Permanent grasslands in Europe: land use change and intensification decrease their multifunctionality

René L.M. Schils[a], Conny Bufe[a] , Caroline Rhymer[b], Richard Francksen[b], Valentin H. Klaus[c], Mohamed Abdalla[d], Filippo Milazzo[e], Eszter Lellei-Kovács[f], Hein ten Berge[a], Chiara Bertora[g], Anna Chodkiewicz[h], Claudia Dămătîrcă[g], Iris Feigenwinter[c], Pilar Fernández-Rebollo[i], Shiva Ghiasi[c*], Stanislav Hejduk[j], Matthew Hiron[k], Maria Janicka[h], Raoul Pellaton[f], Kate Smith[l], Rachel Thorman[l], Tom Vanwalleghem[e], John Williams[l], Laura Zavattaro[g**], Jarl Kampen[m], Ria Derkx[n], Pete Smith[d], Mark J. Whittingham[b], Nina Buchmann[c], Paul Newell Price[l]

[a]Agrosystems Research, Wageningen Plant Research, Droevendaalsesteeg 1, 6708 PB Wageningen, The Netherlands

[b]School of Natural and Environmental Sciences, Newcastle University, United Kingdom

[c]Department of Environmental Systems Science, Institute of Agricultural Sciences, ETH Zürich, Switzerland

[d]Institute of Biological and Environmental Sciences, University of Aberdeen, United Kingdom

[e]Department of Agronomy, ETSIAM, University of Córdoba, Spain

[f]Institute of Ecology and Botany, MTA Centre for Ecological Research, Hungary

[g]Department of Agricultural, Forest and Food Sciences, University of Torino, Italy

[h]Department of Agronomy, Faculty of Agriculture and Biology, Warsaw University of Life Sciences, Poland

[i]Department of Forestry, ETSIAM, University of Córdoba, Spain

[j]Department of Animal Nutrition and Forage Production, Mendel University, Czech Republic

[k]Department of Ecology, Swedish University of Agricultural Sciences, Sweden

[l]ADAS, United Kingdom

[m]Biometris, Department of Plant Sciences, Wageningen University, The Netherlands

[n]Library, Wageningen University and Research, The Netherlands

*Current address: Water Protection and Substance Flows Group, Agroscope Reckenholz, Switzerland

**Current address: Department of Veterinary Sciences, University of Torino, Italy.

Corresponding author: René L.M. Schils

E-mail: rene.schils@wur.nl

Abstract

Permanent grasslands cover 34% of the European Union's agricultural area and are vital for a wide variety of ecosystem services essential for our society. Over recent decades, the permanent grassland area has declined and land use change continues to threaten its extent. Simultaneously, the management intensity of permanent grasslands increased. We performed a systematic literature review on the multifunctionality of permanent grasslands in Europe, examining the effects of land use and management on 19 grassland ecosystem service indicators. Based on the evidence in 696 out of 70,456 screened papers, published since 1980, we found that both land use change and intensification of management decreased multifunctionality. In particular, preventing conversion of permanent grasslands to croplands secured the delivery of multiple ecosystem services. A lower management intensity was associated with benefits for biodiversity, climate regulation and water purification, but impacted the provision of high-quality animal feed. Increasing the number of species in the sward enhanced multifunctionality of permanent grassland without significant trade-offs such as losses in production. Our review covered many aspects of land use, management and ecosystem services, but we also identified areas with no or only few studies. The most prominent gaps were related to comparisons between permanent and temporary grasslands, and effects of management practices on the provision of cultural values, and on erosion and flood control. We suggest that, despite apparent changes in human dietary preferences, the protection of permanent grasslands in Europe must be prioritised. At the same time, considering the need to reduce ruminant livestock's contribution to climate change, the time seems ripe to increase support for low-intensity grassland management to optimise the provision of essential ecosystem services from Europe's permanent grasslands.

Keywords

agro-ecology, ecosystem services, grassland, land use change, systematic literature review

1. Introduction

Permanent grasslands cover 34% of the European Union’s agricultural area (Eurostat, 2020) and are vital for human wellbeing as they contribute to a wide variety of essential ecosystem services (O'Mara, 2012; Habel *et al.*, 2013; Bengtsson *et al.*, 2019). Thus, any change in their area or the capacity of grassland to provide ecosystem services will have significant societal impacts. For centuries, permanent grasslands have been the basis for livestock production and the main pillar of nutrient cycling on farms all over Europe (Green, 1990; Lemaire *et al.*, 2011; Hejcman *et al.*, 2013). After the Second World War, the goal of self-sufficiency in food production stimulated the improvement and intensification of management of permanent grasslands, or their conversion to temporary grasslands or croplands. In less versatile areas, like mountainous regions or wet lowlands, large areas of permanent grasslands were abandoned or afforested (Habel *et al.*, 2013; Boch *et al.*, 2020). While statistical data on the loss of permanent grasslands are fragmented, the available figures illustrate the significant loss during the last decades. For example, in the EU-6 countries (Belgium, Netherlands, Luxemburg, France, Former West Germany, Italy), permanent grassland losses have been estimated at about 30% between 1967 and 2007 (Huyghe *et al.*, 2014). Regionally, losses have been even higher, as in Upper Normandy, France, where about 50% of the permanent grassland area was lost between 1970 and 2000 (Van Den Pol-Van Dasselaar *et al.*, 2019). In Eastern Europe, the political transformations at the end of the 1980s triggered large scale abandonment of permanent grasslands, as in Slovakia where 42% of permanent grasslands were left unused (Kizeková *et al.*, 2018).

Today, grass is still among the cheapest high-quality feed sources for efficient ruminant meat and dairy production (van den Pol *et al.*, 2018). In addition to the provision of feed, permanent grasslands sustain a broad range of additional ecosystem services, including climate regulation through carbon sequestration (Soussana *et al.*, 2010), cultural values (Hussain *et al.*, 2019), protection against erosion and flooding (Macleod *et al.*, 2013), and pollination of food crops (Klein *et al.*, 2007; Scheper *et al.*, 2013).

Permanent grasslands across Europe are very diverse in appearance (Fig. 1). This is partly driven by inherent factors such as climate and soil, but also by varying intensities of grassland management, resulting in continuous gradients of fertilisation and defoliation (mowing or grazing) intensities (Blüthgen *et al.*, 2012). Some studies have addressed aspects of multifunctionality of grasslands for a specific region (Allan *et al.*, 2015) or specific experimental sites (Werling *et al.*, 2014; Meyer *et al.*, 2018). Others focused on temperate grasslands (Pilgrim *et al.*, 2010), cultivated grasslands (Sollenberger *et al.*, 2019), (semi)-natural grasslands (Bengtsson *et al.*, 2019) or grazing lands (D'Ottavio *et al.*, 2018). For European permanent grasslands we thus have a restricted understanding of land use and management effects on multifunctionality, which limits our ability to understand and predict the effects of land use change and management intensification on the provisioning of vital grassland ecosystem services. Here, we analyse the body of, mainly monodisciplinary, studies across Europe in a comprehensive multidisciplinary systematic literature review with a focus on experimental contrasts in land use and management aspects. Our aim was to understand the effects of land use change and management intensification on the provision of several major grassland ecosystem services. We considered the "big five" grassland ecosystem services, i.e. *provision of animal feed*, *biodiversity*, *climate regulation*, *water purification,* and *cultural values* (Isselstein and Kayser, 2014), and added a sixth important service, *erosion and flood control*.

Our study addressed two central research questions: first, what are the reported effects of land use change, i.e. the conversion to other land uses such as temporary grassland, cropland or forest, on the delivery of grassland ecosystem services? Second, what are the reported effects of intensification and specific management options on the delivery of ecosystem services by permanent grassland? The outcomes of this review draw a comprehensive overview of ecosystem service delivery from permanent grasslands across Europe, including an integrated assessment of multifunctionality. Furthermore, we identified relevant gaps in ecosystem service research that limit the understanding of land use and management effects on multifunctionality required for policy and farm management decisions.

2. Methods

2.1 Permanent grassland

We used the European Union's definition of permanent grassland, as land used to grow grasses or other herbaceous forage that has not been included in the crop rotation of the holding for a duration of five years or longer (EU, 2004).

2.2 Indicators of ecosystem services

We selected a set of indicators (Table S2) that comprised a cross-cutting representation of biodiversity and ecosystem services of permanent grasslands. We are aware of the multiple roles of biodiversity in the delivery of ecosystem services, as a regulator of ecosystem processes, as a service in itself and as a good (Mace *et al.*, 2012). For clarity, we consider biodiversity as one of the ecosystem services.

2.3 Search strategy – inclusion criteria

In the fourth quarter of 2019, we searched the Scopus and CAB abstracts databases for grassland studies on 19 indicators of ecosystem services in Europe, published in the English language from 1980 onwards (Table S3). Scopus and CAB abstracts were used for this systematic review because both databases can effectively perform complex Boolean searches with regards to precision, recall and reproducibility, which is a prerequisite for systematic searching (Gusenbauer and Haddaway, 2020). CAB Abstracts is the leading database on applied life sciences, including crop sciences and grasslands, animal science, environmental science, and recreation/tourism. The multidisciplinary database Scopus is the largest abstract and citation database of peer-reviewed literature in the field of science, technology, medicine, and social sciences.

Search strings were evaluated and refined in several steps by assessing the relevance of the papers returned, and by checking against key papers in the field. A wide range of search terms were used to cover the diversity of methods used to assess the provision of ecosystem services of permanent grasslands. We developed a search string for the concept "grass", and combined this, using an AND-operator, with the search string for each one of the 19 ecosystem service indicators.

We combined the 19 sets of search results into de-duplicated Endnote libraries, one for each ecosystem service. We collected a total of 70,456 papers, varying from 7,181 papers for *water purification* to 16,201 papers for *biodiversity* (Table S1). These papers, including abstracts, were uploaded to the dedicated systematic review analysis software 'EPPI reviewer 4 tool' (http://eppi.ioe.ac.uk/cms/), as six corresponding reviews.

2.4 Exclusion criteria

Titles and abstracts were screened in two stages, using the following same set of exclusion criteria:

- Not in the English language.
- Outside these Natura 2000 biogeographic zones of interest: Alpine, Atlantic, Boreal, Continental, Mediterranean or Pannonian. Biogeographical boundaries are a combination of official delineations used in the Habitats Directive (92/43/EEC) and for the EMERALD Network under the Convention on the Conservation of European Wildlife and Natural Habitats (Bern Convention). They are independent of political boundaries of Emerald Network countries or EU Member States (https://www.eea.europa.eu/data-and-maps/data/biogeographical-regions-europe-3).
- Outside these countries in Europe: Member states of the EU-28 or Albania, Belarus, Bosnia Herzegovina, Kosovo, Macedonia, Moldova, Montenegro, Norway, Serbia, Switzerland or Ukraine.
- Unit of study was not grassland.
- The outcome was not one of the 19 indicators of interest.
- Papers on urban amenity grasses.

- Reviews.
- Modelling studies.
- Experiments under controlled conditions: laboratories, greenhouses or pots.

2.5 Study selection on contrasts

The papers retained after the title and abstract screening contained the body of literature on European experimental studies, published after 1980 and in the English language, and on one or more of the 19 indicators for grassland. From this set of 11,619 papers, we selected papers that contained at least one of eight experimental contrasts in land use (permanent grassland versus cropland, forest or temporary grassland) or contrasts in management (sward renewal, legume presence, number of species, defoliation frequency and nitrogen input).

2.6 Data extraction

After screening for eligible contrasts, we retained 3,664 studies for full text screening. Retrieved papers were read and either extracted or excluded with reasons (Fig. S1 and Table S1). For time management reasons, we developed a stepwise sampling procedure among eligible papers within the ecosystem services *biodiversity* and *provision of animal feed*, which each had more than 1,000 eligible papers. We took consecutive random samples of 300 papers out of the eligible papers for data extraction until a maximum of 300 extracted papers. Eventually, 510 papers out of the 1,313 papers of the *provision of animal feed* domain were not included in the sample.

Data from valid sampled full text papers were extracted using a data extraction form, developed in MS Excel, consisting of two sections (Table S4). The first form (Study) was used to extract data per paper: bibliographical identification, study type, geography, experimental contrasts, and methods for assessment of the relevant indicators. If a paper was excluded at this stage, the reason was recorded in this form as well. The second form (Contrast) was used to extract data on the experimental contrasts. Each paper consisted of at least one contrast and in total the 696 papers contained 1032 eligible experimental contrasts, which we define as a 'case'. Here, we registered the outcome: no conclusion, favourable, neutral, or unfavourable (Table S5). The outcome was based on the numerical data and statistical significance in tables, figures, or text, or based on authors' claims in the text. This approach allowed us to combine the extremely heterogeneous data and metrics across ecosystem service indicators, allowing a greater number of studies to be compared for a more comprehensive answer to our research questions. Rather than simply counting which studies had outcomes in a certain direction, sometimes referred to as 'vote-counting' (Stewart, 2010), we applied strict criteria for the inclusion of studies and for the assessment of the direction of interventions on the outcome of ecosystem service indicators.

2.7 Data analysis

The outcomes from the data extraction form were tabulated per contrast. For statistical analysis, the outcomes were transformed to numerical values (favourable = 1, neutral = 0, unfavourable = -1). Cases with no conclusion were discarded from the analysis. A one-sample t-test was carried out, with H_0 assuming no effect (outcome = 0). The analysis was carried out with the facilities of SPSS version 25 (SPSS, 2020).

2.8 Reviewer bias

Screening and data extraction were carried out by expert teams, consisting of a lead-reviewer and at least one co-reviewer per ecosystem service. The assessment of the lead-reviewer, an expert in the field, was the benchmark against which the co-reviewers' assessments were compared. To align the scoring in screening and extraction, intermediate results including arising disputes were discussed and resolved. At least 5% of the papers were double-screened, independently by the lead-reviewer and one or more co-reviewers. We assessed the number and proportion of 'false exclusions', i.e. when the co-reviewer excluded a paper that was included by the lead-reviewer. If the proportion of false exclusions was higher than 10%, we reconciled the issues.

3. Results and Discussion

3.1 Spatial and temporal outline of the evidence

We considered 70,456 papers, identified for 19 indicators of grassland ecosystem services (Table S1) across Europe, published since 1980 (Fig. S1 and Table S2). After screening, we included 696 papers in the final analysis (1%). While we found papers covering almost all regions of Europe, the majority were found in a broad northwest to southeast range, roughly stretching from the British Isles to Eastern Europe (Fig. 2). Although most of the papers included in this review were identified in regions where over 40% of the utilised agricultural area (UAA) was covered by permanent grasslands, regions with less than 20% permanent grasslands were also represented. Around two thirds of the extracted papers originated from the Atlantic or Continental biogeographic regions (Fig. S2). Studies on the environmental ecosystem services *water purification* and *climate regulation* were overrepresented in the Atlantic region, most likely related to the high grassland productivity (Smit *et al.*, 2008) and higher intensity of livestock farming in these areas (Leip *et al.*, 2015).

