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RESEARCH ARTICLE

A set of ecosystem service indicators for European grasslands based on botanical surveys

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Abstract

Background: Grasslands provide a wide range of ecosystem services (ESs). However, there is currently no method for easily diagnosing the level of ESs produced. Our aim was to develop ES indicators based on botanical surveys, which are readily available data and integrative of grassland spatiotemporal variability.

Methods: Based on academic knowledge and expertise, we identified several simple vegetation criteria that we aggregated using a multicriteria analysis tool to construct indicators of the level of ESs provided by grasslands. In this study, the indicators were calculated from over 2000 botanical surveys spread over a wide biogeographical gradient.

Results: Analyses of correlation between the various indicators show that "forage supply" and "diversity conservation" were not correlated. "Forage availability" and "nitrogen availability for the vegetation" were positively linked together and negatively linked to the robustness of the plant community to extreme events. A temporal approach highlights that the "biodiversity conservation" score decreased from 1970 to 2010 and that "nitrogen availability for the vegetation" was lower in 1970 and 1980 than in 2000 and 2010.

Conclusions: These results show that our aggregation method based on a large data set of botanical surveys could be appropriate for studying temporal dynamics of ESs.

KEYWORDS

biodiversity conservation, ecosystem resilience, environmental modelling, forage, functional traits, meadows, nitrogen availability, plant communities

INTRODUCTION

Permanent grasslands are major ecosystems that cover 26% of the world land area (Food and Agriculture Organization of the United Nations, 2020) and 28% of utilized agricultural areas in Europe. Their type and intensity of management is diverse, ranging from extensive mowing or free grazing to very intensive grassland utilization. Grasslands have often been considered a biodiversity hot spot due to the numerous plant species (flora) that they shelter (Habel et al., 2013). Grasslands provide many ecosystem services (ESs) (Bengtsson et al., 2019). ESs are the many and varied benefits provided by an ecosystem for human well-being. The main one could well be their contribution to livestock production by supplying feed for domestic (Peyraud & Peeters, 2016) and wild animals. Forage provision can be described by different components: the quantity of forage produced, the forage nutritional value (Gardarin et al., 2014), or the production period (Baumont et al., 2012). Many grasslands contain legumes and are thus important in nitrogen cycling. They also contribute to climate regulation services (Walker, 1956). Indeed, grassland soils stock large amounts of carbon (Conant & Paustian, 2002; Klumpp et al., 2011; Soussana et al., 2004; Soussana & Tallec, 2010).

Grasslands are also the habitat of many animal and plant species and thus contribute to conserving biodiversity (Bloor et al., 2021; Nielsen & Wall, 2015). Some of the animals fed in grasslands also provide services. For example, many pollinator species are present in grasslands and ensure pollination services in surrounding ecosystems (Öckinger & Smith, 2007).

Defining and assessing ESs is a goal of many collective initiatives, such as CICES (Towards a Common Classification of Ecosystem Services) (Haines-Young & Potschin, 2012), MAES (Mapping of Ecosystems and their Services in the European Union) (Maes et al., 2012), or EFESE (French Ecosystem Service Evaluation) (Therond et al., 2017). Much work has been undertaken on ES assessment and valuation. ESs are often measured in the field (Richter et al., 2021), but fieldwork to evaluate simultaneously multiple ESs is difficult and very costly, so indirect assessments are proposed. For instance, land cover maps are generally used (Martínez-Harms & Balvanera, 2012), with one value attributed to each service and each land cover type. Grasslands are generally considered through only one or two cover types, so the difference in ES provision between the different types of grasslands is not acknowledged (Richter et al., 2021). When grassland types are more precisely distinguished (Villoslada et al., 2018), the difficulty is to choose the appropriate category of grassland. Categories are diverse and based on phytosociology, agronomy, or functional approaches, but they are rarely unified (Mesbahi et al., 2019).

Another approach is to use indirect measurements of ESs, such as biodiversity metrics. These methods are based on the fact that the biodiversity within grassland vegetation is the support for many ESs (Sala et al., 1996). Some of the previous studies on plant diversity and productivity (biodiversity experiments) showed that species-rich grassland communities are associated with high-level delivery of aboveground biomass (Hector et al., 1999). However, these relationships are less established and still under-debated under more realistic grassland management conditions (Freitag et al., 2023). More recent studies have focused on the diversity of the functional traits of different plant species within the grassland plant community (de Bello et al., 2010; Gross et al., 2017). A functional trait is any morphological, phenological, or chemical feature measurable at an individual level that is linked to the fitness of the individuals (Violle et al., 2007). The functional traits linked to nutrients and photosynthesis, such as the specific leaf area (SLA) or leaf dry matter content (LDMC), are generally linked to biochemical cycles and ESs (Duru et al., 2009; Lavorel et al., 2013). Floral trait diversity of grasslands can be related to pollinator visits (Goulnik et al., 2020, 2021). Plant functional trait values can be experimentally measured or obtained from international databases, such as the TRY database (Kattge et al., 2020). They can be cross-referenced with the botanical survey to calculate different functional diversity metrics linked to ES.

Plant biodiversity metrics have already been used as ES indicators. In many studies, one diversity metric is directly linked to one ES (Duru et al., 2009). However, several metrics can be linked to the same ecosystem process, and an ES is generally supported by several ecosystem processes. Another option is to aggregate different vegetation criteria to produce synthetic scores (Dumont et al., 2022; Johansen et al., 2019; Lavorel et al., 2011; Plantureux et al., 2014). In these different studies, the indicators use criteria that are not all calculated from a botanical survey but, for example, based on management method or on information on the biomass. This greatly limits the use of these indicators with data sets that comprise only a botanical survey of grasslands, while botanical survey (list and abundance of the plant species) is widely used alone to describe the vegetation of grasslands. Many historical botanical surveys of grasslands are available (Plantureux & Amiaud, 2010; Taugourdeau et al., 2019). A combination of botanical surveys and database functional traits can produce analyses of functional diversity on large temporal and spatial scales (Violle et al., 2015).

