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Management to Support Multiple Ecosystem Services from Productive Grasslands

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Abstract: Sustainable intensification will require the development of new management systems to support global food demands, whilst conserving the integrity of ecosystem functions. Here, we test and identify management strategies to maintain or enhance agricultural production in grasslands whilst simultaneously supporting the provision of multiple ecosystem services. Over four years, we investigated how the establishment of three plant functional groups (grasses, legumes, and other flowering forbs), using different cultivation (minimum tillage and deep ploughing) and management (cutting, grazing and their intensity) techniques, affected provision and complementarity between key ecosystem services. These ecosystem services were agronomic production, pollination, pest control, food resources for farmland birds, and soil services. We found that the establishment of floristically diverse swards, particularly those containing grasses, legumes and forbs, maximised forage yield and quality, pollinator abundance, soil nitrogen, and bird food resources, as well as enhancing populations of natural predators of pests. Cutting management increased bird food resources and natural predators of pests without depleting other services considered. However, a single management solution to maximise the delivery of all ecosystem services is unlikely to exist, as trade-offs also occurred. Consequently, management options may need to be tailored to strategically support localised deficits in key ecosystem services.

Keywords: agri-environment schemes; birds; cultural service; ecosystem service; grassland enhancement; pollination; pest control; soil; sustainable intensification

1. Introduction

Agricultural intensification has driven widespread declines in biodiversity and a variety of ecosystem services [1–4]. To help mitigate the negative impacts of modern farming practices, agri-environment schemes (AES) were introduced by the European Community in 1985 (Council Regulation (EEC) No 797/85 on agricultural structures). These schemes incentivise farmers to manage their land in a more environmentally friendly manner. Despite the vast land coverage and enormous expense (EU expenditure totalling nearly €20 billion between 2007–2013 [5]), the ability of AES to protect biodiversity and deliver meaningful environmental benefits has been repeatedly questioned [6–9]. However, such evaluations of the efficacy of AES are typically based on assessments of biodiversity responses [6,9] and rarely take account their ability to support a range of ecosystem services (however, see [10–12]).

Costanza et al. [13] define ecosystem services (ES) as 'benefits human populations derive directly or indirectly from ecosystem functions' and specify these to be (i) supporting services, (ii) provisioning services, (iii) regulating services, and (iv) cultural services. While more recent definitions classify supporting services as underpinning processes [14], we

retain the original classification to consider a full range of services. In Europe, agricultural ecosystems are primarily managed to deliver provisioning services, predominantly supporting food production [7,15]. These systems rely heavily on a range of supporting and regulating services to remain productive, including soil formation, nutrient cycling, pollination, and pest control [3,15]. However, intensive agriculture often severely degrades natural assets responsible for these services [16]. For example, conventional tillage used when re-sowing production grasslands can lead to soil erosion and reduced fertility [17].

Selective herbicides, nutrient addition, and reseeding have been used on the majority of UK grasslands (58% of grasslands, equivalent to 7.2 million ha. and nearly 40% of the total UK agricultural area), with the goal of increasing levels of livestock production [2,18]. These practices have resulted in floristically species-poor swards and have impacted negatively on a range of ecosystem services including soil health, pollination, pest control, and populations of culturally significant taxa, such as farmland birds [2]. However, there is considerable potential to enhance these grasslands to support many of these important, but degraded, services. For instance, grasslands could be managed to create favourable habitats for important taxa and improve the spatial distribution of key resources at local and landscape scales. These grasslands might then act as source habitats from which pollination and pest control services could spill-over into cropped land, thereby improving service delivery [19–21]. For example, greater availability of highly biodiverse grasslands can enhance landscape composition and habitat connectivity, promoting the stability and size of both pollinator and natural enemy communities [22,23]. The challenge is to satisfy the growing global demand for provisioning services whilst maintaining the integrity of other supporting and regulating ecosystem services required to ensure production capacity is maintained long-term [7,24]. While agri-environment schemes have the potential to support multiple ecosystem services, and so contribute to these goals, the extent to which this is practical needs to be quantified [6].

Here, we describe a 4 year, field-scale experiment that investigates the extent to which grassland agri-environment schemes can be used to maintain forage production and quality whilst enhancing multiple ecosystem services, specifically pollination, pest control, soil quality (bulk density, total nitrogen, and total carbon), and the provisioning of food resources for farmland birds (birds providing cultural services [10,25]). We tested the hypothesis that the enhancement of these services can be achieved by the establishment of key plant functional groups (grasses, legumes, and non-leguminous forbs) and appropriate management (seed bed cultivation, as well as cutting and grazing management). We predict that synergies will exist between the provision of regulating (pollination, pest control, and soil services) and cultural services (food resources for birds), with the shared driver of enhanced floral diversity having a positive effect on all these services [12]. We also predicted that management enhancing agricultural production would diminish the provision of both regulating and cultural services [26].

