

GRASSLAND-BASED LIVESTOCK FARMING AND BIODIVERSITY

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ABSTRACT

Grasslands dominate land cover nationally and globally, and their composition, structure and habitat value are strongly influenced by the actions of domestic and wild grazing animals that feed on them. Different pastures are characterised by varying opportunities for selective feeding by livestock; agronomically improved, sown swards generally consist of a limited range of plant species whereas longer-term leys and semi-natural grasslands are characterised by a more diverse mixture of plants. In the case of botanically diverse permanent pastures/grazing lands, the dietary preferences of different grazers have a more pronounced effect on the botanical composition of the sward in the longer term. Selection of a dominant species within the sward can give less abundant components a chance to compete, increasing community evenness and species richness. Conversely, the selection of minor components reduces sward compositional heterogeneity and hence plant species richness and evenness. Body size, gut type (foregut vs hindgut fermentation), physiological status (growing, pregnant, lactating), metabolic status (extent of body reserves) and environmental conditions all influence the nutrient requirements of a given animal and related foraging priorities. The diet selected is also strongly influenced by the availability of preferred food items, and their vertical and horizontal distribution within the sward. In general, larger animals, such as cattle and horses, are less selective grazers than smaller animals, such as sheep and goats. They are quicker to switch to consuming less-preferred sward components as the availability of preferred resources declines due to their greater forage demands, and as a result can be very effective in controlling competitive plant species consistently avoided by more selective grazers. As a result, low-intensity mixed grazing of cattle and sheep has been shown to improve the diversity and abundance of a range of taxa within grazed ecosystems. Mixed/co-species grazing with different animals exploiting different grassland resources is also associated with increased pasture use efficiency in terms of the use of different sward components and related improvements in nutritional value. In situations where cattle are not available, for example if they are not considered commercially viable, alternative species such as goats, ponies or South American camelids may offer an opportunity to diversify income streams and maintain productive and biodiverse pastures/grazing lands. Stocking rate and timing of grazing also have a considerable role in determining the impact of grazing. Regardless of the species grazing or the pasture grazed, grazing systems are dynamic since selective grazing impacts the future availability of sward components and subsequently dietary choices. New technologies under development provide opportunities to monitor plant/animal interactions more closely and in real time, which will in future support active management to deliver targeted biodiversity gains from specific sites.

Keywords: *Diet selection, Grassland, Grazing pressure, Habitat, Sward composition*

INTRODUCTION

Grasslands cover approximately 40% of the earth's surface (White et al., 2000), and this dominance as a land cover means that they have enormous potential to deliver environmental services in addition to the supply of livestock-based products (Millennium Ecosystem Assessment, 2005). Grasslands can be divided into three main categories, and when considering the role livestock farming can play in supporting biodiversity, it is necessary to consider the key characteristics of each of these. Temporary grasslands are land on which vegetation consists of forage species kept for a short period of time; generally only a few years (Allen et al., 2011). Such swards may form part of arable rotations or may be pastures that undergo frequent reseeding as part of more intensively managed livestock systems, and as such these grasslands are generally found on more fertile soils and under more benign climate conditions. In many cool, temperate regions, these are predominantly comprised of *Lolium* (ryegrass) spp., often in combination with *Trifolium* (clover) spp. The second category, permanent pastures, are longer-term swards that have undergone agricultural improvement and may include cultivated or naturalised forages. In many situations,

particularly in the uplands, it may be decades since they were re-seeded, and over time the plant species sown (usually mixtures consisting mainly of *Lolium perenne* (perennial ryegrass), with *Phleum pratense* (timothy), *Festuca rubra* (red fescue) and *Trifolium repens* (white clover) added to varying degrees) have since been replaced by unsown species such as *Agrostis* (bents) spp., *Poa* (meadow grass) spp., *Holcus lanatus* (Yorkshire fog), and *Nardus stricta* (mat grass) (Wilman et al., 1999). This process is exacerbated if fertiliser inputs are reduced or ceased (Yu et al., 2010), a highly pertinent issue considering the rising costs of inorganic fertiliser production and the link between its application and emissions of nitrous oxide (Cardenas et al., 2010). The third category, semi-natural rough grazings or rangelands, are managed ecosystems dominated by indigenous or naturally occurring grasses (Allen et al., 2011) that have been shaped by human intervention, principally through the grazing regimes imposed. In the United Kingdom (UK), semi-natural grasslands are more generally found in hill and upland areas rendered marginal by climatic, edaphic, topographic and socio-economic challenges, and many of the associated vegetation communities are habitats recognised as having international importance from a nature and landscape conservation perspective (Thompson et al., 1995). Thus, when comparing the three pasture types, productive efficiency generally decreases along a continuum from improved to semi-natural grasslands, but there is a simultaneous increase in the delivery of public goods such as biodiversity, water retention and purification, and carbon storage (Fig. 1).

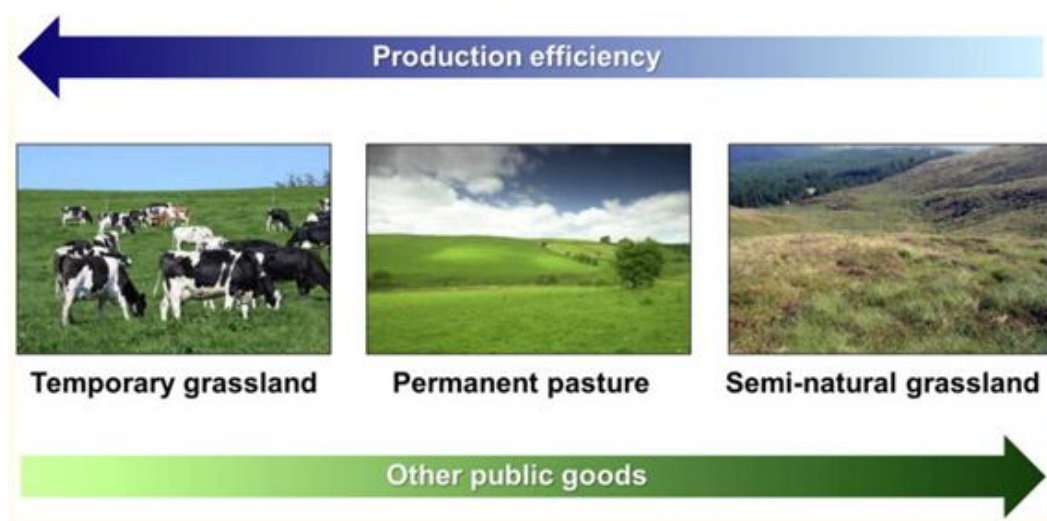


Fig. 1. Schematic representation of the opposite gradients of delivery of private and public goods across the three main grassland types (photos: M.D. Fraser, J.M. Moorby)

