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Original Articles

Indicators for assessing the multifunctionality of agriculturally used grasslands

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ABSTRACT

Grasslands are highly multifunctional ecosystems, providing forage to livestock and many regulating and cultural ecosystem services (ES). Agri-environmental schemes (AES) often aim at sustaining and increasing especially non-production ES, i.e., those services not primarily relevant for production but for society as a whole. An open question restricting the implementation of such AES for grassland ES multifunctionality is how to effectively measure and monitor multifunctionality without separately accounting for all single ES.

To address this question, we measured 30 plot-level ES indicators, including plant species richness, in 88 permanent grasslands along a fertilization intensity gradient in Switzerland. We explored the correlative structure among all ES indicators and the potential of each indicator to approximate non-production ES multifunctionality. We finally discuss potentially suitable ES-multifunctionality indicators for future result-based AES.

The analyses revealed two distinct bundles within the comprehensive list of ES indicators considered in the study. The first bundle consisted of ten ES indicators, including aesthetic appreciation, fungal richness, plant richness, and several ES indicators for reduced adverse environmental impacts (e.g., lower nutrient leaching risk). This bundle was strongly negatively related to the second bundle, composed of twelve ES indicators that were mostly directly related to intensive forage production (e.g., nutrient supply, yield quantity and yield quality). Plant species richness (positive) and fertilization intensity (negative) were the two measures most closely related to non-production multifunctionality, highlighting their potential to be put to use as multifunctionality indicators.

We argue that due to the policy relevance of biodiversity conservation, plant species richness could find application as indicator for AES designed to increase and monitor grassland non-production multifunctionality. While plant species richness is rather stable over time, considering changes (reductions) in fertilization intensity could be an option for a more responsive indicator to be used to facilitate ES-positive grassland management on the short term. Integrating our findings in future agricultural policies could be a significant step towards rewarding land users for the non-production benefits provided by their agroecosystems.

1. Introduction

Ecosystem services (ES) are essential for human well-being. Grassland ecosystems, which cover about 70 % of the global agricultural land area, offer provisioning services such as high-quality protein-rich forage for livestock as well as many important regulating and cultural services (Bengtsson et al., 2019; Schils et al., 2022; Richter et al., 2024). Despite of the potentially high ES multifunctionality of permanent grasslands, i.e., the ability to simultaneously supply many services (Manning et al., 2018), ecological degradation considerably threatens the provision of many relevant ES (Bardgett et al., 2021). Due to strong direct effects of management activities on most plot-level ES, decision-making by farmers and associated agri-environmental policies considerably affect the ES provided by permanent grasslands (Van Vooren et al., 2018;

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Sollenberger et al., 2019; Neyret et al., 2021; Le Provost et al., 2023). Especially management intensity is further seen as the major cause for plot-level trade-offs between different grassland ES (Allan et al., 2015). If a specific form of management strengthens a set of ES while weakening several others, the formation of bundles of correlated ES can be expected (Teixeira et al., 2023). An ES bundle is a set of ecosystem services appearing together across space or time (Saidi and Spray, 2018). Such bundles could help to streamline the approximation of ES multifunctionality by using only some of these highly correlated indicators, and they can support decision-making by reducing the dimensionality of ecosystem multifunctionality (Raudsepp-Hearne et al., 2010; Saidi and Spray, 2018). Yet, with respect to permanent grasslands, these ES-indicator bundles are not sufficiently explored to enable an application for management and policy decisions (Dumont et al., 2019). A mechanistic understanding of the underlying drivers of the formation of ES bundles is crucial to inform decision-making (Dade et al., 2019).

Sustaining ES supply and ES multifunctionality are targets of agricultural policies and respective schemes at many places. As policy support is particularly important for those ES that do not have a market value, payments for ES have been suggested to link agricultural subsidies to non-monetary benefits (i.e., societally relevant regulating and cultural ES) provided by agricultural land (Engel, 2015). In this paper, the set of ES of primarily societal relevance and not only linked to increasing provisioning ES is termed *non-production multifunctionality*, which could be a target of future agricultural policies. To link payments to realized outcomes, result-based agri-environmental schemes (AES) have been suggested. Result-based AES are particularly effective policies because they inherently contain the monitoring of the outcomes and are more flexible and more motivating for farmers than purely action-based schemes (Matzdorf et al., 2008; Matzdorf and Lorenz, 2010; O'Rourke and Finn, 2020). However, such result-based schemes require reliable, cost-effective, and broadly accepted indicators to assess and monitor grassland (non-production) multifunctionality. This may also include adverse environmental impacts associated with intensive grassland use such as the emission of reactive nitrogen compounds. Many indicators for single ES or adverse environmental impacts have been suggested for various policy goals such as soil carbon stocks (Manning et al., 2015), soil functions (Griffiths et al., 2016), and biodiversity (Elmiger et al., 2023). However, indicator systems are less developed for cultural ES (Plieninger et al., 2013). As the lack of suitable indicators for multifunctionality hampers the potential to implement result-based AES for grassland multifunctionality (van Oudenhoven et al., 2018; O'Rourke and Finn, 2020), identifying such indicators is high on the research agenda.

Accounting for ES multifunctionality in an AES requires either all single ES to be measured, which is unrealistic for large-scale programs due to financial and technical constraints. Alternatively, but currently unknown, one or few specifically selected multifunctionality indicators could approximate overall ES multifunctionality. One such candidate indicator for multifunctionality might be plot-level plant species richness, because many experimental and observational studies have shown grassland multifunctionality to be positively correlated to the richness of vascular plants (e.g., Allan et al., 2015; Meyer et al., 2018; Le Provost et al., 2023). Yet, recent studies found fertilization to strongly modify the effect of plant species richness on multifunctionality (Pichon et al., 2024), and stated the absence of an increase in grassland multifunctionality after plant species richness was experimentally enhanced (e.g., Freitag et al., 2023). Moreover, while plant diversity is considered a suitable indicator for the ecological quality of a grassland, it is not fully understood if it also correlates with an increase in non-production ES multifunctionality. Thus, whether plant species richness is a suitable and strong indicator for changes in the non-production ES multifunctionality of permanent grasslands still needs to be examined. To be widely applicable, such potential multifunctionality indicators need to be tested using a set of grasslands covering all typical management practices such as mowing and grazing, organic vs. conventional farming, and intensive (with fertilization) as well as extensive (no fertilizer) management.

In this work, we analyzed a dataset containing 30 ES indicators based on field measurements, which were associated with 22 different ecosystem functions and twelve final ES according to the CICES framework (Haines-Young and Potschin-Young, 2018; Table 1). The comprehensive list of ES indicators was recorded in 88 agriculturally managed permanent grasslands in Switzerland, spanning a wide but realistic gradient in fertilization intensity. We assessed synergies and trade-offs, i.e., correlations among ES indicators, to identify bundles of ES. We further tested potential multifunctionality indicators to inform result-based AES in the future. This study builds on a large dataset on how different grassland management practices drive ecosystem services (Richter et al., 2024). Specifically, we hypothesized:

1) The correlative structure in the ES-indicator dataset results in distinct bundles of grassland ES.
2) The formation of ES-indicator bundles is strongly driven by fertilization intensity.
3) Plant species richness is the most promising candidate to be used as multifunctionality indicator.