2. Materials and Methods

2.1. Study Site and Experiment

This study was undertaken between 2008–2012 on an agriculturally improved grass ley in Warfield, Berkshire, UK (grid reference: SU9073), dominated by *Lolium perenne* (Poaceae) and *Trifolium repens* (Fabaceae). In April 2008, a multi-factorial experiment was established using a randomised split-split-split-plot design, replicated across four blocks. The treatment levels (described below) were intended to assess how enhancement of sward floral functional diversity, consequent management, and seed bed cultivation interacted to affect the delivery of provisioning, regulating, supporting, and cultural ecosystem services. During the experiment, no treatments received inorganic fertiliser.

The experiment had 24 treatment levels, split across 96 plots of an average size of approximately 875 m^2. Three seed mixture main treatments (SEED) were applied at the whole-plot level. (1) The first was a 'grass'-only seed mix (G), comprising five grass species selected for good agronomic performance under low fertiliser input. These were sown

at 30 kg ha^{-1} costing approximately €83 ha^{-1}. This re-seeding with productive grasses represented a control treatment; all other treatments were compared to this. (2) The second was a 'grass and legume' seed mix (GL), comprising the same five grasses as G and seven agricultural legume varieties sown at 34 kg ha^{-1} (€120 ha^{-1}), and the third was a (3) 'grass, legume, and forb' seed mix (GLF), comprising the same five grasses and seven legumes as GL, along with six forbs sown at 33.5 kg ha^{-1} (approximately €190 ha^{-1}). See Supplementary Material Table S1 for seed mix composition. The second treatment was sward management (MANAGEMENT), which represented the split-plot treatment superimposed over SEED. This treatment had two levels represented by either cattle grazing (three livestock units ha^{-1}) or cutting for silage to a height of 10 cm. Superimposed on MANAGEMENT was the split-split-plot treatment of management intensity (INTENSITY). This was either intensive (cattle grazing from May–October, or silage cuts in May and August) or extensive (grazing as before, but suspended June–August, or a single silage cut in May). The extensive management was intended to provide a summer window allowing plants to flower and seed [27]. A final split-split-split-plot treatment was superimposed over INTENSITY to investigate the effects of seed bed establishment technique (CULTIVATION). CULTIVATION occurred in autumn 2008 and had two levels: (1) "deep ploughing": herbicide application (Glyphosate at 5 L ha^{-1} *a.i.*) followed by inversion tillage using a conventional reversible plough turning soil to a depth of 25–30 cm; and (2) non-inversion "minimum tillage": surface soil disturbance over approximately 40% of its area to a depth of approximately 5 cm. See Supplementary Material Figure S1 for the layout of the four treatment levels. See Supplementary Table S2 for the categories and indicators of ecosystem services measured. Ecosystem service assessments (detailed below) were taken between 2009 and 2012.

2.2. Provisioning Services (Agronomic Production; Forage Yield and Quality)

Agricultural productivity was assessed as the dry mass and quality of silage [28] annually. These were assessed only in the 48 plots where cutting management was applied. Following cutting with a 3 m wide mower (10 cm from the ground), a 5 m strip of the cut grass was weighed. From this, a homogeneous sample of 0.5 kg was removed and oven dried at 80 °C until it reached constant mass. The ratio of dry to wet weight was used as a conversion factor to determine the herbage dry matter yield. Where two sward cuts were taken in a year (under intensive management), the total yield was summed for a given plot. To assess nutritional quality percentage, total nitrogen for the first cut of the year (May) was determined (%N) (LECO Instrumente Plzen, Plaska, Czech Republic).

2.3. Regulating Services (Pollination and Pest Control)

The abundance of all bees, butterflies, and hoverflies was used as a proxy measure to evaluate the potential for the treatments to support pollination services in the wider landscape. While we focus here on abundance as a measure of pollination provision, the response of species richness was qualitatively similar (for these results, see Supplementary Material Table S3). Pollinator assessments were undertaken three times annually between May–August within two permanent and parallel 20 × 2 m transects in each experimental plot. Each transect was surveyed between 10.00–16.00 h following weather conditions specified in Pollard and Yates [29]. For each plot, pollinator abundance was summed for a given year.

The potential of the treatments to support natural pest control in the wider landscape was estimated using the abundance of predatory beetles (Carabidae and Staphylinidae) as a proxy [30–32]. Beetles were sampled using a Vortis suction sampler (Burkland Ltd., UK) in June and September on dry days between 10.00 and 16.00 h. Each plot sample comprised 55 suctions of ten seconds' duration [33]. Again, species richness was not considered further, although its response was qualitatively similar to abundance (see Supplementary Material Table S3).

