oriented systems and policies. This trend has led to significant changes in many landscapes, with a shift towards more homogeneous landscapes dominated by monocultures and biodiversity losses. At the same time, land abandonment is also an important phenomenon in some parts of Europe, particularly in marginal rural areas where farming is no longer socio-economically viable. While abandonment may have some benefits for biodiversity in some cases, it can also have negative impacts on grassland biodiversity as well as on various ecosystem services such as fire prevention and cultural services. Hence, these changes in land uses have consequences on climate mitigation and adaptation potential of European landscapes, as well as on their ability to prevent extreme weather events such as wildfires.

Yet, we are lacking an overview of the type(s) of grazing, and grazing-relating management that could provide multiple ecosystem services while addressing the challenges of land use change and the threats of climate change and extreme weather events, which I am providing in this thesis. A more specific objective is to explore the potential of rewilding with large herbivores as a land management which could be suitable for areas with land abandonment. Finally, while there is quite abundant literature about farmers' motivation and adoption of sustainable practices, we lack a comprehensive overview of what factors help, or hinders land users to engage in sustainable grazing management.

The aim of my thesis is to improve our understanding of how grazing management practices in Europe could enhance multiple ecosystem services. Through my study, I am able to offer novel insights on the diverse practices and management strategies associated with grazing for the provision of multiple ecosystem services. Additionally, I explore ways in which these practices could be implemented and incentivized. What sets my research apart is its inclusion of grazing systems beyond livestock, such as rewilding and semi-wild grazing, which are used for comparison. Through interdisciplinary methods drawing both from the social and ecological sciences, I use different methods (literature reviews, case studies, semi-structured interviews), to answer the following questions: Under which conditions, and by what mechanisms, can grazing mitigate wildfires? (Chapter 1). How does grazing contribute to multiple ecosystem services and what are the trade-offs and synergies between them? (Chapter 2). What could facilitate rewilding with large herbivores? (Chapter 3). And finally, what motivates land users to engage in sustainable grazing practices and what are the drivers, challenges and barriers in doing so? (Chapter 4). In the following, I shortly give an overview of each of the four chapters comprising my thesis.

Chapter 1

In chapter one, my focus is on the role of grazing on wildfire prevention, which has received relatively little attention compared to other ecosystem services. Through a systematic literature review, I obtain new insights into the effectiveness of large herbivores in mitigating wildfires. Specifically, I find that they can reduce wildfire frequency by promoting grass-dominated landscapes, and also reduce fire intensity by consuming vegetation and creating landscape features that reduce fuel loads. However, the effectiveness of large herbivores depends on the type of vegetation and diet preferences of the animals. Management practices associated with livestock grazing can also influence fire ignition.

I provide management and policy recommendations on how large herbivores can contribute to fire mitigation in a way that can also support other ecosystem services and be cost-efficient compared to other fuel management methods. I also highlight the importance of considering other ecosystem services in the implementation of wildfire prevention methods. This chapter expands on previous reviews by covering a broad range of grazing systems and types of animals, and makes an important contribution to our knowledge on nature-based wildfire mitigation strategies.

Chapter 2

In my second chapter, I investigated through a literature review the relationship between grazing management and several ecosystem services in Europe, namely habitat for biodiversity, climate change mitigation, soil quality, wildfires prevention and cultural services. I also examine synergies and trade-offs among these ecosystem services. The main focus is to identify what type of grazing management could provide multiple ecosystem services with minimal trade-offs.

Some of the key findings are that extensive grazing generally performs better than intensive grazing, and that a greater diversity of grazers, whether domestic or wild, is beneficial for both biodiversity and a range of ecosystem services. Diminishing grazing pressure is particularly beneficial in arid environments, but low intensity grazing is also often beneficial to maintain mosaic landscapes that have high value for biodiversity and ecosystem services in other types of environments. In contrast, intensive livestock grazing, and management practices associated with it (e.g. ploughing and seeding grasslands or deworming) are often detrimental to both biodiversity and multiple ecosystem services.

This chapter also nuances findings in different bioclimatic contexts in Europe. It identifies the synergies and trade-offs between ecosystem services, for example trade-offs between fire prevention and biodiversity or between different cultural ecosystem services. Based on these findings, I identify which policies can facilitate this sustainable grazing management in a European context, especially in the context of the Common Agricultural Policy.

Chapter 3

The third chapter of my research, where I contribute as the last author, focuses on the role of domestic animals in rewilding projects, which represents an important research gap in rewilding research. I describe how domestic and semi-wild herbivores can contribute to rewilding projects and make them more inclusive for rural communities, using case studies to illustrate the role of domestic livestock in different rewilding projects. The main aim of this chapter is to formulate recommendations on how to use domestic animals more successfully in rewilding projects.

The novelty of this chapter lies in the proposal to expand the perception of rewilding along a spectrum of naturalness, human modification, and management, ranging from "true" wilderness areas to activities such as wildlife-friendly farming or agricultural rewilding. However, this flexibility in the concept of rewilding could create confusion and limit its usefulness, so this chapter contributes to clarifying this spectrum of rewilding. This chapter concludes that the degree to which animals should be managed is highly context-dependent, and it is important to incorporate a safe operating space into the rewilding principles. This safe operating space should allow for hands-off management while the system fluctuates within a set of predefined boundary conditions. This safe operating space should also incorporate a component of the socially acceptable operating environment, as defined by the stakeholders and community engaged with the rewilding project.

Chapter 4

Finally, in the fourth chapter of my thesis I aim to identify the challenges faced by land users engaged in environmentally-sustainable grazing management. This chapter is based on semi-structured interviews with 88 land users from 8 case studies in Europe. By conducting a phenomenological analysis, I gain insights into the land users' experiences and identified the determinants of their behaviour towards sustainable grazing practices using the Behaviour Change Wheel framework. This chapter is novel in that it looks at a broad range of land users who defines themselves as practising any form of sustainable grazing management, including managers of rewilding areas and land users using semi-wild grazers, across a range of different bioclimatic and socio-economic regions.