Within grazed agroecosystems, livestock primarily influence biodiversity through their impact on sward structure and floristic composition since this in turn impacts the habitat value of the grassland for other taxa including invertebrates, birds, reptiles, and small mammals. For the most part, within a grazing system, key plant/animal interactions in terms of biomass removal, patterns of nutrient retention and loss, and the dynamic relationship between availability of preferred food items and the diet selected are similar regardless of the type of grassland being grazed or grazer (Fig. 2). Factors such as body size, gut type (foregut vs hindgut fermenter), physiological status (growing, pregnant, lactating), metabolic status (extent of body stores), and environmental conditions all have a fundamental role in determining the nutritional requirements of a given animal and related dietary preferences (Mellado et al.,

2005, Christianson and Creel, 2007, Allegretti et al., 2012). The botanical composition, structure, and chemical composition of the sward (Pauler et al., 2020b), together with the vertical and horizontal distribution within this of preferred food items (Wallis de Vries and Daleboudt, 1994, Wang et al., 2010), also strongly influence the choices made. The nutrient supply from the biomass that has been selected and consumed by the animal will influence subsequent performance in terms of growth, fertility and meat and milk production, as well as the volumes and concentrations of excreta plus enteric gaseous emissions (Fraser et al., 2014a; Wilson et al., 2020). The selective removal of biomass through grazing then changes both the botanical and chemical composition of the pasture, in turn altering future choices made by the animal. These processes are further influenced by seasonality of plant growth and the grazing pressure imposed via stocking rates. This review will concentrate on these plant/animal interactions and related implications for biodiversity. It will focus on four key factors: (1) what is grazed, (2) which livestock species/breeds are grazing, (3) the timing of grazing, and (4) grazing pressure, before going on to consider (5) the value of integrated grassland systems.

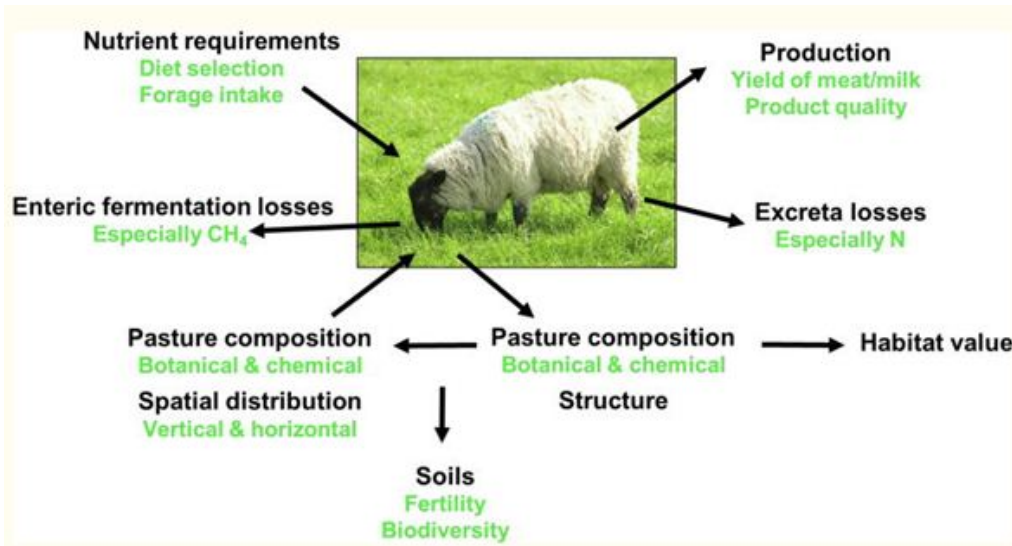


Fig. 2. Summary of the main plant/animal interactions within a grassland system (photo: M.D. Fraser)

What is being grazed

Even within botanically simple grass swards, grazing rather than cutting can increase structural diversity (Rook et al., 2004; Tonn et al., 2019). Habitats that are more structurally complex have been found to host a greater variety of invertebrates, and attract a greater species richness, abundance and distribution of insectivorous and granivorous birds, small mammals and bats in comparison to uniformly structured habitats. It has been suggested that this is because spatially heterogeneous habitats offer a greater variety of microhabitats to support more species (Morris, 2000). More marked improvements in biodiversity (and productivity) can be brought about by increasing the number and diversity of plant species within pastures. Forage legumes such as *Trifolium* spp, *Medicago sativa* and *Lotus* spp. provide nectar and pollen sources for pollinators and seed-dispersing insects as well as a sustainable source of feed protein, in addition to reducing the need for external nitrogen inputs through their association with nitrogen-fixing bacteria (Thomas, 1992; Louarn et al., 2016). Crucially, both livestock performance and nutrient use efficiency can also be substantially

improved by incorporating forage legumes into ruminant diets (Peyraud et al., 2009; Luscher et al., 2014; Phelan et al., 2015; Delaby et al., 2016). Furthermore, including legumes within swards leads to a greater variety of roots and associated benefits in terms of soil structure, in turn leading to greater below-ground biodiversity (Marshall et al., 2016; Lehmann et al., 2020). Mixed swards also offer opportunities for selective grazing, and more selective livestock species, such as sheep, preferentially consume clovers (Rutter, 2010). This frequently leads to these becoming uncompetitive against neighbouring grasses and, over time, being lost from swards. Understanding these sward dynamics together with developing and testing new varieties of forage legumes more resilient to grazing is essential to developing seed mixtures and management protocols that deliver persistent mixed-species pastures (Norman et al., 2020).

More recently, there has been growing research and agricultural industry interest in multispecies swards, and the potential that these offer for simultaneous delivery of environmental gains along with improved livestock performance (Huyghe et al., 2012; Grace et al., 2019; McCarthy et al., 2020; Cummins et al., 2021). More complex grasslands, such as these and semi-natural grasslands, allow greater opportunities for selective feeding, and the choices made by grazing animals can have a marked effect on floristic diversity. If a dominant plant species is preferentially grazed, this can allow minor sward components to successfully compete, increasing their overall contribution to the sward (Fig. 3). Higher plant community evenness stimulates the associated biodiversity by offering a more consistent supply of a wider range of food sources for invertebrates and small mammals, which in turn support wider above- and below-ground food webs (Wardle et al., 2004; Evans et al., 2015; Brunbjerg et al., 2018; van Eekeren et al., 2022) (Fig. 4). Conversely, if minor sward components are selectively grazed, this will further reduce their competitive ability and may result in their loss from the sward (Fig. 3). The impact that grazing has in such situations is frequently determined by the grazing livestock species and type (breed, physiological state), as well as the growth characteristics of the plant species.