2.4. Supporting and Regulating Services (Soil Processes)

Low soil fertility and soil compaction have negative impacts on grassland productivity [28]. Soil compaction was assessed as the bulk density within the 0–10 cm soil horizon, in October 2009, 2010, and 2012. In each of these years, five individual soil cores (8 cm diameter, 10 cm depth) were taken at 2 m intervals. Following turf removal, the volume of cores was assessed by water displacement. Cores were then sieved to remove stones (>3 mm diameter) and large roots, and their volume was measured by water displacement. Remaining soil was dried until constant mass at 80 °C and weighed. Soil bulk density was defined as the volume of the core (minus the volume of stones and large roots) divided by soil dry weight and was averaged across the five cores from each plot. Soil bulk density was only assessed in the 48 plots of the 'intensive' level of management INTENSITY. A further five additional soil cores (35 mm diameter × 75 mm deep) were taken from these same 48 plots in October 2009, 2010, and 2012. These were homogenised, and a 50 g sub-sample was removed to determine total nitrogen (%N) and total carbon (%C) [34,35].

2.5. Cultural Services (Food Resources for Farmland Birds (BIRDFOOD))

Wild birds can contribute to all four categories of ecosystem services [25], but in the UK, their most often cited contribution to human wellbeing is cultural [10,36]. For instance, they have considerable symbolic, acoustic, and aesthetic value, and are the focus of a variety recreational activities such as art, photography, nature documentaries, citizen science projects, and bird watching activities [25,36]. Indeed, the RSPB's Big Garden Birdwatch is the world's biggest garden wildlife survey. The organization also has a membership of over 1 million people, making it the UK's largest nature conservation charity [37]. Similarly, birdwatching activities contributed nearly $80 billion to the US economy in 2016 [38]. However, many wild bird species have suffered considerable declines, partly due to the loss of invertebrate food [39,40]. The total biomass of all beetles from vortis suction samples (described above) was used as a measure of food provision for insectivorous farmland birds [41] (henceforth referred to as BIRDFOOD). Biomass was determined as a product of abundance, and individual species biomass was determined from the length vs. mass relationship described by Rogers et al. [42].

2.6. Data Analysis

All analyses were undertaken using general linear mixed effects models in R version 3.0 (R Development Core Team) with the 'lme4' package [43]. We applied a multi-model inference approach using the 'MuMIn' [44] package to assess the separate responses of the eight ecosystem service delivery measures to the treatments of SEED, MANAGEMENT, INTENSITY, and CULTIVATION, as well as YEAR. All models used the same hierarchical structure of random effects to account for the split-split-split-plot design, with CULTIVATION nested within INTENSITY nested within MANAGEMENT nested within SEED nested within BLOCK. This hierarchical structure also accounted for the repeated measures from plots over the four years. The exception to this model structure was for models where the response was a soil service (bulk density and total soil nitrogen and carbon), which excluded the INTENSITY treatment, as only 'intensively' managed plots were sampled. Similarly, agricultural productivity services (dry matter yield and herbage nitrogen content) excluded the MANAGEMENT treatment, as only herbage collected from cut plots could be sampled. Count data were modelled using a Poisson error distribution and log link function following assessment of model residuals; all other models were normally distributed. A maximum likelihood approach was used for all parameter estimations.

The multi-model inference approach was used to provide an unbiased method for estimating parameter importance by considering all potential model combinations. We used Akaike's information criterion (AIC) to compare model fits [45]. For each ecosystem service response, models representing all possible combinations of the fixed effects (excluding interactions) were tested and ranked on the basis of the AIC value (32 models where five fixed effects were present, 16 for those with only four fixed effects). For each of these

models, an AIC difference (Δ_i) was calculated as the difference in the AIC values between any given model and the best fitting model (lowest AIC). We considered any model within a Δ_i of less than 2 to have equivalent power in explaining variation in the data [45], referred to as the ΔAIC < 2 model sub-set. From this sub-set of models, we produce averaged parameter estimates across models within the ΔAIC < 2 sub-set by weighting with Akaike weights (w_i). These provide a measure of the relative support for each model and represent the probability that it would be selected as the best fitting model if the data were collected again under identical conditions [45]. To assess the relative weight of evidence in support of each fixed variable, an importance score is calculated as the sum of the w_i scores ($\sum w_i$) for models within the ΔAIC < 2 subset, where a score of 1 indicates a fixed effect present within all models of the ΔAIC < 2 subset. Any fixed effect with an importance score of less than 0.5 was excluded. To provide an overall indication of goodness of fit, we derived a marginal R^2 value for the global model [46].

3. Results

Establishment success of sown seed mixes was high, with the floristic composition of the experimental plots being dominated by the sown plant groups (G, GL, and GLF); legumes were the dominant functional group in the GL treatment, GLF plots were largely comprised of non-legume forbs, and vegetation cover in the G treatments was almost exclusively grasses. Further details are given elsewhere [47]. Over the four-year sampling period, 6320 bees, 728 butterflies, 1524 hoverflies, and 4575 ground beetles were recorded.