I find that many land users struggle to maintain grazing-related activities due to rural depopulation, land abandonment, and lack of economic incentives, but traditional grazing management has a strong cultural and traditional value that land users want to perpetuate despite challenges. Some regulations and policies also hinder sustainable practices, particularly those associated with semi-wild grazing. Using the Behaviour Change Wheel, I identify policy instruments that could enable more sustainable practices, such as subsidies for agri-environmental measures and environmental restructuring. My research highlights that land users' motivation is based on multiple factors beyond economic drivers, including knowledge and awareness, physical opportunities, and an intrinsic motivation for practising good management for nature. These insights can help develop effective and realistic policies that take into account other drivers of behaviour beyond financial incentives and allow for adaptation to local contexts.

Synthesis

Overall, I find that the majority of my results demonstrate the potential of grazing as a solution to the various challenges and crises of the Anthropocene, but only when done in the right way.

Several key themes emerge from the results of my chapters, starting with the importance of an interdisciplinary approach in grazing research and the taking in consideration of different aspects of socio-ecological systems when looking at grazing systems and sustainability. Indeed, the provision of ecosystem services is affected by social processes that occur at multiple scales, emphasising the need for managers and policymakers to have a comprehensive understanding of land users and social communities, in addition to ecological data. Moreover, my thesis shows that because of the complexity and context-dependency of the effect of grazing on ecosystem services, coordinated grazing research in different areas with contrasting bio-climatic and socio-economic conditions is necessary to provide specific management recommendations, since a "one size fits all" type of management does not exist. This research also highlights the role and the potential of rewilding and semi-wild grazing systems as land management for provision of multiple ecosystem services that could be especially relevant in areas undergoing land abandonment. The results of this thesis also implies a shift in meat production and consumption as well as potential new pathways for human-livestock relations. Finally, this thesis also points to the fact that agricultural policies such as the Common Agricultural Policy (CAP) can play a crucial role in incentivising sustainable grazing management and should be improved to support extensive grazing and extensification, including practices associated with rewilding and semi-wild grazing.

Zusammenfassung

Die Beweidung durch große Pflanzenfresser, ob Wild- oder Haustiere, hat die europäischen Landschaften geprägt und spielt eine entscheidende Rolle bei der Erhaltung wichtiger Ökosysteme und der Bereitstellung ihrer Ökosystemleistungen. Weidesysteme, insbesondere die Haltung von Haustieren, spielen eine Schlüsselrolle bei der Gestaltung der stark antropisierten Ökosysteme Europas, sind aber auch von kultureller Bedeutung. Die meisten Weideflächen in Europa sind heute Teil von Fleisch- und Milchproduktionssystemen und stellen nicht vorrangig andere Ökosystemleistungen als die der Ernährung bereit. Darüber hinaus stellt der Wandel der Landnutzung eine große Herausforderung für die europäischen Landschaften dar und kann eine Reihe von Auswirkungen auf die biologische Vielfalt, die Ökosystemleistungen und den Klimawandel haben. Gegenwärtig ist die Intensivierung der Landwirtschaft, die eine Steigerung der Produktionseffizienz und der Erträge durch den Einsatz von chemischen Düngemitteln, Pestiziden und intensiven Weidepraktiken beinhaltet, in den neueren Mitgliedstaaten der Europäischen Union besonders ausgeprägt und wird durch produktionsorientierte Systeme und Politik efördert. Dieser Trend hat zu erheblichen Veränderungen in vielen Landschaften geführt, mit einer Verschiebung hin zu homogeneren, von Monokulturen dominierten Landschaften und Verlusten an biologischer Vielfalt. Gleichzeitig ist die Aufgabe von Flächen in einigen Teilen Europas ein wichtiges Phänomen, insbesondere in marginalen ländlichen Gebieten, in denen die Landwirtschaft sozioökonomisch nicht mehr lebensfähig ist. Die Aufgabe von Flächen kann zwar in einigen Fällen Vorteile für die biologische Vielfalt mit sich bringen, sie kann sich aber auch negativ auf die biologische Vielfalt von Grünland sowie auf verschiedene Ökosystemleistungen wie Brandverhütung und kulturelle Leistungen auswirken. Diese Veränderungen in der Landnutzung haben daher Auswirkungen auf das Klimaschutz- und Anpassungspotenzial der europäischen Landschaften sowie auf ihre Fähigkeit, extreme Wetterereignisse wie Waldbrände zu verhindern.

Dennoch fehlt uns ein Überblick über die Art(en) der Beweidung und des damit verbundenen Managements, die mehrere Ökosystemleistungen erbringen und gleichzeitig die Herausforderungen des Landnutzungswandels und die Bedrohungen durch den Klimawandel und extreme Wetterereignisse bewältigen könnten, was ich in dieser Arbeit darstelle. Ein spezifischeres Ziel ist die Erforschung des Potenzials der Wiederbewaldung mit großen Pflanzenfressern als Landbewirtschaftung, die für Gebiete mit aufgegebenem Land geeignet sein könnte. Schließlich gibt es zwar reichlich Literatur über die Motivation der Landwirte und die Einführung nachhaltiger Praktiken, doch fehlt uns ein umfassender Überblick darüber, welche Faktoren Landnutzer dabei unterstützen oder daran hindern, sich für ein nachhaltiges Weidemanagement einzusetzen.

Ziel meiner Dissertation ist es, unser Verständnis dafür zu verbessern, wie Weidemanagementpraktiken in Europa mehrere Ökosystemleistungen verbessern könnten. Durch meine Studie bin ich in der Lage, neue Erkenntnisse über die verschiedenen Praktiken und Bewirtschaftungsstrategien im Zusammenhang mit der Beweidung zur Erbringung verschiedener Ökosystemleistungen zu liefern. Außerdem untersuche ich, wie diese Praktiken umgesetzt und gefördert werden könnten. Was meine Forschung von anderen abhebt, ist die Einbeziehung von Weidesystemen jenseits der Viehhaltung, wie z.B. Rewilding und halbwilde Weidehaltung, die zum

Vergleich herangezogen werden. Durch interdisziplinäre Methoden, die sowohl aus den Sozial- als auch aus den Ökowissenschaften stammen, verwende ich verschiedene Methoden (Literaturrecherchen, Fallstudien, halbstrukturierte Interviews), um folgende Fragen zu beantworten: Unter welchen Bedingungen und durch welche Mechanismen kann die Beweidung Waldbrände abmildern? (Kapitel 1). Wie trägt die Beweidung zu verschiedenen Ökosystemleistungen bei und welche Kompromisse und Synergien gibt es zwischen ihnen? (Kapitel 2). Was könnte die Wiederbewaldung mit großen Pflanzenfressern erleichtern (Kapitel 3)? Und schließlich: Was motiviert Landnutzer, sich für nachhaltige Weidepraktiken einzusetzen, und was sind die Triebkräfte, Herausforderungen und Hindernisse dabei? (Kapitel 4). Im Folgenden gebe ich einen kurzen Überblick über jedes der vier Kapitel, aus denen meine Arbeit besteht.

