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Improving biodiversity in agricultural grassland systems

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1 Introduction

Agricultural grasslands include some of the most biodiverse habitats in the world, but also some of the most species-poor and inhospitable environments to non-farmland species. In attempts to make grassland-based agricultural production more sustainable, one must ensure that the biodiversity of grasslands and the multiple ecosystem services supported by above- and below-ground biodiversity are maintained or reinstated. In their global review, Zhao (2023) identified biodiversity conservation and restoration as among the emerging research challenges in the domain of sustainable grassland management, with a steadily growing curve of scientific contributions. In many parts of the world, natural grasslands are the ecosystems most extensively transformed by human activities, mostly for food and biofuel production (Carbutt, Henwood and Gilfedder, 2017 for temperate grassland biomes). Grasslands are also among ecosystems that are projected to undergo the largest biodiversity losses in the

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future due to their sensitivity to the main drivers of biodiversity erosion, notably land use changes (Sala et al., 2000). Apart from the biodiversity occurring within the grasslands themselves, it is also important to consider that grassland-based production directly or indirectly affects a large fraction of the biodiversity in other habitats than grasslands. Such biodiversity includes, e.g. forests and wetlands that are converted into agricultural grasslands and aquatic species affected by pollutants of agricultural origin. In most instances, the expansion of agricultural land, including grassland, into the native natural ecosystems has impoverished if not annihilated their native biodiversity (Newbold et al., 2016; Ramankutty et al., 2018). The increasing human population and dietary shifts towards animal-sources foods accompanied by the rapid globalisation of modern food production systems also mean that indirect impacts on biodiversity extend far beyond the boundaries of countries and continents, via for instance the widespread and increasing reliance on mineral fertilisers and feed, and massive production of feed, i.e. agricultural processes that increase greenhouse gas emissions.

Natural grasslands are found in areas where forests cannot grow due to climate constraints (e.g. in steppe or alpine zones) and where hydrology, soil conditions, relief and/or natural disturbances such as grazing of woody vegetation by large wild herbivores or forest fires prevent tree growth (Dengler et al., 2014). For long grazed by wild ungulates, pre-existing open landscapes have seen their native herbivore community progressively replaced by domesticated animals, involving controlled pasturing and hay mowing. This also occurred in predominantly forested regions, including most of Europe, where widespread grazing by large native herbivores had created semi-open woodlands, i.e. an intricated mosaic of forest stands and grassy clearings (Pearce et al., 2023) (Fig. 1a). It is the species adapted to such semi-open conditions that later colonised expanding agricultural landscapes. The potential for agricultural grasslands to support high levels of biodiversity is considerable, providing that the intensity of management is not too high. All depends on how many species of different groups – plants, invertebrates, birds – are tolerated, maintained or encouraged during production on grasslands. The diversity of species typically inhabiting grasslands will thus primarily depend on both landscape structural diversity and grassland management practices (e.g. Vickery & Arlettaz, 2012).

A significant and increasing fraction of modern agricultural grasslands across the world are secondary grasslands: they result from the expansion of agricultural land into natural ecosystems such as forests and wetlands, and their mosaics (e.g. review in Porqueddu et al., 2016). Some of these grasslands are among the most floristically diverse habitats in the world (Wilson et al., 2012) (Fig. 1b, Fig. 2a,b,c). They are most common in regions where traditional forms of agricultural use predominate, as it is a case for High Nature Value farmland in the context of Europe (Keenleyside et al., 2014), or in rangelands

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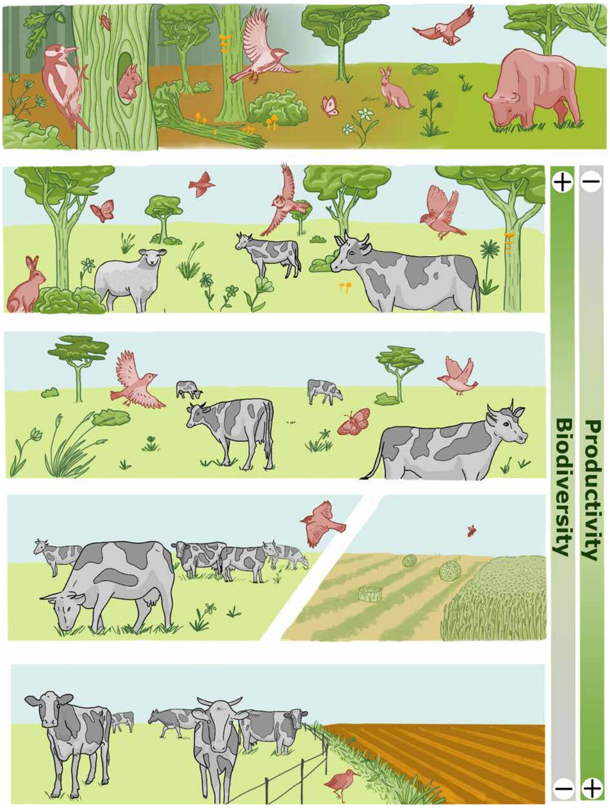

Figure 1 General relationship between biodiversity and biomass production by agriculture across main grassland types: (a) pre-agricultural ecosystem with wild herbivores maintaining native grasslands and creating mosaics of semi-open grassy patches in woodland; (b) semi-natural grassland grazed by domesticated herbivores or used for traditional haymaking; (c) and (d) agronomically improved permanent grassland under different levels of management intensity for pasturing and forage production; (e) rotational grasslands cultivated as part of arable field rotations. Image by Lola Fernández Multigner.

with native vegetation. Such grasslands are often referred to as 'semi-natural'. Because they are managed with local (not imported) fertiliser inputs and are not reseeded, their species composition is largely determined by natural processes, albeit mediated by grazing or haying (Peeters et al., 2014). These grasslands, or rangelands, depend on livestock grazing and/or mowing to prevent succession to scrub and woodland, and are common in major regions dominated by ruminant production (e.g. Brazil (Leidinger et al., 2017), South Africa (Bengtsson et al., 2019), North America (Bartolome et al., 2014) and Mediterranean climate zones around the world (Porqueddu et al., 2016)). Biodiversity in such grasslands is threatened by intensification of production in

Figure 2 Overview of secondary grasslands under different management and land use intensities: (a) traditional agroforestry system with extensive pasture areas (Image by HNV-Link); (b) extensively managed mountainous pasture (Image of Wikipedia, https://commons.wikimedia.org/wiki/File:Pojejena,_Romania_-_panoramio.jpg); (c) extensively managed permanent subalpine hay meadow; (d) intensively managed permanent grassland; (e) cultivated grass-legume ley; (f) intensively managed cultivated pasture for dairy production (Aino Pietikäinen). All other images by Jean-Yves Humbert.

many regions (Dengler et al., 2014; Porqueddu et al., 2016) but also large-scale abandonment in other regions (Dengler et al., 2014). In the boreal region of Europe, e.g. the current extent of semi-natural grasslands is only a few percent of what it was 100 years ago due to both processes (Herzon et al., 2022). Other impacts come from pesticide drift (Bullock et al., 2024; Newton et al., 2012), invasive species and nutrient deposition from agricultural and industrial sources (Maskell et al., 2010).

By improving conditions for production – through drainage, irrigation, liming, reseeding or additional seeding of existing swards, addition of organic and/or mineral fertilisers and other agrochemicals, increased mowing frequency and/or stocking rates – the biodiversity of natural and semi-natural grasslands has been progressively reduced, resulting in highly productive but species-poor grasslands (Habel et al., 2013, Fig. 1c, Fig. 2d). There is a wealth of research on the biodiversity of permanent grasslands across a range of productivity levels (reviewed in Schils et al., 2022). The lowest levels of biodiversity tend to be on permanent grasslands with particularly high fertiliser inputs, grazing pressure, frequent mowing operations and temporary grasslands (also called leys or artificial grasslands), which are regularly re-seeded with one or more species of grass or grass-legume mixtures, either on the same plot or in crop rotations (Fig. 1d, Fig. 2e,f). The latter are particularly common in dairy production and are part of organic arable farming. Relatively few studies have focused on the biodiversity of grasslands under intensive use for high productivity (reviews in Plantureux et al., 2005; Tiainen et al., 2020), apart from research on the diversification of seed mixes for sown crops (Nyfeler et al., 2009).