Over the past 40 years, the scientific literature on permanent grasslands in Europe has been dominated by studies on the *provision of animal feed* (Fig. S3). We found that the number of papers focusing on other grassland ecosystem services increased gradually, in line with developments in societal debates (Hall *et al.*, 2004) and European Union's regulations like the Nitrates Directive (EU, 1991), Birds and Habitats Directive (EU, 1992), Soil strategy (EU, 2006), climate change policies (Jordan and Rayner, 2010) and greening measures in the Common Agricultural Policy (Hauck *et al.*, 2014). Despite the change in policy priorities, permanent grasslands' role as provider of animal feed remained among the top priorities of the research agenda.

While our review allowed us to cover many important aspects of land use, management and ecosystem services, some study topics were underrepresented such as the comparison between permanent and temporary grasslands, effects of species diversity on climate regulation, the relation between grassland management and cultural values, and the topics erosion and flood control (Fig. S5 and S7). Moreover, we did not find any eligible papers on pesticides leaching into ground and surface water from permanent grasslands.

3.2 Preserving permanent grasslands secures vital ecosystem services

We found that most studies reported favourable outcomes for permanent grasslands compared to croplands across all ecosystem service indicators, except for forage yield and energy content (Fig. 3a, Fig. S4 and Fig. S5). A significantly high proportion of studies reported favourable outcomes for permanent grasslands on threatened species (e.g. Bretagnolle *et al.*, 2011), carbon sequestration (e.g. Gregory *et al.*, 2016) and nitrogen losses to water (e.g. Webster *et al.*, 1999). Furthermore, the favourable outcomes of all indicators for *climate regulation, water purification, erosion and flood control,* and *cultural values* were supported by at least five cases.

Only a few studies compared permanent to temporary grasslands, with the outcomes generally supported by less than five cases. We found no consistent evidence, with only seven cases available, of higher grass yields from temporary grasslands compared to permanent grasslands, contrary to the common expectation when converting permanent grasslands into temporary grasslands (Søegaard *et al.*, 2007). Temporary grasslands are, by definition, always part of a rotation with other crops. This implies that the outcomes of the comparison with croplands are also relevant for the assessment of the conversion from permanent to temporary grassland.

Even though permanent grasslands are extremely diverse across Europe, a common denominator is that the livelihood of farms with permanent grasslands depends to some extent on ruminant animal production. Therefore, the current feed-food debate (Tilman and Clark, 2014; Di Paola *et al.*, 2017) and the interlinked urgency to reduce methane emissions from ruminant livestock (Gerber *et al.*, 2013) is highly relevant for the future of permanent grasslands. So, while in some areas there may be arguments for conversion of suitable permanent grassland to cropland for direct human food production, such conversion would clearly come with an impact on vital ecosystem services such as carbon sequestration*, biodiversity and water purification*.

The European Union's Common Agricultural Policy recognises the value of the ecosystem services provided by permanent grasslands (EU, 2013). Under the current policy, a so-called "green direct payment" is provided. The measure aimed to limit declines in the ratio of permanent grassland to total utilised agricultural area to less than 5%, and to protect the most environmentally sensitive permanent grasslands from conversion. In future, these payments will fall under the new conditionality element of the post-2020 Common Agricultural Policy (EU, 2019). Enhanced management of permanent grasslands will be promoted under the new eco-schemes in which national authorities have more flexibility and can be more ambitious to direct and extend these measures.

When permanent grasslands were compared to forests, the reported outcomes suggest trade-offs between the studied ecosystem services (Fig. 3b). We found consistent evidence of studies reporting a better performance of forests regarding all indicators for *erosion and flood control* (Fig. S4 and Fig. S5). In contrast, most studies reported higher levels of *biodiversity* and *cultural values* for permanent grasslands compared to forests, in particular for the indicators threatened species and aesthetic value. The reported outcomes on *climate regulation* and *water purification* did not show a consistent effect. A small majority of cases (9 versus 6; Fig. S5) showed higher soil carbon sequestration in forests (e.g. Prescher *et al.*, 2010). However, our assessment did not include the overall ecosystem carbon sequestration of forests which is typically higher than in permanent grasslands due to the long term build-up of above ground biomass (Schulze *et al.*, 2009). For harvested woodlands, the timing of harvest and the fate of the harvested wood determines its overall carbon sequestration effect (Ciais *et al.*, 2008).

Our findings on the comparison between permanent grasslands and forests are also relevant for the broader land use debate. Withdrawal of permanent grasslands from agriculture and subsequent afforestation, as suggested for example by the Bonn

Challenge could reduce the environmental impacts of livestock, if dietary demand by consumers declined in parallel. However, such conversion to forest would not be able to sustain the high multifunctionality provided by permanent grasslands under reduced or extensive management (Temperton *et al.*, 2019). To integrate the advantages of forestry in agricultural land use, there is also a role for silvopastoral systems in conserving biodiversity and enhancing broad ecosystem service provision, including animal feed (Torralba *et al.*, 2016).

We identified a lack of studies that compared permanent to temporary grasslands, especially across the whole spectrum of non-feed ecosystem services (Fig. S5). These research gaps can be addressed by either long-term plot experiments under controlled conditions or monitoring campaigns at the scale of fields or landscapes, depending on the targeted ecosystem service indicator.

3.3 Reduced management intensity benefits multifunctionality

We found consistent trade-offs in the reported outcomes between indicators for feed and non-feed ecosystem services for three types of management options that represent increasing management intensity, i.e. nitrogen input, increasing defoliation frequency and grass renewal (Fig. 4a). For nitrogen input, we found significantly unfavourable effects on all indicators for *biodiversity, water purification*, and *climate regulation*, except carbon sequestration (Fig. S6 and Fig. S7). In contrast, there were significantly favourable effects of nitrogen on forage yield and protein content. Yield and quality were oppositely affected by defoliation frequency. With increasing frequency, we found a significant improvement of forage quality, but a significantly lower forage yield (e.g. Hopkins *et al.*, 1990; Nerusil *et al.*, 2008). There were few studies on the effect of defoliation frequency on the non-feed ecosystem services. We found a limited number of studies for *climate regulation (7)* and *water purification (6)* but no cases for *erosion and flood control* or *cultural values.* However, the overall negative effects of increasing defoliation frequency on all indicators of *biodiversity* and on nitrogen losses to water were supported by at least five cases. Finally, grass renewal showed significant favourable effects on forage yield, but no consistent effect on forage quality, across 30 cases for energy content and 28 cases for protein content (e.g. Badia *et al.*, 1994; Butkuviene and Butkute, 2007). In contrast, we found that grassland renewal significantly increased nitrous oxide emissions (e.g. Merbold *et al.*, 2014) and nitrogen losses to water (e.g. Velthof *et al.*, 2010). It is remarkable that only 40% of the studies stated the sward age at renewal. Of these, the dominant sward age at renewal was between 5 and 25 years, while only 10% were younger than 5 years (e.g. Vliegher and Carlier, 2007) and 20% older than 25 years (e.g. Bommele *et al.*, 2006).

In addition to the above interventions which relate to intensity of management, diversification of the sward was studied as a separate category of management options, which we do not consider as a dimension of intensity. The reported outcomes of increased number of species in the sward showed mainly favourable effects on the indicators for *biodiversity, cultural values* and *water purification* and mixed effects on *provision of animal feed* (Fig. 4b). An increased number of species significantly increased the number of pollinators and threatened species. There were less than five cases for *cultural values* and *water purification*, but they consistently reported a favourable effect of number of species in the sward. An increased number of species significantly increased yield, but decreased the energy content, and showed no consistent effect on protein content.

We found that papers comparing swards with and without legumes, with similar nitrogen fertiliser inputs, reported significant favourable effects of legumes on yield and protein content, whereas energy content was not affected. Papers on the non-feed ecosystem services of legume presence were relatively underrepresented. A consistent favourable effect of legumes, based on eight cases, was reported for the abundance of pollinators (e.g. Woodcock *et al.*, 2014). The papers on nitrogen losses to water showed a small unfavourable effect of the presence of legumes (e.g. De Vries *et al.*, 2006).

Our findings on the key role of grassland management in regulating the provision of ecosystem services are in line with earlier non-systematic reviews, limited to temperate grasslands in lowland Europe (Pilgrim *et al.*, 2010) or cultivated grasslands (Sollenberger *et al.*, 2019). Over the past 60 years, the average management intensity of European grasslands has clearly increased (Hopkins and Wilkins, 2006). In many regions permanent grasslands also experienced increasing livestock densities, received higher nutrient inputs, and were subjected to higher cutting frequencies, modulated by drainage, irrigation, resowing and oversowing with improved cultivars, as well as weed control with herbicides (Peeters, 2009). We found that an increased management intensity of permanent grasslands substantially decreased multifunctionality and especially had unfavourable impacts on *biodiversity*, *climate regulation* and *water purification*. Therefore, we argue that a low or reduced management intensity of permanent grasslands can help to better strike the balance between the environmental impact of ruminants and the utilisation of herbage on these areas. First, in regions like Eastern Europe where intensification is still ongoing in some areas (Török *et al.*, 2020), the main aim should be to identify options to support management that enables securing the current level of all ecosystem services and avoid drastic intensification. Second, in regions with predominantly intensive grasslands, simply reducing management intensity will not lead to an immediate recovery of all ecosystem services as the extensification pathway is not the exact inverse of the intensification pathway (Bakker and Berendse, 1999). While, for instance, greenhouse gas emissions would decrease relatively fast, the response of biodiversity will be rather slow, and might require active measures of ecological restoration (Isselstein *et al.*, 2005; Klaus *et al.*, 2016). Besides technical innovations, effective restoration requires integrated socio-economic solutions including recognition of grasslands in global policy and enhancing knowledge transfer and data sharing on restoration experiences (Bardgett *et al.*, 2021).

Prioritising non-feed ecosystem services comes at a cost of the *provision of animal feed*. While this trade-off is clear for reducing nitrogen input, other management interventions show mixed or even synergistic outcomes and thus should be implemented more frequently. For instance, we found that a higher number of species in the sward is favourable for *biodiversity* and *provision of animal feed*, albeit with predominantly lower herbage energy content. Introduction of multiple species in species-poor swards, including legumes, will however require some form of sward renewal, which itself can have unfavourable effects on *climate regulation* and *water purification.* Grassland renewal should thus only be carried out infrequently, with as little soil disturbance as is manageable to achieve the seeding objective and when conditions are favourable to maximise the probability of successful establishment. The proposed shift from feed to non-feed ecosystem services will come with a reduced stocking rate and thus lower milk or meat production per hectare with potential negative effects on farm income, as long as payments for public goods are widely lacking (Pe'er *et al.*, 2020). However, increasing the number of species in the sward for example, can also have positive effects on magnitude and stability of economic revenues, in particular for risk-averse farmers (Binder *et al.*, 2018; Schaub *et al.*, 2020).

With regard to management interventions, we identified several options with a limited number, or even a complete lack, of studies (Fig. S7). Especially, clarification of management effects on indicators of *cultural values,* and on *erosion and flood control* will require additional research efforts in the future. Furthermore, we found underrepresentation of studies looking into effects of plant richness in the sward, defoliation frequency and legume presence on indicators of *climate regulation*.

3.4 Outlook for permanent grassland

In this extensive systematic review of the literature on permanent grasslands across Europe, we found that preventing the conversion of permanent grassland to cropland or temporary grassland secures the provision of multiple ecosystem services. In addition, we found that intensification of existing permanent grasslands threatens multifunctionality. These findings are important for the future of permanent grasslands in view of the impact of our food system, and especially ruminant livestock, on environmental change.

When addressing the question of land use change, it is important to consider that permanent grasslands are not by default without alternatives for other land uses (Van Zanten *et al.*, 2018). As such, non-agricultural options, for instance re-wilding and afforestation, may be viable alternatives as well, though come with their own social and ecological implications (Navarro and Pereira, 2015). In areas where other agricultural land uses are possible as alternatives for permanent grassland, many factors need to be considered when planning the most sensible and beneficial land use. Societal developments, including the changing demand for red and white meats, but also an increasing shift towards vegetarian and vegan diets will exert pressures that may shift the ratio between grassland and cropland (Garnett *et al.*, 2017), and thereby affect biodiversity (Crenna *et al.*, 2019), and the overall land footprint of food production (Rizvi *et al.*, 2018). The need to mitigate global warming prompts action to protect carbon stocks that have meanwhile accumulated in permanent grasslands. In the light of climate change, permanent grasslands' significant role in reducing erosion and flooding risk is also likely to increase, as the frequency of extreme events is expected to rise (Tabari, 2020). Livestock numbers play a key role in the total greenhouse gas budget of grasslands, including methane (Chang *et al.*, 2021). Although grassland-based ruminant livestock production systems contribute a minority to the total ruminant livestock emissions (Garnett *et al.*, 2017), they still produce a potent greenhouse gas, which should be evaluated within the widely acknowledged need to stabilise or reduce total ruminant livestock numbers (Gerber *et al.*, 2013). Finding the optimal role for permanent grassland in sustainable land use configurations requires systemic analyses at regional scales that include consideration of land capability, consumer preferences, farmer livelihoods and environment, but also biodiversity and cultural values (Poux and Aubert, 2018; Le Clec'h *et al.*, 2019).

Our review showed that, in general, a lower management intensity allows for a higher multifunctionality. At the same time, we identified that prioritising non-feed ecosystem services comes at a cost for the provision of animal feed. Here, we need to emphasise that there is no simple general blueprint for the implementation of a reduced management intensity. Extensification is more than just reducing inputs and may require some kind of ecological restoration including the supply of affordable seed mixtures for diverse grasslands (Schaub *et al.*, 2021). Moreover, multifunctionality is likely to be optimised differently depending on the local context (Text S1). An optimal configuration on a farm in the Italian Alps might not work for farms on the west coast of Ireland. That level of detail has not been drawn out in this assessment. However, many farmers are locked in production-orientated systems, influenced by persistently low prices for milk and meat (Erisman *et al.*, 2016). Therefore, a wide-scale transition to more reliance on extensively managed permanent grasslands requires a multifaceted approach, including knowledge transfer, policy development and alternative payment schemes for ecosystem service delivery. Runhaar (2021) reasoned that these types of regime changes are only possible if four conditions are met, (i) concrete goals or actions, (ii) political and societal pressure, (iii) a broad coalition for change, and (iv) institutions to support and sustain the regime change. The presence of these conditions will vary widely in different contexts across Europe. Furthermore, different stakeholders hold different views towards permanent grassland which may affect their priorities and goals (Tindale *et al.*, 2020).

Over recent decades, the permanent grassland area suffered significant losses. The outcomes of our review suggests that, in spite of apparent changes in dietary preferences, the protection of permanent grasslands in Europe has to be prioritised to prevent further losses of the area and thus the provision of multiple ecosystem services. At the same time, in view of the need to reduce ruminant livestock's impact on climate change, the time seems ripe to increase support for low-intensity management on existing permanent grasslands. The combined approach of protection and extensification will help secure multiple benefits from Europe's permanent grasslands.

Acknowledgments

We acknowledge the financial support of this work by European Union Horizon 2020 research and innovation programme, under grant agreement 774124, project SUPER-*G* (Developing Sustainable Permanent Grassland Systems and Policies).

Data availability

The data that support the findings of this study are available at https://doi.org/10.4121/17888573.

Author Declarations

The authors declare no conflicts of interest or competing interests.

Author Contributions

RS, CBu, CR, RF, VK, MA, FM, EL, HB, TV, RD, JK, PS, MW, NB, PN designed research.