Kapitel 1

Im ersten Kapitel konzentriere ich mich auf die Rolle der Beweidung bei der Verhütung von Waldbränden, die im Vergleich zu anderen Ökosystemleistungen relativ wenig Beachtung gefunden hat. Durch eine systematische Literaturrecherche gewinne ich neue Erkenntnisse über die Wirksamkeit großer Pflanzenfresser bei der Eindämmung von Waldbränden. Insbesondere stelle ich fest, dass sie die Häufigkeit von Waldbränden verringern können, indem sie grasdominierte Landschaften fördern, und auch die Brandintensität reduzieren, indem sie Vegetation verbrauchen und Landschaftsmerkmale schaffen, die die Brennstofflast verringern. Die Wirksamkeit großer Pflanzenfresser hängt jedoch von der Art der Vegetation und den Ernährungspräferenzen der Tiere ab. Auch die Bewirtschaftungspraktiken im Zusammenhang mit der Viehbeweidung können die Entzündung von Bränden beeinflussen.

Ich gebe Empfehlungen für das Management und die Politik, wie große Pflanzenfresser auf eine Art und Weise zur Brandbekämpfung beitragen können, die auch andere Ökosystemleistungen unterstützt und im Vergleich zu anderen Methoden des Brennstoffmanagements kosteneffizient ist. Ich betone auch, wie wichtig es ist, andere Ökosystemleistungen bei der Umsetzung von Methoden zur Verhütung von Waldbränden zu berücksichtigen. Dieses Kapitel erweitert frühere Übersichten, indem es ein breites Spektrum von Weidesystemen und Tierarten abdeckt, und leistet einen wichtigen Beitrag zu unserem Wissen über naturbasierte Strategien zur Eindämmung von Waldbränden.

Kapitel 2

In meinem zweiten Kapitel untersuchte ich anhand einer Literaturrecherche die Beziehung zwischen Weidemanagement und verschiedenen Ökosystemleistungen in Europa, nämlich Lebensraum für die biologische Vielfalt, Klimaschutz, Bodenqualität, Verhütung von Waldbränden und kulturelle Leistungen. Ich untersuche auch Synergien und Kompromisse zwischen diesen Ökosystemleistungen. Das Hauptaugenmerk liegt darauf, herauszufinden, welche Art des Weidemanagements mehrere Ökosystemleistungen mit minimalen Kompromissen erbringen kann.

Einige der wichtigsten Ergebnisse sind, dass eine extensive Beweidung im Allgemeinen besser abschneidet als eine intensive Beweidung und dass eine größere Vielfalt an Weidevieh, ob Haus- oder Wildtiere, sowohl für die biologische Vielfalt als auch für eine Reihe von Ökosystemleistungen von Vorteil ist. Eine Verringerung des Weidedrucks ist vor allem in trockenen Gebieten von Vorteil, aber auch die Beweidung mit geringer Intensität ist oft von Vorteil, um Mosaiklandschaften zu erhalten, die

in anderen Gebieten einen hohen Wert für die biologische Vielfalt und die Ökosystemleistungen haben. Im Gegensatz dazu sind die intensive Beweidung und die damit verbundenen Bewirtschaftungspraktiken (z. B. das Pflügen und Säen von Grasland oder die Entwurmung) häufig sowohl für die biologische Vielfalt als auch für mehrere Ökosystemleistungen schädlich.

In diesem Kapitel werden auch die Ergebnisse in verschiedenen bioklimatischen Kontexten in Europa nuanciert. Es zeigt die Synergien und Zielkonflikte zwischen Ökosystemleistungen auf, z. B. die Zielkonflikte zwischen Brandverhütung und biologischer Vielfalt oder zwischen verschiedenen kulturellen Ökosystemleistungen. Auf der Grundlage dieser Erkenntnisse zeige ich auf, welche politischen Maßnahmen dieses nachhaltige Weidemanagement im europäischen Kontext, insbesondere im Rahmen der Gemeinsamen Agrarpolitik, erleichtern können.

Kapitel 3

Das dritte Kapitel meiner Forschungsarbeit, an dem ich als letzter Autor mitwirke, befasst sich mit der Rolle von Haustieren in Auswilderungsprojekten, die eine wichtige Forschungslücke in der Auswilderungsforschung darstellt. Ich beschreibe, wie Haus- und halbwilde Pflanzenfresser zu Auswilderungsprojekten beitragen und sie für ländliche Gemeinschaften integrativer machen können, indem ich Fallstudien verwende, um die Rolle von Haustieren in verschiedenen Auswilderungsprojekten zu illustrieren. Das Hauptziel dieses Kapitels ist es, Empfehlungen zu formulieren, wie Haustiere erfolgreicher in Auswilderungsprojekten eingesetzt werden können.

Die Neuheit dieses Kapitels liegt in dem Vorschlag, die Wahrnehmung von "rewilding" entlang eines Spektrums von Natürlichkeit, menschlicher Veränderung und Management zu erweitern, das von "echten" Wildnisgebieten bis hin zu Aktivitäten wie wildtierfreundlicher Landwirtschaft oder landwirtschaftlichem "rewilding" reicht. Diese Flexibilität des Konzepts des "rewilding" könnte jedoch Verwirrung stiften und seine Nützlichkeit einschränken, weshalb dieses Kapitel dazu beiträgt, das Spektrum des "rewilding" zu verdeutlichen. Das Kapitel kommt zu dem Schluss, dass das Ausmaß der Tierhaltung in hohem Maße kontextabhängig ist und dass es wichtig ist, einen sicheren Handlungsspielraum in die Rewilding-Prinzipien einzubeziehen. Dieser sichere Betriebsraum sollte ein "hands-off"-Management ermöglichen, während das System innerhalb einer Reihe von vordefinierten Randbedingungen schwankt. Dieser sichere Betriebsraum sollte auch eine Komponente des sozial akzeptablen Betriebsumfelds beinhalten, wie es von den am Rewilding-Projekt beteiligten Interessengruppen und der Gemeinschaft definiert wird.