This study aimed to develop a set of ES indicators for grasslands that relies solely on historical botanical surveys combined with existing functional trait databases. First, existing academic knowledge and scientific expertise were used to develop and assess these indicators. The hypotheses put forward to support this work were: (i) ES provided by grassland can be evaluated solely from plant diversity information and (ii) we can reach a scientific consensus on the relationship existing between diversity and ES to develop indicators based on current knowledge. The indicators assess services by assigning a score between 0 (*worst provision*) and 1 (*best provision*).

Then, we tested these indicators on a botanical survey database containing 2000 surveys to evaluate the distribution of the outputs, that is, scores of the indicators. The more dispersed the scores, the better the indicators are able to express ES variability. We were thus able to identify links between the vegetation criterion and the ES score. Moreover, we compared the ES score between the date and the location of the survey and analyzed the link between the different ES scores. We carried out these analyses to demonstrate the efficiency of the indicators.

MATERIALS AND METHODS

General method

The main objective was to build decision trees for different grassland ESs from botanical survey data. The general architecture of each tree is described in Figure 1.

For each decision tree (related to one specific ES), vegetation criteria were calculated from botanical surveys. Vegetation criteria were aggregated as indicators by a multicriteria tool named TATALE (Taugourdeau & Messad, 2017), which will be described below. Indicators are proxies of different functions, processes, or components necessary to estimate the values of the ES. In each successive step of decision, tree construction expert knowledge was mobilized.

Expert knowledge steps

We organized a 2-day workshop with 20 experts in June 2018 (Table 1).

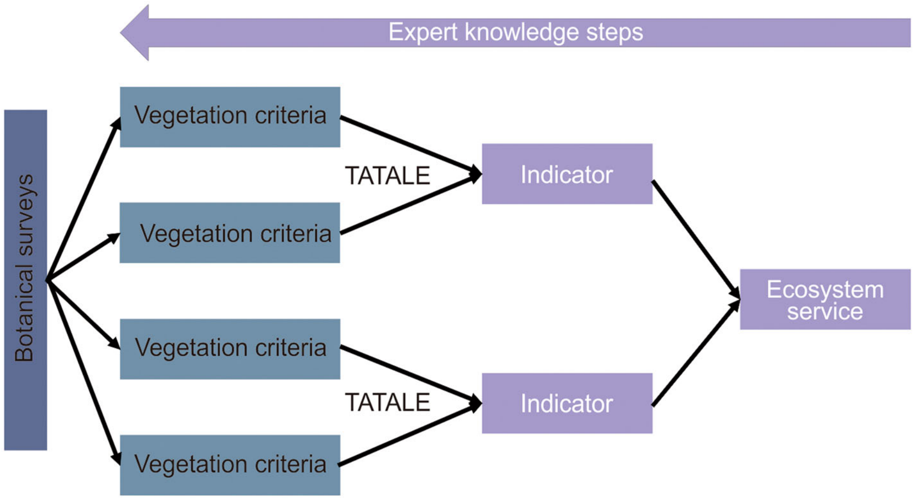

FIGURE 1 General architecture of decision tree for each ecosystem service (ES) and expert knowledge successive steps: (1) selection of ecosystem service, (2) identification of indicators related to the ecosystem service, (3) listing of vegetation criteria calculated from botanical surveys, and (4) using of multicriteria tool TATALE to aggregate vegetation criteria into indicator scores from 0 (*lowest ES provision*) to 1 (*highest ES provision*).

TABLE 1 List of experts in the different workshops.

Workshop	Leader	Expert
Biomass and biogeochemical cycles	Frédérique Louault (INRAE UREP, France)	Olivier Huguenin Elie (Agroscope, Switzerland) Yoann Le Bagousse-Pinguet (King Juan Carlos University, Spain)
	Claude Patrick Millet (INRAE UREP, France)	Catherine Picon Cochard, Sébastien Fontaine, Katja Klumpp (INRAE UREP, France)
Forage quality	Denis Bastianelli (CIRAD SELMET, France)	Gaelle Maxin, Donato Andueza (INRAE UMRH, France)
Pollination	Sylvain Plantureux, Alice Michelot-Antalik, Lena Yentur (Université de Lorraine, Laboratoire Agronomie et Environnement, France)	Colin Fontaine (CNRS, France) Mathilde Baude (Université d'Orléans, France) Philippe Jeanneret (Agroscope, Switzerland)
Biodiversity	Simon Taugourdeau (CIRAD SELMET, France)	François Munoz (Université de Grenoble LECA, France)
	Pascal Carrère (INRAE UREP, France)	Julien Pottier (INRAE UREP, France)

Abbreviations: CIRAD, Centre international de recherche agronomique pour le développement; CNRS, Centre national de la recherche scientifique; INRAE, Institut national de recherche pour l'agriculture, l'alimentation et l'environnement; LECA, Laboratoire d'écologie alpine; SELMET, Systèmes d'élevage méditerranéens et tropicaux; UREP, Unité mixte de recherche sur l'écosystème prairial.