2. Material and methods

2.1. Study system

For this work, we studied 88 permanent grasslands in the Swiss Canton of Solothurn. This region presents a wide range of environmental conditions, stretching from the lowlands with rather intensive agriculture (400–500 m a.s.l.) in the south to the undulating Jura mountains in the north of the canton (up to 1450 m a.s.l.). The canton's agriculture is characterized by permanent grassland, covering about two thirds of the agricultural area, with rather small parcels (average 0.9 ha) and farms (on average 23 ha; Le Clec'h et al., 2019).

We selected 88 permanent grasslands belonging to 36 cattle farms across the region. Grasslands were selected to cover the full gradient of management intensity, from unfertilized to highly fertilized grasslands, and the whole study region. Grassland parcels had to be at least 0.25 ha and covered a wide and representative gradient in management intensity, ranging from intensively used meadows and pastures with fertilization of up to 200 kg available nitrogen (N; defied as the sum of organic and synthetic fertilizers, excluding animal excreta during grazing) to extensively managed AES meadows and AES pastures without any fertilization. In total, 42 % of the grasslands included in our study were such unfertilized meadows and pastures belonging to an AES specifically designed to facilitate biodiversity conservation in extensive grasslands. Besides the ban of fertilization, AES regulations for these extensive grasslands require a delayed first cut (mid-June in the lowlands) and minimum management activities per year (grazing or mowing at least once), while forbidding biodiversity-damaging techniques such as mulching (Klaus et al., 2023). Four intensive grasslands did not receive any fertilizer during 2020 and 2021 but were still categorized as intensive due to two reasons: First, other management practices violated the regulations of AES, such as early mowing, and second, farmers might occasionally add fertilizer. In addition, both organic and conventional management occurred equally across the intensity gradient. See Richter et al. (2024) for further details on plot selection. Grasslands spanned an elevational gradient from 435 to 1145 m a.s.l. These gradients in environment and management can be seen as representative not only for the region but also for many other Central European landscapes dominated by agricultural grasslands (Blüthgen et al., 2012).

2.2. Data surveys and laboratory analyses

In 2020 and 2021, intensive field and lab work campaigns as well as

Table 1
Ecosystem-service (ES) indicators (based on field measurements and land use data; Richter et al., 2021) included in this study, and their respective ecological functions and final ecosystem service following CICES (Haines-Young and Potschin-Young, 2018). The notion of'1-x' indicates that a measure has been reversed to convert a disservice into a service, meaning higher ES values always show increasingly positive outcomes. This can also be seen in the addition of 'less' to an indicator, showing a higher service at lower indicator values. ES indicators with a 'yes' were included in the calculation on non-production multifunctionality, with only one indicator selected per function.

ES indicator	Associated ecosystem function	Associated ecosystem service (CICES)	Included in non-production multi-functionality
Provisioning services			
Aboveground plant biomass (first cut relative to temperature sum)	Yield quantity	Cultivated plants and reared animals (1.1.3.1)	no
Sward height	Yield quantity	Cultivated plants and reared animals (1.1.3.1)	no
Digestibility (first cut)	Forage quality	Cultivated plants and reared animals (1.1.3.1)	no
Protein content (first cut)	Forage quality	Cultivated plants and reared animals (1.1.3.1)	no
Forage quality (indicator value)	Forage quality	Cultivated plants and reared animals (1.1.3.1)	no
Regulating and supporting services			
Root mass (topsoil)	Soil stability	Control of erosion rates (2.2.1.1)	yes
Soil cover (1-bare soil)	Erosion control	Control of erosion rates (2.2.1.1)	yes
Less bulk density (topsoil)	Water infiltration	Hydrological cycling including flood prevention (2.2.1.3)	yes
Nectar provision	Resources for pollinators	Pollination (2.2.2.1)	yes
Plant species richness	Number of vascular plant species	Nursery populations and habitat incl. gene pool protection (2.2.2.3)	yes
Bacterial diversity (number of prokaryotic ASVs)	Richness of soil bacteria and archaea	Nursery populations and habitat incl. gene pool protection (2.2.2.3)	yes
Fungal diversity (number of ASVs)	Richness of soil fungi	Nursery populations and habitat incl. gene pool protection (2.2.2.3)	yes
Weed control (1-abundance of weed plants)	Weed control	Pest control (2.2.3.1)	no
Less plant pathogens (1-relative abundance of plant pathogenic fungi in soil)	Pathogen control	Pest control (2.2.3.1)	no
Less herbivory (1-leaf damage by arthropods)	Herbivory control	Pest control (2.2.3.1)	no
Earthworm abundance (topsoil)	Soil health	Decomposition and fixing processes and their effect on soil quality (2.2.4.1)	yes
Less copper (1-soil Cu content)	Soil health	Decomposition and fixing processes and their effect on soil quality (2.2.4.1)	no
Less zinc (1-soil Zn content)	Soil health	Decomposition and fixing processes and their effect on soil quality (2.2.4.1)	no
Soil microbial biomass (microbial C in topsoil)	Soil fertility	Decomposition and fixing processes and their effect on soil quality (2.2.4.1)	no
Soil P availability (Olsen)	Soil fertility	Decomposition and fixing processes and their effect on soil quality (2.2.4.1)	no
AM fungi (relative abundance of arbuscular mycorrhizal fungi)	Phosphorus acquisition	Decomposition and fixing processes and their effect on soil quality (2.2.4.1)	no
N fixation (N fixation by legumes, first cut)	Nutrient fixation	Decomposition and fixing processes and their effect on soil quality (2.2.4.1)	no
Less eutrophication risk (1-soil surface P content)	Eutrophication prevention	Chemical composition of freshwaters (2.2.5.1)	yes
Less nitrate leaching risk (1-leaching risk)	Groundwater safety	Chemical composition of freshwaters (2.2.5.1)	yes
Soil organic C stock	Carbon storage	Chemical composition of the atmosphere (2.2.6.1)	yes
Less N_2O emissions (1-emission)	Low greenhouse gas emissions	Chemical composition of the atmosphere (2.2.6.1)	yes
Cultural services			
Edible plants (abundance)	Recreation	Active recuperation, enjoyment, recreation (3.1.1.1)	yes
Attractive fungi (relative abundance in soil)	Recreation	Active recuperation, enjoyment, recreation (3.1.1.1)	no
Livestock presence (duration grazing periods)	Animal watching	Passive recuperation, enjoyment, recreation (3.1.1.2)	yes
Aesthetic appreciation	Aesthetic	Aesthetic (3.1.2.4)	yes

a questionnaire survey were carried out to record 30 indicators representing twelve ES according to the CICES typology (Table 1; Haines-Young and Potschin-Young, 2018; Richter et al., 2024). For each parameter, all grasslands were sampled during the same time period, but due to the high number of ES indictors studied, a set of indicators had to be measured in 2020 and a second set in 2021 (see below for further details). For a detailed discussion of the suitability of ES indicators and how these relate to final ES, see Richter et al. (2021) and references therein. We are aware that provisioning services such as yield quantity and quality as well as some regulating services such as less leaching risk are strongly depending on external inputs like fertilization (Bethwell et al., 2021). Thus, we acknowledge that a comparison of the ES provided by, for example, extensive vs. intensive farming, should account for all inputs affecting the ES provided. We approached this by including indicators for (reduced) adverse environmental impacts such as for lower N_2O emission and less leaching risk (Table 1).