Kapitel 4

Im vierten Kapitel meiner Dissertation möchte ich die Herausforderungen aufzeigen, mit denen Landnutzer konfrontiert sind, die ein ökologisch nachhaltiges Weidemanagement betreiben. Dieses Kapitel basiert auf halbstrukturierten Interviews mit 88 Landnutzern aus 8 Fallstudien in Europa. Durch eine phänomenologische Analyse gewinne ich Einblicke in die Erfahrungen der Landnutzer und ermittle die Determinanten ihres Verhaltens in Bezug auf nachhaltige Beweidungspraktiken, indem ich den Rahmen des Verhaltensänderungsrades verwende. Dieses Kapitel ist insofern neuartig, als es ein breites Spektrum von Landnutzern untersucht, die sich selbst als Praktiker einer nachhaltigen Weidewirtschaft bezeichnen, darunter Manager von Wiederbegrünungsgebieten und Landnutzer, die halbwilde Weideflächen nutzen, und zwar in einer Reihe verschiedener bioklimatischer und sozioökonomischer Regionen.

Ich stelle fest, dass viele Landnutzer aufgrund von Landflucht, Landaufgabe und fehlenden wirtschaftlichen Anreizen Schwierigkeiten haben, weidebezogene Aktivitäten aufrechtzuerhalten. Die traditionelle Weidewirtschaft hat jedoch einen starken kulturellen und traditionellen Wert, den die Landnutzer trotz der Herausforderungen beibehalten wollen. Einige Vorschriften und politische Maßnahmen behindern ebenfalls nachhaltige Praktiken, insbesondere im Zusammenhang mit der halbwilden Weidehaltung. Mithilfe des Verhaltensänderungsrads ermittle ich politische Instrumente, die nachhaltigere Praktiken ermöglichen könnten, wie etwa Subventionen für Agrarumweltmaßnahmen und ökologische Umstrukturierungen. Meine Forschung zeigt, dass die Motivation der Landnutzer nicht nur auf wirtschaftlichen Faktoren beruht, sondern auch auf Wissen und Bewusstsein, physischen Möglichkeiten und einer intrinsischen Motivation für ein gutes Management der Natur. Diese Erkenntnisse können dazu beitragen, wirksame und realistische politische Maßnahmen zu entwickeln, die über finanzielle Anreize hinaus auch andere Verhaltensfaktoren berücksichtigen und eine Anpassung an lokale Gegebenheiten ermöglichen.

Synthese

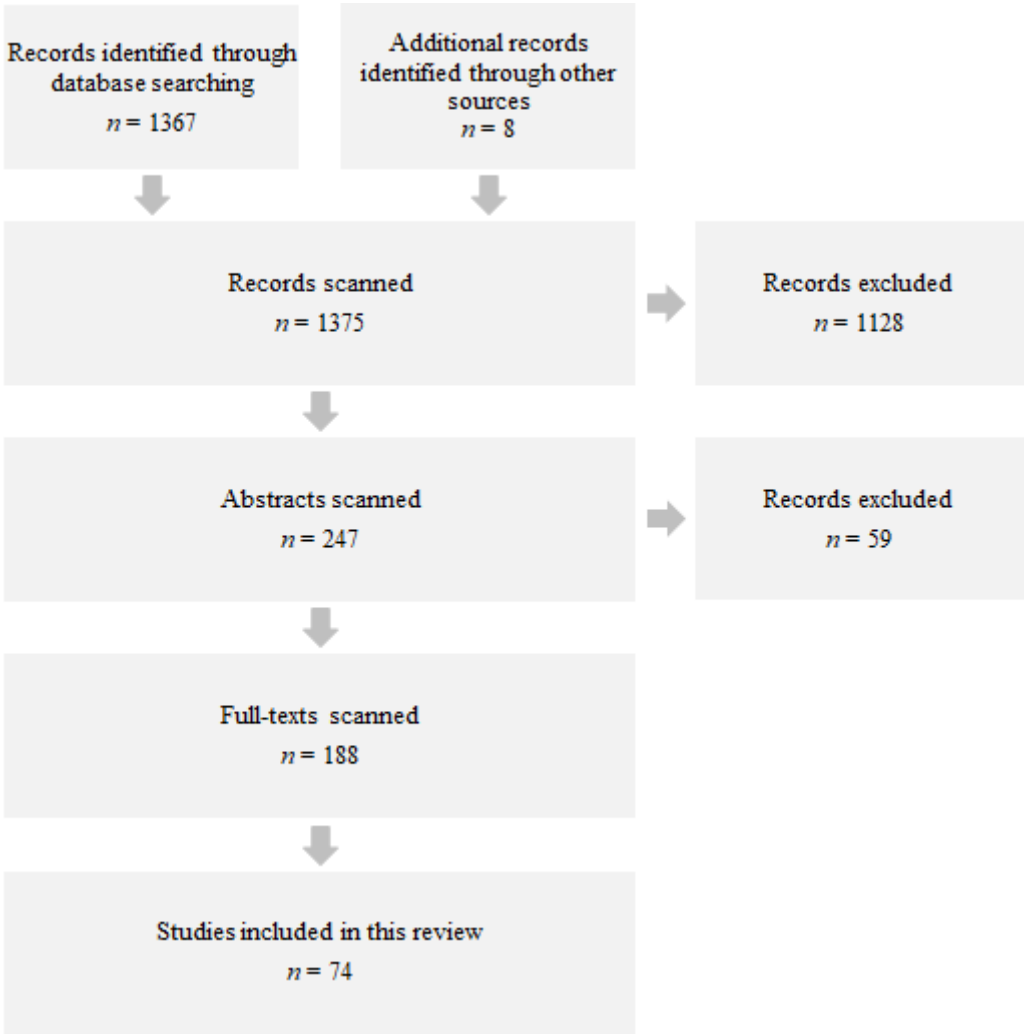
Insgesamt stelle ich fest, dass die meisten meiner Ergebnisse das Potenzial der Beweidung als Lösung für die verschiedenen Herausforderungen und Krisen des Anthropozäns aufzeigen, allerdings nur, wenn sie auf die richtige Art und Weise erfolgt.