In general, permanent agricultural grasslands are known to support higher levels of biodiversity than arable land, at least for some taxa (reviewed in Schils et al., 2022). For example, species richness of earthworms, collembolans and oribatid mites is lower in arable systems than in intensive grasslands across Europe (Rutgers et al., 2016; Tsiafouli et al., 2015). A global meta-analysis showed that intensive grasslands have higher arthropod species richness, especially in the decomposer guild, than arable systems, but no such difference was found for predator species richness (Attwood et al., 2008). On the other hand, farmland with flowering crops, but not with livestock systems, increased wild bee species richness (four European countries; Le Féon et al., 2010). A bioenergy crop of *Miscanthus* increased earthworm diversity compared to intensive grassland (McCalmont et al., 2017). Also, there is some evidence that the biodiversity of high-intensity ley grasslands does not exceed that of arable fields (Toivonen et al., 2013), though comparative studies are few.

The wide range of land use histories, soil conditions and production intensities of grasslands makes generalisations on biodiversity patterns in this type of farmland difficult. Yet, one pattern is consistent across reviews: the intensification of grassland use decreases its multifunctionality, including biodiversity (Lindborg et al., 2023; Porqueddu et al., 2016; Ribeiro et al., 2023; Schils et al., 2022). After analysing a dataset of over 4,000 species from 12 trophic groups, Gossner et al. (2016) showed how even moderate increases in local land-use intensity lead to biotic homogenisation, i.e. loss of the fairly rare specialist species, across the microbes, plants and animals typical of grasslands, and for both above and below ground communities.

There are well-documented approaches to increasing biodiversity in all types of grassland, this for many different taxa. In this chapter, we review recent research on the effects of agricultural management of grasslands in temperate regions on different groups of organisms and synthesize the available scientific evidence on the effectiveness of different management options for enhancing their biodiversity. We focus primarily on the biodiversity typically inhabiting grasslands but also consider the key role of grasslands for biodiversity in both the overall agri-food system and wider landscape. Though the largest body of reviewed evidence comes from European grasslands, many of the findings and management implications raised here are relevant to all grasslands used for agricultural production globally. However, the development of locally specific measures to enhance grassland biodiversity must account for differences in agricultural contexts, notably ecosystem and farming histories and amenable agricultural practices.

2 Grassland management practices and biodiversity

Key features beneficial for biodiversity on grassland are the permanence of the vegetation compared to annual cropping, low levels of disturbance that allow a diversity of species to colonise and persist, low use of pesticides, grazing at moderate-to-low stocking rates that create a diverse vegetation structure within a parcel, or combination of high-stocking grazing with long rest periods that creates a mosaic of vegetation within the grassland matrix at the landscape scale. Due to a long history of evolutionary co-adaptation between native herbivores and other species, grazing by domesticated livestock is generally associated with higher pastoral biodiversity and is widely used also as a conservation tool. Increasing management pressure along any of the above aspects is likely to adversely affect biodiversity. The levels of biodiversity in grasslands are strongly influenced also by the availability of natural and semi-natural habitats at farm and landscape levels (see Case study).

Few plant species, including non-native cultivars, can tolerate the high soil nutrients and defoliation rates under grazing or mowing in intensively used agricultural grasslands. Low plant diversity leads to low arthropod diversity due to shrinkage of ecological space (Attwood et al., 2008; Simons et al., 2015). This is due to a reduction in floristic diversity per se, but also because the swards become structurally homogeneous and lack flowers or seed heads to support other taxa (Bendel et al., 2018; Humbert et al., 2010b, 2021; Woodcock et al., 2007b). For example, silage grassland in Germany – usually managed for high productivity – had an 86% lower level of the butterfly conservation value indicator than traditionally managed hay grassland (Hannappel & Fischer, 2020).

Frequent cutting, rendered possible by regular mineral fertiliser inputs, further reduces arthropod abundance and diversity (Humbert et al., 2010b), especially among specialist species (Gossner et al., 2016). Declines in farmland birds across Europe are associated with reduced seed and arthropod prey availability, frequent mowing or high grazing pressure (Donald et al., 2002; Strebel et al., 2015; Vickery et al., 2001, Vickery & Arlettaz, 2012). In particular, early-season mechanised mowing for silage, which destroys nests and kills chicks, has been shown to be a major cause of population decline of several formerly common species – such as the critically endangered corncrake (*Crex crex*), skylark (*Alauda arvensis*) and whinchat (*Saxicola rubetra*) – from grasslands across Europe (Buckingham et al., 2015; Donald et al., 2002; Fay et al., 2021; Green & Gibbons, 2000). Intensive grazing has been shown to exert negative effects on biodiversity and habitat conservation in Mediterranean landscapes (review in Ribeiro et al., 2023). In arid climates, bare ground cover created by the excessing grazing can reduce seed germination for species that rely on standing biomass for shelter from aridity, leading to lower diversity and/or native cover (Lunt et al., 2007), although bare ground may benefit ground-foraging insectivorous vertebrates (Schaub *et al.*, 2010). Overgrazing is particularly detrimental to above and below-ground biodiversity, also in the long term (Donovan & Monaghan, 2021; Eldridge et al., 2013).

On rotational grassland, high fertiliser inputs as well as repeated defoliation for silage or bioenergy impede species colonisation and completion of their breeding cycle after the establishment. For example, quasi-experimental multi-taxa surveys across field types in Finland found few differences in plant and arthropod multi-taxa diversity between cultivated pasture, grass ley field and several types of arable crops (Toivonen et al., 2022).

3 Enhancing biodiversity on grasslands

3.1 Introducing plant species

There is increasing interest in establishing more biodiverse vegetation on agronomically improved but species-poor grasslands, such as herbal leys, to enhance forage production, minimise inputs and provide additional resources for wild species, such as pollen and nectar for pollinators (Finn et al., 2013). For example, the increasingly species-rich swards (from five grass species to up to 18 species of grasses, legumes and native forbs) also supported increasing diversity of phytophagous beetles (Woodcock et al., 2012), predatory beetles (Woodcock et al., 2013) and bees, butterflies and hoverflies (Woodcock et al., 2014). The addition of forbs was particularly important for maintaining biodiversity gains. In these and other studies, the use of multi-species seed mixtures in grasslands also led to increased productivity (reviewed in Ashworth et al., 2018). However, such studies mostly manipulate low levels of diversity (below 10 species), and production gains with an increase of diversity from one to several sown species appear to stop at low levels (Ashworth et al., 2018). Such diversity levels of vegetation are well below those achievable in semi-natural grasslands.

3.2 Leaving uncut refuges

Harvesting of grassland biomass, from mowing to baling, kills a large proportion of invertebrates: up to 65–85% of orthopteran populations in some studies (Humbert et al., 2010a, 2010b). Mortality of small mammals such as European hare, roe deer, amphibians, reptiles and ground-nesting birds is also substantial (reviewed in Oppermann et al., 2000; Broyer, 2003; Saumure, Herman & Titman, 2007; Humbert, Ghazoul & Walter, 2009; Grendelmeier, 2011; Grüebler et al., 2012). There is evidence that intensification of grassland production has turned formerly biodiversity-friendly grasslands into so-called sink habitats or even ecological traps (Müller et al., 2005). This means that organisms, such as birds, start breeding on grasslands, but are unable to reproduce due to intensified agricultural practices, thus becoming ecologically trapped in their choice of breeding habitat (Britschgi et al., 2006). As no biomass harvesting method is damage-free (see 3.4. Delaying and modifying mowing patterns), leaving uncut grass strips or patches as refugia between each harvest could to some extent mitigate some of the negative impacts (Humbert et al., 2018; Schwarz et al., 2023; Fig. 3).