The experts were divided into four workshops (biomass and biogeochemical cycles, forage quality, pollination, and biodiversity). Literature reviews on each theme were prepared before the workshop. The leaders of each group led the discussions and endeavored to reach a consensus.

The first step of the discussion (Figure 1) defines the different ESs on the basis of the CICES framework (Haines-Young & Potschin-Young, 2018). We started with a list of potential ESs: forage production (CICES code 1.1.3.1), climate regulation (code 2.2.6.1), habitat maintenance (code 2.2.2.3, biodiversity conservation), fertility (code 2.2.4.2), and pollination (code 2.2.2.1). This first list of ES was established according to their importance for grasslands in Europe. This list was then discussed with the experts until a consensus was reached for the different ESs. The experts considered that some ESs were not related enough to botanical surveys and removed them (e.g., ESs related to climate regulation). For other ESs, such as "forage production" or "habitat maintenance," two pathways were created in the decision tree to represent different ES components.

At the first step ending, a list of six ESs was produced:

- *Forage provisioning* was the capacity of the ecosystem to produce forage in sufficient quantity and quality for domestic livestock animals.
- *Forage flexibility* refers to the temporal distribution of the forage production and to the quality stability, which determine the flexibility of management, that is, the ability of the sward to be used at a flexible time without strongly affecting its use value (Duru et al., 2010).

- *Plant biodiversity conservation* considers the capacity of grasslands to host plant species. Conservation was evaluated on the basis of the species actually present in the survey.
- *Robustness to extreme events* was the capacity of the plant community to resist/recover from extreme climatic events (drought, heatwave). The underlying assumption is that diversity enhances the capacity of the community to respond to environmental conditions.
- *Nitrogen availability* represents the quantity of nitrogen available through ecosystem processes (nitrogen recycled by the ecosystem, nitrogen fixation). For this ES, we assessed the capacity of the vegetation to provide/recycle nitrogen.
- *Pollination* corresponded to the transfer of pollen from stamens to styles of flowers, thereby enabling plant reproduction. Value of grasslands in pollination was related to habitat quality for pollinator species. Thus, grasslands contribute to pollinator conservation and were identified as sources of pollinators for surrounding crops.

The second step (Figure 1) was to identify indicators related to the ES considered and their respective weight for ES final value on the basis of expert discussions during workshops. The third step (Figure 1) involved expert identification of vegetation criteria that were related to indicators. During the discussion, the relationships between one (many) criteria and the indicator considered were established, and the confidence level was estimated (from sure to hypothetical).

For the last step (step 4 in Figure 1), we used the multicriteria tool TATALE (Taugourdeau & Messad, 2017) to aggregate vegetation criteria into indicator scores from 0 (*lowest ES provision*) to 1 (*highest ES provision*) (Figure 1). This tool relies on a simple logic function that can be easily understood and allows much freedom in its utilization (possibility of both discrete and continuous criteria, missing data, and no limit to the number of aggregations). Furthermore, it is possible to provide intermediate or direct final scores. The TATALE tool is an open-source development (freely available on https://agritrop.cirad.fr/582591/ and https://umr-selmet.cirad.fr/outputs-and-publications/atlas-tools-technical-documents-thematic-websites/tools/tatale). Use of TATALE involved two steps. First, each vegetation criterion (continuous or discrete) was transformed into scores between 0 and 1. For this, we used a preset form (Figure 2), which was selected by experts during the workshops. For example, with the preset form "Linear Increase," the score increased linearly with the vegetation criteria. Second, these scores were aggregated in indicators using basic mathematical rules (mean score value, minimum or maximum of the scores). These thresholds were defined by the scientific experts at step 3 of our methodology (see before). Finally, the final score of each ES resulted in successive aggregations of indicators according to the decision tree architecture.

The different trees for the six services are presented in Supporting Information: (Part B for plant biodiversity conservation, Part C for forage provisioning, Part D for forage production timing, Part E for robustness to extreme event, Part F for nitrogen availability and Part G for pollination).