3.1. Provisioning Services (Agronomic Production, Forage Yield, and Quality)

For forage yield (% dry matter yield), the variance was best described by a ΔAIC < 2 subset of 3 models (R^2 = 0.68) (Table 1). All four fixed effects (SEED, INTENSITY, CULTIVALTION, and YEAR) were included, with SEED ($\sum w_i$ = 1.00) and YEAR ($\sum w_i$ = 1.00) having higher importance scores than either INTENSITY ($\sum w_i$ = 0.77) or CULTIVATION ($\sum w_i$ = 0.77). Weighted parameter estimates (Table 1) suggest that seed mix (SEED) had the greatest overall effect, with dry matter yield increasing with plant species richness. On average, intensive management resulted in a 13% increase in forage yield compared to extensive management, and minimum tillage resulted in a 12% increase compared to deep ploughing. Yield varied over the course of the experiment, although it showed an overall pattern of decline (Supplementary Material Table S3).

Table 1. Summary weighted model average outputs based on the ΔAIC < 2 sub-set of models. $\sum w_i$ = Importance score (summed w_i), a relative measure of the importance of an individual fixed effect, calculated as the sum of the w_i scores for models within the ΔAIC < 2 subset. Explanatory factors with an importance score < 0.5 are considered to be of marginal importance, and weighted mean parameter estimates are not provided; μ = weighted mean parameter estimate derived using the w_i importance score. G = grasses; GL = grasses and legumes; GLF = grasses, legumes, and forbs; Ext. = extensive management incorporating a summer rest period to allow plant growth; int. = intensive management with no rest period; Min.till. = minimum tillage cultivation; Deep = deep ploughing cultivation; For year, only the establishment (yr1) and final year of monitoring (yr4) parameter estimates are presented to indicate the direction of temporal trends. For model output for each year, see Table S3.

Response	Models ΔAIC < 2	Seed Mix	Management	Management Intensity	Cultivation	Year
Agronomic Production; Forage Yield and Quality						
Dry Matter Yield	3	**GLF > GL > G** (μ: 7.83 > 6.94 > 3.33) $\sum w_i$ = 1.00	–	**Int. > Ext.** (μ: 7.36 > 6.94) $\sum w_i$ = 0.77	**Min.till. > Deep** (μ: 7.3 > 6.94) $\sum w_i$ = 0.71	**Yr1 > Yr4** (μ: 6.94 > 2.73) $\sum w_i$ = 1.00
Herbage Nitrogen Content	3	**GLF > GL > G** (μ: 1.98 > 1.97 > 1.64) $\sum w_i$ = 1.00	–	$\sum w_i$ = 0.16	$\sum w_i$ = 0.42	Yr1 > Yr4 (μ: 1.97 > 1.10) $\sum w_i$ = 1.00

Table 1. *Cont.*

Response	Models ΔAIC < 2	Seed Mix	Management	Management Intensity	Cultivation	Year
Pollination & Pest Control						
Pollinator Abundance	2	**GLF > GL > G** (μ: 92.4 > 50.2 > 3.50) $\sum w_i$ = 1.00	**Cut > Graze** (μ: 50.2 > 32.5) $\sum w_i$ = 1.00	**Ext. > Int**. (μ: 50.4 > 31.4) $\sum w_i$ = 1.00	**Deep > Min.till**. (μ: 50.2 > 46.7) $\sum w_i$ = 0.79	**Yr1 > Yr4** (μ: 50.2 > 27.9) $\sum w_i$ = 1.00
Predator Abundance	3	**GL > GLF > G** (μ: 32.6 > 32.2 > 10.0) $\sum w_i$ = 1.00	$\sum w_i$ = 0.25	**Ext. > Int**. (μ: 32.6 > 19.4) $\sum w_i$ = 1.00	$\sum w_i$ = 0.25	**Yr1 > Yr4** (μ: 32.6 > 11.4) $\sum w_i$ = 1.00
Soil Processes						
Bulk Density	6	$\sum w_i$ = 0.24	$\sum w_i$ = 0.23	–	$\sum w_i$ = 0.24	$\sum w_i$ = 0.20
Total Carbon	6	$\sum w_i$ = 0.24	$\sum w_i$ = 0.19	–	**Min.till. > Deep** (μ = 2.88 > 2.7) $\sum w_i$ = 1.00	$\sum w_i$ = 0.34
Total Nitrogen	6	**GLF = GL > G** (μ: 0.26 = 0.26 > 0.25) $\sum w_i$ = 0.69	$\sum w_i$ = 0.17	–	**Min.till. > Deep** (μ: 0.27 > 0.26) $\sum w_i$ = 1.00	$\sum w_i$ = 0.39
Cultural Services (Food Resources for Farmland Birds (BIRDFOOD))						
Total Invertebrate Biomass	1	**GLF > GL > G** (μ: 144.3 > 133.5 > 67.8) $\sum w_i$ = 1.00	**Cut > Graze** (μ: 133.5 > 112.2) $\sum w_i$ = 1.00	**Ext. > Int**. (μ: 133.5 > 107.3) $\sum w_i$ = 1.00	**Min.till. > Deep** (μ: 149.7 > 133.5) $\sum w_i$ = 0.90	**Yr1 > Yr4** (μ: 133.5 > 65.5) $\sum w_i$ = 1.00