A long-term experimental field study in Switzerland showed that, compared to controls without a refuge, grasslands with an uncut grass refuge had: (1) higher species richness of specialist butterflies (Bruppacher et al., 2016; see also Konvicka et al., 2008); (2) twice the density and 23% higher species richness of orthopterans (Buri, Arlettaz and Humbert, 2013; see also Humbert *et al.*, 2012; Kaláb, Šipoš & Kočárek, 2020; Schwarz et al., 2023); (3) higher abundance and species richness of wild bees and hoverflies, this due to an enhanced

Figure 3 Examples of a mowing refuge on a grassland. Images by Jean-Yves Humbert.

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and prolonged availability of pollen and nectar (Buri et al., 2014; Meyer et al., 2017); and 4) higher abundance of ground beetles (van Klink et al., 2019). Yet, no such effects were found for rove beetles, moths, plant- and leafhoppers and spiders (Buri et al., 2016; van Klink et al., 2019). Other studies have shown that the spider community in wet litter meadows benefits from annual uncut grass strips that remain in the same place for at least 1 year, providing overwintering habitat (Cattin et al., 2003; Frenzel et al., 2022; Schmidt et al., 2008).

Sward architecture is a primary factor to promote phytophagous and predatory grassland arthropod species and biomass in general (Andrey et al., 2014; Woodcock et al., 2009). Therefore, leaving some uncut areas when harvesting biomass is an important measure for ensuring the continuity of complex vegetation during the growing season. This is especially relevant in landscapes where most of the grasslands are mown within a narrow time window. To avoid changes in the plant community, the location of the uncut refuge(s) needs to change at each mowing operation (Rossier et al., 2023; van Klink et al., 2017). Leaving unmown refuges has proven or is highly likely to be beneficial also for mammals, amphibians, reptiles and ground-nesting birds (e.g. Broyer, 2003). Intensive research on an endangered bird, the Corncrake (*Crex crex*), has demonstrated that 10-m-wide strips should be considered as the absolute minimum width for refuge during mowing operations (Arbeiter et al., 2017).

Leaving a grassland parcel fallow for one to several years, or following an arable field with a seed mix of grasses and forbs, is an efficient way of creating biodiversity refugia at the landscape scale. Such biodiversity features have been successfully tested and are now financially supported in several European countries (including Hungary, Finland). Together with long-term set-asides, such low- or non-productive grasslands have been shown to be beneficial for numerous plant taxa, pollinators and other invertebrates, and birds (Hertzog et al., 2023; Herzon et al., 2011; Revaz et al. 2008; Toivonen et al., 2013). In some cases, the use of such fields for extensive production (single late mowing for forage, or low-intensity grazing) may be compatible with biodiversity (Toivonen et al., 2013). A similar approach can work on also pastures, including those managed under rotational grazing: refuges without grazing are left during the most sensitive times of the year (see 3.6. Grazing management).

3.3 Maintaining non-productive margins

Similar to the use of field margins on arable land, non-productive margins on intensively managed grassland can be used to enhance biodiversity. This is achieved by renouncing agrochemicals, fencing off livestock from the margins for the duration of the breeding season and/or late single mowing, and sowing diversified seed mixtures of grass and herb species (Fig. 4). Benefits

Figure 4 Partially fenced-out margin along a stream: a combination of the grazed and fenced-out parts creates a diversity of conditions that benefit numerous organisms. Image by I. Herzon.

of establishing 10-m-wide margins on intensive livestock farms, managed so as to increase sward architectural complexity and promote floral species richness, enhanced abundance and species richness of beetles (Woodcock et al., 2007a), bumblebees and butterflies (Potts et al., 2009). Fencing was required to exclude livestock during flowering to prevent negative impacts on a wide range of arthropods (Anderson et al., 2013; Cole et al., 2012). Also, 1.5–3.5 m wide fenced margins of permanent, intensively grazed pastures harboured more springtails (Collembola: Anthropleona) and spiders (Araneae) than control margins (Sheridan et al., 2008). Margins that were rotavated and allowed to regenerate naturally also had more flies (Diptera) and plant species than control plots (ibidem). Birds may also benefit due to increased abundance of large aerial insects (Wiggers et al., 2016), although such a positive effect could not be demonstrated in other studies on birds (Davey et al., 2010) and hares (Zellweger-Fischer et al., 2011).

Margins occupy a relatively small part of the field, have a fairly limited impact on overall production (Pywell et al., 2015), and act as refuges for some species (see 3.2. 3.2. Leaving uncut refuges). These are especially important for amphibians when placed around ponds in sensitive areas (Schuler et al., 2013). Such margins along watercourses also operate as buffer zones for water protection.

3.4 Delaying and modifying mowing patterns

Delaying first mowing and modifying mowing practices can potentially benefit grassland biodiversity. A review of 24 studies showed that delaying the first mowing date in European grasslands has either positive or neutral effects on biodiversity (Dicks et al., 2020). Benefits included: higher plant species richness, higher densities of two rare arable weeds, more insect species and individuals visiting flowers, higher abundances of some spiders and ground beetles, and higher breeding densities of wading birds. On the other hand, delaying the first cut to the end of the growing season (September in central Europe) can reduce plant species richness (Humbert et al., 2012b). Reduced mowing frequency, omission of mowing in parts of the grassland (refuges), or extensive grazing instead of mowing have been shown to be of the greatest benefit for arthropod populations (Berger et al. 2024).

Mowing from the centre of the field outwards has also been recommended to avoid concentrating individuals of highly mobile species such as birds, mammals and insects in the centre of the field and to facilitate their escape (Fig. 5; Green et al., 1997; Tyler, Green & Casey, 1998; Prochnow & Meierhöfer, 2003; Saumure, Herman & Titman, 2007). Some studies recommend the use of cutter bar mowers over rotary and flail mowers to reduce mortality of mobile species, but the relative reductions in mortality are still poorly understood for most growing conditions, especially for less mobile species (reviewed in Flade et al., 2006; Humbert et al., 2009). Some studies have reported that higher cutting heights are less damaging to field-dwelling animals (reviewed in Humbert et al., 2009). Also abstaining from some operations, such as conditioning, rolling and levelling at critical times for sensitive species is regarded as beneficial for many taxa (Gottwald & Stein-Bachinger, 2016; Humbert et al., 2010b). However, there is little research on the overall mortality caused by the various steps of the harvesting process, including the removal of baled grass. For example, most of the common skylark (*Alauda arvensis*) nest failures are caused by being run over by machinery during the entire silage collection process (Peach et al., 2007), which is particularly difficult to mitigate in practice for small passerine species. A large study in the UK testing ways to improve the reproductive output of the species by manipulating silage harvesting at the field level had limited success: changes in the timing and method of harvesting, or cutting height, proved insufficient to increase breeding success above the rate required for population stability (Buckingham et al., 2015).