Aus den Ergebnissen meiner Kapitel ergeben sich mehrere Schlüsselthemen, angefangen bei der Bedeutung eines interdisziplinären Ansatzes in der Weideforschung und der Berücksichtigung verschiedener Aspekte sozio-ökologischer Systeme bei der Betrachtung von Weidesystemen und Nachhaltigkeit. Die Bereitstellung von Ökosystemleistungen wird nämlich von sozialen Prozessen beeinflusst, die auf verschiedenen Ebenen ablaufen. Dies unterstreicht die Notwendigkeit, dass Manager und politische Entscheidungsträger neben ökologischen Daten auch ein umfassendes Verständnis der Landnutzer und sozialen Gemeinschaften haben müssen. Darüber hinaus zeigt meine Arbeit, dass aufgrund der Komplexität und Kontextabhängigkeit der Auswirkungen der Beweidung auf die Ökosystemleistungen eine koordinierte Beweidungsforschung in verschiedenen Gebieten mit kontrastierenden bioklimatischen und sozioökonomischen Bedingungen erforderlich ist, um spezifische Bewirtschaftungsempfehlungen zu geben, da es keine "Einheitsgröße" für die Bewirtschaftung gibt. Diese Forschungsarbeit unterstreicht auch die Rolle und das Potenzial von Wiederbewaldung und halbwilden Weidesystemen als Landbewirtschaftung für die Bereitstellung mehrerer Ökosystemleistungen, die besonders in Gebieten, in denen Land aufgegeben wird, von Bedeutung sein könnten. Die Ergebnisse dieser Arbeit implizieren auch eine Verlagerung der Fleischproduktion und des Fleischkonsums sowie potenzielle neue Wege für die Beziehungen zwischen Mensch und Vieh. Schließlich weist diese Arbeit auch auf die Tatsache hin, dass agrarpolitische Maßnahmen wie die Gemeinsame Agrarpolitik (GAP) eine entscheidende Rolle bei der Schaffung von Anreizen für eine nachhaltige Weidehaltung spielen können und verbessert werden sollten, um die extensive Weidehaltung und die Extensivierung zu unterstützen, einschließlich Praktiken im Zusammenhang mit der Wiederverwilderung und der halbwilden Weidehaltung.

Appendix

Appendix Chapter One

Figure S1.1 *Flowchart of the review of the literature. We retained 74 studies out of 1,375 studies found on Web of Science, with 8 additional studies (Moher et al., 2009)*



Appendix Chapter Two

Table S2.1. *Detailed methods of literature search and inclusion*

Search	Date	Service	Search string	Systematic literature search: Papers found	Abstracts read	Full papers scanned	Papers included in review	Papers included through cross-refencing	Total number of included papers
1	190405	climate change mitigation	TS=(belowgro*-carbon-stora* OR soil-carbon-sto* OR soil-organic-carbon) AND TS=(grazin*) NOT TS=(afric* OR americ* OR asia OR austral* OR united-stat* OR chin* OR prair*)	266	266	68	4	8	13
2	190418	climate change mitigation	TS=(belowgro*-carbon-stora* OR soil-carbon-sto* OR soil-organic-carbon) AND TS=(grazin* OR herbivor* OR brows* OR graze* OR rewildi* OR livestock OR cow* OR hors* OR sheep OR goat* OR bison OR donke* OR deer* OR chamoi* OR ibex OR reinde* OR moos*) NOT TS=(afric* OR americ* OR asia OR austral* OR tropic* OR indones* OR united-stat* OR india OR chin* OR prair* OR USA OR tibet* OR mongol* OR inner-mongol* OR russ* OR brazi* OR keny* OR iowa OR califor* OR subtrop* OR new-zeal* OR south-afric* OR mexic* OR canad* OR north-amer*) NOT YEAR PUBLISHED: (2019). Exclusion of papers of search 1.	164	164	12	0		
3	190520	climate change mitigation	TS=(Soil-Organic-Matter) AND TS=(grazin* OR herbivor* OR brows* OR graze* OR rewildi* OR livestock OR cow* OR hors* OR sheep OR goat* OR bison OR donke* OR deer* OR chamoi* OR ibex OR reinde* OR moos*) NOT TS=(afric* OR americ* OR asia OR austral* OR tropic* OR indones* OR united-stat* OR india OR chin* OR prair* OR USA OR tibet* OR mongol* OR inner-mongol* OR russ* OR brazi* OR keny* OR iowa OR califor* OR subtrop* OR new-zeal* OR south-afric* OR mexic* OR canad* OR north-amer*) NOT PY=(2019)	447	447	31	1		
4	190528	Fire mitigation	TS=(wildfire-damage OR wildfire-prevention OR wildfire-hazard OR fire-damage OR fire-prevention OR fire-hazard OR fuelbreak OR fuel-load* OR fire-break) AND TS=(cattle OR grazin* OR herbivor* OR brows* OR graze* OR rewildi* 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*) NOT TS=(afric* OR americ* OR asia OR austral* OR tropic* OR indones* OR united-stat* OR india OR chin* OR prair* OR USA OR tibet* OR mongol* OR inner-mongol* OR russ* OR brazi* OR keny* OR iowa OR califor* OR subtrop* OR new-zeal* OR south-afric* OR mexic* OR canad* OR north-amer*) NOT PY=(2019)	81	81	26	8	2	12
5	190606	Fire mitigation	TS=(wildfire OR wild-fire) AND TS=(cattle OR grazin* OR herbivor* OR brows* OR graze* OR rewildi* 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*) NOT TS=(afric* OR americ* OR asia OR austral* OR tropic* OR indones* OR united-stat* OR india OR chin* OR prair* OR USA OR tibet* OR mongol* OR inner-mongol* OR russ* OR brazi* OR keny* OR iowa OR califor* OR subtrop* OR new-zeal* OR south-afric* OR mexic* OR canad* OR north-amer*) NOT PY=(2019). Exclusion of papers of search 4.	198	198	22	0		