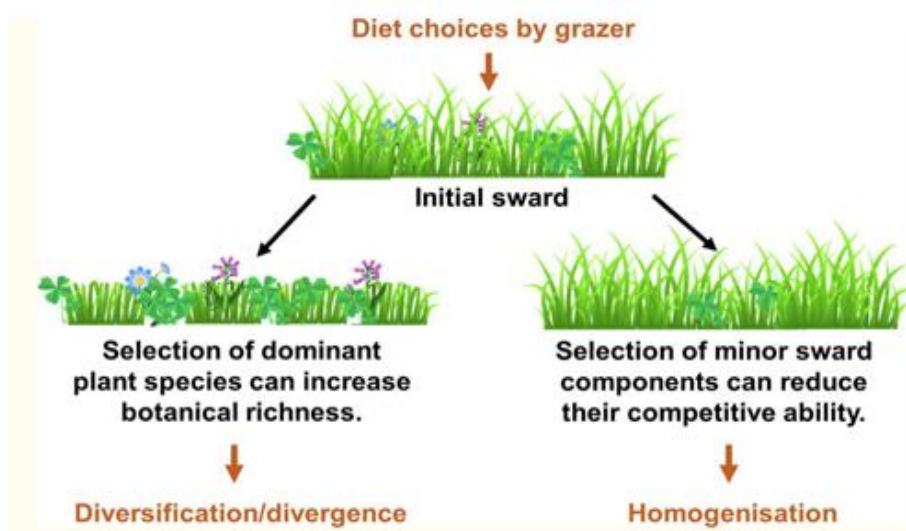


Fig. 3. Impact of preferential selection by grazers of dominant or minor sward components on plant community composition, structure, and plant species richness

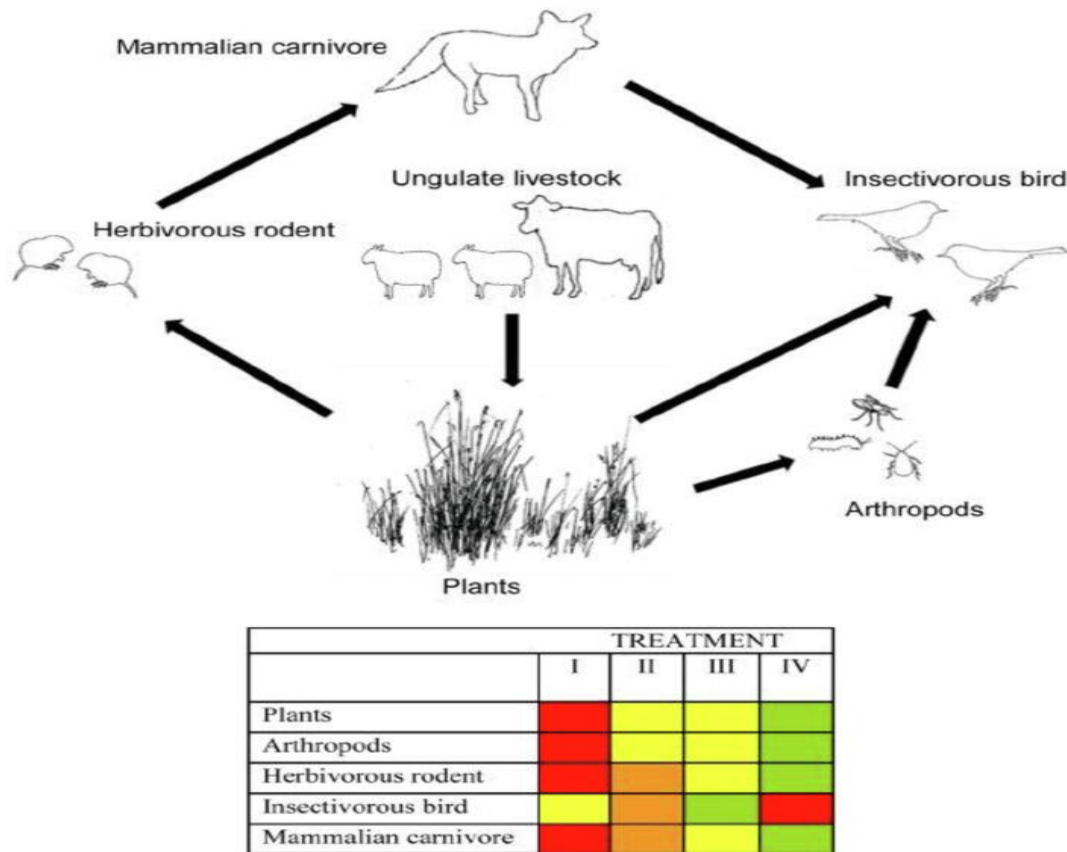


Fig. 4. Diagrammatic representation of impacts of grazing management on an upland ecosystem (reproduced from Evans et al., 2015). Measurements were made of the response in vegetation biomass, arthropod abundance, the number of *Anthus pratensis* (meadow pipit) breeding territories, *Microtus agrestis* (short-tailed field vole) density and *Vulpes vulpes* (red fox) activity of different grazing regimes: Treatment I = 2.72 ewes ha⁻¹, Treatment II = 0.91 ewes ha⁻¹, Treatment III = mixed sheep and cattle equivalent to 0.91 ewes ha⁻¹, and Treatment IV = ungrazed. For each trophic level, the effects of treatment were ranked from red (highest) to green (lowest)

Dietary preferences of grazers are strongly influenced by the nutritional value of individual food items, particularly in terms of energy and protein provision, plus the presence of any defensive measures that plants may have developed against herbivores. Mechanical defences include thorns, spines, waxy cuticles, or trichomes; sharp hair-like structures on the surface of plants that in some species can dispense chemical irritants. Chemical defences are synthesised by the plant in addition to primary chemical components such as lipids, proteins, and carbohydrates, and are not directly involved in plant metabolic processes associated with growth and reproduction. This group of secondary compounds includes alkaloids, tannins, essential oils, organic acids and glucosides (Mithofer and Boland, 2012). The concentration and chemical structure within the plant largely determine if these secondary components have beneficial or adverse effects on the grazing animal. For example, condensed tannins in low to moderate concentrations can have anthelmintic properties and slow protein degradation throughout the digestive system to allow more effective use of proteins by the animal (Piluzza et al., 2014). However, consumption of forages and plants that contain high levels of tannins,

including common dwarf-shrubs such as *Calluna* spp., *Vaccinium* spp. and *Erica* spp., can be associated with detrimental health affects in ruminants. In such situations, the tannins can disrupt the function of digestive enzymes, decreasing protein digestibility and voluntary intake (Lamy et al., 2011).