In several countries in Europe, there are schemes, in which volunteers carry to search for nests of wader birds, such as Black-tailed Godwit (*Limosa limosa*), and mark them, so that farmers can avoid nest destruction during the operations (Herzon et al., 2018). Despite nest protection locally, there is somewhat inconsistent evidence about the success of such interventions on the species

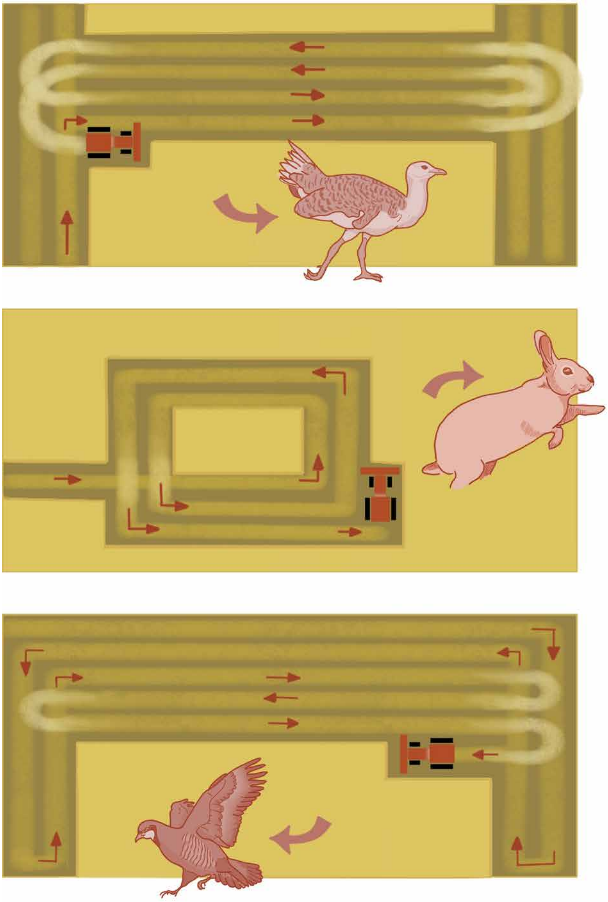

Figure 5 Adapted mowing for mobile species, which allows species to escape the mowing equipment towards outer edges of the mown grassland. Image by Lola Fernández Multigner.

populations in The Netherlands (e.g. Verhulst et al., 2007). A potential reason is that approaching and designating the nests and leaving uncut areas during mowing can increase predation rates, so that nest success may not be increased, or that predation rate in production grasslands is too high for meadows birds regardless of nest protection (Grüebler et al., 2012). On the other hand, such collaborative partnership between a farmer network and an NGO has been shown to contribute to farmers' knowledge about the conservation of birds on their grasslands and to recognition of the conservation role of farmers among citizens, decision-makers and agri-food companies (Runhaar & Polman, 2018).

The effectiveness of different methods to scare mammals and birds away from mowers has been researched, but the evidence is still limited (Green, 2007 for ducks in the USA). Loud noises, scarecrows, dogs or extension arm bars were found to be inefficient in reducing mortality of fawns (Fackelmeier & Biebl, 2009; Lehner et al., 2015). This is partly because young mammals try to hide by lying down when frightened. However, scaring female deer with offspring away from grassland to be mown in consequent days seems to work (Jarnemo, 2002). Mechanical or recently developed electronic acoustic and visual scaring devices can be used (Leune et al., 2022).

In summary, modern biomass harvesting on agricultural grassland managed for maximum attainable productivity, whether for feed or bioenergy, poses a serious challenge to biodiversity conservation on grassland. Nevertheless, there is modest evidence for the benefits of modifying harvesting practices for some species. The use of new technologies may also help to resolve the conflict between grassland production and biodiversity. The importance of creating landscape-level variation in management across grasslands in collaboration among producers as well as NGOs is also needed.

3.5 Reducing agrochemical inputs

Some research has shown that reducing fertiliser or pesticide inputs can benefit plants, invertebrates and birds, while other studies have shown no or little effect (reviewed in Dicks et al., 2020). One reason may be that many improved grasslands receive such substantial amounts of organic and/or mineral fertiliser that they have accumulated soil phosphorus reserves in the long run. Reducing or even temporarily stopping inputs therefore makes relatively little difference to plant communities on intensively managed grasslands, as indirectly confirmed by an EU-wide survey (Kleijn et al., 2008). The benefits are likely to be indirect through a concomitant reduction in stocking density, and a delay in the first mowing or grazing date, i.e. via an overall extensification of management (see 3.7 Extensifying management).

The type of fertiliser is likely to be important. Using farmyard manure was shown to lead to both production benefits and biodiversity gains (plant and insect communities), while the addition of mineral fertilizer at the highest tested level (of about 100 N t kg^{-1} $year^{-1}$) had the most negative impact on biodiversity (Villa-Galaviz et al., 2023). Production benefits aside, additional fertilisation of grassland decreases plant diversity irrespective of the source of nutrients, as compared to a complete lack of fertilizer (Villa-Galaviz et al., 2023). According to Onrust et al. (2019), replacing slurry and slit-injection-based management with the use of farmyard manure increases surface soil moisture to benefit earthworms and the birds that feed on them.

3.6 Grazing management

Grazing is generally considered to be more benign for farmland biodiversity than mowing forage (Metera et al., 2010; Tälle et al., 2016). However, it has declined in many regions in favour of indoor housing of ruminants, especially in the dairy sector (van den Pol-van Dasselaar et al., 2020). It is therefore important to maintain grazing, at least for part of the herd, if biodiversity maintenance within grassland-based systems is desired. Three factors are key in designing livestock grazing on grasslands to benefit biodiversity: (i) livestock type, (ii) grazing intensity and (iii) grassland type such as semi-natural or sown, dry or mesic, etc. (Peco et al., 2012; Tóth et al., 2018). Due to the high variability of grazing regimes, the most appropriate management for biodiversity needs to be adapted to the region, climate, soil type, land-use history and evolutionary co-existence of species with herbivores. It should be further fine-tuned at parcel level and adjusted between years and within a year, ideally following biomass production, vegetation structure and plant or bird indicator species (review in Herzon et al., 2018, and see Case Study).

Livestock identity has been shown to have a strong influence on the effects of grazing on grassland biodiversity (Jerrentrup et al., 2015; Tóth et al., 2018). Most research has focused on cattle and sheep with evidence for other livestock species or wild grazers being limited (Metera et al., 2010). The grazing strategy of livestock is influenced by grassland type such as semi-natural (e.g. Mládek et al., 2013), and pasture management (e.g. rotational or mob grazing forces grazers to mass foraging), and may change over the years (Zhang et al., 2023). Because of the evolutionary adaptation to the past conditions, continuity in the use of the livestock type best adapted to the biophysical conditions (soil, terrain, climate) is also likely to be best for species communities adapted to specific grazing regimes. This includes also less common herbivores, such as pigs (e.g. Iberian agroforestry systems), and mixed grazing (e.g. sheep and cattle or cattle and horses). For example, the fact that most pre-agricultural grassland communities in Europe were formed by and adapted to wild bovine and equine herbivores, may explain why cattle grazing has been shown to be more beneficial for maintaining grassland biodiversity than sheep grazing (Bullock et al., 2001), especially those characterised by high forb diversity, such as in loess steppe grasslands or other forb-rich grasslands (Török et al., 2018). In the global context, however, the benefits of cattle grazing for grassland butterflies revealed only slightly more positive effects than negative, with many inconclusive results due to variability in management, environmental and evolutionary factors (Bussan, 2022). Even the replacement of a wild bovine species (such as bison) by a related one (cattle) may lead to changes in biodiversity due to differences in their behavior and management (Lueders et al., 2006). In some parts of the world, such as Australia, grazing by cattle and sheep has been transplanted on the original open habitats with no history of such type of herbivory (Lunt et al., 2007). A review on the use of domestic herbivores for ecosystem management in Mediterranean landscapes demonstrated highly varied effects on biodiversity and habitat conservation (Ribeiro et al., 2023).

As shown above, maintaining a diverse vegetation structure and plant composition is a basis for overall biodiversity in grasslands (see 2. Grassland management practices and biodiversity). Therefore, grazing regimes should ideally vary in both space and time, also reflecting small-scale spatial and temporal variation in primary productivity. For example, in a semi-arid rangeland, grazing affected the diversity of annual plant communities differently along the gradient of community productivity (Osem et al., 2002). In each grazing year, some pastures could be kept at relatively low grazing levels to provide a diversity of flowering resources and safe breeding of ground-nesting birds. Creating grazing exclusion zones or having sufficiently long rest periods in paddocks under rotational grazing, can also enhance overall biodiversity especially species sensitive to trampling and defoliation. It works similarly to refuges left during mowing (see 3.2. Leaving uncut refuges).