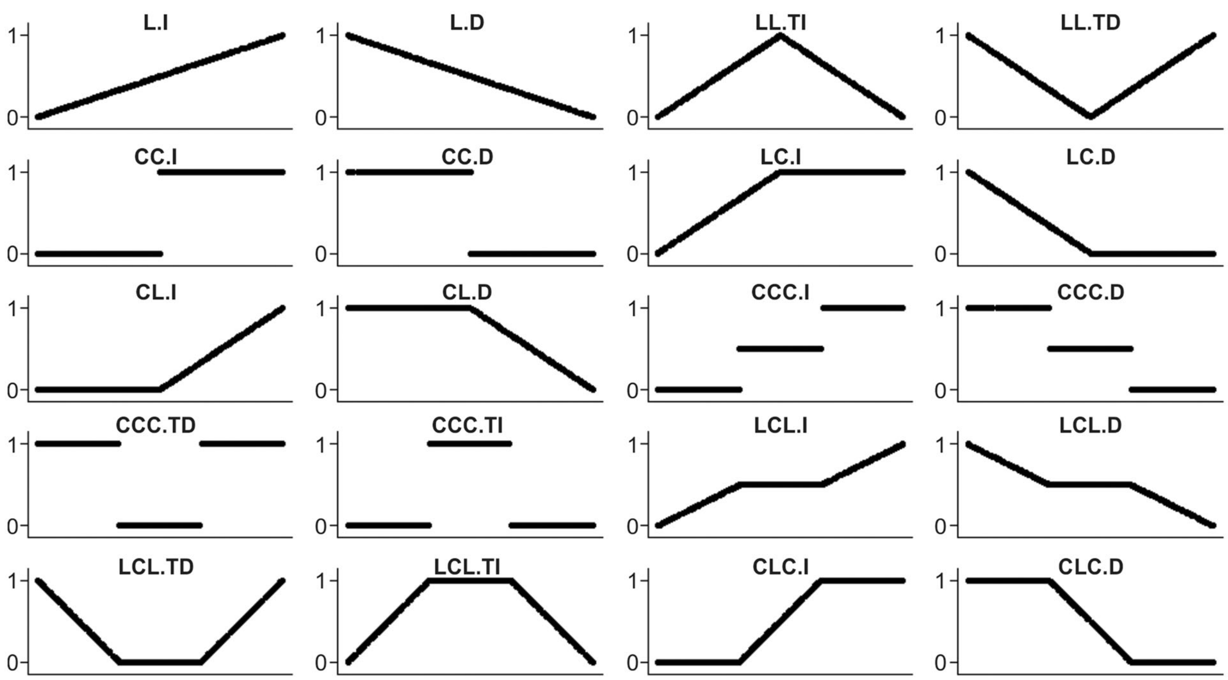

FIGURE 2 The different preset forms implemented in the TATALE tool (Taugourdeau & Messad, 2017). The vegetation criteria can be transformed using a preset form. The preset form describes a way of transforming the vegetation criteria into a score. For example, the linear increase form represents a transformation where the score of 0 is obtained for the minimum value of the vegetation criteria and the score of 1 is obtained for the maximum value of the vegetation criteria, with a linear regression between these two scores. C, flat; D, decreasing; I, increasing; L, linear; T, variation with an extremum.

Calculation of ES scores from a large botanical survey database

We calculated the ES values on a large database of botanical surveys, except for pollination because of the lack of trait values in databases.

We used a large data set of 2030 botanical surveys in France that was obtained by grouping three data sets: e-FLORA-sys (1971 surveys) (Plantureux & Amiaud, 2010), Aeole (51 surveys; https://www.sidam-massifcentral.fr/developpement/aeole), and long-term experiment ACBB (eight surveys) (Louault et al., 2017). The abundances of the different species were harmonized into a relative abundance. Braun–Blanquet notations were transformed into the center of the category (Valcheva et al., 2021). Thus, we divided the species abundances in a survey by the sum of all the abundances in the survey. We obtained relative abundances for 928 species.

For some vegetation criteria, we needed information on the species characteristics. We used the e-FLORA-sys database to calculate different vegetation criteria at the community level, such as the pastoral value, percentage of legumes, and flowering duration. For the functional diversity indexes, the traits were extracted from the TRY database (Kattge et al., 2020). We only used the traits known for at least 60% of the 928 species from the list of species. For the traits with more than 60% of known values (less than 40% of missing data), we used an imputation method developed in Taugourdeau et al. (2014) to replace the missing data. For the other traits, we did not use imputation methods and directly integrated missing values. The functional diversity indexes were computed using the FD package (Laliberté & Shipley, 2014). For phylogenetic diversity, we used phylogenetic information at the genus level. We corrected the systematic using the Taxize package to adjust to the NCBI (National Center for Biotechnology Information) species ID. The "rotl" package was used to extract phylogenetic information and calculate the phylogenetic tree. The phylogenetic tree was calculated for the whole set of species and, for each survey, the tree was calculated for the species only in that community. We calculated the different indexes (such as the Faith index) and the PAE (Phylogenetic Ancestral Endemism) index. We used the "picante," "ape," "caper," and "Phytools" packages to carry out this procedure.

Data analysis

Distribution of ES scores

We visually evaluated the distribution of the transformed vegetation criteria and the different scores obtained using a histogram. The more widely the score was distributed between 0 and 1, the greater the discrimination of the ES was found to be. The distribution of the scores (intermediate or final) was also informative about their importance in the aggregation, especially in the mean aggregation. Indeed, a vegetation criterion with a wider distribution contributed more to the aggregation.

Relationships between ES indicators

We carried out two principal component analyses to explore the relationships between parameters. The first principal component analysis (PCA) relates specifically to the ES of conservation of plant biodiversity and describes the relationship between input variables and intermediate and final indicators. The second PCA describes the links between the five final ES indicators. Both tables were calculated from 2000 botanical surveys carried out on French pastures covering a wide biogeographical gradient.

Changes in ES in time and space

We conducted two analyses using metadata from the botanical survey (temporal and spatial information) to compare the ES scores between the decades, latitudes, and altitudes. For temporal analysis, e-FLORA-sys data measured in Eastern France was used (1038 surveys), and the surveys were grouped per decade (1970s, 1980s, 2000s, and 2010s). We compared the final scores of the five ESs between the decades. The numbers of surveys were not similar between the decades, so we randomly resampled 150 surveys in each decade. We carried out Welch's analysis of variance (Welch, 1951) to compare the scores between the decades.

For spatial analysis, we used a data set across France, but only for the Years 2000s (see Supporting Information: Part H). We tested the effect of latitude–longitude and altitude of each survey location (at the scale of municipality) on the ES score using linear regression. We used the surveys from the 2001 to 2018 period (1057 surveys), for which the Global Positioning System position was available covering most of France. The altitude was derived from a digital terrain model. The map and the distribution of all botanical surveys used are available in Supporting Information: Part H.

RESULTS

Distribution for the plant biodiversity conservation scores

Some vegetation criteria in the set of botanical surveys had a normal distribution, such as functional richness and divergence (Figure 3). Others had more of a uniform distribution, such as the ubiquity index or specific richness. Some were totally unbalanced (with few high or low values), such as phylogenetic richness and divergence.