Which animals are grazing

All grazing animals are selective feeders, and this selectivity can be thought of as occurring at various hierarchical levels. Firstly, within a feeding bout, an animal may be able to choose which plant community to feed on; e.g., grassland in preference to heathland. Secondly, within a particular plant community, grazers usually select certain plant functional types and species over others; e.g., clover in preference to grass (Rutter, 2010). Thirdly, they may be able to select particular morphological units from the preferred plant species; e.g., green leaf in preference to stem (Grant et al., 1985). The scope for diet selection depends on the heterogeneity of the vegetation the animal is feeding from plus the spatial distribution of different plant components. While simple, temporary pastures may offer comparatively little opportunity for selective feeding, more diverse grasslands may be composed of a mosaic of different vegetation types and/or patches of contrasting plant species. Differences in the chemical composition of plant species, together with their horizontal and vertical distribution, lead to trade-offs between the energetic cost of searching for preferred food items and the improvement to diet quality achieved when they are consumed (Roguet et al., 1998; Searle et al., 2005; Huang et al., 2018; Koczura et al., 2019). Biomass extraction through ingestion to provide nutrient gain for the animal removes material from pools of photosynthetic mass, in turn altering the subsequent growth form of individual plants as well as the species balance within vegetation communities (McNaughton, 1984; Mouissie et al., 2008). Thus, through consistent plant selection, the animal may alter the composition of the sward or community (Fig. 3).

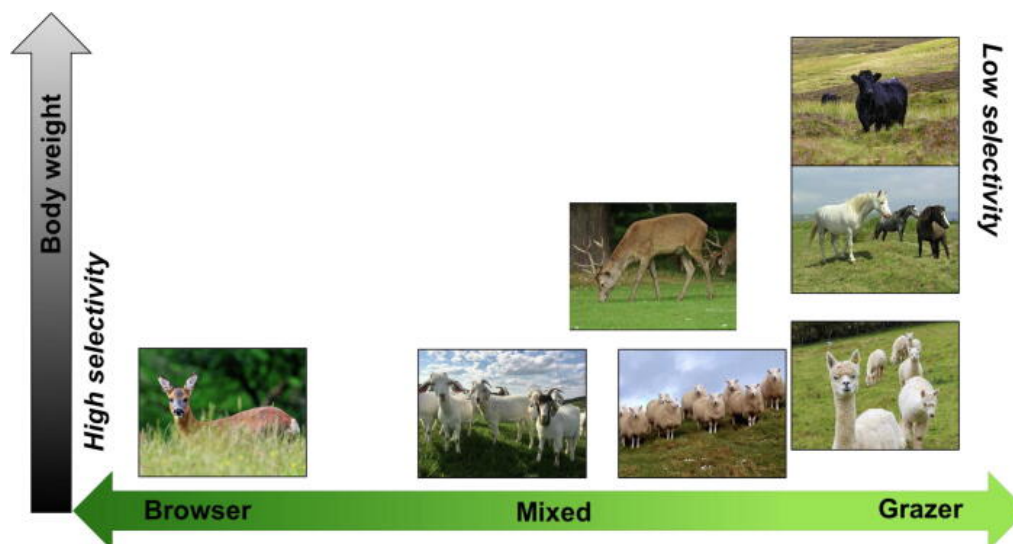


Fig. 5. Classification of different types of large herbivore based on their feeding preferences (source: Hofmann, 1989). Smaller animals are generally more selective feeders (photos: M.D. Fraser, J.M. Moorby)

Previous studies have highlighted that intensely grazing a sward with a single herbivore species has a negative effect on the biodiversity and composition of grasslands (Marriott et al., 2004; Evans et al., 2006). Different species of grazing animals are known to exhibit different

foraging strategies, which impact related diets. Over the years, there have been various attempts to classify the food choices of different grazers based on anatomical and functional differences. A common approach is illustrated in Fig. 5, which summarises the feeding strategies associated with large herbivores commonly found in the UK. It is based on three classifications of herbivores as defined by Hofmann (1989) that cover both ruminant and non-ruminant herbivores: browsers (concentrate feeders), grazers, and mixed or intermediate feeders. These classifications can be thought of as partially overlapping, and, as indicated previously, the associated preferences are further influenced by factors such as sward heterogeneity and the nutritional requirement of the individual, plus environmental challenges and learned or inherited behaviours (Shipley, 1999; Barros and Fernandes, 2013).

A key factor influencing herbivore feeding behaviour and dietary requirements is overall body size, as this determines the time and energy constraints associated with acquiring and consuming food. Larger animals require a greater total quantity of nutrients per day, but have less time per unit of nutrient to spend foraging than smaller animals with a lower overall requirement (Demment and Van Soest, 1985), and generally prioritise maintaining the quantity rather than the quality of feed consumed. Thus, larger animals are generally less selective than smaller ones. Body size and related digestive capacity are also strongly correlated with turnover and retention time of forage in the digestive tract, which are further influenced by gut type. All herbivores break down cellulose with the aid of microbial symbionts, and grazers have evolved complex and specialised digestive systems that enable them to process, ferment and obtain nutrients from highly (ligno-)cellulose-rich forage. For ruminants (such as cattle and sheep), fermentation occurs within a complex multi-chambered stomach, whereas hindgut fermenters (such as horses and ponies) rely on more rapid nutrient extraction via fermentation within the caecum and colon. Hindgut fermenters can process food faster and have higher nutrient extraction rates than foregut fermenters (Duncan et al., 1990; Santos et al., 2011). This faster throughput is an advantage that outweighs their lower digestive efficiency, particularly on poor-quality forages, allowing them to ingest large amounts of fibre-rich forage. South American camelids are classified as pseudo-ruminants as they have a three-chambered forestomach rather than the four-chambered forestomach associated with true ruminants. While all these gut types rely on symbiotic gastrointestinal microbiota to help digest parts of the forage consumed, and while it is known that the complex communities of bacteria, fungi, archaea and protozoa found within both foregut and hindgut fermenters are altered by changes in diet (Huws et al., 2018), we currently have little understanding of the role such communities, and related metabolic cues, might play in shaping dietary choices.