Using native prairies as rangelands, in which domesticated bovines and sheep, mimic the ecological functions of native herbivores, is often regarded among sustainable agricultural systems because it allows production in original grassland ecosystems, preserving their biodiversity. Research from North America indicates that such multiple benefits arise at comparatively low stocking rates and grazing intensities on multispecies permanent grasslands with low to no additional inputs (Lusk & Koper, 2013). For example, maintaining a gradient of grazing regimes on such farms maximizes the availability of suitable nest sites for various species in mixed-grass prairies in production (Pintaric et al., 2019). There is also evidence that the ecological effects of cattle grazing differ in numerous ways from historical effects of bison grazing, due to different selections of grass vs. forbs, and use of the landscape (Lueders et al., 2006).

On low-productive grasslands grazed for biodiversity conservation, research often focuses on year-round free grazing (e.g. Köhler et al., 2016) or grazing with shepherds (Török et al., 2016a) (see 3.8 Restoring and managing semi-natural grasslands). In some landscapes, such as extensive grasslands on alkaline soils, the effects on species and functional grassland biodiversity were similar under both year-round free and low-intensity seasonal grazing with a shepherd (Török et al., 2016b). Rotational or mob grazing has been promoted recently for its potential production and environmental benefits. However, research to date shows that this grazing regime does not universally promote biodiversity due to heavy trampling and intensive defoliation (reviewed in Morris, 2021). Additional measures are needed to manage also for biodiversity under this regime. For example, leaving wildlife refuges on central paddocks that are excluded from grazing during the breeding season is promoted as beneficial for some typical grassland bird species in the USA (Fig. 6; Undersander et al., 2000), but evidence for improved nest survival is still scarce.

When planning fine-tuned management at the pasture and landscape level, traditional knowledge of experienced herders (Molnár et al., 2020), extensive research on modern pastures and innovative technological tools for monitoring pasture development and indicator species can be integrated in a complementary way to achieve the multiple benefits of pasture-based production. The importance of the landscape structure, into which pastures are embedded – the presence of trees, bushes, water courses, buffer zones, woodland etc. – will heavily influence biodiversity. Retention or planting of trees and shrubs on pastures also improves carbon sequestration without compromising overall pasture quality (Tölgyesi et al., 2023), and provides shade for grazing animals and other benefits to production (England et al., 2020).

Finally, biodiversity includes species that challenge pasture-based production: apex predators such as wolves, wolverines and eagles. For many pastoralists worldwide, the conflict between wildlife and grazing animals is seen as a severe problem (e.g. Bisi et al., 2010; The World Bank, 2023). Several studies have demonstrated the effectiveness of various methods of resolving such conflicts by the use of shepherd dogs and specially designed fences (Bruns et al., 2020). Some of these also minimise the risk of disease transmission from wildlife to livestock (Jori et al., 2021). In some cases, the conflict is managed through payments to herders linked to the confirmed breeding cases of predators of conservation importance (review by Herzon et al., 2018). There is an emerging understanding of the importance

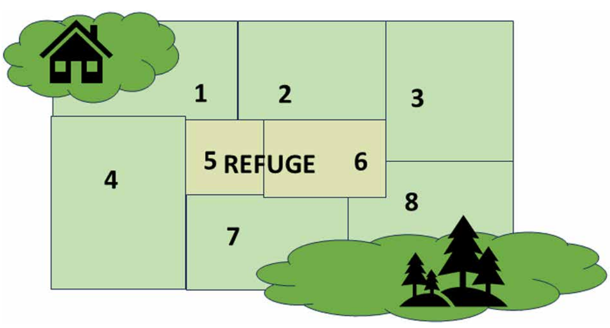

Figure 6 Refuge for ground nesting meadows birds recommended for grassland managed under rotational, or mob grazing. It is recommended to place it in central paddocks away from trees or farmsteads and exclude it from grazing during the breeding season of birds species sensitive to trampling. Re-drawn from Undersander et al. (2000).

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of bringing stakeholders together in conflict resolution processes and developing national policies for human-wildlife conflict (e.g. Salvatori et al., 2020; The World Bank, 2023).

In summary, grazing is an important and perhaps most appropriate form of management on grasslands due to the evolutionary adaptation to herbivory by large mammals on native grasslands. As a rule of thumb, low to moderate grazing intensities on multi-species grasslands without high additional inputs of agrochemicals would support the highest multi-taxa diversity. Due to the high variability of grazing regimes, the most appropriate management for biodiversity needs to be adapted to the region, climate, soil type, land-use history and evolutionary coexistence of species with herbivores. As with other forms of grassland management, there are trade-offs between production and conservation in pastoral systems. One type of conflict specific to pastoral systems is that between native apex predators and domesticated grazers. Conflict resolution processes for human-wildlife conflicts should also apply to this conflict context.

3.7 Extensifying management

As shown above, reducing input and land use intensity on grasslands has been confirmed to have biodiversity benefits, at least for some taxa. Many studies involve changing two or more management practices at the same time. For example, a replicated controlled study in the UK (Peach et al., 2007) found that plant seed heads and invertebrates, including those important as food for birds, were more abundant on plots with reduced overall management intensity (lighter grazing, seasonal removal of livestock, reduced fertiliser application). Noxious weed cover remained low on all plots throughout the study. Similarly, the index of the extensity of grassland management, as indicated by the levels of fertilisation, mowing frequency and grazing, positively affected species richness of several insect taxa, especially pollinators (Panassiti et al., 2023). Focusing on an overall reduction in the intensity of grassland use, rather than on individual practices, may allow producers to choose options that best suit their production type and achieve benefits for biodiversity while optimising overall productivity and resource use. This is exemplified in the Farming for Biodiversity project (see Case Study). Implementing extensification of agricultural management for biodiversity and other ecosystem services is disproportionately more costly in intensively managed areas than in extensively managed ones (e.g. Kleijn et al., 2008), and for some livestock systems than others (e.g. dairy is more dependent on high-energy forage than suckler cow production). Solutions and support systems need to be developed in a context-specific approach (see Case Study).

3.8 Restoring and managing semi-natural grasslands

Due to the exceptional biodiversity and currently high levels of endangerment of many types of semi-natural grasslands, research on the restoration of such grasslands is prolific in Europe. However, similar research exists in other regions with native grasslands used for livestock production under a range of intensities (e.g. Bartolome et al., 2014 for North America). Active restoration of semi-natural grasslands can be separated into two main categories: (1) the re-creation of grasslands; and (2) the restoration of existing but degraded or intensively managed, species-poor grasslands. Both are possible but may take time (Pywell et al., 2002; Török et al., 2011). Re-creation from arable land appears to be easier than restoration on intensive grassland, where the intact vegetation provides few opportunities for introduced species to establish and persist (Kiehl et al., 2010). In addition, high soil fertility in intensive grasslands may limit the success of plant introductions (Janssens et al., 1998). To restore a comparable plant community as in the past, grassland restoration often requires active measures, mainly the addition of seeds after soil disturbance such as ploughing, which facilitates seed germination (Klaus et al., 2017; Poschlod & Biewer, 2005; Pywell et al., 2007). Sowing a seed mixture and direct seeding by transferring hay from a freshly mown biodiversity-rich donor grassland are the two most common methods of seed addition used in semi-natural grassland restoration (Hedberg & Kotowski, 2010; Klimkowska et al., 2010). A recent meta-analysis of the respective effectiveness of these methods in restoring temperate grasslands provides quantitative evidence that such operations are generally effective (Slodowicz et al., 2023), supporting previous narrative reviews on the same topic (Hedberg & Kotowski, 2010; Kiehl et al., 2010). Restoration success of plant species richness is best achieved by combining seeds from a species-rich donor grassland with commercial seeds or solely using the seeds of a species-rich donor grassland.