RS, CBu, CR, RF, VK, MA, FM, EL, HB, CBe, AC, CD, IF, PF, SG, SH, MH, MJ, RP, KS, RT, TV, JW, LZ performed research.

RS, CBu, CR, RF, VK, MA, FM, EL, JK analyzed the data.

RS, CBu, CR, RF, VK, MA, FM, EL, HB, TV, PS, MW, NB, PN wrote the paper.

References

Allan, E., Manning, P., Alt, F., Binkenstein, J., Blaser, S., Blüthgen, N., Böhm, S., Grassein, F., Hölzel, N., Klaus, V.H., Kleinebecker, T., Morris, E.K., Oelmann, Y., Prati, D., Renner, S.C., Rillig, M.C., Schaefer, M., Schloter, M., Schmitt, B., Schöning, I., Schrumpf, M., Solly, E., Sorkau, E., Steckel, J., Steffen-Dewenter, I., Stempfhuber, B., Tschapka, M., Weiner, C.N., Weisser, W.W., Werner, M., Westphal, C., Wilcke, W., Fischer, M., 2015. Land use intensification alters ecosystem multifunctionality via loss of biodiversity and changes to functional composition. Ecology Letters 18, 834-843.

Badia, D., Marti, C., Terreros, J., 1994. Nutritional value of semi-arid pastures: influence of soil type and grass sowing. Agricoltura Mediterranea 124, 289-300.

Bakker, J.P., Berendse, F., 1999. Constraints in the restoration of ecological diversity in grassland and heathland communities. Trends in Ecology & Evolution 14, 63-68.

Bardgett, R.D., Bullock, J.M., Lavorel, S., Manning, P., Schaffner, U., Ostle, N., Chomel, M., Durigan, G., L. Fry, E., Johnson, D., Lavallee, J.M., Le Provost, G., Luo, S., Png, K., Sankaran, M., Hou, X., Zhou, H., Ma, L., Ren, W., Li, X., Ding, Y., Li, Y., Shi, H., 2021. Combatting global grassland degradation. Nature Reviews Earth & Environment.

Bengtsson, J., Bullock, J.M., Egoh, B., Everson, C., Everson, T., O'Connor, T., O'Farrell, P.J., Smith, H.G., Lindborg, R., 2019. Grasslands—more important for ecosystem services than you might think. Ecosphere 10, e02582.

Binder, S., Isbell, F., Polasky, S., Catford, J.A., Tilman, D., 2018. Grassland biodiversity can pay. Proceedings of the National Academy of Sciences 115, 3876.

Blüthgen, N., Dormann, C.F., Prati, D., Klaus, V.H., Kleinebecker, T., Hölzel, N., Alt, F., Boch, S., Gockel, S., Hemp, A., Müller, J., Nieschulze, J., Renner, S.C., Schöning, I., Schumacher, U., Socher, S.A., Wells, K., Birkhofer, K., Buscot, F., Oelmann, Y., Rothenwöhrer, C., Scherber, C., Tscharntke, T., Weiner, C.N., Fischer, M., Kalko, E.K.V., Linsenmair, K.E., Schulze, E.-D., Weisser, W.W., 2012. A quantitative index of land-use intensity in grasslands: Integrating mowing, grazing and fertilization. Basic and Applied Ecology 13, 207-220.

Boch, S., Biurrun, I., Rodwell, J., 2020. Grasslands of Western Europe. In: Goldstein, M.I., DellaSala, D.A. (Eds.), Encyclopedia of the World's biomes. Elsevier, Oxford, UK.

Bommele, L., Reheul, D., Maes, I., Eekeren, N.v., 2006. White clover content in mixed swards installed in fields with different preceding crop. (Grassland Science in Europe, Volume 11). In: Lloveras, J., Gonzalez-Rodriguez, A., Vazquez-Yanez, O., Pineiro, J., Santamaria, O., Olea, L., Poblaciones, M.J. (Eds.). Sustainable grassland productivity

Sociedad Espanola para el Estudio de los Pastos (SEEP), Madrid, pp. 336-338 331 ref.

Bretagnolle, V., Villers, A., Denonfoux, L., Cornulier, T., Inchausti, P., Badenhausser, I., 2011. Rapid recovery of a depleted population of Little Bustards Tetrax tetrax following provision of alfalfa through an agri-environment scheme. Ibis 153, 4-13.

Butkuviene, E., Butkute, R., 2007. The changes of sward botanical and chemical composition depending on pasture improvement measures. (Grassland Science in Europe Volume 12). In: Vliegher, A.d., Carlier, L. (Eds.). Permanent and temporary grassland

Belgian Society for Grassland and Forage Crops, Merlbeke, pp. Proceedings of the 14th Symposium of the European Grassland Federation, Ghent, Belgium, 13-15 September 2007; 2007 2118-2121 2008 ref.

Chang, J., Ciais, P., Gasser, T., Smith, P., Herrero, M., Havlík, P., Obersteiner, M., Guenet, B., Goll, D.S., Li, W., Naipal, V., Peng, S., Qiu, C., Tian, H., Viovy, N., Yue, C., Zhu, D., 2021. Climate warming from managed grasslands cancels the cooling effect of carbon sinks in sparsely grazed and natural grasslands. Nature Communications 12, 118.

Ciais, P., Schelhaas, M.J., Zaehle, S., Piao, S.L., Cescatti, A., Liski, J., Luyssaert, S., Le-Maire, G., Schulze, E.D., Bouriaud, O., Freibauer, A., Valentini, R., Nabuurs, G.J., 2008. Carbon accumulation in European forests. Nature Geoscience 1, 425-429.

Crenna, E., Sinkko, T., Sala, S., 2019. Biodiversity impacts due to food consumption in Europe. Journal of Cleaner Production 227, 378-391.

D'Ottavio, P., Francioni, M., Trozzo, L., Sedić, E., Budimir, K., Avanzolini, P., Trombetta, M.F., Porqueddu, C., Santilocchi, R., Toderi, M., 2018. Trends and approaches in the analysis of ecosystem services provided by grazing systems: A review. Grass and Forage Science 73, 15-25.

De Vries, F.T., Hoffland, E., Van Eekeren, N., Brussaard, L., Bloem, J., 2006. Fungal/bacterial ratios in grasslands with contrasting nitrogen management. Soil Biology & Biochemistry 38, 2092-2103.

Di Paola, A., Rulli, M.C., Santini, M., 2017. Human food vs. animal feed debate. A thorough analysis of environmental footprints. Land Use Policy 67, 652-659.

Erisman, J.W., Eekeren, N.v., Wit, J.d., Koopmans, C., Cuijpers, W., Oerlemans, N., Koks, B.J., 2016. Agriculture and biodiversity: a better balance benefits both. AIMS Agriculture and Food 1, 157-174.

EU, 1991. Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources.

EU, 1992. Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora.

EU, 2004. Commission Regulation (EC) No 796/2004 of 21 April 2004 laying down detailed rules for the implementation of cross-compliance, modulation and the integrated administration and control system provided for in of Council Regulation (EC) No 1782/2003 establishing common rules for direct support schemes under the common agricultural policy and establishing certain support schemes for farmers.

EU, 2006. Proposal for a Directive of the European Parliament and of the Council establishing a framework for the protection of soil and amending Directive 2004/35/EC.

EU, 2013. Regulation (EU) No 1307/2013 of the European Parliament and of the Council of 17 December 2013 establishing rules for direct payments to farmers under support

schemes within the framework of the common agricultural policy and repealing Council Regulation (EC) No 637/2008 and Council Regulation (EC) No 73/2009.
EU, 2019. The post-2020 common agricultural policy: Environmental benefits and simplification.
Eurostat, 2020. Share of main land types in utilised agricultural area (UAA) by NUTS 2 regions.
Garnett, T., Godde, C., Muller, A., Röös, E., Smith, P., De Boer, I., zu Ermgassen, E., Herrero, M., Van Middelaar, C., Schader, C., 2017. Grazed and confused?: ruminating on cattle, grazing systems, methane, nitrous oxide, the soil carbon sequestration question-and what it all means for greenhouse gas emissions. FCRN.
Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., Tempio, G., 2013. Tackling climate change through livestock: a global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations (FAO).
Green, B.H., 1990. Agricultural intensification and the loss of habitat, species and amenity in British grasslands: a review of historical change and assessment of future prospects†. Grass and Forage Science 45, 365-372.
Gregory, A.S., Dungait, J.A.J., Watts, C.W., Bol, R., Dixon, E.R., White, R.P., Whitmore, A.P., 2016. Long-term management changes topsoil and subsoil organic carbon and nitrogen dynamics in a temperate agricultural system. European Journal of Soil Science 67, 421-430.
Gusenbauer, M., Haddaway, N., 2020. Which Academic Search Systems are Suitable for Systematic Reviews or Meta-Analyses? Evaluating Retrieval Qualities of Google Scholar, PubMed and 26 other Resources [OPEN ACCESS]. Research Synthesis Methods 11, 181-217.
Habel, J.C., Dengler, J., Janišová, M., Török, P., Wellstein, C., Wiezik, M., 2013. European grassland ecosystems: threatened hotspots of biodiversity. Biodiversity and Conservation 22, 2131-2138.

Hall, C., McVittie, A., Moran, D., 2004. What does the public want from agriculture and the countryside? A review of evidence and methods. Journal of Rural Studies 20, 211-225.

Hauck, J., Schleyer, C., Winkler, K.J., Maes, J., 2014. Shades of Greening: Reviewing the Impact of the new EU Agricultural Policy on Ecosystem Services. Change and Adaptation in Socio-Ecological Systems 1, 51.

Hejcman, M., Hejcmanová, P., Pavlů, V., Beneš, J., 2013. Origin and history of grasslands in Central Europe – a review. Grass and Forage Science 68, 345-363.

Hopkins, A., Gilbey, J., Dibb, C., Bowling, P.J., Murray, P.J., 1990. Response of permanent and reseeded grassland to fertilizer nitrogen. 1. Herbage production and herbage quality. Grass and Forage Science 45, 43-55.

Hopkins, A., Wilkins, R.J., 2006. Temperate grassland: key developments in the last century and future perspectives. The Journal of Agricultural Science 144, 503-523.

Hussain, R.I., Walcher, R., Eder, R., Allex, B., Wallner, P., Hutter, H.-P., Bauer, N., Arnberger, A., Zaller, J.G., Frank, T., 2019. Management of mountainous meadows associated with biodiversity attributes, perceived health benefits and cultural ecosystem services. Scientific Reports 9, 14977.

Huyghe, C., De Vliegher, A., Van Gils, B., Peeters, A., 2014. Grasslands and herbivore production in Europe and effects of common policies. éditions Quae.

Isselstein, J., Jeangros, B., Pavlu, V., 2005. Agronomic aspects of biodiversity targeted management of temperate grasslands in Europe–a review. Agronomy Research 3, 139-151.

Isselstein, J., Kayser, M., 2014. Functions of grassland and their potential in delivering ecosystem services. Grassland Science in Europe 19, 199-214.

Jordan, A., Rayner, T., 2010. The evolution of climate policy in the European Union: an historical overview. In: Jordan, A., Huitema, D., Berkhout, F., van Asselt, H., Rayner, T. (Eds.), Climate Change Policy in the European Union: Confronting the Dilemmas of Mitigation and Adaptation? Cambridge University Press, Cambridge, pp. 52-80.

Kizeková, M., Hopkins, A., Kanianska, R., Makovníková, J., Pollák, Š., Pálka, B., 2018. Changes in the area of permanent grassland and its implications for the provision of bioenergy: Slovakia as a case study. Grass and Forage Science 73, 218-232.

Klaus, V.H., Schäfer, D., Kleinebecker, T., Fischer, M., Prati, D., Hölzel, N., 2016. Enriching plant diversity in grasslands by large-scale experimental sward disturbance and seed addition along gradients of land-use intensity. Journal of Plant Ecology 10, 581-591.

Klein, A.-M., Vaissière, B.E., Cane, J.H., Steffan-Dewenter, I., Cunningham, S.A., Kremen, C., Tscharntke, T., 2007. Importance of pollinators in changing landscapes for world crops. Proceedings of the Royal Society B: Biological Sciences 274, 303-313.

Le Clec'h, S., Finger, R., Buchmann, N., Gosal, A.S., Hörtnagl, L., Huguenin-Elie, O., Jeanneret, P., Lüscher, A., Schneider, M.K., Huber, R., 2019. Assessment of spatial variability of multiple ecosystem services in grasslands of different intensities. Journal of Environmental Management 251, 109372.

Leip, A., Billen, G., Garnier, J., Grizzetti, B., Lassaletta, L., Reis, S., Simpson, D., Sutton, M.A., de Vries, W., Weiss, F., Westhoek, H., 2015. Impacts of European livestock production: nitrogen, sulphur, phosphorus and greenhouse gas emissions, land-use, water eutrophication and biodiversity. Environmental Research Letters 10, 115004.

Lemaire, G., Hodgson, J., Chabbi, A., 2011. Grassland productivity and ecosystem services. ePDF 978-1-8459-3900-7. Cabi.

Mace, G.M., Norris, K., Fitter, A.H., 2012. Biodiversity and ecosystem services: a multilayered relationship. Trends in Ecology & Evolution 27, 19-26.

Macleod, C.J.A., Humphreys, M.W., Whalley, W.R., Turner, L., Binley, A., Watts, C.W., Skøt, L., Joynes, A., Hawkins, S., King, I.P., O'Donovan, S., Haygarth, P.M., 2013. A novel grass hybrid to reduce flood generation in temperate regions. Scientific Reports 3, 1683.

Merbold, L., Eugster, W., Stieger, J., Zahniser, M., Nelson, D., Buchmann, N., 2014. Greenhouse gas budget (CO₂, CH₄ and

N₂O) of intensively managed grassland following restoration. Global Change Biology 20, 1913-1928.

Meyer, S.T., Ptacnik, R., Hillebrand, H., Bessler, H., Buchmann, N., Ebeling, A., Eisenhauer, N., Engels, C., Fischer, M., Halle, S., Klein, A.-M., Oelmann, Y., Roscher, C., Rottstock, T., Scherber, C., Scheu, S., Schmid, B., Schulze, E.-D., Temperton, V.M., Tscharntke, T., Voigt, W., Weigelt, A., Wilcke, W., Weisser, W.W., 2018. Biodiversity–multifunctionality relationships depend on identity and number of measured functions. Nature Ecology & Evolution 2, 44-49.

Navarro, L.M., Pereira, H.M., 2015. Rewilding abandoned landscapes in Europe. Rewilding European Landscapes. Springer, Cham, pp. 3-23.

Nerusil, P., Kohoutek, A., Komarek, P., Odstrcilova, V., 2008. Effects of utilisation intensity and fertilization level on forage production and quality of permanent grassland on a fluvisoil. Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis 56, 153-162.

O'Mara, F.P., 2012. The role of grasslands in food security and climate change. Annals of Botany 110, 1263-1270.

Pe'er, G., Bonn, A., Bruelheide, H., Dieker, P., Eisenhauer, N., Feindt, P.H., Hagedorn, G., Hansjürgens, B., Herzon, I., Lomba, Â., Marquard, E., Moreira, F., Nitsch, H., Oppermann, R., Perino, A., Röder, N., Schleyer, C., Schindler, S., Wolf, C., Zinngrebe, Y., Lakner, S., 2020. Action needed for the EU Common Agricultural Policy to address sustainability challenges. People and Nature 2, 305-316.