For forage quality (herbage nitrogen content), the ΔAIC < 2 subset contained SEED and YEAR (R^2 = 0.60), retaining 3 (Table 1). The nitrogen content of samples taken from the GL and the GLF treatments were relatively similar, but both were considerably higher than the values recorded for samples from the grass-only (G) treatment. Nitrogen content remained stable for the first 2 years of the experiment and then declined, dropping by nearly half from 1.9% to 1.0% w/w from the first to last years. Nitrogen content was independent of CULTIVATION and INTENSITY treatments ($\sum w_i$ = 0.42 and 0.16, respectively).

3.2. Regulating Services (Pollination and Pest Control)

Pollinator abundance was affected by all five fixed effects; SEED, MANAGEMENT, INTENSITY, CULTIVATION, and YEAR (R^2 = 0.90) (Table 1). The ΔAIC < 2 subset contained only 2 models. Weighted parameter estimates (Table 1) show that the composition of the seed mix (SEED) had the greatest overall effect, with GL and GLF seed mixes having the highest pollinator abundances (SEED $\sum w_i$ = 1.00). Pollinators were most abundant in the GLF treatment. Intensive management resulted in a 38% reduction in pollinator abundance compared to extensive management (INTENSITY $\sum w_i$ = 1.00) and grazing almost halved pollinator abundance compared to cutting (MANAGEMENT $\sum w_i$ = 1.00). There was a gradual decline in pollinator abundance over successive years (YEAR $\sum w_i$ = 1.00), although a drought in year 2 depressed the number of pollinators across all treatments. On average, annual rainfall was 55% higher during the main growing period (April–Sept) in the other years of the study [48]. The other years also had, on average, over 40% more days with >1 mm rain during the growing season, compared to year 2 [48]. This drought temporarily depressed all measured ecosystem services. Deep ploughing had a slightly positive effect on abundance compared to minimum tillage (CULTIVATION $\sum w_i$ = 0.79).

For predator abundance, the ΔAIC < 2 subset contained only three models, with SEED, INTENSITY, and YEAR having importance scores > 0.50 (R^2 = 0.78) (Table 1). Predator abundance in the GLF and the GL treatments was virtually identical, but abundance in both was three times higher than in the G treatment (SEED $\sum w_i$ = 1.00). Extensive management supported 59% more predators than intensive management (INTENSITY $\sum w_i$ = 1.00). There

was a successive decline in the abundance of predators over the 4-year sampling period (YEAR $\sum w_i = 1.00$).

3.3. Supporting and Regulating Services (Soil Processes)

3.3.1. Soil Compaction (Bulk Density)

The ΔAIC < 2 subset contained 11 models, although none of the fixed effects had importance scores > 0.50 (SEED $\sum w_i = 0.24$, MANAGEMENT $\sum w_i = 0.23$, CULTIVATION $\sum w_i = 0.24$ and YEAR $\sum w_i = 0.20$; overall $R^2 = 0.04$). This strongly indicates that none of the treatments had any effect on soil compaction as measured by bulk density (Table 1 and Figure 1).
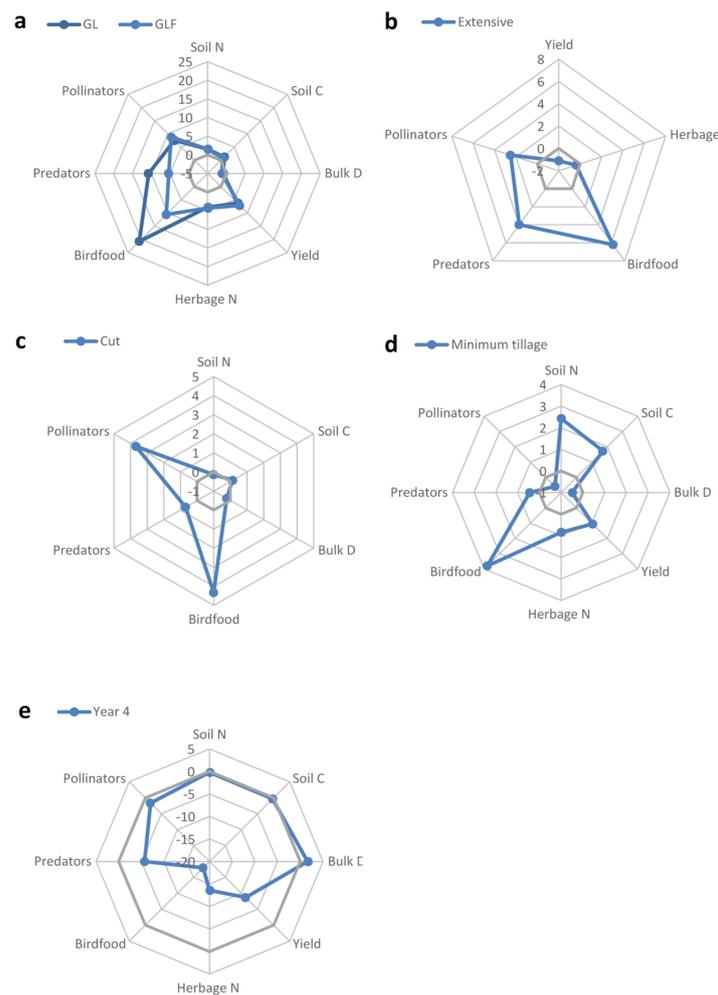
Figure 1. Summary effect sizes for the responses of ecosystem services to different experimental treatments. An effect size represents the difference between the mean population responses of two different treatment groups. This difference is divided by the pooled standard deviation. Note not all ecosystem services were measured for each treatment, and effect sizes differ between treatments (the 0 axes are thickened on each spider diagram for clarity). (**a**). Seed treatment; GL (grasses and legumes), and GLF (grasses, legumes, and forbs) compared to G (grasses). (**b**). Cultivation; minimum tillage compared to conventional deep ploughing. (**c**). Management type; cutting regimes compared to grazing. (**d**). Management intensity; extensive compared to intensive. (**e**). Year; final year (year 4) compared to the establishment (year 1) to indicate the directional trends. The model output for each year is given in supplementary Table S3. Yield = dry matter yield, Herbage N = herbage nitrogen content, Pollinators = pollinator abundance, Predators = predator abundance, Bulk D = bulk density, Soil C = total carbon, Soil N = total soil N, Birdfood = total invertebrate biomass.