The use of selected local breeds has been shown to work best on semi-natural grasslands (Köhler et al., 2016) due to their adaptation to local conditions or specific grassland types, and their ability to exploit more diverse and possibly less nutritious vegetation than on intensive grasslands. All countries with a history of traditional pastoralism have such breeds, and their conservation is supported by national governments. Livestock that move across large areas of grassland or whole landscapes, as in transhumance, can also spread seeds of native species (Ozinga et al., 2009), contributing to active restoration. Grazing management can thus be designed in a way that supports the restoration of diversity in degraded or enhanced grasslands. A solution is to start grazing in high-diversity grasslands and then move the herd towards species-poor grasslands so as to facilitate seed dispersal without any further human intervention.

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Other forms of management, such as controlled burning and removal of the surface layer of litter and soil, can also be effective for such restoration (Valkó et al., 2014), especially in regions with a long history of fire regimes, such as the Mediterranean climates (Porqueddu et al., 2016) or Australia (Lunt et al., 2007).

4 Grassland biodiversity at farm and landscape levels

The diversity of the whole agro-landscape has been emphasised as the best approach to maintain biodiversity (Benton et al., 2003). A modern regional separation of arable and grassland-based production has undermined such diversity. Incorporating some arable crops into grassland-dominated landscapes is known to benefit mobile species that can exploit resources across landscapes and through time (Robinson et al., 2001). For example, some birds can nest on arable crops while moving with their chicks to grasslands to feed (Fig. 7) while some insectivores foraging on the ground require patches of bare ground to access their invertebrate prey base that dwells in the swards (e.g. Arlettaz et al., 2012; Schaub et al., 2010). The diversity of bird species overwintering in intensive grassland landscapes was similarly enhanced by mosaics of fields managed as short-term leys and permanent pastures with low-intensity cattle grazing during autumn and winter (Perkins et al., 2000). The systematic re-integration of grasslands into arable production systems would reinstate the many biodiversity benefits of traditional land management (Liu et al., 2013; Porqueddu et al., 2016). This happens on organic arable farms, which are reliant on grass-legume leys for nutrient management (Stein-Bachinger et al., 2021). The maintenance and restoration of integrated production systems associating

Figure 7 Resource use by mobile species like birds benefit from a spatio-temporal juxtaposition of different land uses across the cultivated landscape, providing feeding grounds, shelter and even nesting opportunities, that is, optimal conditions for any stage of the life cycle. Image by Lola Fernández Multigner.

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grasslands with other types of production generally boost biodiversity (e.g. reviewed for agroforestry in Castle et al., 2022, or traditional systems of China, Liu et al., 2013).

The presence and diversity of various non-cropped areas and landscape features – trees, bushes, water bodies, woodland – in and around agricultural grasslands, which are themselves managed with varied defoliation regimes, is likely to benefit all those elements of biodiversity that have undergone a long co-evolution under the pressure of natural herbivory in woodland-grassland landscapes. Numerous research on the potential benefits of organic production (as a case for more extensive production in terms of some agricultural inputs) for biodiversity have further confirmed that the farm and landscape structure has a considerably higher influence on farmland biodiversity than the very management regime of the fields *per se* (e.g. Schneider et al., 2014; Vickery & Arlettaz, 2012). In order to enhance biodiversity, as well as the ecological functions and ecosystem services it provides, future agriculture should reintegrate natural features into landscapes that are deprived of them following intensification.

Re-creating a range of grazing stages within a shifting mosaic of disturbance intensities in both space and time (from intensive short-period grazing to long rest periods of many months) and allowing diversities of productivities of natural vegetation on heterogeneous soil and terrain conditions – i.e. mimicking natural herbivory regimes – is likely to maintain biodiversity on originally open steppe-like landscapes. The so-called holistic grazing management claims to aim at this, but its implementation remains varied in its ambition and delivery of biodiversity (Morris, 2021).

There is a need for research and development projects that support farms and neighbouring farm clusters too, on one hand, optimise land use management for maximum benefits at the lowest costs to farm enterprise (see Case Study) and, on the other hand, improve public benefits in rural areas, while balancing local and global impacts so as to opt for the most suitable modes of agricultural production. Any such approach should (1) prevent the conversion of ancient permanent grassland to arable or temporary grassland, (2) extensify grassland production to minimise environmental impacts such as erosion and water pollution (Leidinger et al., 2017; Schils et al., 2022), and (3) maintain and restore semi-natural grasslands. Keeping or even increasing management intensity on some grasslands should in any case be compensated for by an extensification on some other grasslands in the same landscape (Qi et al., 2018). Paludiculture, that is often understood as farming systems in areas with high water tables, represents an interesting management option that yields specialised agricultural products (rice, buffalo) and boosts the biodiversity typically encountered in wetlands (Martens et al., 2023). Finally, restoration of pre-agricultural woodland-pasture mosaics, wetlands and forests from some grassland areas, as well as native grassland ecosystems such as prairies, can contribute to the restoration of natural ecosystems, or rewilding, in regions that underwent extensive modification by humans (Garrido et al., 2019; Boyce et al., 2022).

5 Case study

The following example illustrates how farmers involved in both dairy and suckler cow production can increase the diversity of flora and fauna at the farm level, and how emerging conflicts between production and biodiversity can be resolved. Though the approach has been developed and implemented with organic farmers and for organic production systems, the general principles and specific measures are applicable, and indeed are in use, also in other contexts.

The 'Farming for Biodiversity' approach results from one of the first practice-orientated research of this kind, running since 2012 in Germany in organic farming systems (Gottwald & Stein-Bachinger, 2018). Operating in close cooperation with farmers, and drawing on expert knowledge, evidence-based information and their own scientific outputs, researchers have developed, tested and implemented a set of nature management options (overall about 150 options), accounting for the site conditions and farming practices (Stein-Bachinger et al., 2010; Stein-Bachinger & Fuchs, 2012; Gottwald & Stein-Bachinger, 2016). The overall precondition to join the scheme is following the standards of organic farming. To receive the certificate, farmers need to reach 120 points per 100 hectares from measures of their choice. The measures can be applied to arable land, grassland, landscape elements and farmsteads covering a broad range of options (see Table 1 for a selection of measures on grassland and grass-legume leys). Each measure is associated with credit points reflecting its ecological performance and area of implementation (Gottwald & Stein-Bachinger, 2018). The occurrence of special species (e.g. red list species) and habitats (e.g. wetlands) are evaluated as well (result-oriented modules). Since most of these nature conservation options entail additional costs or effort from farmers, or compromised yield and/or quality of agricultural products, every aspect was carefully quantified (Rühs & Stein-Bachinger, 2024), also using bio-economic modelling, which includes cost and benefit calculations alongside ecological gains (Schuler et al., 2013).

Involved land managers could get a premium price for selected products by the wholesaler EDEKA (e.g. meat, potatoes) if they reach a threshold of ecological quality based on a whole farm assessment. Consultants individually advise the farmers on how to implement nature conservation measures and help to identify target species. For example, moderate extensive grazing still allows good productivity for the farm. More biodiversity-friendly options on suitable grassland parcels (e.g. delayed cutting, leaving strips unmown) are

Table 1 Selection of measures on grassland and grass-legume leys offered to organic farmers in 'Farming for Biodiversity' approach in Germany.