Due to their large body size and thus greater herbage requirement, cattle are less selective grazers than sheep (Fig. 5), and this makes them very effective in controlling highly competitive plant species (Grant et al., 1996; Critchley et al., 2008). In areas throughout the UK, overgrazing of upland communities by sheep led to grasses such as *Molinia caerulea* (purple moorgrass) and *N. stricta* that were rejected by livestock out-competing other plant species, leading to substantial reductions in floristic diversity and habitat loss. While cattle will also avoid grazing these grasses where possible, their greater overall daily nutrient requirement means that they are forced to switch to consuming them more quickly than sheep when the availability of preferred items declines. However, despite the biodiversity gains associated with cattle grazing (Cutter et al., 2022), numbers in the uplands have declined, in part due to related labour, infrastructure and disease testing requirements. In such situations, grazing by ponies (Fraser et al., 2019), goats or South American camelids (Fraser

and Gordon, 1997) may offer a more flexible alternative to cattle grazing, and could be supported under future land management schemes that adopt an outcome-driven approach to supporting delivery of public goods rather than primary production. Furthermore, when grazing simpler, improved pastures, less selective grazers such as cattle, goats and South American camelids do not exhibit the same degree of preference for *Trifolium* spp. as sheep but will instead consume mature, stemmy vegetation rejected by sheep. The mixed grazing of cattle and sheep has been shown to lead to improved productivity through greater pasture use efficiency (Wright et al., 2006; Fraser et al., 2013, Jerrentrup et al., 2020), and it is possible that co-species grazing of sheep with other livestock could bring about similar benefits (Del Pozo et al., 1996). Thus, multispecies grazing to deliver biodiversity gains should also facilitate improved production efficiency and lower greenhouse gas emissions. It is important to note, however, that in such situations, it is the combination of complementary grazing animal types (large/less selective, and small/selective) that can lead to simultaneous biodiversity and productivity gains.

As well as choosing the livestock species, farmers and land managers make choices as to the breed types used, and there is a tendency for traditional breeds to be associated with conservation grazing to restore or maintain specific habitats. However, while traditional breeds of cattle may provide aesthetic and cultural value, there is currently little scientific evidence that they deliver additional grazing benefits for biodiversity. Comparative studies have generally found no differences in the diet composition or preferences of different cattle breeds grazing the same pasture (Becerra et al., 1998; Dumont et al., 2007; Fraser et al., 2009b; Fraser et al., 2013), although activity patterns and preferred grazing locations may differ where plant types and communities vary across the enclosure (Saether et al., 2006, Pauler et al., 2020a). At the same time, production efficiencies may be higher, and thus methane emission intensities lower, for breed types physiologically and/or behaviourally adapted to more challenging conditions (Fraser et al., 2014a). The impact of cold, wet weather is reduced for animals with thicker coats and for those that make more effective use of shelter, and this in turn leads to a greater conversion of nutrients into product. There is currently much less information available regarding the dietary preferences of different breed types of sheep. However, since significant differences have been recorded in the diet selected by two common British breeds grazing botanically mixed hill pasture (Fraser et al., 2009b) and two common Norwegian sheep breeds grazing mountain pasture (Steinheim et al., 2005), this is an area that warrants further research to identify opportunities for biodiversity gain through the choice of breed. Likewise, there is comparatively little information available regarding between- and within-animal variation in dietary preferences of different animals within a herd or flock, again limiting opportunities to capitalise on these.

One reason that data on diet composition in free-ranging grazing livestock are comparatively limited is that methodologies for determining this, such as visual observation, faecal cuticle analysis (Cuartas et al., 2000) and n-alkane analysis (Ali et al., 2004), have been comparatively limited in their accuracy and/or are costly in terms of time and money. More recently, high-throughput next-generation sequencing technologies have emerged as a means of determining diet composition (Pompanon et al., 2012), and DNA meta-barcoding offers considerable potential as a non-invasive rapid molecular technique to determine diet composition of both wild and domesticated herbivores (Garnick et al., 2018, Palumbo et al., 2021). However, this analytical approach still has limitations due to biological factors and technical issues that have the potential to influence the end sequencing results and resolution

of taxonomic identification (Lamb et al., 2019). Another crucial factor, and frequent limitation, is the availability of an appropriate botanical reference library. To achieve both qualitative and quantitative diet information with a high taxonomic resolution, the available plant species need to be accurately collated in reference barcode libraries (Garnick et al., 2018, Moorhouse-Gann et al., 2018). At the same time, the speed of development in sequencing technologies is rapid, and metagenomic (shotgun) sequencing of faecal samples offers the opportunity to simultaneously gather information on diet composition together with related factors such as parasite infestation and the gastrointestinal microbiome (Srivathsan et al., 2015, Alberdi et al., 2019). As sequencing costs drop, it will become more cost effective to collect data on the diets consumed by more animals in more situations, which will greatly improve our ability to manage livestock to achieve prescribed biodiversity targets.

While selective grazing is the main means by which livestock can be used to influence biodiversity, their pure presence can also have a substantial impact. Trampling by large animals such as cattle can help to open up dense swards and create disturbance that enables new plant species to emerge from the seedbank (Mitchell et al., 2008). Seeds may also be spread by attachment to animal coats or by passing through their gastrointestinal tracts if consumed (Hogan and Phillips, 2011).

Timing of grazing

Since dietary preferences are strongly influenced by the availability of preferred items, seasonal differences in growth patterns of vegetation resources are an important factor when considering the impact of grazing (Spitzer et al., 2020). The nutritional value of individual plant species changes over time due to phenological differences between species, plus the growth curves and thus seasonal biomass of different species may be different. Preferred food items are depleted over the grazing season as a consequence of selective foraging and feeding. Collectively, these factors can result in a marked difference between seasons in the diets consumed. This is illustrated in Fig. 6, which summarises the response of three different species of grazers (goats, red deer and guanacos; a species of South American camelid) to the seasonal decline in the availability and quality of grass species when grazing heather moorland (Fraser and Gordon, 1997). All three species had a clear preference for grass during early summer when this was actively growing, as evidenced by the proportions in the diets relative to that in the pasture. However, in September, when grass availability was much lower, the response of the different grazers to the changes in availability varied considerably. The red deer greatly increased their consumption of *Calluna vulgaris* (ling heather), a plant species high in condensed tannins, preferentially consuming flowers and new growth from the current growing season. In contrast, the guanacos continued to search out graminoid species. Thus, in a situation where the biodiversity goal is heather recovery, grazing by guanacos would be advantageous because they focus on plant species that are potentially in competition with the target species. Similar seasonal shifts in diet composition have been reported for sheep and cattle grazing heathland (Grant et al., 1987), and it was noted that when cattle shifted to consumption of *C. vulgaris* that their less selective feeding habits meant they caused more damage to woody stems. As a result, while cattle grazing may be beneficial in controlling *M. caerulea* on hill ground, careful consideration should be given to how the animals will respond to this senescing in August/September, and whether late-season grazing will result in damage to plant species that prescriptions are aiming to encourage as part of nature conservation goals.