For the plant biodiversity conservation score, the local richness scores ranked from 0.1 to 0.7 with a balanced distribution, most of the survey scores being between 0.3 and 0.5 (Figure 4). The original habitat scores were more widely distributed, with the score ranging from 0.0 to 0.6. Many surveys had scores between 0.3 and 0.45. The "community with original species" score had a balanced distribution around a score of 0.4, ranging from 0 to 0.8. The number of original species also ranged from 0.0 to 0.8 with a uniform

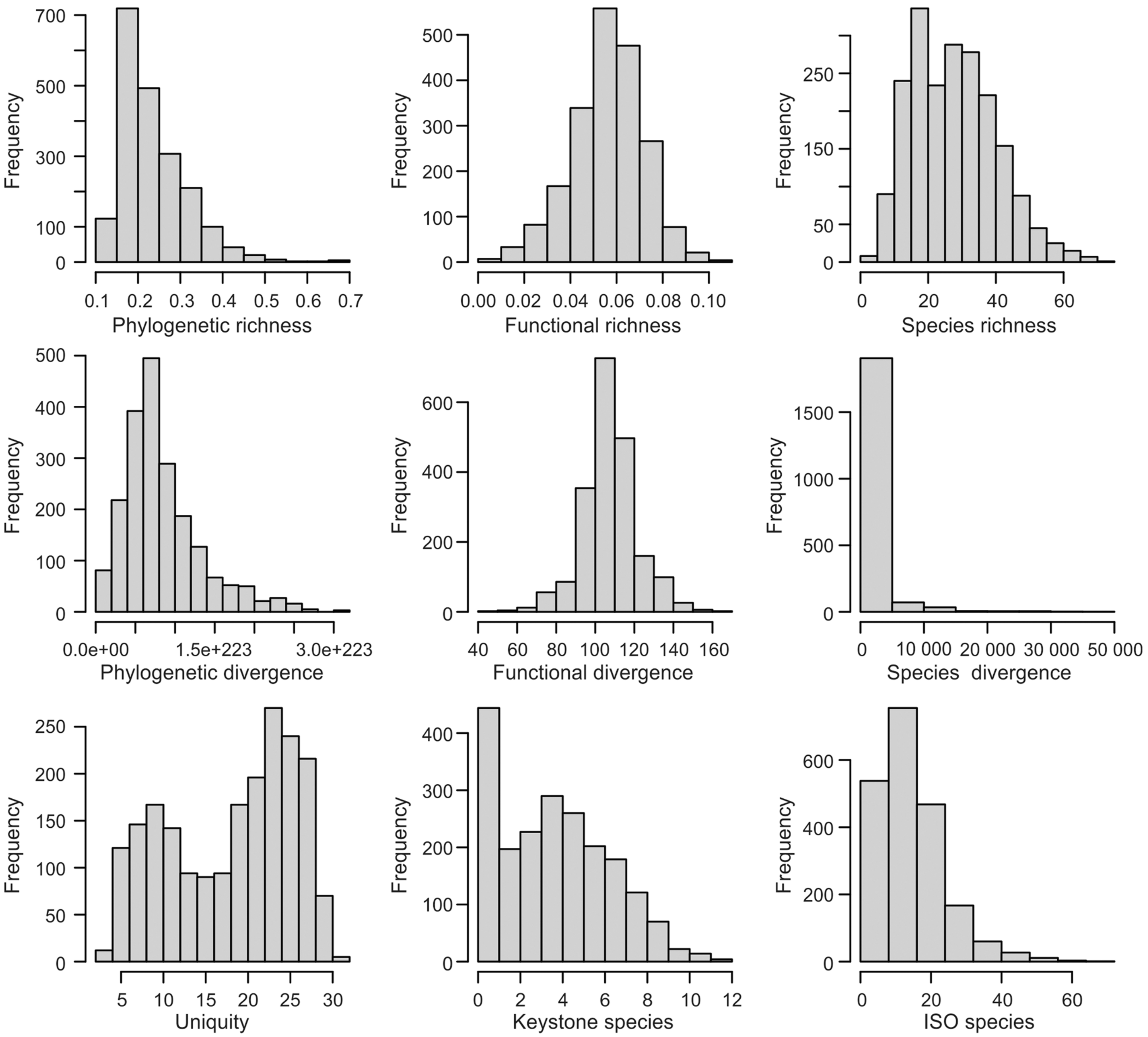

FIGURE 3 Distribution of the different vegetation criteria used for the evaluation of the "plant diversity conservation" ecosystem services based on 2030 surveys (see Supporting Information: Part B).

distribution. Regional originality had a balanced distribution around 0.45, as did the conservation score.

Links between the different scores of the biodiversity conservation indicators

Figure 5a presents the PCA carried out on the different scores for the "plant biodiversity conservation" indicator. The first axis explains 52% of the variability and the second axis explains 31%. The plant biodiversity conservation score was more linked to the regional originality score than to the local richness score. Local richness was related to the original habitat score and number of original species score. Some vegetation criteria were linked to the different scores. The original habitat score was linked to the ubiquity score. The number of original species scores was linked to taxonomic richness. The local richness score was linked to functional richness. The regional originality score was linked to functional diversity. The community with original species score was not linked to a vegetation criterion.

Links between the different scores of ESs

Figure 5b is a PCA variable plot of the five indicators for the ESs. The first axis describes 36% of the score variability, and the second axis describes 21%. The PCA showed that some services were strongly associated with others, but others were independent. Forage provisioning and nitrogen availability for the vegetation were linked in the upper part of the circle. The robustness of the plant community to extreme events was negatively linked to these two services. The last two services (plant biodiversity conservation and forage flexibility) were linked to the first axis and were poorly associated with the previous three services.