Measure	Description
Basic measure	A moderately extensive grassland management (fertilisation according to the standards of organic farming; max. 2 livestock units/ha of the stocking rate, grazing regime adapted to the pasture growth, prevention of overgrazing; leaving grazing residues where possible; max. 2 grass cuts and subsequent grazing, management of problem weed species). There are additional measures available for selected parcels with one or more options.
Extensive grazing on dry grassland or coastal grassland	On sites with very low productivity; max. 0.8 LU/ha, no fertilisation
Reduction of rolling and levelling	For periods when species are sensitive to disturbance (depending on the region and species or avoiding it completely).
8–10 weeks without farming operations during the breeding period of birds or late first utilization for mowing or grazing beginning/middle of July	Ground breeding birds could complete their nesting.Delayed use must be adapted to the vegetation, as in productive and early maturing stands the vegetation often becomes too dense with permanent late utilization.
Leaving refuge (unmown or grazing-free areas within grassland)	About 3–20 % of refuges, also possible on pastures. Especially recommended at flower-rich areas, least productive spots, waterlogged depressions, strips along ditches and fences, etc.
Perennial strips	Strips at least 3 m wide that are not used or disturbed from summer to mid-July of the following year. Available also for legume-grass leys.
High cut on small or large scale	Mowing height at least 12 cm. Due to the lower proportion of stalks, the fodder quality will be better, which reduces the losses for the farmer. Available also for legume-grass leys.
Individual measures	A variety of site-specific measures for biodiversity-rich biotopes (such as semi-natural grasslands), and endangered species (such as corncrake (*Crex crex*)) can be individually added with the help of the advisor.

available additionally, and qualified for higher credit points and reaching the threshold more easily. Besides a premium price when having the 'Farming for Biodiversity' certificate, farmers could claim public financial support through agri-environmental schemes. Further non-monetary support to participating producers is provided by allowing consumers to get to know about biodiversity achievements of the farms through a tracking code (QR code) on the farm products leading to the project homepage (www.landwirtschaft-artenvielfalt.de).

The efficiency of the special measures for promoting biodiversity was analysed, confirming that, if implemented in the right way, combinations of these targeted measures benefit a wide range of taxa among plants, amphibians and birds (Gottwald & Stein-Bachinger, 2018). For example, measures implemented on legume–grass leys, such as 8–10 weeks rest period without farming operations or leaving refuge (Table 1), contributed to the reduction in the direct nest losses caused by mowing operations for four species of birds (Stein-Bachinger & Fuchs, 2012).

Research also confirmed the importance of implementing the most effective measures (ī.e. those that lead to most biodiversity gain), even when run at small scales. Such are, for example, leaving small strips or patches of grassland unused for a prolonged time as refuges for birds (Fig. 8), insects and other animals (Gottwald et al., 2017), or the clearing of woody plants on the south-facing sections of kettle holes for amphibians (Stein-Bachinger et al. 2021). For example, the breeding success of an emblematic meadow bird whinchat (*Saxicola rubetra*) was nearly double on grasslands with measures than on plots without them (Fig. 9). Although some of such measures are expensive to implement (e.g. leaving out unmown strips or postponing mowing of hay or silage grass on dairy farms), the fact that they can be implemented at a small scale might render them economically more acceptable, while they provide advantages for biodiversity as long as there is good connectivity to other suitable habitats (Kruse et al., 2016). Yet, the options most favoured by farmers on grassland were "reduction of rolling and levelling" and 'limitation in fertiliser application', which are relatively easy to implement on large areas (Gottwald & Stein-Bachinger, 2018).

This approach offers to farmers a high degree of flexibility for acquiring the nature conservation certificate. This is important because the feasibility, effectiveness and efficiency of the different measures are highly dependent

Figure 8 A late mown refuge along the field edge, in which Whinchats (*Saxicola rubetra*) predominantly build their nests (Gottwald et al. 2017).

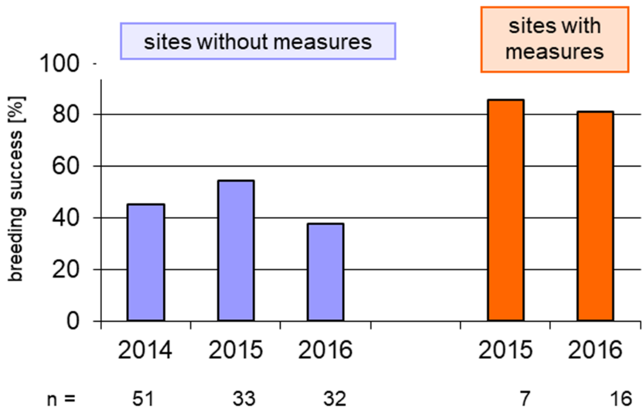

Figure 9 Breeding success of whinchat (*Saxicola rubetra*) (ratio of nests with at least one fledgling) for nest sites with and without measures (Gottwald et al. 2017).

on individual farm conditions, such as soil quality and weather circumstances. Because the measures are chosen mostly according to habitat type (as specified in the scheme) and characteristic species (proposed by advisors with knowledge of species), the approach offers a strategic and pragmatic way for improving biodiversity in any farm context. However, since this scheme is entirely voluntary, the decision to join it is ultimately based on the personal preferences and experiences of the farmers. The scoring scheme can be used by farmers also for a self-evaluation of their ecological performance, with the objective to ameliorate it (Birrer et al., 2014). This approach consisting of a scoring strategy and a series of optional measures for biodiversity promotion could be readily adapted to other geographic contexts and biomes.

Finally, the success of this approach relies largely on a long-term commitment of all actors: producers, advisors and regional agencies as shown in 'Farming for Biodiversity'. Over time, farmers' experience grows while advisors' competence improves, paving the way for consolidating efficient biodiversity-friendly and profitable farming systems into the future. The role of advisors is to help farmers identify target species and select suitable sites, taking both agricultural needs and species' ecological requirements into consideration. This may sound laborious but it is the price to pay for achieving tangible results for biodiversity while minimizing losses for the farmers. Compared to the mostly non-selective distribution of subsidies characterizing conventional input-based incentives, output-based strategies are economically and ecologically rational. Investing in expert advisory services specialised in biodiversity and agriculture is thus no waste of money. To conclude, farmers' readiness to cultivate land with nature objectives in mind increases if they can (1) choose between different measures from a sufficient set of options; (2) properly quantify inherent costs, which may be key for operating measures selection; (3) receive adequate remuneration given the effort and potential loss in production and (4) finally, assess their biodiversity achievements, preferably by themselves.

6 Conclusion

Biodiversity conservation is a rapidly advancing research area in sustainable grassland management. The biodiversity value of grasslands varies widely, primarily influenced by production-driven management intensity. There is considerable evidence by now that intensification of both grassland and arable systems has led to dramatic losses of farmland biodiversity, while the expansion of agricultural production, including of the livestock industry, has caused damages to the biosphere beyond agro-ecosystems. Among all habitat types, grasslands have one of the greatest potentials for supporting biodiversity within human-managed landscapes. Recognizing the impact of expanding grassland-based production on biodiversity is essential for realising this potential.

The well-established mechanisms through which management affects grassland biodiversity are known for many taxa, particularly in European grasslands, but also increasingly in North and South America, Africa, Australia and Asia. Due to ample research on the relationships between biodiversity and grassland management practices, practitioners can now choose from a wide array of approaches to promote and restore farmland flora and fauna, and deliver multiple ecosystem services. Optimal trade-offs between productivity, on one hand, and biodiversity and ecosystem services, on the other, may be difficult to achieve under all circumstances, especially on intensive permanent and temporary ley grasslands. Spatial and temporal optimisation of land use for multiple production and other purposes remains the crux. The underlying idea is to create a spatio-temporal mosaic of highly productive areas, extensively managed parcels, and native vegetation. Specific measures can then be adapted to the prevailing geographic, climatic, agricultural and socio-economic contexts, including the availability of public financial incentives. Sufficient societal and financial support to farmers, as our case study illustrates, are necessities for enhancing sustainability of grassland-based production.