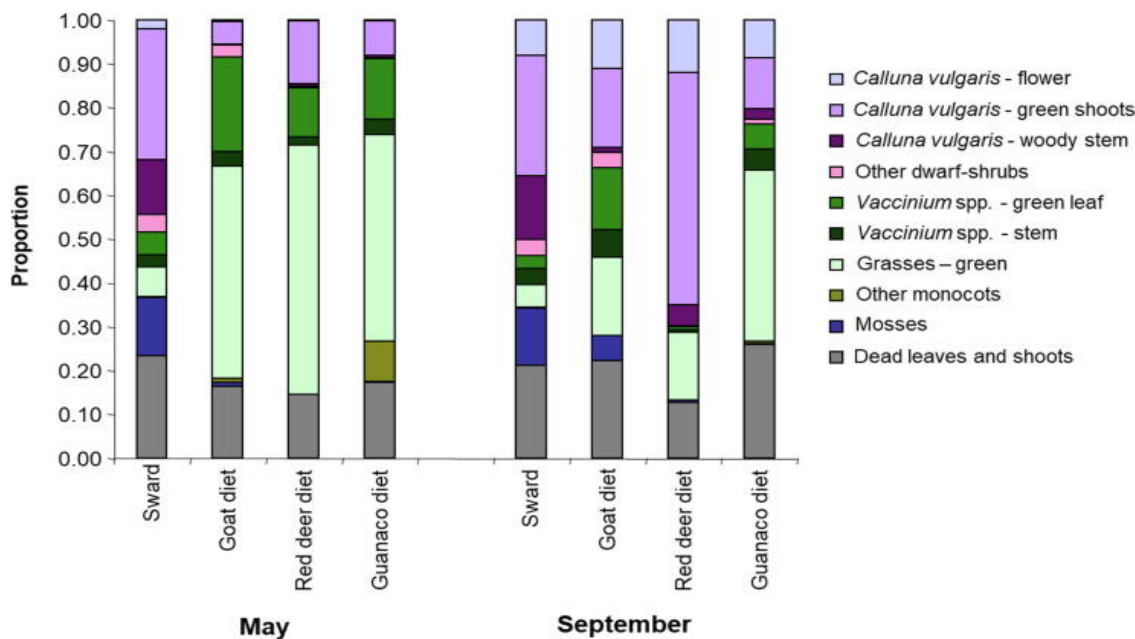


Fig. 6. Seasonal changes in the diet composition of goats, red deer and guanacos when grazing the same area of heathland (source: Fraser and Gordon, 1997). The ‘grasses’ category included the species *Agrostis canina* (velvet bent), *Deschampsia flexuosa* (wavy hair grass), and *Festuca ovina* (sheep’s fescue). The other monocot’ category included *Eriophorum angustifolium* (common cottongrass), *Juncus* (rush) spp., and *Luzula* (woodrush) spp., and the ‘other heaths’ category included *Empetrum nigrum* (crowberry) and *Erica* (bell heather) spp.

Delaying defoliation of grassland can be another very effective way of increasing floristic diversity. In an on-going long-term experiment imposing alternative management regimes on permanent pasture, hay cutting has been found to lead to a marked increase in floristic diversity compared to grazing (Pavlu et al., 2021). The most effective treatment, however, has been hay cutting followed by aftermath grazing, which not only gives an opportunity for forb species to set seed but incorporates subsequent ground disturbance that creates establishment sites for seedlings. The changes in sward botanical composition and increased availability of plant species attractive to pollinators have been shown to lead to corresponding increases in the abundance and species diversity of invertebrates (Garcia and Fraser, 2019). While the treatments within this study that have been associated with biodiversity gain involve the pasture being mechanically cut, it is the delay in defoliation, rather than the method of defoliation, which has the greatest impact. Deferring grazing of formerly improved pasture until late summer has also been observed as leading to a substantial increase in the proportion of forb species, including *Trifolium* spp., *Campanula rotundifolia* and *Leucanthemum vulgare* within the sward (M.D. Fraser, *pers. obs.*). Likewise, biodiversity benefits have been linked to periodic grazing via rotational (Ravetto Enri et al., 2017) and cell (Richards and Lawrence, 2009) grazing management systems, particularly where such systems specifically incorporate paddocks set aside for conservation purposes (Farruggia et al., 2012). Intermittent grazing not only gives slower-growing and preferentially grazed plants an opportunity to compete within the sward, it also promotes structural heterogeneity within a site, in turn benefitting invertebrates (Morris, 2000).

Grazing pressure

While mechanical cutting removes vegetation to a standard height, selective feeding by grazing animals results in differential defoliation, which can in turn alter sward composition.

Well-managed low stocking rates of grazers can help to maintain species-rich habitats by controlling competitive dominant plant species (Gornish et al., 2018), whilst over-exploitation of grazing resources causes instability and a decrease in plant diversity (Olf and Ritchie, 1998), in turn reducing the diversity of food sources available for insects, birds and small mammals. In the UK, overgrazing encouraged by headage-based subsidy payments that paid farmers for the number of sheep or cattle kept resulted in dramatic declines in habitats of international conservation significance (Thompson et al., 1995). This was a particular issue under sheep-only systems given the ability of this species to selectively graze certain plants. Subsequent changes to the Common Agricultural Policy and the decoupling of support from production have reduced grazing pressures in these areas but have not necessarily reversed the habitat decline. Instead, agricultural abandonment of grasslands and heathlands across the European Union has been identified as a specific threat to related habitats and species (Keenleyside and Tucker, 2010; Hermoso et al., 2018), particularly in more marginal areas. Left unmanaged, many of these vegetation communities have become dominated by plant species rejected by stock (e.g. *Deschampsia cespitosa* (tufted hair grass), *M. caerulea*, *Juncus* (rush) spp., *Pteridium* (bracken) spp, *Ulex* (gorse) spp.). Consequently, government agencies and conservation charities are resorting to the mechanical cutting of vegetation (Talle et al., 2018, Valasiuk et al., 2018), as a substitute for grazing, to ensure the long-term survival of Europe's most valuable and threatened habitats and species. This is however costly, does not create the same degree of structural heterogeneity as grazing, and over time leads to nutrient depletion. A build-up of dead, undergrazed vegetation also poses an increasing fire risk (Lasanta et al., 2018; Gonzalez-Hernandez et al., 2020).