In total, we assessed five indicators for provisioning, 21 for regulating and supporting, and four indicators of cultural ES. In the following, the field and lab work to measure these ES indicators is described. In June 2020, a first soil sampling campaign was conducted to measure plant available phosphorus (P, Olsen extraction) content, heavy metal contents (copper and zinc via ICP-OES after aqua regia extraction), organic carbon (C_{org}) content (potassium dichromate method), microbial C (via fumigation), microbial diversities of fungi and bacteria, and the proportions of fungal guilds, especially arbuscular mycorrhizal fungi (AMF), plant pathogenic fungi, and visually-attractive fungi. Per plot, 20 soil cores were taken to a depth of 20 cm along two 18-m transects and subsequently pooled to achieve a representative sample. Microbial diversities and relative abundances of specific guilds were analyzed via DNA metabarcoding. Number of bacterial and fungal amplicon sequence variants (ASVs) per plot were used as diversity measures of the respective group. To separate functional groups of fungi, the sample-observation matrix was used to compute relative percentage ASVs of AMF and plant pathogenic fungi using information from FUNGuild about probable ecological guild-membership of the taxa (Nguyen et al., 2016). Similarly, percentage of visually particularly attractive fungi were computed, including the often very colorful grassland macrofungi of high conservational value (Griffith et al., 2013) known as CHEGD taxa (encompassing the Clavariaceae, Hygrophoraceae, Entolomataceae, Geoglossaceae and Dermoloma taxa; Caboň et al., 2021). For further details on this sampling campaign and the related laboratory analyses, see Appendix 1 'June soil sampling' in Supplementary Material.

In August and September 2020, a second soil sampling campaign was carried out to measure root biomass, bulk density, and soil surface soil P. Per plot, three undisturbed 5 cm × 5 cm cylindrical soil cores (at 0–5 cm and 5–10 cm depth) were taken at different locations (each 8 m apart), and mixed per depth level. Root biomass from 0-5 cm soil depth was washed and used as a proxy for the stability of the topsoil (higher erosion resistance). To assess the organic carbon stock, the C_{org} content (0–20 cm, from June sampling) was multiplied with the fine soil stock at 5–10 cm depth following Poeplau et al. (2017) and corrected for clay content. Surface soil P content was determined in the top 1.5 cm of the soil, i.e., the stratum particularly at risk of erosion, and thus depicts a potential eutrophication risk for freshwater ecosystems. To this end, we collected one tablespoon of mineral soil every 2 m along a 20-m transect, pooled all sub-samples per plot, and analyzed the water-extractable soil P fraction. For further details on this sampling campaign and the associated analyses, see Appendix 2 'August soil sampling' in Supplementary Material.

Between early May and mid-June 2021, vegetation and earthworm surveys were conducted before grasslands were mown or grazed. For vascular plant species richness, all plant species occurring at two 2 m × 2 m quadrats were recorded and summed for a total plant species richness. For each species, the percent soil cover was estimated. The total abundance of edible plants was calculated based on the vegetation survey and literature information (Pfister and auf der Mauer, 2017; Höller and Grappendorf, 2019; Machatschek and Mautner, 2015). Bare soil cover (%) was further estimated visually by examining the vegetation to reveal soil patches potentially prone to erosion. Moreover, the height of the vegetation was measured at the four corners of the vegetation survey plots with a laminated A4 paper sheet that was placed on top of the vegetation. Values were averaged per plot. Indicator values for forage quality according to Briemle et al. (2002), ranging from 1 (poisonous) to 9 (highest forage value), were calculated from vegetation surveys, using cover to weight individual species' contributions to the plot value. Nectar provision in g/ha was calculated using the cover of plant species from vegetation surveys and literature values on nectar provision per species (see Appendix 3 'Nectar provisioning' in Supplementary Material).

The number of agricultural weed plants (or of dense patches for clonal plants) was recorded along two 2 m × 20 m transects per site. The following species were considered relevant weeds: *Anthriscus sylvestris*, *Carlina* spp., *Cirsium* spp., *Colchicum* spp., *Heracleum sphondylium*, *Rhinanthus* spp., *Rumex obtusifolius*, and *Senecio jacobaea*. Leaf damage by herbivorous arthropods was assessed by sampling leaves in the field and subsequent visual examination of damage. For this, every 0.5 m along two 20-m transects, leaves of one legume, one grass, and one forb (if present within a distance of 0.2 m from the transect) were gathered randomly, resulting in 80 leaves per plant functional group per plot. For every leaf, damage by insects was assessed (yes/no). Information about cover of legumes, grasses, and forbs from the vegetation survey was used to subsequently compute total percentage of damaged leaves for each plot. As herbivory increased with time of sampling, we used a linear regression (percentage leaves damaged against day of year within grassland type, i.e., combination of meadow vs. pasture and management with vs. without fertilization) to correct herbivory for sampling date within grassland types. An interaction term was excluded from the final model, as it showed no significant effect.

Aboveground plant biomass was sampled on the plots by cutting four 50 cm × 50 cm quadrats at 1 cm above the surface. In pastures, grazing exclusion cages of 1.25 m × 1.25 m were installed to inhibit grazing prior biomass sampling. Samples were dried at 60 °C. Harvest-date corrected aboveground productivity was calculated by dividing the harvested biomass by the temperature-degree sum until sampling date, following the approach described in Menzi et al. (1991). For this, modelled daily mean temperatures at 2 m above ground in a grid with 1 km × 1 km resolution were calculated to compute an average temperature sum per day of year over all single plots. Biomass samples were analyzed for digestibility (digestible organic matter content) via enzymatic digestion in rumen fluid according to Tilley and Terry (1963) and for protein content by combustion of 400 mg milled sample in an autoanalyzer. Symbiotic N fixation (N fixation hereafter) was calculated based on the aboveground productivity measure described before and taking into account identity, cover and N content of occurring legume species (see Appendix 4 'Nitrogen fixation' in Supplementary Material).

To assess earthworm abundances, three 20 cm × 20 cm × 30 cm soil pits were dug out every 5 m along a transect, and the excavated material was carefully checked for earthworms. Hand-sorting of earthworms is likely to be the most accurate method of earthworm sampling (Lee, 1985). The total number of all live individuals was recorded, and the mean value across the three sample locations was computed. Earthworm numbers were corrected for soil moisture, which varied during the sampling period depending on weather conditions, using a linear regression, as previously described for leaf herbivore damage, correcting for soil moisture recoded the same day as the earthworm sampling.

To assess the aesthetic appreciation of the plant community by society, standardized pictures of each plot, taken prior to the vegetation surveys, were used in a German-language online questionnaire. We asked people for their personal perception of the aesthetic quality of the respective grassland plant community on a 5-point Likert scale from attractive to unattractive. In total, 521 participants completed the questionnaire, yielding on average 55 ratings per grassland picture. These were averaged to compute an indicator for aesthetic appreciation per plot (see Appendix 5 'Aesthetic appreciation' in Supplementary Material).