Peeters, A., 2009. Importance, evolution, environmental impact and future challenges of grasslands and grassland-based systems in Europe. Grassland Science 55, 113-125.

Pilgrim, E.S., Macleod, C.J.A., Blackwell, M.S.A., Bol, R., Hogan, D.V., Chadwick, D.R., Cardenas, L., Misselbrook, T.H., Haygarth, P.M., Brazier, R.E., Hobbs, P., Hodgson, C., Jarvis, S., Dungait, J., Murray, P.J., Firbank, L.G., 2010. Chapter four - Interactions Among Agricultural Production and Other Ecosystem Services

Delivered from European Temperate Grassland Systems. In: Sparks, D.L. (Ed.), Advances in Agronomy. Academic Press, pp. 117-154.

Poux, X., Aubert, P.-M., 2018. An agroecological Europe in 2050: multifunctional agriculture for healthy eating. Findings from the Ten Years For Agroecology (TYFA) modelling exercise, Iddri-AScA, Study N°09/18, Paris, France, 74 p'.

Prescher, A.K., Grunwald, T., Bernhofer, C., 2010. Land use regulates carbon budgets in eastern Germany: from NEE to NBP. Agricultural and Forest Meteorology 150, 1016-1025.

Rizvi, S., Pagnutti, C., Fraser, E., Bauch, C.T., Anand, M., 2018. Global land use implications of dietary trends. PLOS ONE 13, e0200781.

Runhaar, H., 2021. Four critical conditions for agroecological transitions in Europe. International Journal of Agricultural Sustainability 19, 227-233.

Schaub, S., Buchmann, N., Lüscher, A., Finger, R., 2020. Economic benefits from plant species diversity in intensively managed grasslands. Ecological Economics 168, 106488.

Schaub, S., Finger, R., Buchmann, N., Steiner, V., Klaus, V., 2021. The costs of diversity: higher prices for more diverse grassland seed mixtures. Environmental Research Letters 16, 094011.

Scheper, J., Holzschuh, A., Kuussaari, M., Potts, S.G., Rundlöf, M., Smith, H.G., Kleijn, D., 2013. Environmental factors driving the effectiveness of European agri-environmental measures in mitigating pollinator loss – a meta-analysis. Ecology Letters 16, 912-920.

Schulze, E.D., Luyssaert, S., Ciais, P., Freibauer, A., Janssens, I.A., Soussana, J.F., Smith, P., Grace, J., Levin, I., Thiruchittampalam, B., Heimann, M., Dolman, A.J., Valentini, R., Bousquet, P., Peylin, P., Peters, W., Rödenbeck, C., Etiope, G., Vuichard, N., Wattenbach, M., Nabuurs, G.J., Poussi, Z., Nieschulze, J., Gash, J.H., the CarboEurope, T., 2009. Importance of methane and nitrous oxide for Europe's terrestrial greenhouse-gas balance. Nature Geoscience 2, 842-850.

Smit, H.J., Metzger, M.J., Ewert, F., 2008. Spatial distribution of grassland productivity and land use in Europe. Agricultural Systems 98, 208-219.

Søegaard, K., Gierus, M., Hopkins, A., Halling, M., 2007. Temporary grassland-challenges in the future. Permanent and temporary grassland: plant, environment and economy. Proceedings of the 14th Symposium of the European Grassland Federation, Ghent, Belgium, 3-5 September 2007. Belgian Society for Grassland and Forage Crops, pp. 27-38.

Sollenberger, L., Moura Kohmann, M., Dubeux Jr, J., Silveira, M., 2019. Grassland Management Affects Delivery of Regulating and Supporting Ecosystem Services. Crop Science 59.

Soussana, J.-F., Tallec, T., Blanfort, V., 2010. Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands. Animal: an international journal of animal bioscience 4, 334.

SPSS, 2020. IBM Corp. Released 2020. IBM SPSS Statistics for Windows, Version 27.0. Armonk, NY: IBM Corp.

Tabari, H., 2020. Climate change impact on flood and extreme precipitation increases with water availability. Scientific Reports 10, 13768.

Temperton, V.M., Buchmann, N., Buisson, E., Durigan, G., Kazmierczak, Ł., Perring, M.P., de Sá Dechoum, M., Veldman, J.W., Overbeck, G.E., 2019. Step back from the forest and step up to the Bonn Challenge: how a broad ecological perspective can promote successful landscape restoration. Restoration Ecology 27, 705-719.

Tilman, D., Clark, M., 2014. Global diets link environmental sustainability and human health. Nature 515, 518-522.

Tindale, S.J., Elliott, J., Elings, M., Gallardo-Cobos, R., Hunter, E., Lieberherr, E., Miškolci, S., Price, P.N., Quatrini, S., Sánchez-Zamora, P., Schlueter, H., Frewer, L.J., 2020. A systematic review of European farmer and non-farmer attitudes towards landscapes, ecosystem services, and agricultural management practices: Implications for permanent grassland management. bioRxiv, 2020.2006.2012.148585.

Török, P., Dembicz, I., Dajić-Stevanović, Z., Kuzemko, A., 2020. Grasslands of Eastern Europe. In: Goldstein, M.I., DellaSala, D.A. (Eds.), Encyclopedia of the World's Biomes. Elsevier, Oxford, pp. 703-713.

Torralba, M., Fagerholm, N., Burgess, P.J., Moreno, G., Plieninger, T., 2016. Do European agroforestry systems enhance biodiversity and ecosystem services? A meta-analysis. Agriculture, Ecosystems & Environment 230, 150-161.

Van Den Pol-Van Dasselaar, A., Bastiaansen-Aantjes, L., Bogue, F., O'Donovan, M., Huyghe, C., 2019. Grassland use in Europe: A syllabus for young farmers. e-ISBN (pdf): 978-2-7592-3146-1 Quae.

van den Pol, A., Becker, T., Botana Fernandez, A., Hennessy, T., Peratoner, G., 2018. Social and economic impacts of grass based ruminant production. In: Horan, B., Hennessy, D., O'Donovan, M., Kennedy, E., McCarthy, B., Finn, J.A., O'Brien, B. (Eds.), 27th European Grassland Federation General Meeting Cork (EGF 2018). European Grassland Federation EGF, Zürich, pp. 697-708.

Van Zanten, H.H.E., Herrero, M., Van Hal, O., Röös, E., Muller, A., Garnett, T., Gerber, P.J., Schader, C., De Boer, I.J.M., 2018. Defining a land boundary for sustainable livestock consumption. Global Change Biology 24, 4185-4194.

Velthof, G.L., Hoving, I.E., Dolfing, J., Smit, A., Kuikman, P.J., Oenema, O., 2010. Method and timing of grassland renovation affects herbage yield, nitrate leaching, and nitrous oxide emission in intensively managed grasslands. Nutrient Cycling in Agroecosystems 86, 401-412.

Vliegher, A.d., Carlier, L., 2007. The effect of the age of grassland on yield, botanical composition and nitrate content in the soil under grazing conditions. (Grassland Science in Europe Volume 12). In: Vliegher, A.d., Carlier, L. (Eds.). Permanent and temporary grassland

Belgian Society for Grassland and Forage Crops, Merlbeke, pp. Proceedings of the 14th Symposium of the European Grassland Federation, Ghent, Belgium, 13-15 September 2007; 2007 2051-2054 2007 ref.

Webster, C.P., Poulton, P.R., Goulding, K.W.T., 1999. Nitrogen leaching from winter cereals grown as part of a 5-year ley-arable rotation. European Journal of Agronomy 10, 99-109.

Werling, B.P., Dickson, T.L., Isaacs, R., Gaines, H., Gratton, C., Gross, K.L., Liere, H., Malmstrom, C.M., Meehan, T.D., Ruan, L., Robertson, B.A., Robertson, G.P., Schmidt, T.M., Schrotenboer, A.C., Teal, T.K., Wilson, J.K., Landis, D.A., 2014. Perennial grasslands enhance biodiversity and multiple ecosystem services in bioenergy landscapes. Proceedings of the National Academy of Sciences 111, 1652.

Woodcock, B.A., Savage, J., Bullock, J.M., Nowakowski, M., Orr, R., Tallowin, J.R.B., Pywell, R.F., 2014. Enhancing floral resources for pollinators in productive agricultural grasslands. Biological Conservation 171, 44-51.

FIGURE 1 (tif attached separately)

Fig. 1: Permanent grasslands still dominate the agricultural areas in many European regions, especially in places where growth conditions are unfavourable as in mountainous regions (A, Switzerland). Historically, grasslands were relatively nutrient-poor and extensively managed (B, Poland, and C, Germany), but a significant extent of grasslands experienced either intensification of management (D, United Kingdom) or were lost due to conversion to cropland (E, Czech Republic) or abandonment (F, Switzerland). Pictures by V. Klaus (A, C, F), M. Janicka (B), ADAS (D), S. Hejduk (E).

FIGURE 2 (tif attached separately)

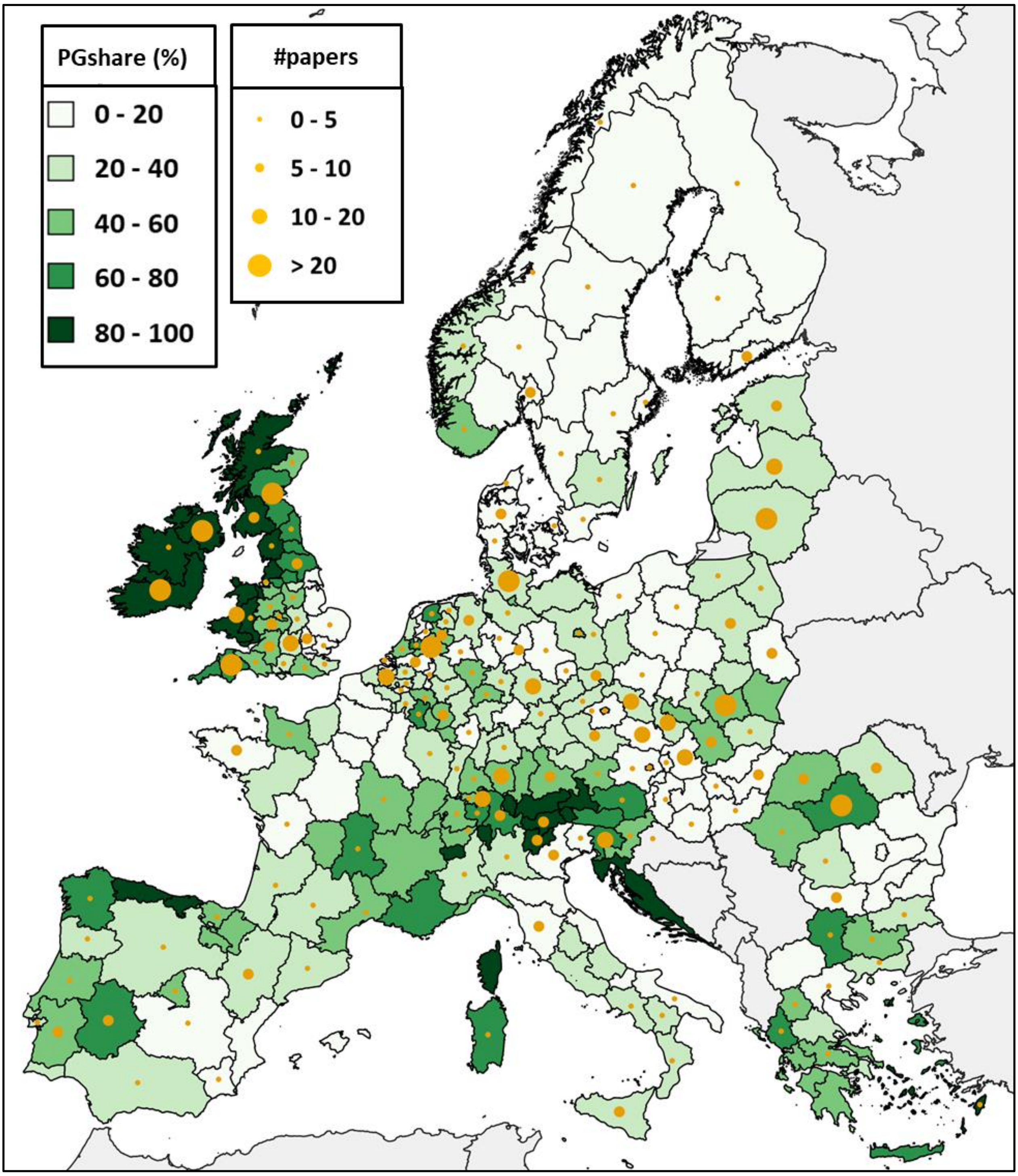
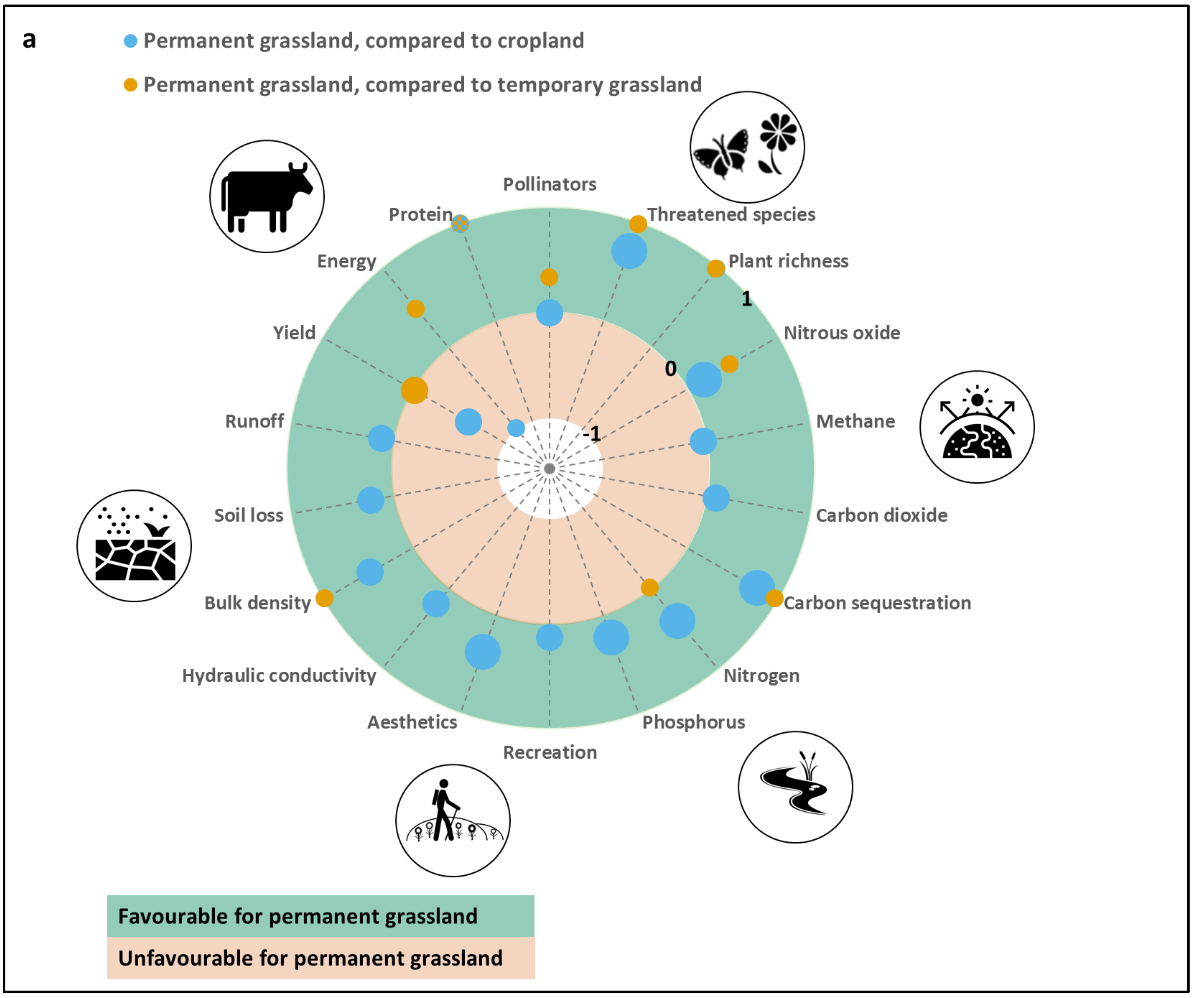


Fig. 2: Geographical distribution, across NUTS2 regions in Europe, of included papers (#papers), published since 1980, and the share of permanent grassland (PGshare) in the total utilised agricultural area (UAA); data from 2016, except Norway and Macedonia from 2013 (Eurostat, 2020); grey areas indicate no data.