The biodiversity benefits of mixed low-intensity grazing systems in such situations have been well documented (Critchley et al., 2008; Fraser et al., 2014b; Evans et al., 2015; Lopez et al., 2017) (Fig. 4), but as indicated previously, hill and upland areas tend to be managed predominately as sheep-only systems. Grazing prescriptions within agri-environment schemes aimed at restoring biodiversity generally specify the species of animal, the number of animals, the duration of grazing, and the season. For the most part, they and the livestock unit (LU) system used to calculate grazing pressure take no account of breed type or the physiological and environmental factors that can influence an individual animal's requirements. Likewise, there is no monitoring of resource availability or utilisation of target plant species. Furthermore, the use of LUs assume uniformity in grazing across a given area, with no allowance made for uneven grazing pressure due to dietary preferences, whereas in reality, on a given site, some areas will be overgrazed and others undergrazed. While this may be beneficial for biodiversity by promoting heterogeneity in sward height and composition in some situations, in others, more floristic diverse patches may be selected by grazing animals at the same time as avoiding less favoured plant species (such as *M. caerulea* or *Pteridium aquilinum*), thereby increasing their promoting their spread and dominance of the swards. Whilst this may not necessarily be a detriment to biodiversity, the issue is that the grazing selection process is often uncontrolled and poorly understood for a given site.

Monitoring animal movements allows farmers and land managers to understand localised grazing pressure more dynamically than simply waiting for changes in sward composition to become apparent. Monitoring of the foraging patterns will predict whether current strategies will have the desired effect on plant community structure, and whether the grazing regime

must be adapted to prevent damage to the pastureland or to improve it. Aside from biodiversity considerations, monitoring animal movements can also offer insight and benefits for animal production and animal health. However, until recently, tracking livestock as part of regular management has been unfeasible. Although commercial global navigation satellite system (GNSS; colloquially GPS) collars, and radio frequency tags for individual animal tracking have been available in the last few decades, their price has restricted their usage primarily to research and species conservation. Their potential as monitoring devices for land managers and farmers for use on livestock is largely unrealised, particularly when the unit price of the tracking equipment (up to about £1 500/€1 700 depending on specifications) often exceeds that of the subject animal several fold. For this reason, observation has remained the only realistic solution until recently, although new developments in open-source GPS loggers (Allan et al., 2013, Cain and Cross, 2018, Foley and Sillero-Zubiri, 2020, McGranahan et al., 2018) have gone some way to addressing this issue. Detailed information on their construction is available, and with low hardware costs reported, these loggers present an attractive avenue for application by farmers.

Other options for recording animal movements have emerged in the last few years. Unmanned aerial vehicles (UAVs; drones) have facilitated the emergence of aerial-based approaches to studying animal movements. The concept of low-cost UAV-based radio tracking has been proven on livestock (Roberts et al., 2020), as has the use of aerial imagery to detect animals (Sarwar et al., 2021; Sant'Ana et al., 2022). Aside from tracking applications, the more conventional use of UAV-derived imagery in vegetation analysis has recently progressed from simple broad habitat classifications, to using high-resolution imagery for the identification of specific plant species (Lu and He, 2017; Gallmann et al., 2022). Such analyses may enable an individual plant species to be monitored over time and thus allow the effect of grazing to be observed with finer granularity for a target sward component. New methodologies also enable the measurement of sward height across a whole site, with both UAV-derived light detection and ranging (LIDAR) and photogrammetric approaches having shown promise in this regard (Forsmo et al., 2018; Jansen et al., 2019; Madsen et al., 2020).

Another aspect where new developments may help understand plant/animal interactions is through detailed monitoring of environmental conditions affecting plant growth and animal behaviour. Microclimatic variations in temperature and air humidity are observable in many plant species swards of different heights and densities. Given that the phenological events of many taxa are heavily dictated by local conditions, altering the sward (either through grazing or cutting) can have an impact (both positive and negative) on different organisms. These effects are particularly well studied for invertebrate populations, where changes in oviposition site availability, nymph development, and adult activity have all been observed (Gardiner and Hassall, 2009; Zhu et al., 2020; Perrin et al., 2021). *In situ* climatic sensors for soil and air can provide the necessary data to measure microclimatic differences within a changing sward, whilst satellite and UAV-derived outputs can offer detailed information on site topology (e.g. slope, aspect), as well as various indices which can be correlated with aspects such as vegetation greenness, plant health and in some cases hydrology. Furthermore, *in situ* sensors are often also able to provide the validation data for remotely sensed outputs, which almost always require ground-truthing, and are particularly useful where repeat samplings are required and thus labour costs/time are high. More generally, combining these observations (remotely and *in situ* sensed outputs) can help provide a more complete interpretation of the plant-animal dynamics on a given site (Fig. 7). A study undertaken by Roberts (2020) used

GPS loggers and UAV-derived imagery to measure different variables hypothesised to affect animal distribution (e.g. water availability, nutrition, and environmental stress). These were then modelled against known positions of animals to assess the animals' response to the different variables and rank their relative impacts on animal distribution. The work aimed to demonstrate how the local environment could be manipulated to alter animal distribution in a way that better suits conservation objectives, e.g. diverting animals away from sensitive vegetation patches and on to undergrazed areas that require management. Whilst the use of temporary fencing may be an effective way of managing grazing pressures within smaller enclosures, on extensive grazing land, such as rangelands, targeting grazing to particular locations can be difficult. In such situations, positive reinforcement through the provision of nutrients (e.g. as feed blocks), water or shelter can be used to optimise localised stocking densities. An alternative to encouraging use of certain resources through environmental enhancements is manipulation of behaviour through negative reinforcement, as used by virtual fencing systems. This approach involves the use of GPS collars that emit an electrical impulse (colloquially shock) to deter animals from moving out of a predetermined area. Modern designs generally incorporate a warning audio cue that will trigger when animals approach the perimeter of an area (Marini et al., 2018; Verdon et al., 2021; Aaser et al., 2022). This is intended to reduce the number of electrical impulses an animal will receive, given that they will learn to respond to the audible signal alone. However, the effectiveness of such systems is still in question, particularly where the positioning signal to the collars may be reduced by obstacles such as trees. There is also an on-going ethical debate about such systems, whereas positive manipulation of animal behaviour through the provision of additional resources would be expected to raise fewer welfare concerns. This considers the underlying reasons as to why an animal chooses to exploit an area, and therefore accommodates nutritional or environmental needs (e.g. shelter) instead of imposing physical restrictions.