The still prevailing mainstream focus on the volumes of agricultural yields negatively affects not only biodiversity but also the multifunctionality of the whole grassland-based production system. There is a growing recognition of the need to improve the sustainability of land use across wider rural landscapes to optimise overall benefits in the future, such as improving landscape hydrology, enhancing carbon storage and restoring nature, in which grasslands can play a crucial role. However, these benefits remain unrealised in most modern, intensively cultivated systems where grasslands occur. If the approaches outlined here are likely to deliver multiple benefits, including for biodiversity, they are likely to cause reductions in yields. Inherent trade-offs between achieving various benefits, including biodiversity, and high yields necessitate systemic changes, such as dietary adjustments on the food system level. Along with the adjustment of management, a shift towards more plant-based human diets is thus a prerequisite for achieving such a change of paradigm in agriculture and society. Only less extravagant patterns of food consumption, especially of animal proteins, in modern industrial societies will allow humanity to achieve multiple sustainability targets in food systems (Röös et al., 2022).

7 Future trends in research

We identify four key avenues of research that may in the future contribute to promote biodiversity and the provision of ecosystem services in cultivated grasslands. First, a rapidly progressing topic concerns the diversification of grassland vegetation through the addition of seed mixtures. Second, research is urgently needed on new modes of grassland management that allow other species to co-exist with production plants. Third, studies should focus on active restoration of biodiversity across grassland landscapes for improving whole-farm economic performance, while at the same time enhancing biodiversity and boosting key ecosystem services (Soliveres et al., 2016). Fourth, research should deal with minimising the indirect impacts of grassland-based production on biodiversity globally, including climatic impacts that fall outside of this chapter's focus.

Traditionally, research and education in the fields of grassland-based production and grassland conservation, respectively, tended to be separated by disciplinary lines (e.g. Herzon et al., 2021), but this is rapidly changing (Zhao, 2023). We need to seek adaptive solutions that include perspectives of ensuring adequate production and biodiversity conservation through flexible and goal-oriented management, and that are developed in close collaboration between scholars of grassland and ruminant production, grassland ecologists and producers (Durant et al., 2008). Such research should expand into regions with relatively little or no history of grazing by domesticated ruminants, such as Australia, so that the costs and benefits of grazing can be compared with the pros and cons of other sources of ecosystem disturbance aiming at maintaining grassy habitats, such as fire (Lunt et al., 2007).

Further research on ecosystem services of grasslands from a landscape-centered multi-scale perspective is essential (Zhao et al., 2020). Biodiversity must be measured across the whole range of present and potentially restorable farmed ecosystems devoted to grasslands-based production so that trade-offs can be grasped and balanced. Solutions should be developed across sectoral policies and their impacts modelled to minimise both direct and indirect impacts of grassland-based production on biodiversity at regional and global scales. The need to quantify the multifunctionality of grasslands has also been highlighted in view of monetary compensations to producers for efforts that go beyond production (e.g. EIP-AGRI, 2018; Lyons et al., 2023).

Research is also needed to improve and refine guidelines for successful implementation of specific biodiversity measures in grasslands, especially since today available methods are considered to be less efficient than on arable crops (e.g. Staggenborg & Anthes, 2022). Several gaps in knowledge have been highlighted in this chapter. In particular, we need controlled experiments that can tease apart which grazing and mowing modes are most beneficial to flora and fauna. In this respect, the impact of different types of grazers, combinations thereof and the influence of different grazing intensities across a variety of environmental conditions deliver precious information for sustainable management. However, given that processes at multiple levels are hardly amenable to controlled experimental trials, one must use novel methodological approaches based on modelling and simulations in order to integrate spatial and temporal processes at the relevant scale (e.g. Durant et al., 2008).

Research into belowground grassland biodiversity has made huge advances (Zhao, 2023), which is of prime importance considering the vital contribution of such biodiversity to soil fertility, plant nutrient uptake, disease suppression and carbon sequestration, as well as above-ground biodiversity (Lyons et al., 2023).

There is a need to streamline proper definitions of grassland types (Török & Dengler, 2021). This will ease the collection of statistics and the combination of remote-sensed data of different origins, and the development of common indicators. It will also help alerting about the grassland state and assist in decision-making for optimal management strategies. For now, there is a lack of studies comparing the functioning of permanent and temporary grasslands across the whole spectrum of ecosystem services as concluded in the review of Schils et al. (2022).

A further research agenda should be launched for combatting the degradation and promoting the restoration of grasslands for biodiversity, ecological functions and ecosystem services, while in the same time accounting for the long-term success of different restoration tactics from a socio-economic perspective (Bardgett et al., 2021).

Innovative technology development and deployment in all areas of environmental sustainability of grassland production has been particularly fast in recent times (Zhao, 2023). Potential negative impacts on biodiversity must be assessed critically while synergetic opportunities must be sought. The domain of alternative methods of grassland-based protein production that can be more compatible with wildlife conservation is an interesting avenue (Jori et al., 2021).

8 Acknowledgements

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9 Where to look for further information

The following articles and books provide a good overview of the subject:

Articles:

- Bengtsson, J. et al. (2019) 'Grasslands—more important for ecosystem services than you might think', *Ecosphere*, 10(2), p. e02582. Available at: https://doi.org/10.1002/ECS2.2582.
- Bullock, J.M. et al. (2020) 'Biodiversity in intensive grasslands: is a compromise possible?', *Grassland Science in Europe*, 25, pp. 384–393. Available at: https://www.europeangrassland.org/fileadmin/documents/Infos/Printed_Matter/Proceedings/EGF2020.pdf.
- Lindborg, R. et al. (2023) 'Ecosystem services provided by semi-natural and intensified grasslands: Synergies, trade-offs and linkages to plant traits and functional richness', *Applied Vegetation Science*, 26(2), pp. 1–13. Available at: https://doi.org/10.1111/avsc.12729.
- Plantureux, S., Peeters, A. and McCracken, D. (2005) 'Biodiversity in intensive grasslands: Effect of management, improvement and challenges', *Agronomy Research*, 3(2), pp. 153–164.
- Schils, R.L.M. et al. (2022) 'Permanent grasslands in Europe: Land use change and intensification decrease their multifunctionality', *Agriculture, Ecosystems and Environment*, 330(January). Available at: https://doi.org/10.1016/j.agee.2022.107891.

Books:

- Squires, V. R. Dengler, J., Hua, L., Feng, H. (eds.) (2018), *Grasslands of the World: Diversity, Management and Conservation*. CRC Press, ISBN 9780367780937 pp. 426.
- Grasslands and Shrublands - Sea of Plants. 2020. In: Goldstein, M. I. and DellaSala, D.A. (eds) *Encyclopedia of the World's Biomes*. Volume 3. Section

6. Elsevier. Available at: https://www.sciencedirect.com/referencework/9780128160978/encyclopedia-of-the-worlds-biomes: the most recent overview of grassland biomes of the world.
- Petermann J. S. and O. Y. Buzhdygan. 2021. Grassland biodiversity. *Current Biology* 31, 1195–1201, https://doi.org/10.1016/j.cub.2021.06.060.

Key research and research-based resources in this area can be found at the following organisations:

- Conservation Evidence (https://www.conservationevidence.com/): a free, authoritative information resource designed to support decisions about how to maintain and restore biodiversity; includes several summaries of evidence from the scientific literature about the effects of conservation actions on grasslands.
- Result based payment (RBP) network: https://www.rbpnetwork.eu/: a meeting point for sharing experiences on result based payments in Europe, of which many target grasslands.
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- HNV-Link (http://hnvlink.eu/): a networking project focusing on High Nature Value farmland and farming systems, and innovative solutions to increasing the socio-economic viability of such biodiverse systems.
- Biodiversity exploratories (https://www.biodiversity-exploratories.de/en/): a German large-scale project with research articles on grasslands ecology and biodiversity
- The Eurasian Dry Grassland Group (EDGG, https://edgg.org/): a European network of researchers and conservationists interested in natural and semi-natural grasslands.
- (https://www.biodivers.ch/): a webpage with practical guidelines and references for the management and restoration of divers habitat, including grasslands (in French and German).
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