6	190923	Fire mitigation	TS=(wildfire OR wild-fire) AND TS=(cattle OR grazin* OR herbivor* OR brows* OR graze* OR rewildi* 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*)	580	580	201	2		
7	210228	Wildfire mitigation	TS=(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*)	1367	1367	238	0		
8	190815	Biodiversity	TI= (species-richn* OR species-divers* OR biodivers*) AND TS= (insect* OR arthropo* OR butterfl* OR beetl* OR groundbeet* OR grasshopp* OR bee* OR fly OR aphid*) AND TS= (grazin* OR herbivor* OR brows* OR graze* OR rewildi* OR livestock OR cow* OR hors* OR sheep OR goat* OR bison OR donke* OR deer* OR chamoi* OR ibex OR reinde* OR moos*) AND review articles	70	70	10	1	25	27
9	190815	Biodiversity	TI= (species-richn* OR species-divers* OR biodivers*) AND TS= (bird* OR avian OR belowground-organis* OR eartworm* OR microbes OR fungi OR bacteria OR nematode* OR mite* OR mammal* OR rodent* OR reptil* OR amphibi*) AND TS= (grazin* OR herbivor* OR brows* OR graze* OR rewildi* OR livestock OR cow* OR hors* OR sheep OR goat* OR bison OR donke* OR deer* OR chamoi* OR ibex OR reinde* OR moos*) AND review articles	33	33	4	1		
10	200218	Cultural ESS	TS=(cultural-ecosystem-service* OR non-material OR intangible OR aesthetic* OR recreation OR sense-of-place OR spiritual OR inspiration OR environmental-education OR relational-service* OR eco-tourism OR human-wildlife-conflict* OR ecotourism) AND TS=(rewildi* OR pastoral* OR large-herbivores OR wild-horses OR herding OR grazing) NOT TS=(pastoral-care)	1064	1064	14	12	6	18
11	210202	Soil quality	TS= (soil-organic-matter OR soil- organic-carbon* OR soil-erosion OR soil-qual* OR nutri*-leach* OR water-qual*) AND TS= (grazin* OR herbivor* OR brows* OR graze* OR rewildi* 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 tillage) NOT TS= (afric* OR americ* OR asia OR austral* OR tropic* OR indones* OR united-stat* OR india OR chin* OR prair* OR USA OR tibet* OR mongol* OR inner-mongol* OR russ* OR brazi* OR keny* OR iowa OR califor* OR subtrop* OR new-zeal* OR south-afric* OR mexic* OR canad* OR north-amer*) NOT PY=2021 AND review articles	296	296	56	2	9	11

Table S2.2

						Geographical aspect																Effect of grazing on the ESS
	Ecosystem service	*Found through*	*Reference**	*Review or case study*	*Number of studies*	*Country*	*Habitat type*	*Grazing (intense)*	*Grazing (extens)*	*Grazing (wild_n)*	*Grazing (semi-w)*	*pastoral*	*mowing*	*ploughing*	*grazer diversity*	*presence of mixed-feeders*	*external fodder inputs*	*fertilizer application*	*deworming medication*	*burning management*	*hunting activities*	
1	climate change r	Search #1	Byrnes et al., 20	review	64	global	across ecosy	yes	yes	no	no	no	no	no								Mixed
2	climate change r	Search #1	Conant et al., 20	review	64	global	across ecosy	yes	yes									yes		yes		Mixed
3	climate change r	Cross-referenc	Eze et al., 2018	review	136	global	across ecosy	yes	yes	no	no	no	no	no				yes				Negative
4	climate change r	Cross-referenc	Köster et al., 20	study	NA	Finland	boreal coniferous forest				yes											Neutral
5	climate change r	Search #1	McSherry & Ritcl	review	17	global	grasslands	yes	yes	no	no	no	no	no								Mixed
6	climate change r	Search #3	Stark et al., 201	study	NA	Finland	arctic tundra	no	no	no	yes	yes	no	no								Neutral
7	climate change r	Search #1	Tanetztap & Coo	review	NA	global	across ecosy	yes	yes	yes	yes	yes	no	no								Negative
8	climate change r	Cross-referenc	Zhou et al., 201	review	115	global	grasslands	yes	yes	no	no	no	no	no								Mixed
9	climate change r	Cross-referenc	Lai et al., 2020	review	287	global	across ecosy	yes	yes													Negative
10	climate change r	cross-referenc	Girona-García, 2	study	NA	Spain	grasslands					yes								yes		Negative
11	climate change r	cross-referenc	Rivera et al. 202	review	NA	Global	grasslands	yes	yes													Negative
12	climate change r	cross-referenc	Stoll-Kleeman et	study	NA	NA	NA															Negative
13	climate change r	cross-referenc	Rose et al. 2013	study	NA	Germany	grasslands	yes														Neutral
14	wildfire mitigation	Search #4	Jauregui et al., 2	study	NA	Spain	heathlands									yes						Positive
15	wildfire mitigation	Search #6	Johnson et al., 2	review	NA	global	across ecosy	no		yes												Positive
16	wildfire mitigation	Search #4	Lasanta et al., 2	study	NA	Spain	shrubland	no	yes											yes		Mixed
17	wildfire mitigation	Search #4	Lovreglio et al.,	review	NA	global	across ecosy	no				yes										Positive
18	wildfire mitigation	Search #4	Mitsopoulos & D	study	NA	Greece	forest	no	yes											yes		Mixed
19	wildfire mitigation	Search #4	Oteros-Rozas et	study	NA	Spain	agrosylvopas	no				yes										Positive
20	wildfire mitigation	Cross-referenc	Rouet-Leduc et	review	62	global	accross ecos	yes	yes	yes	yes	yes			yes	yes				yes		Mixed
21	wildfire mitigation	Search #4	Ruiz-Mirazo et al	study	NA	Spain	forest					yes				yes						Positive
22	wildfire mitigation	Search #4	Ruiz-Mirazo et al	study	NA	Spain	forest	no				yes				yes				yes		Positive
23	wildfire mitigation	Search #4	Kramer, K. et al., 20	study	NA	Netherland	forest			yes	yes				yes	yes						Positive
24	wildfire mitigation	Search #5	Mancilla-Leytón, JM	study	NA	Spain	forest		yes							yes						Positive
25	wildfire mitigation	cross-referenc	Nepstad et al. 2008	study	NA	Brazil	forest										yes			yes		Negative
26	biodiversity cons	cross-referenc	Allan et al., 201	study	NA	Germany	grasslands	yes	yes				yes					yes				Negative
27	biodiversity cons	cross-referenc	Bakker et al., 20	study	NA	US, Nethe	grasslands		yes													Mixed
28	biodiversity cons	Search #7	Doboszewski, Pr	study	NA	Poland	grasslands		yes		yes								yes			Positive
29	biodiversity cons	cross-referenc	Foster et al., 20	review	96	Global	across ecosy	yes	yes													Negative
30	biodiversity cons	cross-referenc	Gao & Carmel 2	review	98	Global	across ecosy	yes	yes													Mixed
31	biodiversity cons	cross-referenc	Herrero-Jáuregu	review	48	Global	across ecosy	yes	yes													Mixed
32	biodiversity cons	Search #8	Joern & Laws 2(	review	37	Global	grasslands	yes	yes											yes		Mixed
33	biodiversity cons	cross-referenc	Le Provost et al.	study	NA	Germany	grasslands	yes	yes				yes	yes				yes				Mixed
34	biodiversity cons	cross-referenc	Olff & Ritchie 19	review	NA	Global	grasslands	yes	yes													Mixed
35	biodiversity cons	cross-referenc	Pöyry et al., 200	study	NA	Finland	grasslands	yes	yes													Mixed
36	biodiversity cons	cross-referenc	Proulx & Mazum	review	30	Global	across ecosy	yes										yes				Mixed
37	biodiversity cons	cross-referenc	Scimone et al., 2	study	NA	UK, Franc	grasslands	yes	yes													Mixed
38	biodiversity cons	cross-referenc	Suominen and (	review	NA	Fennosca	arctic tundra				yes					yes						Positive
39	biodiversity cons	cross-referenc	Takagi & Miyash	review	71	Global	across ecosy	yes	yes													Negative
40	biodiversity cons	cross-referenc	van Klink et al.,	review	141	Global	grasslands &	yes	yes													Negative