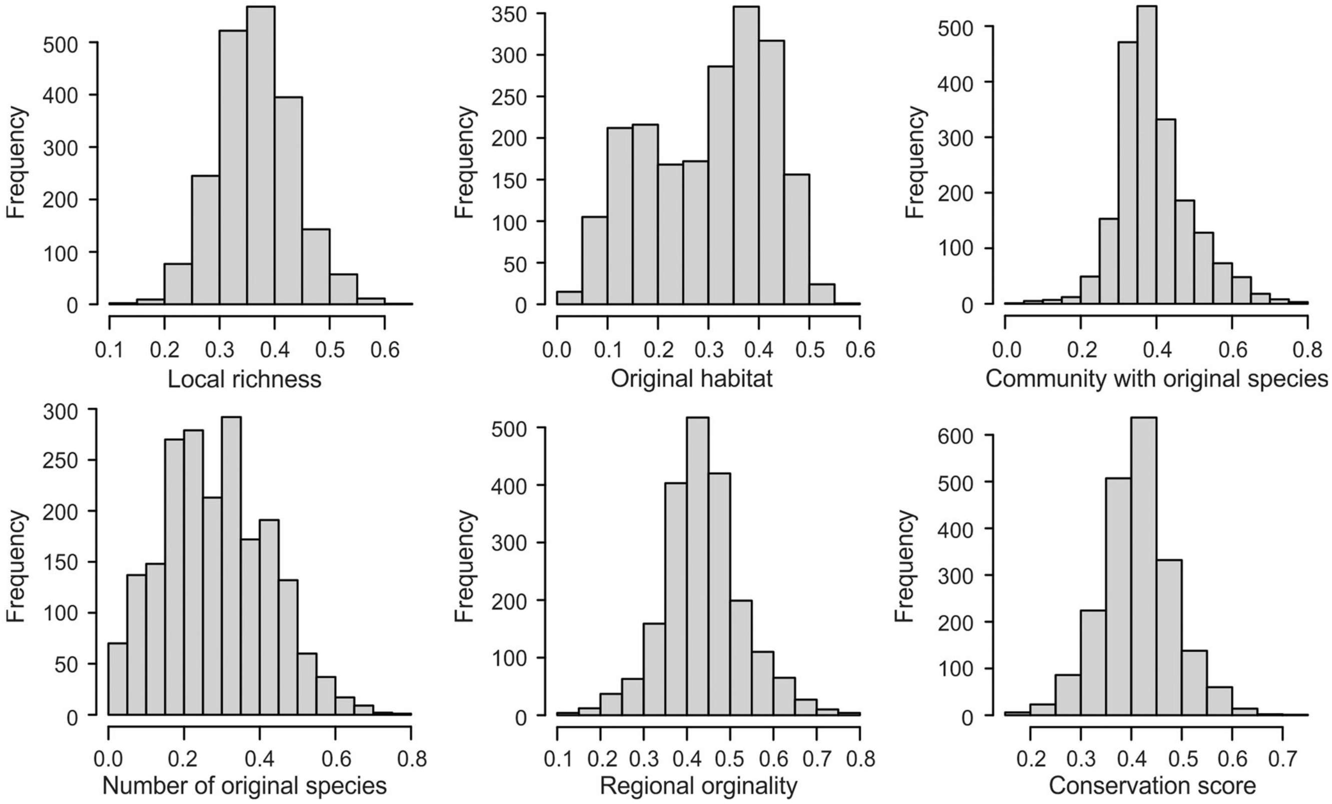

FIGURE 4 Distribution of the intermediate scores (local richness, original habitat, community with original species, number of original species, regional originality) and final score for conservation over the 2030 surveys.