3.3.2. Soil Nutrients: Total Carbon and Total Nitrogen

The ΔAIC < 2 subset contained six models and indicated that total soil carbon responded to the CULTIVATION treatment alone (R^2 = 0.15, CULTIVATION $\sum w_i$ = 1.00) (Table 1), with deep ploughing reducing soil carbon by 6% when compared to minimum tillage. In the case of soil nitrogen, CULTIVATION and SEED were retained in the ΔAIC < 2 subset, which contained six out of a possible 16 models (R^2 = 0.20) (Table 1). As with soil carbon, deep ploughing reduced soil nitrogen compared to minimum tillage by approximately 5% (CULTIVATION $\sum w_i$ = 1.00). Both the GL and GLF seed treatments contained similar levels of nitrogen, which in the case of the GL seed treatment was 8% higher than that of the G seed treatment (SEED $\sum w_i$ = 0.69).

3.4. Cultural Services (Food Resources for Farmland Birds (BIRDFOOD))

Considering invertebrate biomass as an indicator of resource provision for farmland birds, the ΔAIC < 2 subset was based on a single model 1 that included all the fixed effects of CULTIVATION, SEED, MANAGEMENT, INTENSITY, and YEAR (R^2 = 0.51) (Table 1). Biomass was greatest in the most diverse seed treatment (GLF) and was markedly higher than the average biomass from both the GL and G seed treatments (SEED $\sum w_i$ = 1.00). Cutting increased invertebrate biomass provision by 42% over grazing, while extensive management caused a 53% increase when compared to intensive management (MANAGEMENT $\sum w_i$ = 1.00, INTENSITY $\sum w_i$ = 1.00). Cultivation had lower importance ($\sum w_i$ = 0.9) compared to the other fixed effects, although biomass was 23% lower where deep ploughing was used to establish the plots. Consistent with the other variables, there was an overall decline in invertebrates over the 4 years.

4. Discussion

4.1. Using Seed Treatments to Achieve Multiple Ecosystem Service Delivery

From an agronomic perspective, the core role of grasslands is the production and husbandry of livestock. In the absence of inorganic fertilisers, GL and GLF seed treatments provide an effective approach for improving agricultural production by increasing the dry matter yield and herbage nitrogen content. Specifically, the introduction of legumes into grassland swards translated into improved provision of pollination, pest control, total invertebrate biomass (BIRDFOOD), and soil nitrogen services (Figure 1a). Furthermore, the addition of non-leguminous flowering plants had direct benefits for pollination, cultural services (BIRDFOOD), and agricultural production (forage yield and quality) (Figure 1a). Both the GL and GLF treatments yielded 8.0 and 8.3 t ha^{-1}, respectively, in year 1, which are comparable to typical yields of 7.4–9.8 t ha^{-1} of improved grasslands receiving nitrogen fertiliser in the UK [49]. While this yield was maintained (excluding drought year 2) until year three of the experiment (GL = 6.9 t ha^{-1} and GLF = 9.4 t ha^{-1}), yield collapsed after this period. The use of simple seed mixture therefore has the potential to provide a cost effective and sustainable alternative that minimises inorganic fertiliser inputs, but possibly requires regular re-sowing. Re-sowing may be required because, over time, many of the flowering plants (particularly legumes) decline due to their low ability to persist in existing swards [47,50]. Consequently, improvements in ecosystem service provision associated with plant diversity eventually diminish without active management [47,51,52].