						Geographical aspect																Effect of grazing on the ESS
	Ecosystem service	Found through	Reference*	Review or case study	Number of studies	Country	Habitat type	Grazing (intense)	Grazing (extens)	Grazing (wild_n)	Grazing (semi-w)	pastoral	mowing	ploughing	grazer diversity	presence of mixed-feeders	external fodder inputs	fertilizer application	deworming medication	burning management	hunting activities	
42	biodiversity cons	cross-referenc	Wang et al., 201	review	116	Global	grasslands	yes	yes													Mixed
43	biodiversity cons	cross-referenc	Milchunas et al.,	review	NA	Global	grasslands	yes	yes													Mixed
44	biodiversity cons	cross-referenc	Austrheim et al.	study	NA	Norway	grasslands							yes								Negative
45	biodiversity cons	cross-referenc	Barlow et al. 20	study	NA	Brazil	forest															Negative
46	biodiversity cons	cross-referenc	Liu et al. 2016	study	NA	England	grasslands							yes								Negative
47	biodiversity cons	cross-referenc	Floate et al. 200	review	NA	NA	NA												yes			Negative
48	biodiversity cons	cross-referenc	Lumaret et al. 2	review	NA	NA	NA												yes			Negative
49	biodiversity cons	cross-referenc	de Souza et al.	review	NA	NA	NA												yes			Negative
50	biodiversity cons	cross-referenc	Evans et al. 200	study	NA	Scotland	grasslands		yes						yes							Positive
51	biodiversity cons	cross-referenc	Foster et al., 20	review	96	Global	NA	yes	yes													Negative
52	biodiversity cons	cross-referenc	Bobbink et al. 2	review	41	Global	across ecosystems											yes				Negative
53	cultural ecosyste	Search #10	Balčiauskas et a	study	NA	Lithuania	NA				yes										yes	Positive
54	cultural ecosyste	cross-referenc	Berkel & Verbur	study	NA	Netherlan	across ecosystems															NA
55	cultural ecosyste	cross-referenc	Burel & Baudry,	study	NA	France	NA															NA
56	cultural ecosyste	Search #10	Genovese et al.	study	NA	Italy	NA		yes			yes										Positive
57	cultural ecosyste	Search #10	Greaves, 2019	study	NA	NA	NA			yes												Positive
58	cultural ecosyste	cross-referenc	Koninx 2018	study	NA	Sweden	NA			yes	yes											Mixed
59	cultural ecosyste	Search #10	López-Santiago	study	NA	Spain	NA					yes										Positive
60	cultural ecosyste	cross-referenc	Maldonado et al	study	NA	Spain	NA		yes			yes										Positive
61	cultural ecosyste	Search #10	Martino & Muen	study	NA	Romania	NA		yes				yes									Positive
62	cultural ecosyste	Search #10	Navarro & Perei	study	NA	Europe	NA			yes	yes											Mixed
63	cultural ecosyste	Search #10	Oteros-Rozas et	study	NA	Spain	NA					yes										Positive
64	cultural ecosyste	cross-referenc	Perino et al., 20	study	NA	NA	NA			yes	yes											Mixed
65	cultural ecosyste	Search #10	Plieninger et al.,	study	NA	Europe	wood pastures		yes			yes										Positive
66	cultural ecosyste	Search #10	Prior & Brady 20	study	NA	NA	NA			yes	yes											Mixed
67	cultural ecosyste	Search #10	Raatikainen & B	study	NA	Finland	NA		yes													Positive
68	cultural ecosyste	cross-referenc	Rouet-Leduc &	study	NA	Sweden	NA				yes											Positive
69	cultural ecosyste	Search #10	Surová et al., 2(	study	NA	Portugal a	Montado/Dehesa		yes			yes										Positive
70	cultural ecosyste	Search #10	Wehn et al., 201	study	NA	Norway	grasslands		yes													Positive
71	soil quality	cross-referenc	Bilotta et al. 200	review	NA		grasslands	yes	yes													Negative
72	soil quality	cross-referenc	Collins et al., 20	study	NA	UK	grasslands	yes														Negative
73	soil quality	cross-referenc	Greipsson 2012	study	NA	Iceland	heathland	yes														Negative
74	soil quality	Search #11	Haddaway et al.	review	NA	Global								yes								Negative
75	soil quality	Search #11	Hooda et al. 20(	review	NA	UK	grasslands	yes										yes				Negative
76	soil quality	cross-referenc	Kéfi et al., 2007	study	NA	Spain, Gre	grasslands/s	yes														Negative
77	soil quality	cross-referenc	Mayel et al., 202	review	NA	Global	grasslands	yes	yes				yes				yes	yes				Mixed
78	soil quality	cross-referenc	Sakadevan & N	review	NA	Global	grasslands	yes	yes				yes				yes	yes				Mixed
79	soil quality	cross-referenc	Schrama et al., 2	review	37	Global	accross ecosystems		yes													Mixed
80	soil quality	cross-referenc	Feamside, 2002	study	NA	Brazil	across ecosystems										yes					Negative
81	soil quality	Cross-referenc	Francini et al., 2	study	NA	Finland	arctic tundra				yes											Mixed