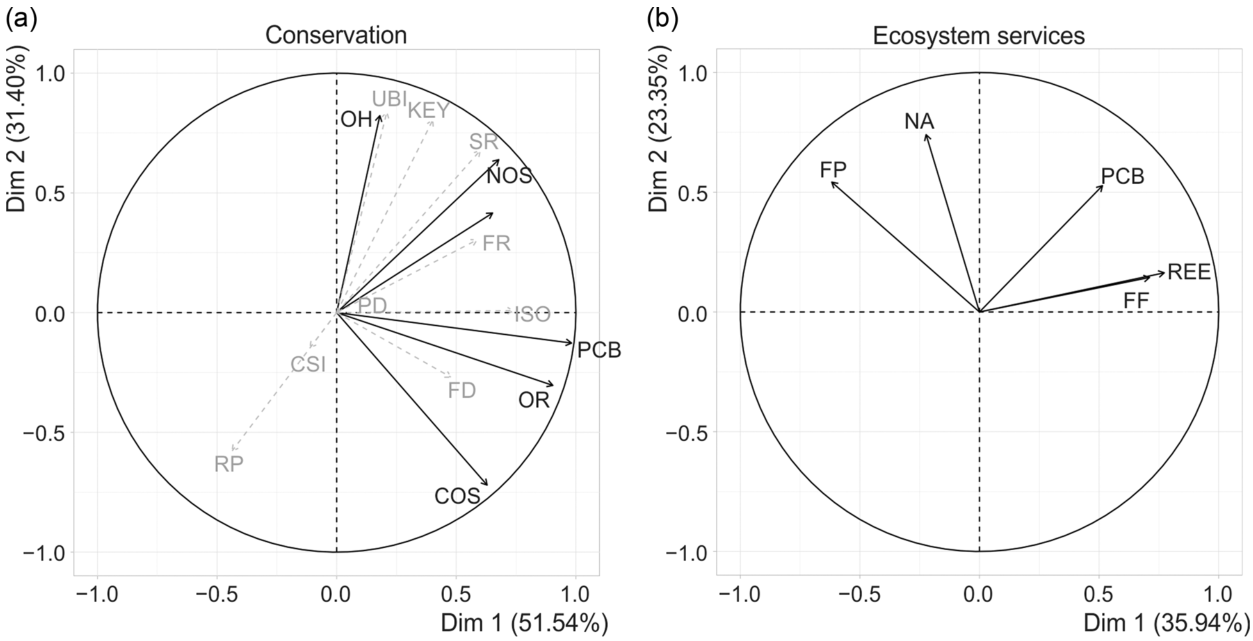

FIGURE 5 Principal component analysis (PCA) between the different scores. (a) PCA for plant biodiversity conservation with the score (intermediate and final) in black and the input score in gray. (b) PCA for all ecosystem services. COS, community with original species; CSI, community specialization index; DF, functional distinctiveness; DP, phylogenetic diversity; FF, forage flexibility; FP, forage provisioning; ISO index; KEY, keystone species; LR, local richness; NA, nitrogen availability; NOS, number of original species; OH, original habitat; OR, regional originality; PCB, plant biodiversity conservation; REE, robustness to extreme events; RF, functional richness; RP, phylogenetic richness; RS, species richness; UBI, ubiquity.

Changes in ESs in time and space

All of the five ES scores displayed a significant difference ($p < 0.05$) between the decades, but the differences showed temporal trends for only two of them (Figure 6). The plant biodiversity conservation score decreased over time. Indeed, the highest average score was for the survey made in the 1970s (average score =

0.46) and the 1980s (score = 0.43). The 2000s had the lowest score of 0.38, with 0.41 for the 2010s. Nitrogen availability scores were lower in the earliest two decades (1970s = 0.32 and 1980s = 0.28) than the latest two decades (0.36 for the 2000s and 0.38 for the 2010s).

Concerning spatial effect, we found a significant ($p = 0.02$) positive relation between latitude and the plant biodiversity conservation score (Table 2). For longitude, we found a positive relation with biodiversity conservation and forage provisioning and a