Farmers were interviewed to acquire detailed insight into grassland management in 2020 and 2021, such as the presence of livestock on the parcels (i.e., the sum of days livestock was grazing a parcel, irrespective of the stocking density). Besides grazing information, the total amount of organic and synthetic fertilizers applied in kg available N per ha, averaged for both years, was used as a measure for fertilization intensity (hereafter fertilizer N). Annual N_2O emissions per ha were calculated according to the IPCC guidelines (IPCC, 2019), using the previously described fertilizer data and Switzerland-specific information on livestock from Richner et al. (2017). We did not include plot-level estimates of CO_2 and CH_4 emissions since these are not informative given the system boundaries and the timeframe of our study. Information on fertilization and grazing was also used to estimate potential nitrate leaching using a tool accounting for fertilizer N and N in animal excreta with equations for grassland dairy systems (Martin et al., 2021); see Richter et al. (2024) for further details.

2.3. Statistical analyses

After 0–1 normalization (min value = 0, max value = 1), which made the ranges of all ES indicators comparable, all measurements for a disservice, such as weed abundance and eutrophication risk, were transformed to ES indicators by subtracting from one to indicate a higher benefit at higher values (see indicators with 'less' in Table 1). Furthermore, some ES indicators were log or sqrt transformed to achieve normal distribution. Less eutrophication risk, less N leaching risk, attractive fungi, livestock presence, N fixation, nectar provisions, and soil P availability were log transformed; weed control, less N_2O emissions, livestock presence, protein content and fertilizer N were sqrt transformed. A principal component analysis (PCA) of all 30 ES indicators was calculated to reveal patterns within the whole indicator dataset. The PCA was computed with the function prcomp in the package vegan (version 2.5–7; Oksanen et al., 2019) on a z-score standardized matrix of ES indicators and plotted with the autoplot function as part of the ggfortify package (version 0.4.14; Tang et al., 2016). PCA biplots were extracted with all axes with ≥ 10 % explained variance. Fertilization intensity was added to the biplot as overlay. As not all ES indicators were equally represented by these axes, we produced a correlation matrix using Spearman correlations, also based on the z-score standardized matrix. We identified bundles of related ES indicators using the PCA ordination and the correlation matrix: As a first step, the ordination biplot was checked for major bundles of ES indicators separating along the axes. Further ES indicators were added to these bundles if they (i) had at least three significant positive correlations with the ES indicators already included in that bundle, and (ii) did not have any significant negative correlation within the bundle ($p < 0.05$).

Finally, *non-production multifunctionality* was computed based on ES indicators not mainly linked to agricultural products, i.e., so-called public ES. This led to the exclusion of all ES indicators related to functions relevant only to production, such as yield, pest control, and N fixing processes. In addition, where many ES indicators were available for the same ecosystem function (i.e., soil health and recreation), we only included one ES indicator per function to avoid double counting (Table 1). For this, we selected the one indicator that represents the most direct and integrative measurement, such as earthworm abundance integrating several aspects of soil health, while less copper and zinc contents were rather specific indicators (Table 1). This procedure resulted in 15 functions (ES indicators) entering the calculation of non-production multifunctionality. We decided for an averaging approach using all non-production ES indicators, normalized from 0 to 1, using the min and max of the respective functions, to obtain one value for multifunctionality per grassland. Due to the averaging, some ES can mathematically compensate each other (Dooley et al., 2015), which we regard as justified in this specific case for two reasons. First, by leaving out provisioning ES and those directly supporting these, there are less issues with strongly negatively correlated indictors compensating each other, as it would arise from trade-offs between especially provisioning and cultural services (Allan et al., 2015). Second, averaging might be a realistic scenario when a payment scheme is being developed to reward field-scale multifunctionality irrespective of potential (unavoidable) trade-offs. Note that multifunctionality based on 0–1 scaling according to min and max values was highly correlated with values based on alternative standardizations (i.e., dividing with the maximum value of the respective ES indicator: Spearman $r = 0.98$, $p < 0.001$; z-scaled values: $r = 0.99$, $p < 0.001$). Spearman correlations were used to relate all ES indicators and fertilizer N (i.e., total amount of available N applied per year) to non-production multifunctionality to assess their ability to serve as indicator for non-production multifunctionality. For this, to avoid circularity, we re-calculated multifunctionality values for each single correlation without the respective ES indicator, meaning that multifunctionality was calculated based on 14 indicators if not correlated with fertilization intensity (which was not considered an ES indicator). In addition, we used linear regression to relate the best performing indicators, identified with the previous analysis, to non-production multifunctionality, and ANOVA to compare non-production multifunctionality between extensive (i.e., AES without fertilization) and intensive grasslands. R (version 4.2.0; R Core Team, 2022) was used for all statistical analyses.

3. Results

3.1. ES-indicator bundles

Analyses revealed strong relationships between many ES indicators. The PCA ordination resulted in three axes (components) with more than 10 % explained variance each, capturing in total half of the variance in the dataset (49.4 %; Fig. 1). As expected, there was also a significant proportion of variance in the dataset not included in these axes. Therefore, we additionally assessed the correlation matrix to identify significant positive or negative relationships among all ES indicators (Fig. 2) and included further ES indicators into these bundles if they had at least three significant positive correlations with the ES indicators of that bundle, and did not have any significant negative correlation within the bundle (Figs. 1 and 2). This aggregation approach resulted in two large bundles and some independent ES indicators that did not match these bundles.

Although ordination revealed ES indicators to cover the entire ordination space, indicating both strongly correlated as well as uncorrelated indicators, the majority of ES indicators formed two major bundles, clustering in the left and the right part of the ordination biplot (Fig. 1a and b). Consequently, the two bundles were strongly negatively related to each other. The first ES-indicator bundle was positively related to the first axis and was composed of ten ES indicators linked to low-input management, such as low N_2O emissions, less nitrate leaching risk, high plant species richness, low eutrophication risk, high abundances of attractive fungi and AM fungi, high aesthetic appreciation, less plant pathogens, high fungal diversity, and high nectar provision (blue arrows in Fig. 1). This was the 'extensive bundle' due to its negative relation with fertilization intensity. Some further ES indicators were weakly positively associated with this bundle, meaning they showed less than three positive correlations with the extensive bundle and some negative correlations with the bundle on the left side of the biplot (Fig. 2). These ES indicators associated with the 'extensive bundle' were less zinc and less copper contents in soil, root biomass and soil cover. Yet, all of them were too weakly related to be included in the 'extensive bundle'.

The second bundle was correlated negatively with the first PCA axis and thus opposed the extensive bundle. It was composed of twelve ES