FIGURE 3A (tif attached separately)



[Figure caption on next page]

FIGURE 3B (tif attached separately)

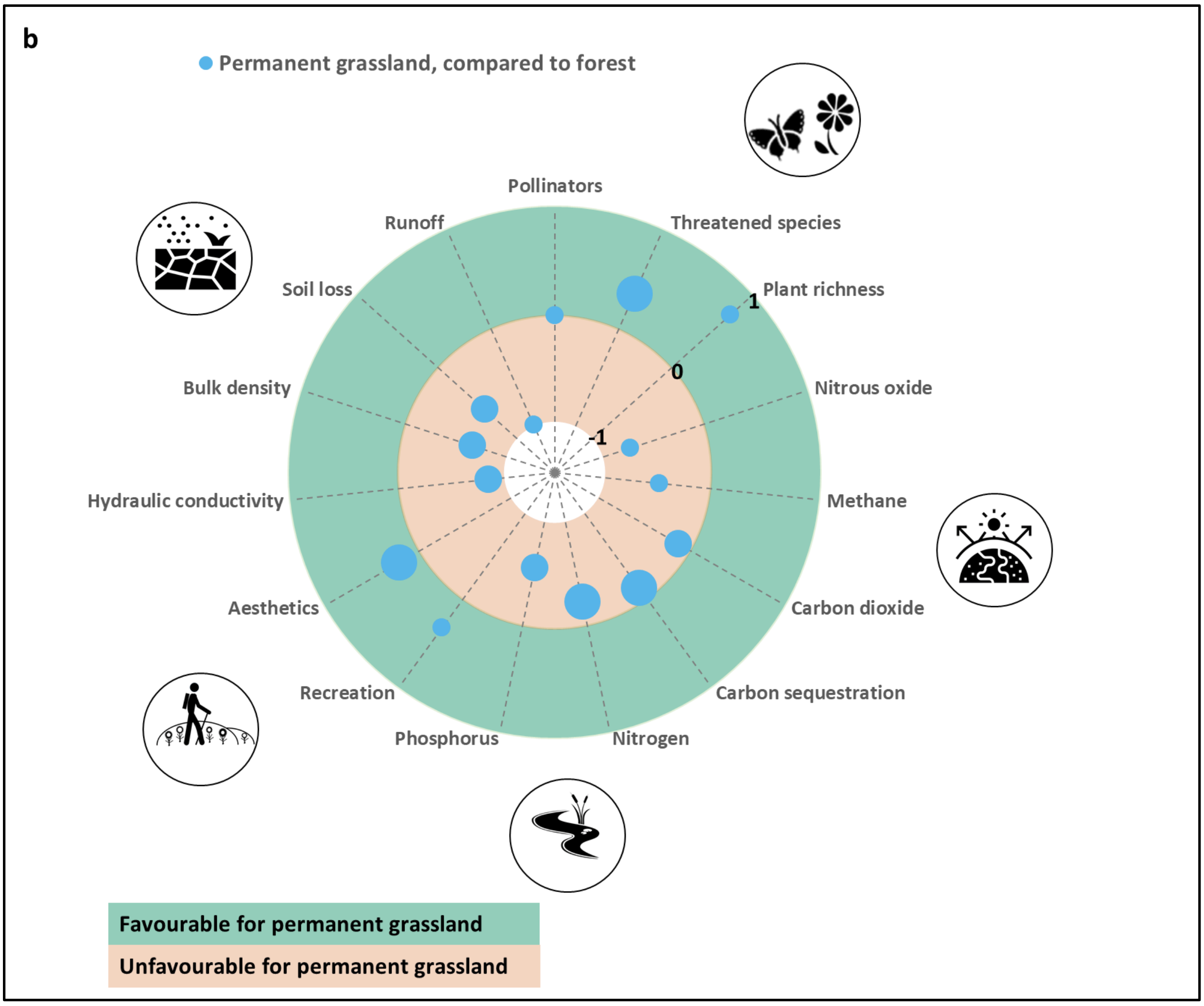
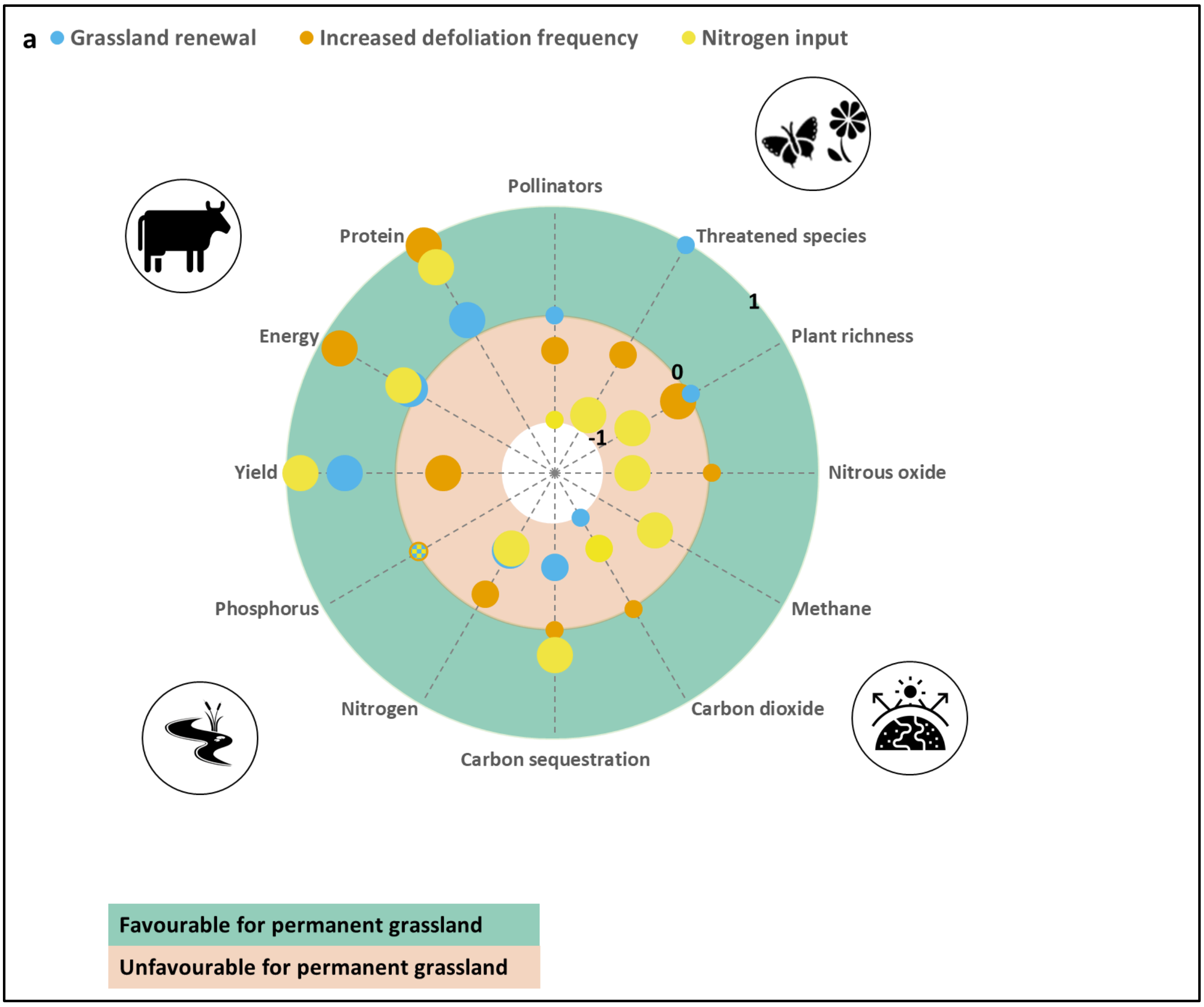


Fig. 3: Comparison between land use types for indicators of ecosystem services, (a) permanent grassland compared to cropland and temporary grassland, (b) permanent grassland compared to forest. The boundary between the outer and inner shaded zones represents a mean score of 0. The shaded outer zone represents a favourable score for permanent grassland (moving outwards, the mean score increases from 0 to 1), the shaded inner zone represents an unfavourable score (moving inwards, the mean score decreases from 0 to -1). Dot size indicates number of underlying cases (small: <5 cases, medium: 5-9 cases. Large: >9 cases). Full statistical data are presented in Fig. S4.

For example, the aesthetics score in the green shaded outer zone (Figure b) indicates a preference of people for permanent grassland over forest but the score was 0.21 which means that some cases showed opposite outcomes, but the overall score favoured permanent grasslands. The large size of the dot indicates the aesthetics score was underpinned by at least 10 cases.

FIGURE 4A (tif attached separately)



[Figure caption on next page]

FIGURE 4B (tif attached separately)

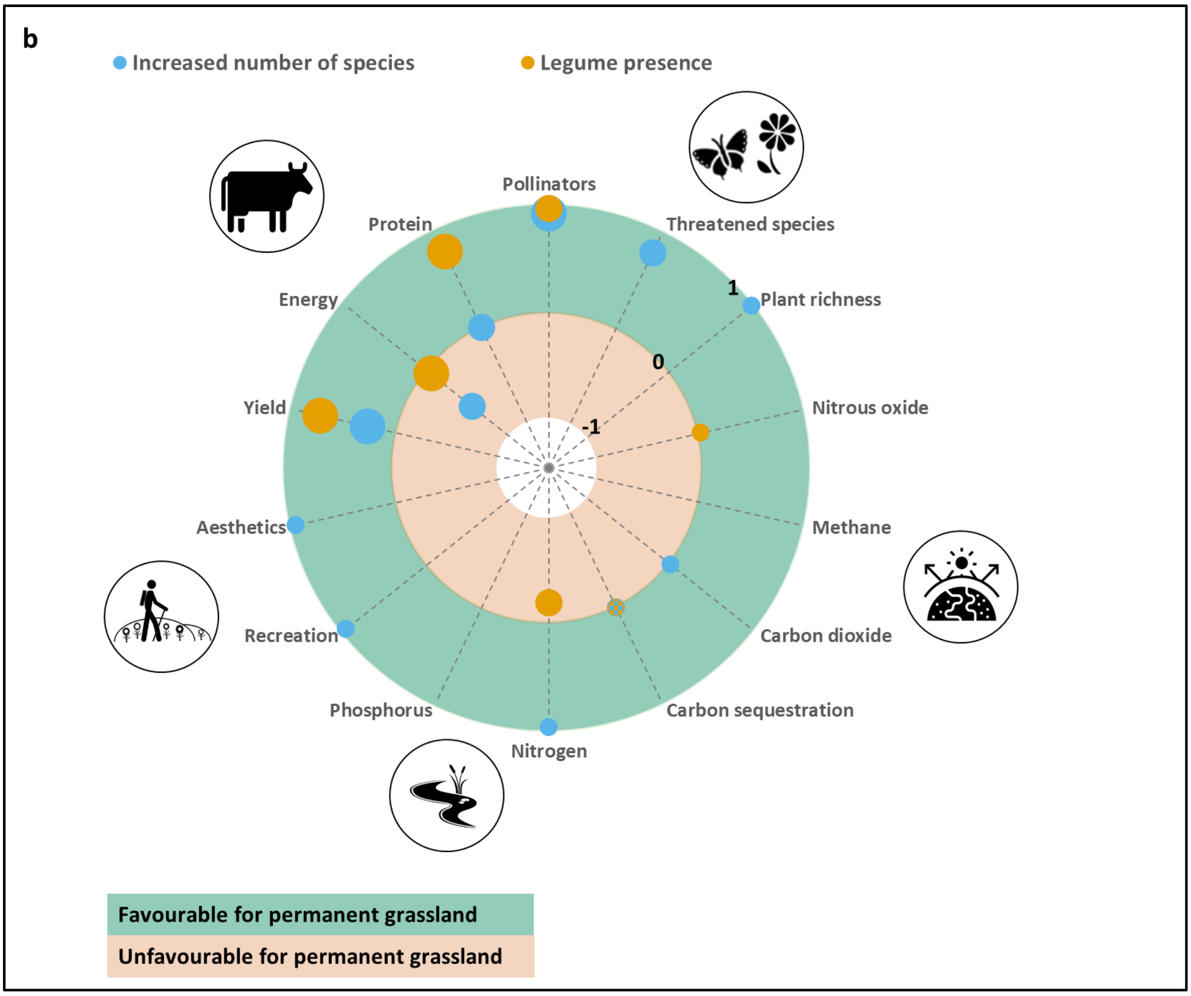
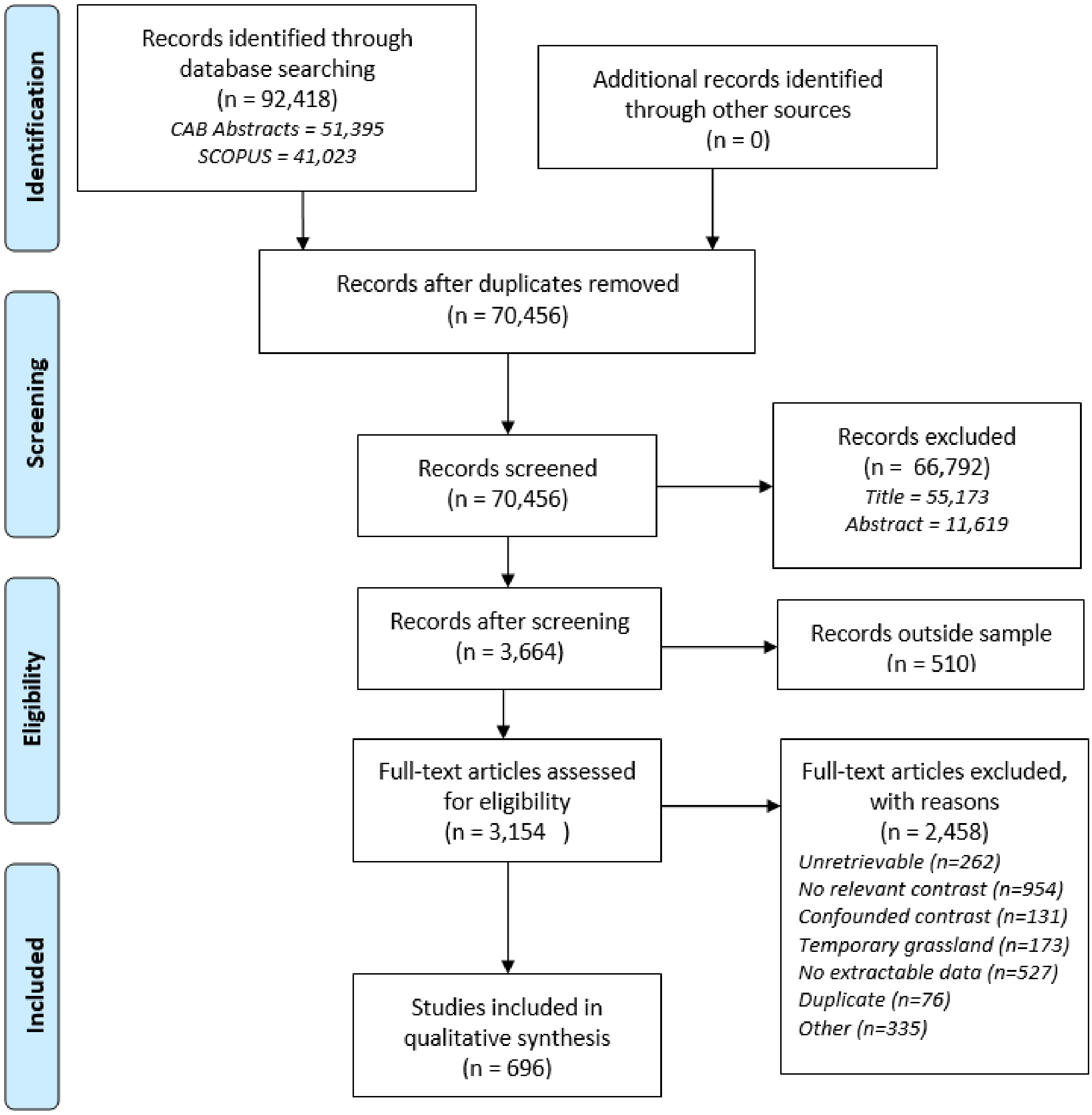