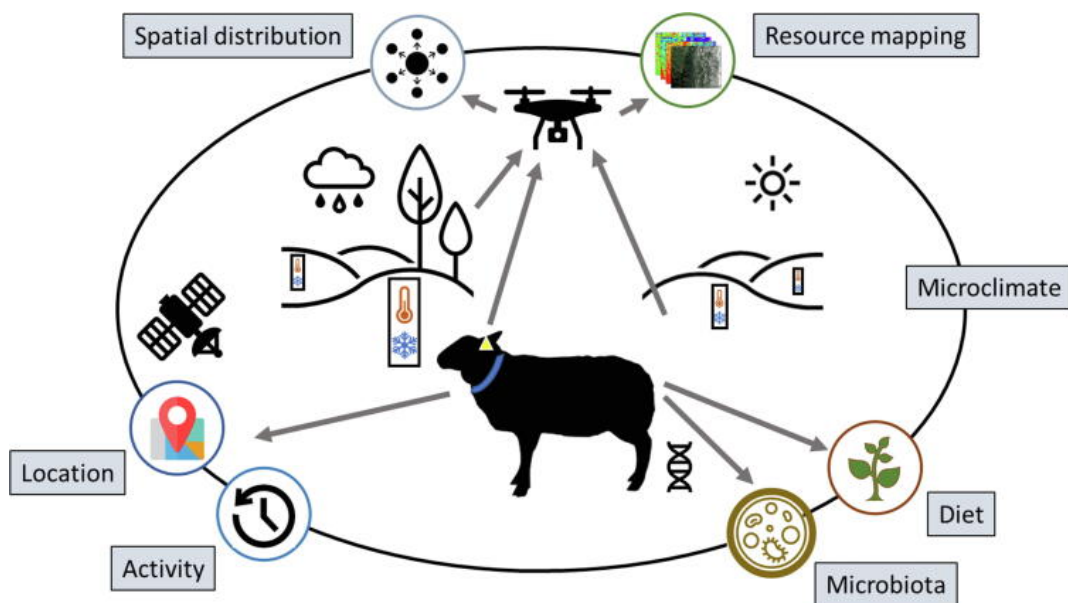


Fig. 7. Diagram summarising ways in which new technological developments could be used to improve our understanding of plant/animal interactions within a grazing system

While various technology-driven approaches have considerable potential to refine grazing management regimes to deliver biodiversity gains more effectively, a major challenge remains

the recording and transfer of data to users for analysis. The use of *in situ* logging has until recently been the only practical approach, however, it requires animals to be regularly handled for data collection and thus limits the ability to dynamically alter grazing strategies, particularly on extensive sites. Although satellite or cellular communications are common approaches for regular collection of data, their use in precision livestock farming to date has been restricted by the additional power requirements, and the cost of subscriptions for data transfer. Recent efforts have been focused on using low-power wide area networks such as LoRa and Sigfox, which are intended to integrate into established Internet of Things (IoT) platforms. A final consideration is the ownership of data produced and more widely the authority to which it can be used (Bahlo et al., 2019). Currently, there are few legal frameworks that establish data ownership in agricultural IoT uses, and as such regulatory changes will be required in order to establish fair collaboration between farmers and technology providers over usage. This will be essential for preventing disputes and will help foster a balanced and unbiased agricultural data market in the long term (Tekin et al., 2021). These considerations aside, the increasing accessibility of user-friendly telemetry solutions for sensing means greater opportunities for practitioners to alter livestock grazing management in response to dynamic changes in pasture and weather conditions.

Integrated systems

Although this paper has focussed on grassland and grazing, most livestock holdings in temperate regions also carry out some form of forage conservation to supply fodder to animals in colder months when plant growth is poor, and/or during periods of drought. As highlighted previously, delaying the date of harvest to allow plant species to mature and set seed is an important consideration when encouraging or maintaining more floristically diverse grasslands, and in the UK, large losses of species-rich hay meadows have been linked to a shift away from hay-making to silage production (Vickery et al., 2001; Jefferson, 2005). Silage preserves the grass at a younger, more nutritious, growth stage and is less reliant upon an extended period of good weather for quality forage to be made, making it a lower-risk option for farmers. However, the drier summers predicted under climate change could result in hay-making being a more viable option. In situations where multiple cuts of silage are common practice, management changes can be made that support wildlife by, for example, leaving patches of seed-setting ryegrass as an additional source of feed (Buckingham and Peach, 2006). Similarly, growing an area of cereals as a source of home-grown energy, whether as grain or whole-crop silage, offers an additional food source for birds and small mammals.

In practice, most livestock farms consist of a combination of grassland types, particularly those in more marginal growing areas. While semi-natural grassland and heathland communities have considerable habitat value when in favourable condition, their nutritional value is lower than that of improved pastures (Fraser et al., 2009a; Fraser et al., 2013). This can result in farmers avoiding using such communities if better quality pasture is available elsewhere on the holding, with the corresponding undergrazing further reducing the vegetation's nutritional value through a build-up in senesced biomass. However, targeting grazing to take advantage of new spring and summer growth of native grasslands can help mitigate the problem of poor forage quality, and while management regimes are imposed on the rough grazing to promote biodiversity, better quality grassland is freed up for finishing stock and forage conservation. In addition, any production losses sustained on poorer pasture may be made up through compensatory growth when stock return to better grazing (Fraser et

al., 2013). At the same time, a mosaic of different pasture types sustains landscape diversity. Although semi-natural grasslands have been shown to support a greater number and diversity of birds and butterflies (common indicator species), there are species that prefer improved pasture (Fraser et al., 2014b), including flocks of winter migrants such as fieldfare (*Turdus pilaris*) and common starling (*Sturnus vulgaris*). Thus, no single grassland type delivers the best habitat for all wildlife, and a mosaic of grassland types is optimal.

While this paper has focussed on grazing lands, another route to improving biodiversity on livestock holdings is to incorporate hedges and woodland, preferably made up of broadleaved tree species. Offering a completely different habitat type in this way supports a much wider range of species within different taxa (Tscharntke et al., 2021). Hedging and woodland also provide opportunities for carbon sequestration (Drexler et al., 2021), as well as crucial shelter and shade for livestock as drought and extreme rainfall events become more common. While the direct integration of trees with grazing in silvopastoral systems offers many ecosystem benefits, there are trade-offs to be considered and new approaches to grassland management may be required (Schmiedgen et al., 2021).

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