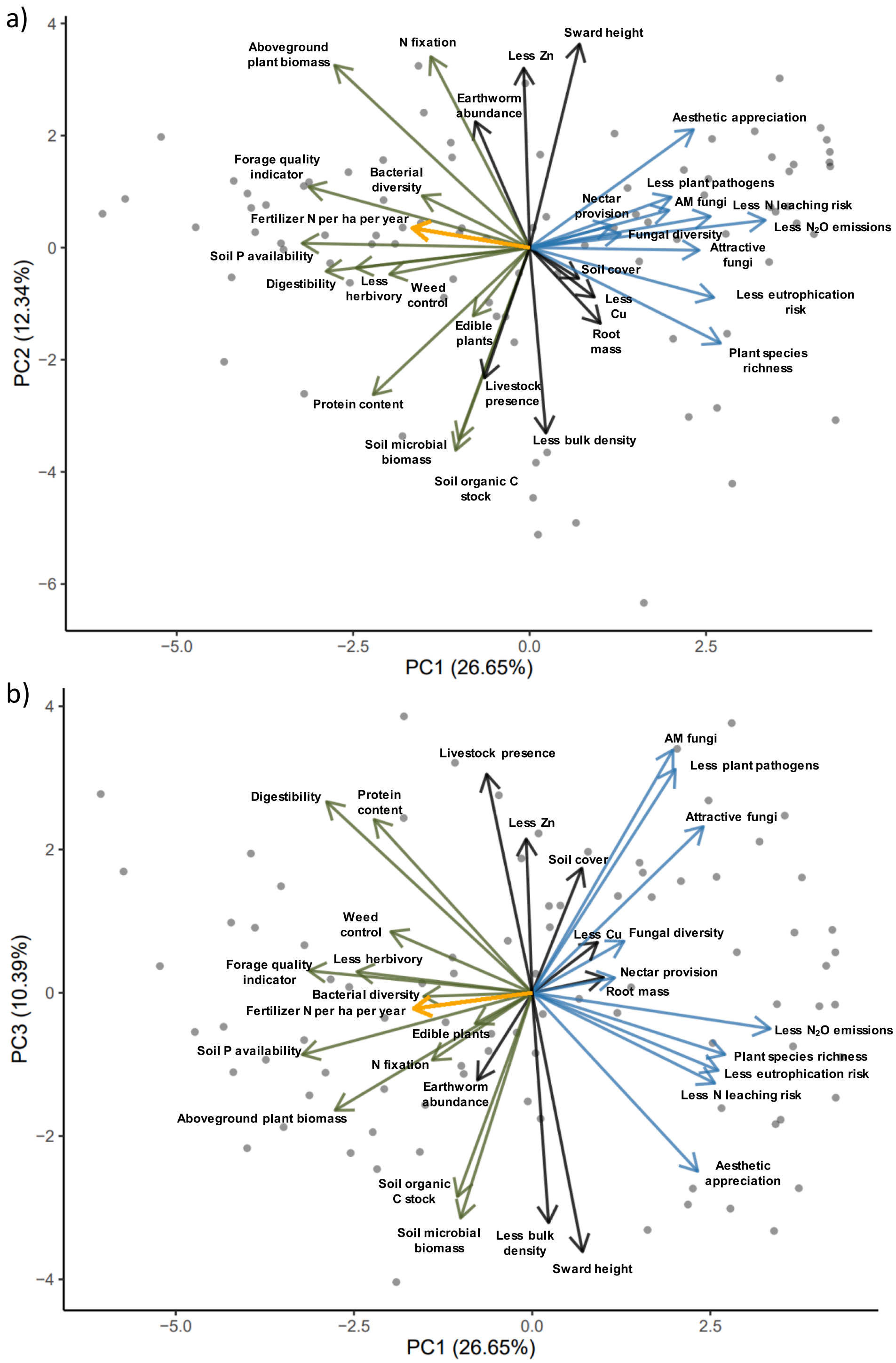

Fig. 1. PCA ordination biplots of (a) axes one and two and (b) axes one and three based on the ES-indicator dataset, with grey dots showing the 88 grasslands. Vectors are scaled according to the correlation of each ES indicator with the respective axis (arrow length). Arrow colors represent ES-indicator bundles according to placement along the PCA axes and the evaluation of the correlation matrix (Fig. 2). Blue arrows show ES indicators associated with the 'extensive bundle', and green arrows those associated with the 'intensive bundle'. ES indicators with black arrows are only weakly or ambiguously related to these two bundles. The yellow arrow represents a post-hoc overlay of fertilization intensity (available fertilizer N ha^{-1} a^{-1}). Details of all ES indicators are given in Table 1. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

indicators (green arrows in Fig. 1) and was positively related to fertilization intensity (i.e., amount of fertilizer N), which approximated overall management intensity of the grasslands. Thus, it could be called 'intensive bundle'. It was composed of soil P availability, yield quantity (aboveground plant biomass) and quality indicators (forage value, protein content and digestibility) as well as less herbivory, weed control, and bacterial diversity (Fig. 2). Further indicators included in the intensive bundle were soil organic C stock, soil microbial biomass, symbiotic N fixation, and edible plants. Earthworm abundance was not included in the intensive bundle, but weakly positively associated as shown by two positive correlations with the respective ES indicators (Fig. 2). Note that not in all cases, indicators for the same ES were part of

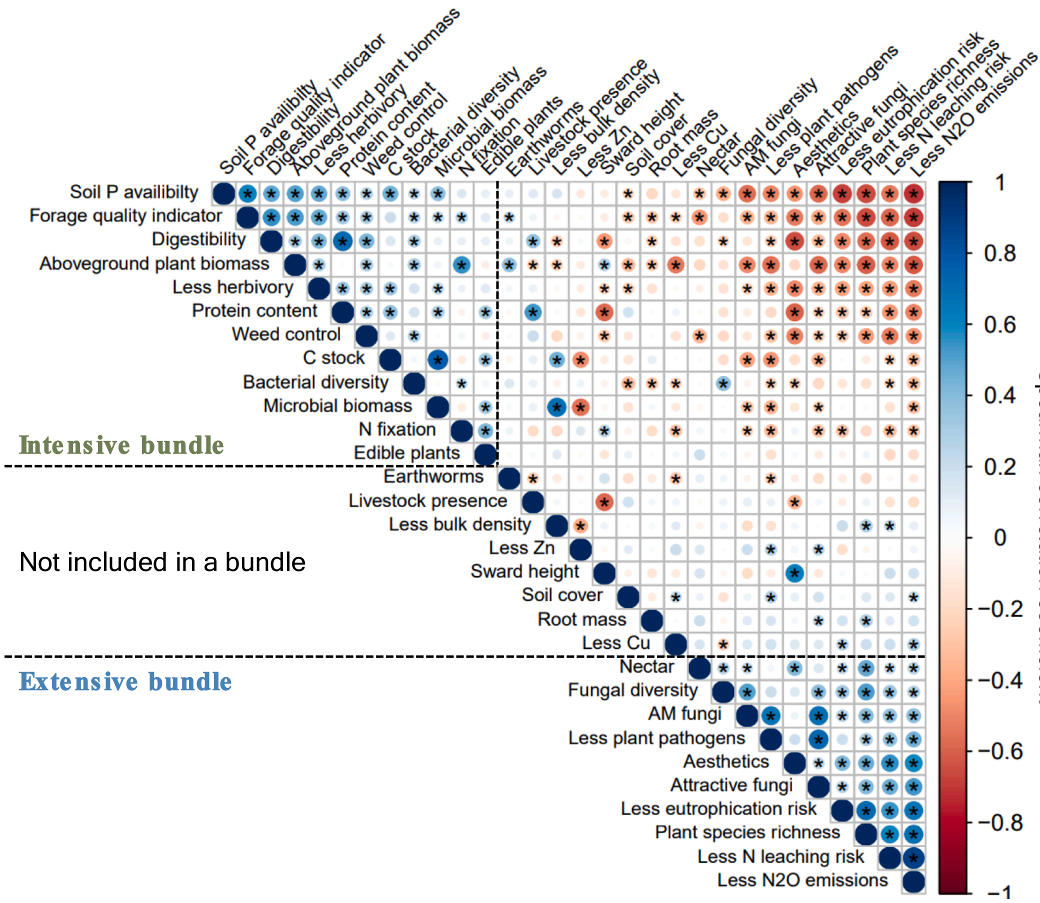

Fig. 2. Spearman correlation matrix of all ES indicators. Significant correlations are indicated by an asterisk (p < 0.05). ES indicators were assigned to the two bundles according to the correlation matrix and placement along the PCA axes (Fig. 1). Details of all ES indicators are given in Table 1.

the same bundle. For example, edible plants and attractive fungi, both indicators for the ES 'Active recuperation, enjoyment, recreation' contributed to two both bundles, i.e., intensive vs. extensive, respectively (Table 1, Fig. 2).