Fig. 4: Effects of management options on indicators for ecosystem services; (a) management interventions related to intensification, (b) management interventions on species in the sward. The boundary of the outer and inner shaded zones represents a mean score of 0. The shaded outer zone represents a favourable score (moving outwards, the mean score increases from 0 to 1), the shaded inner zone represents an unfavourable score (moving inwards, the mean score decreased from 0 to -1). Dot size indicates number of underlying cases (small: <5 cases, medium: 5-9 cases. Large: >9 cases). Full statistical data are presented in Fig. S6.

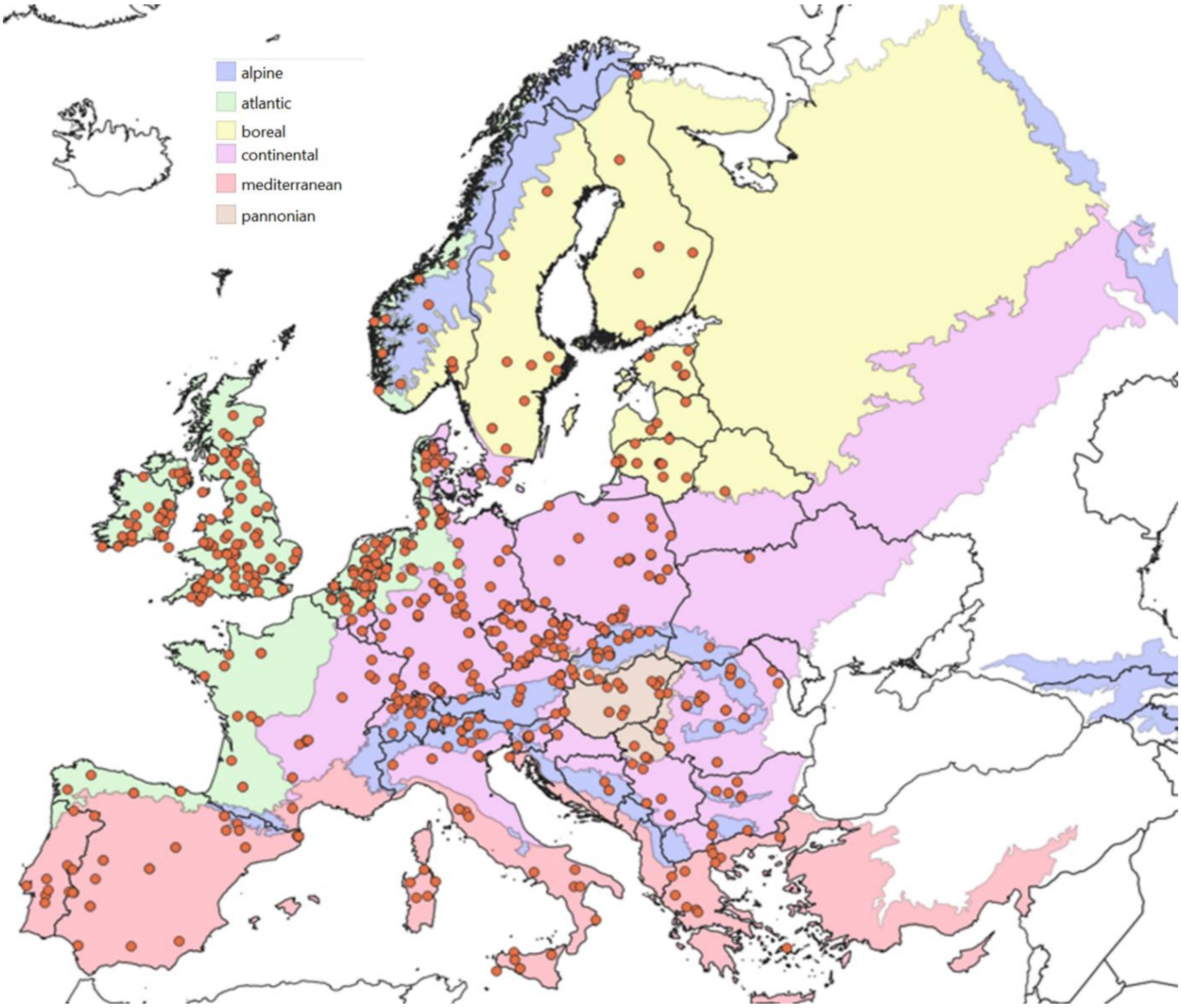
For example, the threatened species score in the green shaded outer zone indicates a favourable effect of the number of species. The score was 0.95 which means that most cases showed consistent favourable outcomes. The medium size of the marker indicates the score was underpinned by 5 to 9 cases.

Supporting information Figure S1. PRISMA flow chart (Moher *et al.*, 2009).

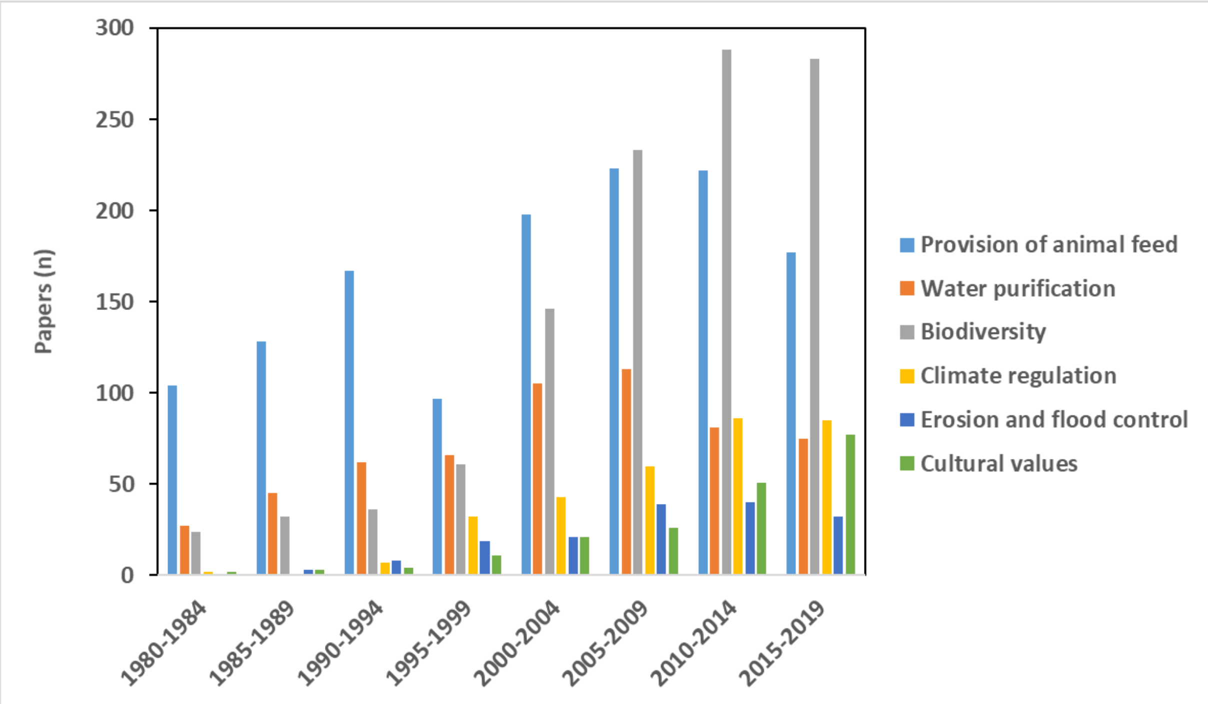


PRISMA flow data per ecosystem service presented in Table S1.

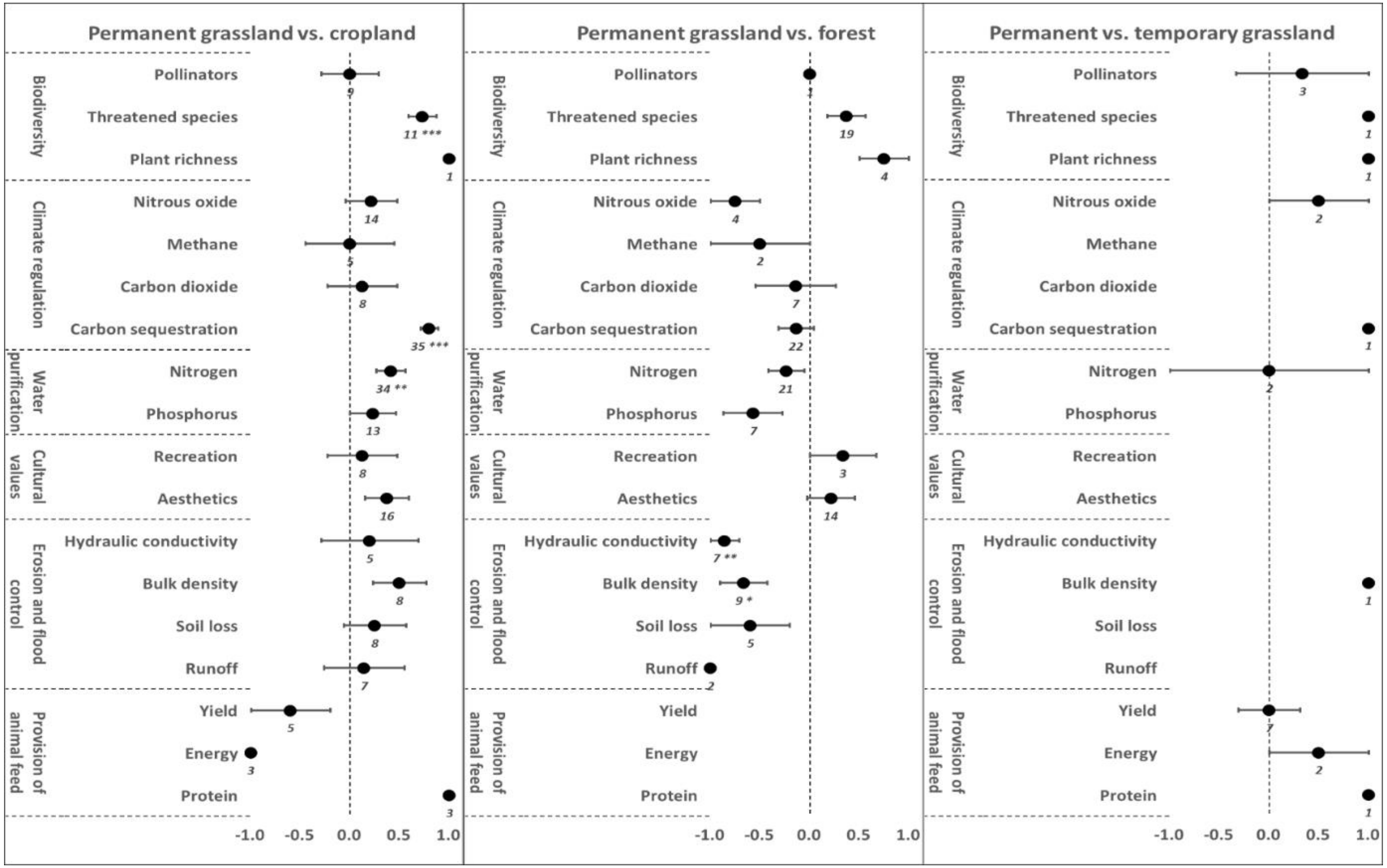
Supporting information Figure S2. Geographical distribution of included papers across biogeographic zones.



Supporting information Figure S3. Temporal trend in the number of included papers per ecosystem service.