The finding that improving grassland species richness produces more biomass is consistent with a wide body of research (e.g., [51–53]). It is most likely due to complementarity, whereby niche partitioning results in improved resource utilisation use over space and time [53]. However, the mechanism for complementarity between non-leguminous plants is not always clear, as it depends on the functional characteristics of the species involved [54]. On the other hand, legumes typically interact positively with other plants by increasing nitrogen availability [52], which can improve primary productivity. Indeed, we found that including legumes in the seed treatment increased soil nitrogen and herbage nitrogen content. Although superior production gains may be made by applying inorganic N-fertilizer, this is costly and considered unsustainable [7,16], with diffuse nitrogen pollution

costing the European Union between €70–320 billion annually [55]. Managing landscapes to improve legume persistence and productivity in grasslands could help enhance soil fertility and reduce the over-reliance on inorganic N-fertilizer, whilst maintaining adequate yields [52]. There is also evidence that mixed-species swards improve other nutritional aspects of forage, with associated benefits to livestock production [52].

Considering invertebrate responses to the treatments, there was clear complementarity between the goals of supporting agricultural production and enhancing the abundance of pollinators and predators of pests (Figure 1a). Increased sward diversity promoted populations of both pollinators and predatory beetles in agreement with the findings of existing studies [22,23,56–59]. Diversifying grassland swards not only provides host plants for invertebrates, but also generates structural niches for a range of species [58,59]. For pollinator populations, variation in both the timing and morphology of floral resources is an important key factor [8,60]. For instance, as pollinators differ in their morphology and foraging behaviour, certain species, e.g., shorter-tongued *B.terrestris* and *B.pratorum*, cannot take full advantage of the recourses provided by legumes [61]. Therefore, the most functionally diverse seed treatment, GLF, will support a greater range and abundance of pollinator species. By ensuring temporal continuity of foraging resources, the GLF treatment could also help maintain pollination services long term, and facilitate spill-over into surrounding landscapes [21]. Another benefit of enhancing these invertebrate populations was substantial increases in the availability of insects as bird food resources in the GLF seed treatments. This addresses one of the probable drivers of widespread declines in populations of farmland birds, with insect availability being particularly important during the breeding season when protein resources are needed for chick growth [40,62]. However, one limitation of this study is that bird populations were not directly measured in response to the treatments. It is possible that an increase in invertebrate resource provisions may only have a positive impact on local bird dynamics where other population limiting factors, such as quantity and quality of suitable nesting sites, are adequate [62]. Therefore, future research should directly assess and quantify the effect of experimental treatments on local bird populations.

Supporting bird life is just one of the many cultural benefits humans derive from grasslands [63]. Grasslands also contribute to landscape aesthetics and cultural heritage, as well as creating opportunities for tourism, recreation, and education [63]. Although delivery of other cultural benefits was not directly assessed in this study, this is seen as an increasingly important area of research [36,63–68]. There is a growing body of empirical evidence demonstrating that contact with the natural environment confers a range of measurable benefits to human health and wellbeing, including positive effects on cognitive performance, social interactions, psychological health, and physiological well-being (for reviews, see [65] and [66]). With mental health disorders predicted to become the leading cause of mortality and morbidity worldwide by 2030 [69], there is an urgent need to understand which particular features of the environment deliver health benefits via cultural pathways [63,67] and better integrate these effects into ecosystem service assessments, models, and land-use planning decisions [63–65]. This is particularly important for green spaces near urban environments where the highest frequency of human–nature interactions are likely to occur.

4.2. Management: Cutting Benefits Multiple Ecosystem Services but Management Intensity Creates Trade-Offs

Arthropods typically benefit from increased sward structural complexity [23,52,60]. Therefore, management practices that facilitate the development of key structures, such as flowers, stems, foliage, fruits, and seeds, will have the greatest positive impact on their abundance. For this reason, pollination, pest control, and cultural services were all maximised under extensive management regimes, as suspending grazing or cutting provides an opportunity for important plant structures to re-grow (Figure 1b). Pollinators and cultural services also had strong positive responses under cutting regimes as opposed to grazing (Figure 1c). This suggests that sward structural complexity re-generated better

under cutting regimes. This is possibly because cutting is a one-off event, and although it is immediately destructive, the sown plant species quickly recovered before the next cut occurred. Even extensive grazing is a gradual and continuous process, preventing the re-growth of key structures and potentially causing prolonged disturbance to vegetation and insects. Previous studies comparing mowing and grazing have yielded conflicting results (e.g., [56,70,71]), and a recent meta-analysis found that although grazing often has the greatest biodiversity benefits, this benefit is modest and site specific [72]. Consequently, the choice between cutting and grazing may need to be made at local scales and take certain factors into account, such as geography, type of grazing animal, and historical management [23,72]. It is also worth noting that the relatively small plot sizes in this study may have inadvertently created relatively intense grazing, artificially heightening grazing's detrimental impact.