Besides, eight ES indicators (e.g., bulk density, root mass, and sward height) were weakly or ambiguously related to the two previously characterized ES-indicator bundles (black arrows in Fig. 1). Despite the aforementioned weak associations, these eight ES indicators did not form an individual bundle. In contrast to the first PCA axis, the indicators included in the two bundles were not separated but strongly mixed along the second and third PCA axes (Fig. 1).

3.2. *Indicators for non-production multifunctionality*

Non-production multifunctionality, defined as the average of ES indicators not of relevance for only the production of feed but of broader societal interest (Table 1), ranged from min = 0.28 to max = 0.74 (*mean* + *SE* = 0.50 + 0.01). The 15 ES indicators included in the metric were spread across the whole ordination space (Fig. 1). Seven ES indicators belonged to the extensive bundle, three to the intensive bundle, and five being independent of the two bundles.

Non-production multifunctionality was most closely correlated with plant species richness and fertilization intensity (i.e., fertilizer N), with plant species richness being positively and fertilization negatively related (Fig. 3). Yet, the relationship was stronger with plant species richness compared to fertilization intensity. Consequently, plant species richness was also found to be strongly decreased by the gradient in fertilization intensity (linear regression $R^2 = 0.40$, $p < 0.001$).

Both plant species richness (linear regression $R^2 = 0.62$) and fertilization intensity (linear regression $R^2 = 0.54$) were considerably better predictors of non-production multifunctionality than the categorization into intensive and extensive grasslands (i.e., AES without fertilization; ANOVA $R^2 = 0.32$; Figs. 3a, b and 4a). The comparably poor separation of non-production multifunctionality by intensive vs. extensive management appears to be related to the significant albeit moderate difference in plant species richness between intensive and extensive grasslands (ANOVA $R^2 = 0.38$; Fig. 4b). While the average species richness between both groups differed significantly, with on average 14 more plant species on 8 m^2 in extensive compared to intensive grasslands, there was also considerable overlap between the two management categories. Yet, all grasslands with highest plant species richness were extensively managed, while the 23 grasslands with ≤ 25 plant species on 8 m^2 were found among the intensive grasslands. Besides, three other ES indicators were considerably positively correlated with non-production multifunctionality ($r > 0.5$, Fig. 3c). These were reduced N leaching, eutrophication, and N_2O emissions, respectively. There were generally few negative correlations with non-production multifunctionally, and these were all weak and mainly with three indicators from the intensive bundle.

4. Discussion

In this study, we explored a comprehensive dataset of 30 ES indicators measured in 88 permanent grasslands managed from low to high intensity. Ordination and correlation analyses revealed distinct patterns in the ES-indicator dataset, which are related to synergies and trade-offs among single ES. Such a correlative structure of plot-level ES was previously also found particularly for provisioning ES opposing

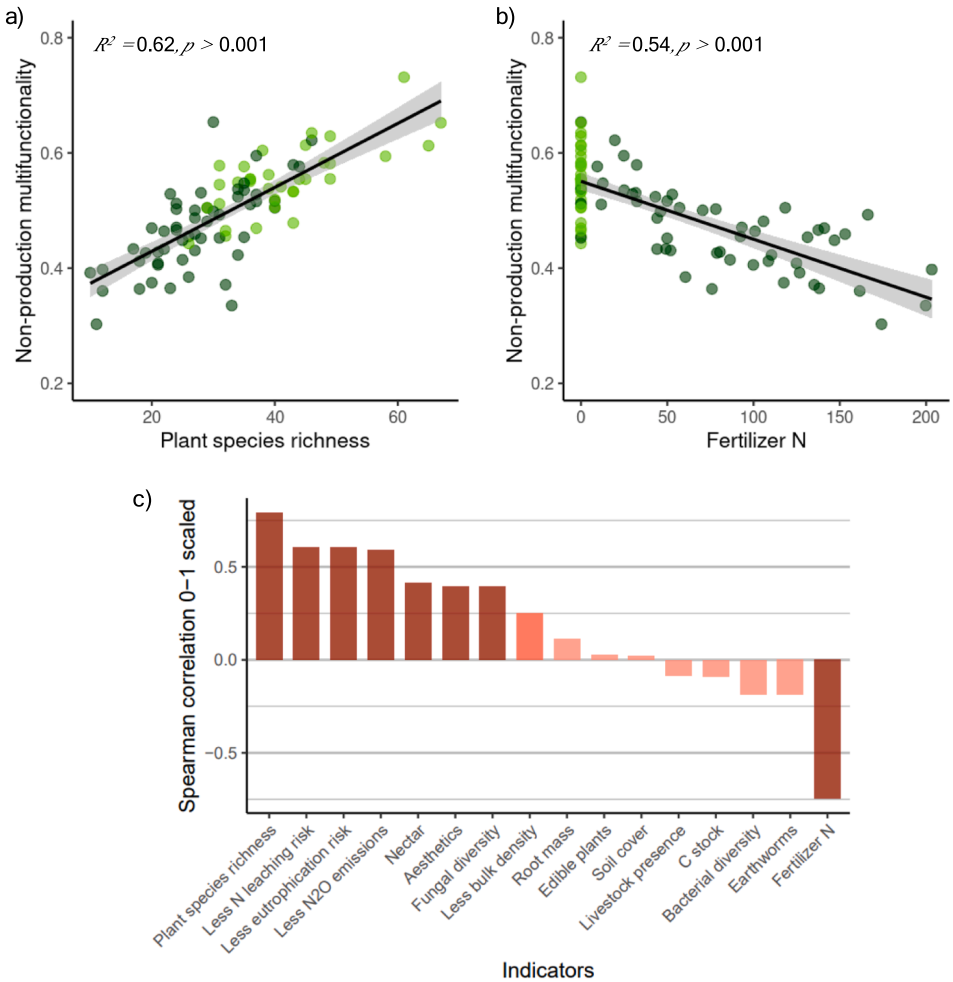

Fig. 3. Relationships between non-production multifunctionality and different ES indicators. The strongest positive correlation was with (a) vascular plant species richness, and the strongest negative with (b) fertilization intensity, i.e., available fertilizer N ha^{-1} a^{-1}. Extensively managed grasslands in light color and intensively managed in dark color. Panel (c) shows all correlations of non-production multifunctionality with the 15 ES indicators included in the calculation of the non-production multifunctionality, plus a correlation of the latter with fertilization intensity. Non-production multifunctionality was calculated as the average of the 15 min–max (0–1) scaled ES indicators (Table 1). Panels (a) and (b) contain the results of linear regressions. Shading around regression lines depict standard errors.

cultural and (some) regulating ES such as in alpine grasslands (e.g., Wu et al., 2017), temperate agricultural grasslands (e.g., Lamarque et al., 2014; Allan et al., 2015), rangelands (e.g., Favretto et al., 2016), agroforestry systems (e.g., Kearney et al., 2019), and forests (e.g., Felipe-Lucia et al., 2018). Many of the previously reported trade-offs and synergies among different ES were driven by ecosystem management (e.g., Saidi and Spray, 2018; Dade et al., 2019), which is in line with the importance of fertilization intensity found in our study.