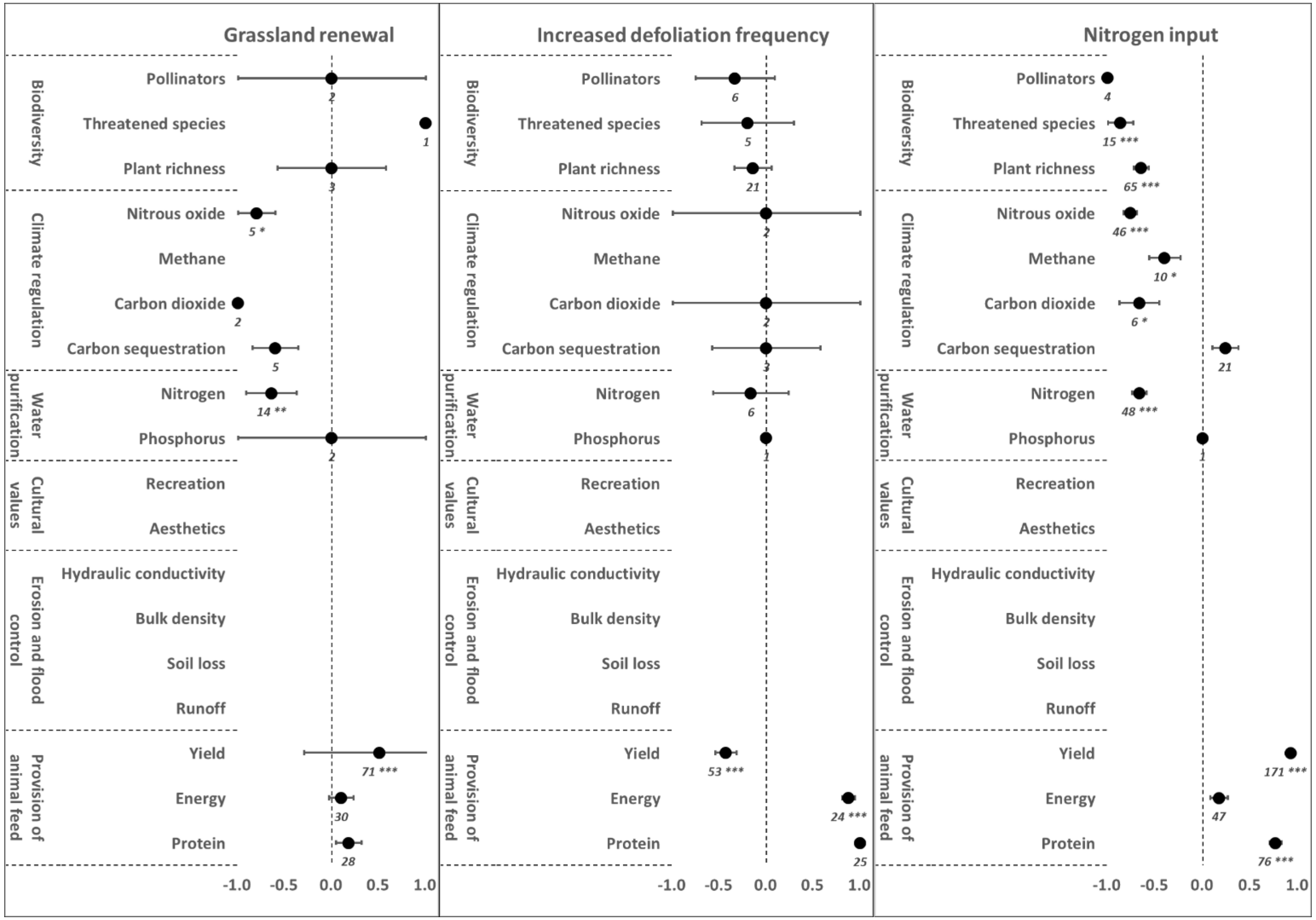
Supporting information Figure S4. Mean and standard error of outcomes (Favourable = +1, Unfavourable = -1, Neutral = 0) of studies that report on the effect of land use on the delivery of ecosystem services. Significance levels indicated with * (P<0.05), ** (P<0.01), *** (P<0.001).



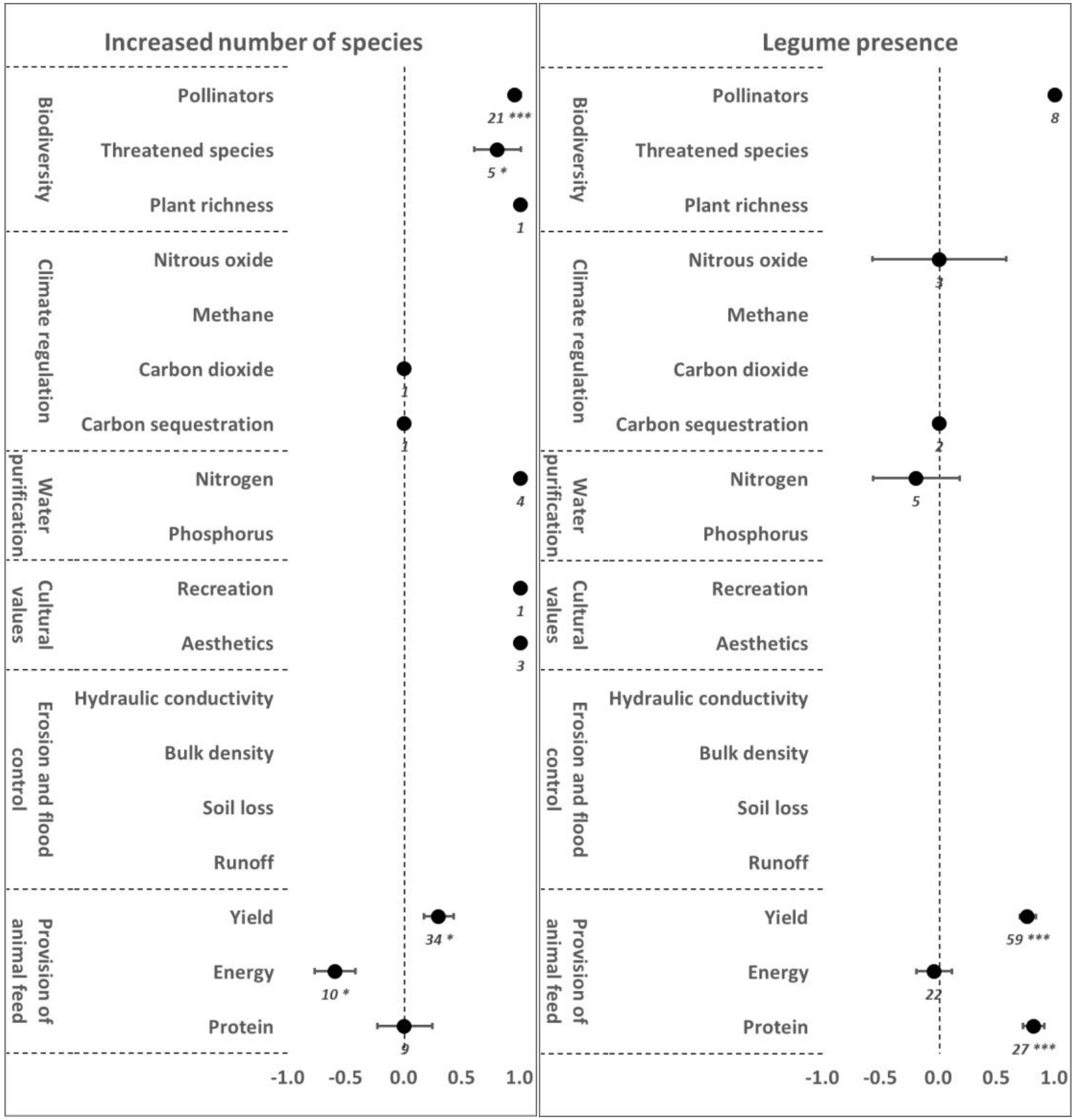
Supporting information Figure S5. Outcomes of studies that report on the effect of land use on the delivery of ecosystem services. Green = favourable, yellow = neutral, orange = unfavourable; number of cases inside doughnuts.

Contrast	Biodiversity			Climate regulation				Water purification		Erosion and flood control				Cultural values		Provision of animal feed		
	Pollinators	Threatened species	Plant richness	Nitrous oxide	Methane	Carbon	Carbon sequestration	Nitrogen	Phosphorus	Hydraulic conductivity	Bulk density	Soil loss	Runoff	Recreational value	Aesthetics	Yield	Energy	Protein
Permanent grassland, compared to cropping	9	11	1	14	5	8	35	34	13	5	8	8	7	8	16	5	3	3
Permanent grassland, compared to forest	1	19	4	4	2	7	22	21	7	7	9	5	2	3	14	0	0	0
Permanent grassland, compared to temporary grassland	3	1	1	2	0	0	1	2	0	0	1	0	0	0	0	7	2	1

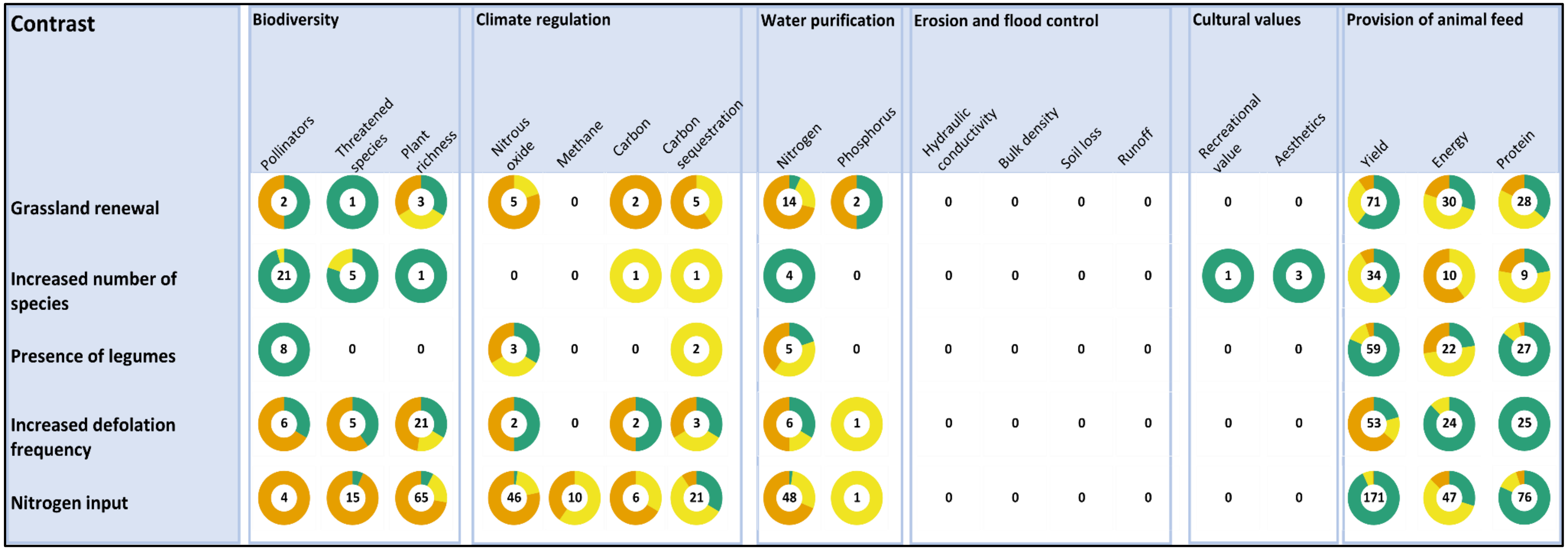
Supporting information Figure S6. Mean and standard error of outcomes (Favourable = +1, Unfavourable = -1, Neutral = 0) of studies that report on the effect of management on the delivery of ecosystem services. Significance levels indicated with * (P<0.05), ** (P<0.01), *** (P<0.001).



Supporting information Figure S6 continued.



Supporting information Figure S7. Outcomes of studies that report on the effect of management on the delivery of ecosystem services. Green = favourable, yellow = neutral, orange = unfavourable; number of cases inside doughnuts.



Supporting information Table S1. Flow of information through the different phases of the review (Moher *et al.*, 2009)

	Provision animal feed	Climate regulation	Water purification	Erosion flood control	Cultural values	Biodiversity	Total
Identified through database searching	17145	10973	9391	14203	17979	22727	92418
- Scopus	5412	4740	4136	7482	9337	9916	41023
- CAB Abstracts	11733	6233	5255	6721	8642	12811	51395
After removal of duplicates	**13971**	**8331**	**7181**	**11053**	**13719**	**16201**	**70456**
Screened for title	13971	8331	7181	11053	13719	16201	70456
- Excluded based on title	9951	7219	5252	10309	10309	12133	55173
Screened for abstract	4020	1112	1929	744	3410	4068	15283
- Excluded based on abstract	2707	796	1355	581	3215	2965	11619
Eligible studies	1313	316	574	163	195	1103	3664
- Excluded after sampling	510	0	0	0	0	0	510
Full text article assessed	**803**	**316**	**574**	**163**	**195**	**1103**	**3154**
- Excluded with reasons:	514	205	459	137	178	965	2458
-> Unretrievable	61	11	84	5	18	83	262
-> No relevant contrast	146	68	157	117	124	342	954
-> Confounded contrasts	86	6	26			13	131
-> Temporary grassland	78	33	35	2		25	173
-> No extractable data	43	14	52		3	415	527
-> Duplicate	43	6	12	2		13	76
-> Other reasons	57	67	93	11	33	74	335
Studies included	**289**	**111**	**115**	**26**	**17**	**138**	**696**

Supporting information Table S2. Indicators of ecosystem services.

Ecosystem service	Indicator	Description
Biodiversity	Pollinators	The presence, abundance, diversity or species composition of any pollinating invertebrate community/population, or the pollinator visitation rate.
	Threatened species	The presence, abundance, survival or breeding success of any threatened species. 'Threatened' status included species listed as 'vulnerable', '(critically) endangered', or 'red listed' at a global, national or regional level.
	Plant richness	The richness of vascular plant species on a specific area, expressed as the number of species or a diversity index (Shannon, Simpson). Thus, only part of the values included here utilised information on the abundance of the individual species of the respective plant community. Plant richness is the results of (visual) assessments of the aboveground vegetation and does not include soil seed banks or other measures of dark diversity.
Climate regulation	Nitrous oxide	Nitrous oxide emission from soils and ecosystems. It is a powerful greenhouse gas with a global warming potential (GWP) of 265 compared to 1 for carbon dioxide. It contributes to climate change due to its positive radiative forcing effect. Nitrous oxide can be measured using manual/automatic chambers or eddy covariance methods and expressed, among others, in nmol/m2/s or in kg/ha/yr.
	Methane	Methane fluxes (emission and uptake) from soils and ecosystems. It is a potent greenhouse gas with a GWP of 28 compared to 1 for carbon dioxide. It contributes to climate change due to its positive radiative forcing effect. Methane can be measured using manual/automatic chambers or eddy covariance methods and expressed, among others, in nmol/m^2/s or in kg/ha/yr.
	Carbon dioxide	Carbon dioxide fluxes from soils and ecosystems. It is the primary driver of global climate change with a GWP of 1. Carbon dioxide can be measured using manual/automatic chambers with portable infrared gas analyzers or eddy covariance methods and expressed, among others, in μmol/m^2/s or in kg/ha/yr.
	Carbon sequestration	Carbon sequestration is the long-term removal of carbon dioxide from the atmosphere and storage in the soil. It can slowdown or reverse atmospheric CO_2 pollution and mitigate or reverse global warming. Carbon sequestration can be measured using direct soil sampling at two time points and analytical carbon measurements and is expressed in t/ha.
Water purification	Nitrogen	Grasslands receive nitrogen via biological N_2 fixation from legumes, fertiliser, manure, or feces and urine

Ecosystem service	Indicator	Description
		deposition during grazing. Residual soil nitrogen or nitrate is water soluble and can leach to ground and surface water. An indicator of surface and groundwater pollution is the nitrate concentration or the nitrogen load.
	Phosphorus	Grasslands receive phosphorus via fertiliser application or via manure deposition during grazing. Phosphate can leach to ground and surface water. An indicator of water pollution is the phosphorus load or phosphorus concentration in ground and surface water.
	Pesticides*	Pesticides are diverse chemical substances used for pest control, such as herbicides, insecticides and fungicides. Pesticides can be water soluble. Others persist in the soil and breakdown products may leach to surface and ground waters. Indicators of surface and ground water pollution are the measured concentrations of these chemical substances in ground or surface water.
Cultural values	Recreational value	Evaluation of recreational value by inhabitants or visitors, or scoring motivation for visit of an area, expressed in questionnaires of different structure; amount of money that a participant is willing to pay for the maintenance of a grassland landscape against any land use change (Willingness To Pay)
	Aesthetics	Evaluation of aesthetic value by inhabitants, visitors or land users, expressed in questionnaires of different structure; willingness to pay for the maintenance of a grassland landscape against any land use change; species abundance evaluated as a proxy for aesthetic value impact.
Erosion and flood control	Hydraulic conductivity	Hydraulic conductivity (mm/h) is the ease with which water moves through porous spaces in the soil and it is inversely related to the bulk density. It was measured by infiltrometer or laboratory methods.
	Bulk density	Bulk density (g/cm^3) reflects soil compaction, thus the soil pore space. It influences the water and air movement through the profile and was measured by Kopecky rings generally at 20 cm depth.
	Soil loss	Soil loss by water flow (t/ha) is usually assessed using a runoff plot (large > 1 m^2, small <1m^2). It represents the quantity of soil loss after a rainfall event.
	Runoff	Runoff (mm) is the laminar and superficial water flow, that occurs when rainfall intensity is higher than the infiltration into the soil. It is assessed using a runoff plot (large > 1 m^2, small <1m^2).
Provision of animal feed	Yield	Above-ground dry matter yield of herbage, usually expressed in t/ha/year. The dry matter yield was predominantly measured by cutting at around 5 cm stubble height, weighing and sampling for dry matter analysis. Other reported methods were sward height, grazing days, leaf length or energy yield.
	Energy	The energy content of harvested or grazed herbage, usually expressed in MJ/kg dry matter.