Appendix Chapter Four

Table S4.1.: *Original definition and examples of the COM-B model from our study (inspired from Wilson & Marselle, 2016)*

COM-B COMPONENTS AND DEFINITIONS (from Michie et al., 2011)	Examples from the study	Quotes (selected examples)
PHYSICAL CAPABILITY: The physical ability to execute the behaviour including the physical strength and skills.	Participants lack the workforce to engage in the grazing activities they wish, because younger generations are moving out of the areas.	"*No, there is no people who can work, I can create jobs but there is no people*" (RM_4_LU)
	Modernisation and efficiency increases have resulted in intensification, automatisation and fewer employees.	"*The decline of agriculture and forestry does (nearly) not lead to land abandonment, it leads only to raised efficiency and productivity, resulting in the reduction of jobs.*" (OD_3_LU)
	Ageing of population: decrease in physical capability	"*Only old generation practises grazing, young generation largely abandon the area*" (DD_2_LU)
	Activities linked to grazing are physically tough which stops people from engaging in them.	"*The next generation does not want to farm, because it is too hard, too much work. They usually leave abroad and choose easier career options. If grazing could not be carried out here, the areas would simply be abandoned*" (LI_1_LU)
PSYCHOLOGICAL CAPABILITY: Knowledge or psychological skills to engage in a behaviour.	Having access and understanding, knowledge about the rules, on subsidies, legislations and regulations.	"*Farmers are still very vulnerable, lacking financial education, living an isolated life, lacking communication.*" (LI_8_LU) *"veterinary inspectors should get proper training about beef cattle, to learn that they are stronger than dairy cows, that they can graze throughout winter and that the animal welfare does not suffer from this." (LI_5_LU)* *"If I would have known that this bureaucracy would be so much, I maybe would not have started this all."* (OD_2_LU)
	Lack of clarity of the rules and definitions hinders capability to engage in some activities	
SOCIAL OPPORTUNITY: Opportunity afforded by interpersonal influences, social cues	Rural exodus, change in generational structure	*"Young people are not interested, they do not want to farm, do not want to live here, prefer to work abroad."*

and cultural norms.		*(LI_10_LU)* *"It is [a] family tradition, I have worked with animals since I was a child, I have a desire to work with animals. My grandparents were livestock breeders, but my uncle and I started not too long ago. If there is no possibility to breed animals we have to leave [the] area, to search for work abroad" (RM_3_LU)*
	Tradition is an important driver in extensive grazing practices and creates an enabling environment.	*"Animal herding is as old as people. The traditions are old. There are many local and historical knowledge connected to herding animals. (...) Herding in a sense was a man shaping experience: it helped to get to know the surrounding area, the nature, the people, everything." (LI_3_LU)* *"The main reason for the maintenance of this system is that people related with it love the ponies, they "have a fever", and this tradition runs very deep in their hearts." (GA_5_LU)* *"These uses and customs have always existed in my area. As I mentioned, my grandparents and my parents have always lived in communion with the mountain, care for it" (PT_7_LU)*
PHYSICAL OPPORTUNITY: Opportunity given by the environment involving time, resources, location.	Environmental conditions: remoteness, lack of access to water	*"Lack of water is the main problem – in the last month of the hottest period the animals lose weight due to the lack of water and dehydration. (RM_2_LU)*
	Landscape composition: human wildlife conflicts, with predators and between semi-wild and domestic herbivores, conflicts with other types of land use	"*If I'm not present in the area everyday there will be damage, I see wolves every day –yesterday I saw wolves and today again. For 1 month 15 calves were killed by wolves. When we disappear from the area they immediately attack.*" (RM_3_LU) *"there should be more control over the surrounding farms especially for the use of herbicides, fungicides and pesticides. When you farm organically but the nearby farms pollute the*

		environment, then your motivation becomes low." (LI_2_LU) *"There are conflicts between semi-wild pony grazing and land owners (Common Lands) that dedicate the land to afforestation leaving the ponies without good grazing areas. The problem is worse in the case of eucalyptus which dries out the land. The commoners also fence some areas where pines are regenerating and don't allow ponies and cattle to use that land."* (GA_7_LU)
	Legal regulations and policy influence land management	"*The CAP subsidy is essential to maintain the people living on cattle raising in these areas in the mountains*" (GA_10_LU) "*Small farms tend to sell their lands for these big farming companies. [The] number of small farms is definitely reducing, because such farming practice has no big prospects*" (LI_7_LU) "*large farmers size (…) hog up the entire land available for grazing of communities*". (DD_1_LU).
	Economic impacts: Financial aspects	"*Without the payments, we would not have started farming. Because for the first few years, it was like a guarantee that helps you survive. It is more profitable for us to raise calves, which is why we started it.*" (LI_7_LU).
AUTOMATIC MOTIVATION: Processes involving emotional reactions, desires,impulses, and reflex responses.	Habit: Some land managers do what they do because they have always done it.	"*I had horses all my life… I remember all my past generations with horses: my grandfather, my great grandfather, my great-great-grandfather, everyone*" (GA_5_LU)
REFLECTIVE MOTIVATION: Reflective processes involving plans (self-conscious intentions) and evaluations.	Beliefs and values are important drivers of land use practices, such intrinsic care for nature, will to perpetuate a management they believe is good.	"*Money is not everything - and I would not decide to increase farm income at the expense of long-term reduction in value (soil degradation etc.)*" (OD_11_LU) "*Money is not everything - and I would not decide to increase farm income at the expense of long-* *term reduction in value* (soil destruction etc.)" (OD_11_LU)

		"*Highest motivator would be environmental reasons. If it was up to me, there would be only organic farming in the whole of Lithuania. Herbicides or pesticides should not be used at all (...) we have always chosen this pathway because we like nature and natural production*". (LI_2_LU)

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Chapter 1

Dissertation
Julia Rouet-Leduc
Grazing for wildfire prevention, ecosystem service provision, nature conservation and landscape management

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Title: Effects of large herbivores on fire regimes and wildfire mitigation
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Leipzig, den 11.04.2023

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