4.1. Bundles of ES indicators

In the studied permanent grasslands, ES indicators formed two main bundles, which we termed 'intensive' vs. 'extensive bundle', and which were clearly opposing. Their separation was related to, and highly likely also driven by, fertilization intensity, a proxy of the overall management intensity of permanent grasslands (Blüthgen et al., 2012). Previous research examining grassland plot-level ES also found distinct ES bundles (e.g., Lamarque et al., 2014; Allan et al., 2015; Hanisch et al., 2020). Yet, our study considerably adds to the current state of knowledge since previous study rarely used such a comprehensive set of ES indicators to test for strong relationships among ES in the bundles. In addition, ES indicator bundles can only partly be compared among different studies, due to unlike sets of ES indicators, regional differences in environmental settings and drivers of ES, diverse foci of the studies, and different statistical tools applied (Saidi and Spray, 2018; Richter et al., 2021).

We found fertilization intensity to increase the ES included in the intensive bundle and to decreased those in the extensive bundle. This is in line with previous research findings that fertilization and management intensity are key drivers of the ES of permanent grasslands (Allan et al., 2015; Van Vooren et al., 2018; Schils et al., 2022). Mechanistically, fertilization intensity shapes nutrient availability and thus, subsequently, functional types and traits of plants and other taxa shift from resource conservative to exploitative strategies (Neyret et al., 2024). Then, this functional shift drives many grassland ES (Hanisch et al., 2020; Kleyer, 2021). Although our approach to assemble the bundles was widely descriptive, the mechanistic explanation of the observed pattern provides insight in the underlying processes, which is key for well-informed management decisions and policymaking (Dade et al., 2019).

With respect to environmental monitoring, the existence of ES-indicator bundles depicts a chance to ease the assessment of multiple ES that are correlated. For example, ensemble modelling could use the correlative structure within the overall dataset, as suggested by Willcock et al. (2023) for global-level ES mapping. Indeed, the fact that the majority of ES indicators could be grouped into two bundles indicated that few proxies can be selected to evaluate a wide range of ES. This is of

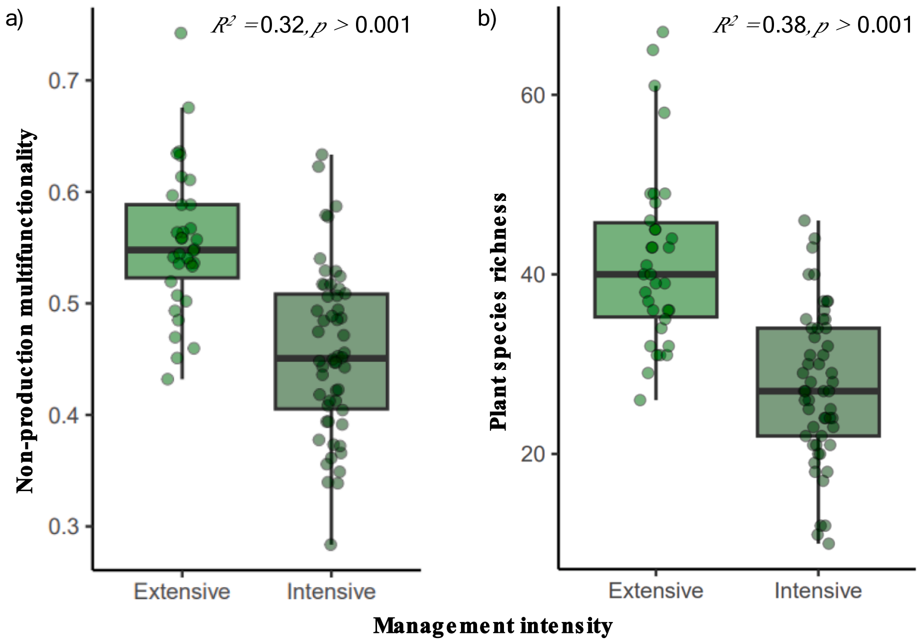

Fig. 4. Effects of extensive (AES without fertilization) vs. intensive management on (a) non-production multifunctionality and (b) the number of vascular plant species (on 8 m^2). Extensive management implies no fertilization and further restrictions such as a delayed first cut, and it is linked to an agri-environmental scheme to support biodiversity in the agricultural landscape of Switzerland (Klaus et al., 2023). Statistical results of ANOVAs shown.

outmost importance when ES evaluations have to be performed for a large area or many farms, as measuring many ES indicators on all fields of the target area is costly and challenging. However, the search for a proxy for a whole bundle of ES has to consider that eight ES, i.e. about 25 % of the ES indicators included in this study, were barely associated with any bundle. Thus, these eight ES cannot accurately be approximated by the extensive or intensive bundle and might be overlooked if not accounted for separately, e.g., by additional sampling efforts. This highlights that the gradient in fertilization intensity does not satisfactorily explain the patterns of all ES, which limits the idea of reducing the total set of ES to only few easily measurable bundles. Therefore, assessing a metric for (non-production) ES multifunctionality appears to be straightforward since it can include all relevant ES indicators.

All ES indicators for provisioning services were found in the intensive bundle, except for sward height that was not included in any bundle. The strong trade-off between the intensive and the opposing extensive bundle (which on the contrary contains many societally relevant non-production ES) carries implications for the assessment of ES multifunctionality in the context of a policy scheme. Using a metric for overall multifunctionality including production and non-production ES could hide changes in ES supply, as an increase in production ES could mathematically counterbalance a decrease in non-production ES, and vice versa (Dooley et al., 2015). We therefore chose to evaluate 'non-production multifunctionality', a metric specifically focused on only non-production ES, avoiding the above-mentioned counterbalancing effect. In addition, such a multifunctionality metric can potentially include weights for each (standardized) ES, corresponding to stakeholder priorities (Manning et al., 2018). Next, an indicator that reliably predicts non-production multifunctionality would considerably advance the potential of future policies to move towards AES or payments for multiple ES (Bartkowski et al., 2021).

4.2. Indicators for non-production multifunctionality

A clear drawback of assessing non-production multifunctionality is the many ES-indicator measurements required for the metric. However, in our study, plant species richness appeared to be a suitable indicator for overall non-production multifunctionality, and it approximated the metric reasonably well ($R^2 = 0.62$). Still, measurements of plant species richness require a significant effort and expert knowledge, although much less than measuring the whole set of ES indicators.

Plant species richness could approximate non-productive multifunctionality also within the set of extensive grasslands (AES without fertilization), which shared the absence of fertilization but varied widely in plant species richness. Therefore, plant species richness appeared to be the most suitable multifunctionality indicator compared to the AES-related categorization into extensive vs. intensive management ($R^2 = 0.32$), with 'extensive' implying mainly the absence of fertilization, among other regulations (e.g., Klaus et al., 2023). The large variability in plant richness within these unfertilized grasslands indicates the great relevance of site history and sward age for plant species richness and correspondingly for non-production ES (Isselstein et al., 2005 and references therein). Thus, the actual plant richness of a permanent grassland integrates multiple environmental and management drivers over time. Hence, we suggest plant species richness as a suitable indicator for non-productive multifunctionality in temperate permanent grasslands.