Ecosystem service	Indicator	Description
		The most used measurements were digestible organic or dry matter and crude fibre. Other reported methods were acid detergent fibre, metabolisable energy or net energy for lactation.
	Protein	The protein content of harvested or grazed herbage, usually expressed in g/kg dry matter. The most used measurements are based on the determination of nitrogen-Kjeldahl or total nitrogen.

* We searched the literature on 19 indicators. During screening all papers on pesticides were excluded. Therefore, pesticides were not included in the results.

Supporting information Table S3. Search strings.

Searches were carried out in CAB Abstracts (shown below) and Scopus (not shown). The ecosystem services *water purification* and *provision of animal feed* used some additional concepts, marked with a hashtag (#).

CAB Abstracts is the leading database on applied life sciences with over 10.4 million records. Amongst many others, topics include crop sciences and grasslands, animal science, environmental science, and recreation/tourism. It includes serials, books, conference proceedings, theses, reports, and bulletins and is a valuable source both for peer-reviewed literature and grey literature. The controlled vocabulary of the CAB Thesaurus with about 2.8 million terms allows comprehensive and specific retrieval, which makes CAB Abstracts a recommended source for literature searches for systematic reviews. The multidisciplinary database Scopus is the largest abstract and citation database of peer-reviewed literature in the field of science, technology, medicine, and social sciences. Scopus includes over 75 million records, including peer reviewed journals, books, trade publications and articles-in-press. Scopus meets all the necessary performance requirements for systematic reviews (Gusenbauer and Haddaway, 2019).

Searches in CAB Abstracts were done in title, abstract and all key word fields (.mp). The wild card character '?' was used in CAB Abstracts to substitute for one or no characters. The adjacency operator ADJ was used to indicate the maximum number of words between two search terms, e.g. "threatened adj8 species" means that a hit is included when threatened and species are within eight words of each other, in any order. The explode command EXP was used in CAB's hierarchal list of thesaurus terms. It tells Ovid to search for the thesaurus term itself, including all its narrower terms, down to all levels, e.g. "exp europe" not only searches for "europe" in the different keyword fields, but also for underlying terms.

Concept	Search string for CAB Abstracts
Grass	(dryland? or grass* or grazed or grazing or hayfield? or hay field? or haymeadow? or herbaceous or herbage? or meadow? or pasture? or rangeland? or range land? or ryegrass* or silvopast* or steppe or steppes or sward? or woodpast*)
Europe	exp europe/ or (albania or andorra or austria or belarus or belgium or bosnia or british isles or bulgaria or croatia or cyprus or czech republic or czechia or czechoslovakia or denmark or england or estonia or estonian soviet socialist republic or estonian ssr or europe* or finland or flanders or france or german democratic republic or german federal republic or germany or great britain or greece or hercegovina or herzegovina or hungary or iceland or ireland or irish republic or italy or kosovo or latvia or latvian ssr or liechtenstein or lithuania or lithuanian soviet socialist republic or lithuanian ssr or luxemb?urg or macedonia or moldova or monaco or montenegro or netherlands or norway or poland or portugal or romania or san marino or scotland or serbia or slovakia or slovenia or spain or sweden or switzerland or uk or ukraine or united kingdom or wales or wallonia or walloon or yugoslavia) not (new england or new south wales)
Pollination	(pollinat* or pollini?er?)
Threatened species	((threatened or endangered) adj8 species) or ((threatened or endangered) adj8 taxa) or red list? or red book? or threatened biodiversity or endangered biodiversity
Plant richness	((plant? adj3 composition?) or (plant? adj3 diversit*) or (plant? adj3 richness) or (botanical adj3 composition? or (botanical adj3 diversit*) or botanical richness or (floristic adj3 composition?) or (floristic adj3 diversit*) or (floristic adj3 richness) or (species adj4 composition?) or (species adj3 diversit*) or (species adj3 richness) or (vegetation? adj3 composition?) or (vegetation? adj 3 richness) or biodiversity or agrobiodiversity) not (anti oxidant? or anti-oxidant? or biochemical composition or biofuel or chemical composition or extract* or medical or medicinal or pharmaceut*)
Nitrous oxide	(Nitrous oxide? or N2O or denitrificat* or nitrificat*)
Methane	(methane or CH4)
Carbon dioxide	(carbon dioxide or CO2)
Carbon sequestration	((carbon adj6 sequestrat*) or (c adj4 sequestrat*) or organic matter or SOM or soil organic carbon or soil organic C or SOC or carbon sink? or c sink? or (carbon adj6 turnover) or (c adj4 turnover) or (carbon adj4 budget?) or (c adj4 budget?))
Water quality[#]	((water or groundwater or freshwater or drainwater) adj4 quality) or ((water or groundwater or freshwater or drainwater) adj4 protection) or ((water or groundwater or freshwater or drainwater) adj4 status)
Nitrate in water[#]	(water or groundwater or freshwater or drainwater or leach*) AND (nitrate* or NO3 or nitrogen or (nutrient? adj3 load*) or (N adj3 load*) or (nutrient? adj3 runoff) or (nutrient? adj3 run-off))
Nitrate in soil[#]	(residu* adj3 nitrogen) or (residu* adj3 nitrate?) or post-harvest mineral nitrogen or post-harvest mineral N or (soil adj4 mineral nitrogen) or (soil adj4 mineral N)
Phosphate	(phosphate? or PO4 or phosphor?us or phosphourus or orthophosphate? or ortho-phosphate? or (P adj3 load*))
Pesticides	(pesticide? or herbicide? or insecticide? or fungicide? or residue? or contamin* or pollut* or active ingredient? or weedicide? or weedkiller? or weed killer?)

Hydraulic conductivity	(hydraulic conductivit* OR k value? OR Ksat OR inundat* OR permeab* OR infiltrat*)
Bulk density	(bulk densit* OR porosit* OR compaction? OR trampl* OR crust* OR biocrust? OR seal*)
Soil loss	(soil loss* OR erosion* OR sediment* OR landslide? OR rill? OR gullies or gully OR wash* OR erod* OR erosivity)
Runoff	(run-off? OR runoff? OR flood* OR overland flow?)
Recreation	ecotouris* or leisur* or recreati* or touris* or outdoor? or cultural or bicycle? or bike? or biking or birding or birdwatch* or (bird? adj1 watch*) or climb* or cyclist? or geocach* or hiker? or hiking or hunting or nature trail? or relax* or riding or rider? or travel* or trekker? or trekking or walk* or sport* or physical activit* or social activit*
Aesthetic value	aesthetic* or esthetic* or beauty or landscape? or photo? or photograph? or photographer? or scenery or sceneries or visitor? or social media or facebook or twitter or instagram or snapchat or pinterest or tumblr or whatsapp or youtube
Yield	(yield? OR producti* OR growth) AND (dry matter OR dry-matter OR drymatter OR DM OR dry weight OR dry-weight OR dryweight OR DW)
Yield-in-TITLE[#]	(yield? OR producti* OR growth)
Protein	(((protein? OR nitrogen?) adj5 (content? OR concentration?)) OR N content? OR N concentration?)
Energy	(gross energy OR net energy OR metaboli* energy OR digestib* OR dom OR omd OR domd OR dmd OR ivdom OR ivomd OR ivdomd OR ivdmd OR vem OR ufl OR sfu OR nel)

Supporting information Table S4. Data extraction form.

STUDY

Attribute	(predefined) values
Nr	Unique number for each study
Include	Yes No
Review	Biodiversity Climate regulation Water purification Erosion and flood control Cultural values Provision of animal feed
Reviewer	Name of reviewer
ID_Import	Unique Eppi ID within a review
Author	Family name of first author
Year	Year of publication
Country	Full name of country where experiment took place
Study_type	Field experiment Farm experiment Regional study Other Unknown
Sites	Number of sites
Location	Name of place, region or country
Lon	Longitude (decimal degrees)

Attribute	(predefined) values
Lat	Latitude (decimal degrees)
Biogeoregion	Alpine Atlantic Boreal Continental Mediterranean Pannonian Multiple Unknown
Start year	First year of experiment
Duration	Number of years
Indicator	Pollinators Threatened species Plant richness Nitrous oxide Methane Carbon dioxide Carbon sequestration Nitrogen Phosphorus Pesticides Recreational value Aesthetics Hydraulic conductivity Bulk density Soil loss Runoff Yield Energy Protein
Reason for exclusion	Text
Remarks	Text

CONTRAST

Attribute	(predefined) values
Study_nr	Unique number for each study
Contrast_nr	a b c ...
Code	number+letter, combined from Study_nr and Contrast_nr
Contrast	Permanent grassland - Cropland Permanent grassland - Temporary grassland Permanent grassland - Forest Undisturbed – Resown or oversown No legumes - Legumes present Number of species Defoliation frequency Nitrogen input
Outcome	No conclusion Increases Does not change Decreases

Attribute	(predefined) values
Evaluation	Numerical, based on statistics Numerical Text
Remarks	any relevant comments

Supporting information Table S5. Appreciation of outcomes.

Indicator	Increase is ...	Decrease is ...
Pollinators	Favourable	Unfavourable
Threatened species	Favourable	Unfavourable
Plant diversity	Favourable	Unfavourable
Nitrous oxide	Unfavourable	Favourable
Methane	Unfavourable	Favourable
Carbon dioxide	Unfavourable	Favourable
Carbon sequestration	Favourable	Unfavourable
Nitrate	Unfavourable	Favourable
Phosphate	Unfavourable	Favourable
Hydraulic conductivity	Favourable	Unfavourable
Bulk density	Unfavourable	Favourable
Soil loss	Unfavourable	Favourable
Runoff	Unfavourable	Favourable
Recreation	Favourable	Unfavourable
Aesthetics	Favourable	Unfavourable
Dry matter yield	Favourable	Unfavourable
Energy content	Favourable	Unfavourable
Protein content	Favourable	Unfavourable

Supporting information Text S1: Reflection on method

Approach

We used a systematic review protocol to assess the effects of land use and management intensity on the provision of ecosystem services of permanent grasslands. Our approach was unique in several ways. First, we used an extensive approach covering permanent grasslands across Europe and including 19 indicators for different ecosystem services. Second, unlike other reviews that used "ecosystem service" and its synonyms as the main search terms (Hauck *et al.*, 2014; Zhao *et al.*, 2020), we spelt out the underlying vocabulary for each indicator, thereby collecting a larger set of relevant studies. Third, to assess the effect of land use and management interventions we focused on studies with direct comparisons of relevant treatments within a similar context.

Definition of permanent grassland

We used the definition of Eurostat to identify which grasslands are permanent grasslands: 'grassland that has not been included in the crop rotation for at least five years'. Studies with temporary grasslands were excluded, except for the contrast permanent versus temporary grassland. It was however surprising to see that the definitions and description used in literature are far from uniform or consistent. For instance, the term 'temporary grassland' is often used to refer to permanent grasslands that were resown. Therefore, we used the contextual information from the method section of the papers to establish whether the studied grassland was permanent or temporary.

Furthermore, we realise that permanent grasslands is a concept which partly overlaps with other European concepts like natural, semi-natural and improved grasslands, or American concepts like prairies or rangelands.

Variability in land use

The land uses cropland, forests, permanent and temporary grassland comprise different types and species. Within the management contrasts, legumes comprise mainly white clover and red clover, but also other legumes. The number of species varies from monocultures to multi-species swards with more than 40 species. Moreover, the variety in species may be the result of sowing or from other historical management practices. The latter types of studies were also included as long as the effect of the number of plant species on the indicator had been isolated from other practices.

Field studies

We used a strict selection protocol for field studies, that excluded laboratory and modelling studies (empirical data in modelling papers were not excluded), greenhouse or pot experiments (lysimeter experiments were not excluded). For some indicators, such as yield and nitrous oxide we only included experiments with year-round measurements. This approach improved the overall robustness of the review but may have reduced the strength of the evidence for indicators with a relatively low number of underlying cases.

System boundaries

Our review focused on the direct provision of ecosystem services of the plant-soil compartment. We did not include effects that occur upstream or downstream in the production chain, such as nitrous oxide emissions during fertiliser production, or notably, methane emissions from enteric fermentation which has large impacts on environmental change by permanent grasslands.

Publication bias

Our evidence is subject to publication bias, as less effective studies might not have been published. Furthermore, our review is biased towards studies published in the English language. The language bias is particularly important for the relatively older publications as many countries like Spain or France had peer reviewed journals in their native language. Some of the language bias may be offset by the inclusion of many papers published at the European Grassland Conferences which have a less strict peer review protocol.

Context

The prospects for the provision of ecosystem services by permanent grasslands cannot be assessed without taking the specificity of site contexts into account. We used a pre-defined protocol to search, select and include studies with comparable experimental contrasts. Nevertheless, it is not surprising that the context of the collected evidence is quite diverse across Europe. Obviously, there is variation between climates and soils, but also between more detailed features like elevation, slope, defoliation type or animal type. Moreover, even within our definitions of land use contrasts, a single term like 'cropland' comprises many different crop types from monocultures like forage maize or arable rotations to fruit or olive orchards. Likewise, permanent grasslands can have a sward age of just five years or more than 50 years. The same goes for definitions of management contrasts. Grassland renewal may involve ploughing and re-seeding, or direct sowing into existing swards, with or without spraying off the old sward with herbicides. Moreover, the number and type of sown species are not necessarily the same as the number and type of existing species. Experiments with continuous variables like nitrogen input or defoliation frequency show many different setups. For example, the range of nitrogen inputs varied from 0 to 900 kg N per ha per year and the contrast between the highest and lowest nitrogen input varied from 40 to 600 kg per ha per year. In this paper, we only reported outcomes as favourable or unfavourable, ignoring the type of response (linear, non-linear).