Importantly, extensive management strategies did not constitute a "win–win" for all services, as yield was maximised under intensive management (Figure 1b). Therefore, the decision over management intensity may result in conflicts between service delivery. Trade-offs are commonly found between provisioning services and other regulating and cultural services [3,26,73–76]. Consequently, the spatial optimisation of management practices will be key to effectively balancing trade-offs and reducing the environmental footprint of intensive grassland agriculture [3,15,77,78]

4.3. Cultivation Techniques Generate Trade-Offs between the Services

As with management intensity, the choice of cultivation technique generated trade-offs between the services studied. BIRDFOOD, dry matter yield, and soil carbon and nitrogen all prospered following minimum tillage, but pollinator abundance did not (Figure 1d). The positive effect of deep ploughing on pollinators may be a reflection of the establishment of non-sown forbs. Forb species not present in sown seed-treatments tended to be present in greater numbers following disturbance of the seed bank by deep ploughing [47].

A key finding of this study was the limited effect of cultivation practices on soil ecosystem services. Although minimum tillage did improve the levels of total soil carbon and total soil nitrogen (Figure 1d), the overall increase in mineralisation was relatively small (Table 1). The low levels of change could be due to the time frame of the experiment. There is often a time-lag associated with the effects of management on soil processes, and it can take five or more years before any impact is detected [79,80]. However, our results are consistent with a growing body of evidence showing that the influence of reduced tillage on soil carbon storage is relatively modest [17,80,81]. In addition, the effects of minimum tillage on yield and soil minerals is not consistent between studies, because their fate partly depends upon climatic conditions, existing management practices, soil texture, and topography [17,81]. Therefore, for it to be an effective tool in the sustainable intensification of agriculture, minimum tillage should be carefully targeted and monitored. The wider benefits of minimum tillage should also be considered, such as reducing production costs and carbon dioxide emissions, as well as improving soil structure and stability, which can, in turn, prevent erosion and water pollution [17].

As this study was only carried out at a single site, the next challenging but essential step will be to evaluate how the flow, delivery, and value of these ecosystem services changes over space (e.g., at landscape and global scales) and time (e.g., in response to factors such as climate change and human population growth) [63]. The rapidly advancing field of ecosystem modelling and mapping may provide the best opportunity to achieve this [63,78,82–84] (e.g., using tools such as GIS, Bayesian Networks, InVEST, ARIES, and SolvES; for comprehensive reviews, see [83,84]). Although many of the modelling tools currently available lack the complexity to deal with multiple ecosystem service interactions adequately and require validation with empirical data, the practice of combining two or more modeling techniques can help overcome certain individual model limitations to help meet practitioner needs [84,85].

5. Conclusions

Productive grasslands make a vital contribution to global food security [86]. However, for agricultural systems to be truly sustainable, they must maintain or increase production by optimizing resource use whilst conserving environmental integrity [16]. Our study reveals that grassland systems have the capacity to maintain high levels of food production and supply multiple services simultaneously. However, the supply of most of the ecosystem services considered declined over the course of the experiment (Figure 1e), emphasising the importance of ongoing management in safeguarding grassland services and likely requiring the regular re-establishment of the key plant functional groups. We show that for a relatively low cost, agronomic production can be maintained while reducing the environmental footprint of intensive grassland agriculture. Across the eight classes of services considered, the establishment of floristically diverse swards (in particular, those containing legumes and forbs) and cutting regimes, was the most likely to achieve this by enhancing not only forage yield and quality, but also pollination, pest control, soil nitrogen, and cultural services. However, a single, nation-wide management solution is unlikely to exist, as trade-offs between services were also identified. For example, intensive management strategies did not constitute a "win-win" for all services, as while yield was increased, other services like pollination and natural pest control were negatively affected (Figure 1b). Consequently, pragmatic decisions will have to be made regarding which particular service or bundle of services, to promote in a given part of the landscape, and may need to be tailored to address local deficits in ecosystem service delivery [87]. For example, extensive management would be necessary where the demand for pollinators exceeds that of production. This could be the case for grasslands surrounded by insect pollinated crops [20]. However, services like pollination and pest control are of greater value to arable than grassland production. Consequently, their strategic enhancement through improved grassland management would likely require financial incentives provided by agri-environment schemes. The complementary use of multiple ecosystem modelling and mapping tools may provide the best opportunity to facilitate spatial allocation decisions at national scales and maximise the supply of multiple ecosystem services [63,78,82,84]. It is only by integrating our understanding of ecological processes into landscape planning procedures that we can strategically target management interventions to enhance synergies, balance trade-offs, and work towards creating sustainable agro-ecosystems to safeguard human, economic, and environmental health.

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