Previous experimental (e.g., Meyer et al., 2018) and observational studies (e.g., Allan et al., 2015) found close links between grassland plant species richness and different measures of overall multifunctionality. This raises the question whether plant species richness is just an indicator for multifunctionality or whether the enhancement of plant species richness could be a practical option, i.e., nature-based solution, to actually increase the multifunctionality of degraded grasslands at the landscape scale. In this regard, there are almost no studies looking at this option specifically for enhancing cultural and regulating ES (but see Bullock et al., 2021; Freitag et al., 2023). Yet, previous work assessed how using (more or less) species-rich grassland seed mixtures changes the whole set of ES including agricultural production (e.g., Bullock et al., 2007; Ladouceur et al., 2020; Suter et al., 2021). A strong positive effect of plant species richness on multifunctionality was found for sown (intensive) grasslands when the number of species was increased from one to four (Suter et al., 2021). Moreover, plant species enhancement and high-diversity sowing were repeatedly found to increase grassland productivity compared to low levels of plant richness (Bullock et al., 2007; Ladouceur et al., 2020). However, a recent study in long-established (non-degraded) permanent grasslands showed only marginal effects of experimentally enhancing plant richness on multifunctionality (Freitag et al., 2023). Therefore, the use of diverse seed mixtures for grassland planting and restoration can be suggested primarily where functional richness is clearly restricted and relevant functional groups such as legumes are missing. In this case, the introduction of plant species might not only increase provisioning ES but highly likely also aesthetic appearance and other cultural ES by increasing, for example, flower abundance (e.g., Bullock et al., 2021). Moreover, introducing target plant species into species-poor extensive grasslands might also make a grassland eligible for result-based payments (Elmiger et al., 2023), which can be economically attractive for farmers and land managers. Although using plant species richness as an indicator might be costly due to the mapping effort required, it can create a strong synergy between multifunctionality and biodiversity conservation, which could further enhance public acceptance of the policy.

When predicting non-production multifunctionality, plant species richness performed slightly better than fertilization intensity (R^2 of 0.62 vs. 0.54, respectively). Nevertheless, current fertilization intensity could still be a useful pressure indicator for non-production multifunctionality. It could, for example, help to identify situations where grasslands of high non-production multifunctionality are at risk, even if plant diversity did not yet decrease. In line with this, previous work showed intensive fertilization to reduce many important grassland ES (Schils et al., 2022) but directly increase, for example, N_2O emissions and N leaching risk (e.g., Langeveld et al., 2007; Feigenwinter et al., 2023). Alleviating such N losses is of high priority on the policy agenda in many countries (e.g., Langeveld et al., 2007) and was thus also included in our multifunctionality metric.

Reduced fertilization intensity can, on the other hand, increase several grassland ES and biodiversity indicators, but decreases provisioning ES such as yield quantity and quality (Van Vooren et al., 2018). In conclusion, fertilization intensity is clearly also a mechanistic driver of non-production multifunctionality. An AES with the graded renumeration of reduced fertilization rates could be an interesting starting point for future policies targeting non-production multifunctionality in rather production-oriented grasslands. Although fertilizer consumption is already used as an agri-environmental indicator for sustainable land management (Bockstaller et al., 2008; Andrade et al., 2022), many established policies addressing fertilizer use require either completely abandoning fertilization, such as required for the extensive grassland management AES (Batáry et al., 2015; Klaus et al., 2023), or they only set a maximum limit for crop-specific fertilization (e.g., Lehtonen and Rankinen, 2015). An AES aiming at a reduction of fertilizer use while still enabling rather intensive forage production could thus be an interesting future policy option.

4.3. Limitations of the approach

Both the bundle and the multifunctionality approaches allow a simplified approximation of the simultaneous supply of many ES, overcoming the need to measure all single ES separately. Nevertheless, both approaches do not perform equally well for all ES considered. Our study helps identifying which ES are well and which are poorly associated with non-productive multifunctionality of permanent grasslands along a gradient in management intensity. In our study, soil C stock, for instance, was poorly associated with non-production multifunctionality. Thus, if soil C stock would be of special policy interest, which can be assumed (e.g., Follett and Reed, 2010), this ES indicator would need to be recoded and evaluated in addition to non-production multifunctionality.

Importantly, plant species richness is rather stable and does not quickly respond to moderate changes in management, except drastic measures are being taken such as sward restoration and reseeding (Isselstein et al., 2005). If an indicator is not responsive to management changes on the short term, an AES using this indicator does likely not encourage farmers to participate in a voluntary scheme. However, policy design could consider the slow change in an indicator, for example, by long-term contracts that enable payments when the outcome has not yet changed. Yet, longer contracts require higher payments to motivate farmers (Engel, 2015) and bear the risk of poor efficiency if the policy target is still missed after several years. In contrast to using plant species richness as a multifunctionality indicator, N fertilization rates depict an (pressure) indicator that immediately reveals environmentally beneficial changes in grassland management. Yet, in this work, we did actually not specifically study how temporal changes in indicators (and land use) affect multifunctionality, but essentially used a space-for-time substitution approach.

In our calculations, indicator data was standardized by the measured min and max values before it was aggregated to the non-production multifunctionality metric. Ideally, target values to define the min and max of a payment scheme would rely on achievable targets or values derived from a reference system (Moldan et al., 2012). This could also account for the need to define regionally specific targets or thresholds according to differences in the biophysical and ecological setting (Díaz and Concepción, 2016), which is likely required for a multifunctionality-oriented AES.

5. Conclusions

Our results have relevant policy implications. We found the ES of permanent grasslands to be mainly arranged in two bundles of correlated ES indicators. Yet, some important ES were not included in these bundles, highlighting the value in calculating a metric for non-production multifunctionality, which could be targeted by future agri-environmental schemes (AES). To ease such schemes and related monitoring efforts, plant richness and fertilization intensity appear to be useful indicators for non-production multifunctionality. This innovative approach of assessing non-production multifunctionality based on these indicators, potentially in combination, makes AES aiming at monitoring and financially rewarding grassland ES a realistic policy option. The next steps forward would be to define the most suitable policy design by, for example, setting thresholds in indicator values that should be achieved in a given environmental setting and a suitable time.

The indicator plant species richness highlights how closely related biodiversity conservation and facilitating ecosystem services are. Thus, we need to strengthen efforts to conserve existing species-rich grasslands, which are likely to perform better in terms of non-production multifunctionality than recently de-intensified grasslands. In addition, to increase the ES multifunctionality (and biodiversity) of existing permanent grasslands, a separate AES is required to stimulate the restoration of plant species richness after de-intensification. Integrating our findings in future agricultural policies and payment schemes could thus be a significant step towards rewarding farmers and other land managers for the non-production benefits their agroecosystems provide to society.

CRediT authorship contribution statement

Valentin H. Klaus: Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Franziska J. Richter:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **Nina Buchmann:** Writing – review & editing, Supervision. **Martin Hartmann:** Writing – review & editing, Supervision, Methodology. **Andreas Lüscher:** Writing – review & editing, Supervision, Methodology, Funding acquisition. **Olivier Huguenin-Elie:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2024.112846.

Data availability

Data will be made available on request.

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