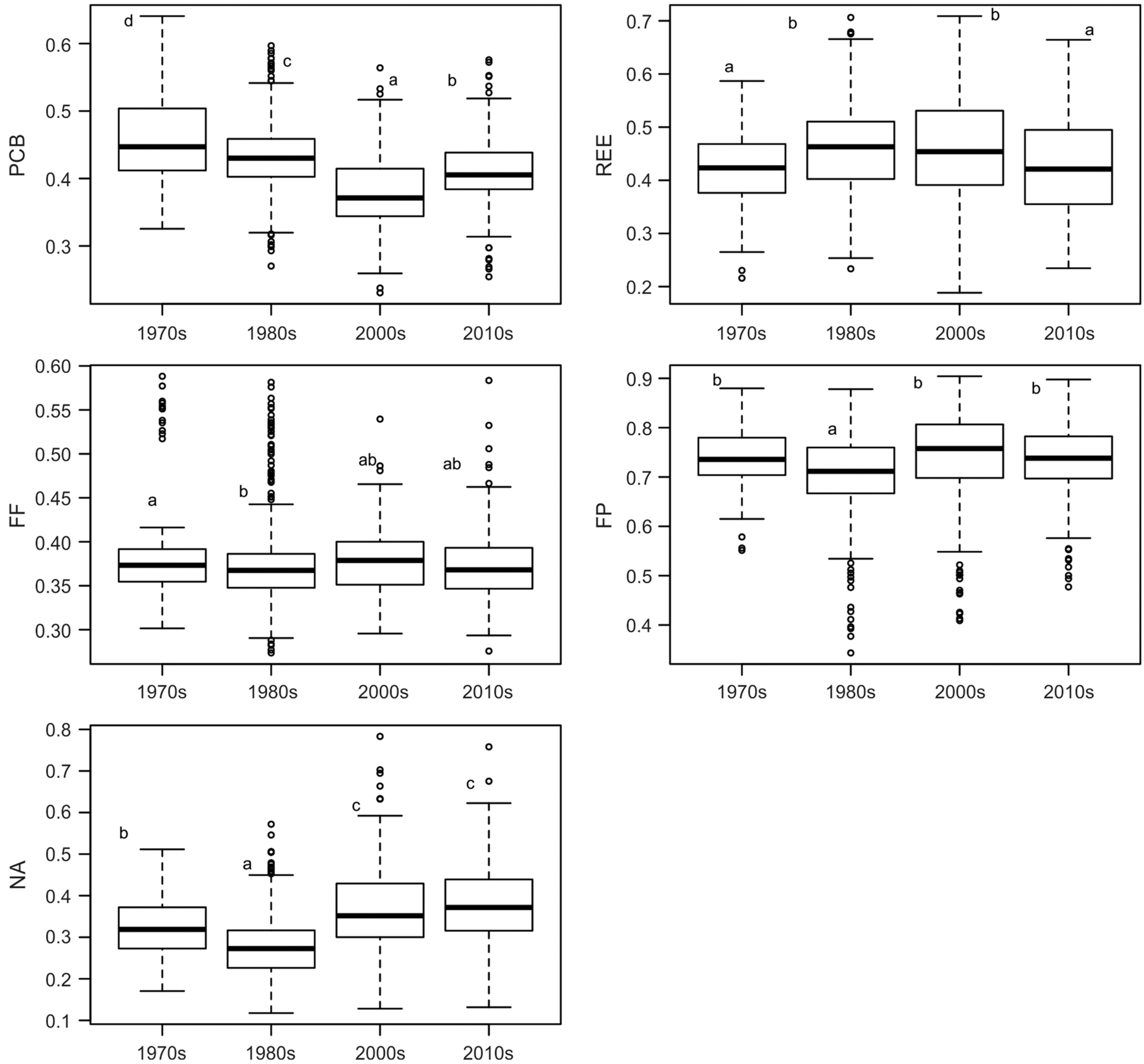

FIGURE 6 Difference in ecosystem services provisioning between the different decades (1970s, 1980s, 2000s, 2010s). The letter represented the differences obtained from the test. FF, forage flexibility; FP, fodder provisioning; NA, nitrogen availability; PCB, plant biodiversity conservation; REE, robustness to extreme events.

TABLE 2 Impact of latitude, longitude, and altitude on the different ecosystem services.

Item	Latitude	Longitude	Altitude
Plant biodiversity conservation	**0.007 (0.02)**, +	**0.09 (<0.0000)**, +	**0.047 (<0.0000)**, +
Robustness to extreme events	0 (0.59)	0 (0.89)	0 (0.26)
Forage provisioning	0 (0.73)	**0.01 (0.0003)**, +	0 (0.27)
Nitrogen availability	0 (0.99)	**0.02 (0.0007)**, −	**0.07 (<0.0000)**, −
Forage flexibility	0 (0.41)	**0.014 (0.001)**, −	0 (0.12)

Note: R^2 of the relationship is presented with the p value in brackets. Plus (+) or minus (−) indicates the direction of the correlation. In bold the relationships with p value lower than 0.05.

negative relation with nitrogen availability and forage flexibility.

For altitude, we found a positive relation with plant biodiversity conservation and a negative relation with nitrogen availability.

DISCUSSION

Decision tree construction methodology: Demonstration by an example

The construction of "plant conservation biodiversity" ES was used as a common thread to describe the methodology used in our approach and its capacity to integrate the different aspects of a concept as broad as biodiversity. In this study, plant conservation biodiversity is community-centered (not population-centered) by considering two main aspects: the local richness and the originality of the species present. The first criterion considers the width of the autecological spectrum permitted by the grassland; the second identifies the presence of species that are not very abundant (subordinate species) but may have original properties. Indeed, subordinate species may have a greater influence on ecosystem functioning than their relative abundance would suggest (Mariotte et al., 2013). Considering original species makes sense from a functional perspective of biodiversity and its role in the provision of ES.

To justify the pertinence to construct composite indicators, we have analyzed the links between the different criteria considered (Figure 5) to be sure that they are complementary and to avoid redundancy. Local richness and regional originality were not linked and represented different aspects of biodiversity conservation. Functional and taxonomic richness were more linked together and explained the local richness indicators. Links between functional richness and taxonomic richness have already been found in some studies (Mouchet et al., 2010). To characterize the originality of a grassland (community with original species), we used different distinctiveness metrics (based on either functional or phylogenetic features). Average distinctiveness and the IUCN score were not linked, so the "community with original species" scores were not linked specifically to one metric. The absence of a link between phylogenetic and functional distinctiveness was shown for mammals on a species scale in Violle et al. (2017). To determine the number of original species, present in one survey, the scientific experts proposed constructing an "index of species originality" metric (ISO) which counted the number of species in the survey that contained at least one originality (functional, phylogenetic, or IUCN status). This index of species originality was most strongly related to biodiversity conservation score. This example of plant biodiversity conservation indicators shows the merits of composite indicators that can combine the different aspects of biodiversity conservation. In this sense, they are more robust than simple indicators, such as the number of species, which are too restrictive for a full assessment of biodiversity in the provision of ES.

Merits and limitations of the expert-based approach

In this work, we used a collective expert-based approach to develop the indicators, as it was already developed in previous studies on ESs (Johansen et al., 2019). But generally, such studies were only based on the literature and author's expertise. In this work, we mobilize more than 20 researchers distributed in different thematic groups (Table 1). The indicators were produced by consensus inside the thematic groups resulting from a collective knowledge coming from the debate between the different disciplinary experts. Sometimes compromises were necessary to reach a consensus between the different disciplines (e.g., between a functional ecologist and a grassland agronomist). A merit of the expert-based approach is to implement parameters that are only hypotheses. It is a way to identify knowledge gaps (indirect supplementary output of the approach). A limit is that the issue of the indicator construction could be dependent on the experts and their perception of how principles are to be applied in a particular context. To limit this side effect, our methods mobilize a multicriteria tool (TATALE) conceived to be easily used by non-specialists in indicator creation. The experts first compare their representation of the biological process with the predefined shapes (Figure 2) proposed in TATALE, and then data sets are used to calibrate the thresholds and parameters required to implement the selected shape. This combination of expertise and calibration using data sets is a significant improvement over other available tools (Bohanec & Raikovic, 1990; Guillaume & Charnomordic, 2011), even if the latter are still useful for developing ES indicators (Dumont et al., 2022; Ricou et al., 2014). In the literature, indicators can be used to assess general concepts such as sustainable development (Lairez et al., 2016) or biodiversity, not all aspects of which can be simply quantified. One of the merits of composite indicators is their ability to grasp such "concepts" globally using criteria of different natures: continuous or discrete, quantitative or qualitative, as discussed above for the plant biodiversity conservation indicators.

In this study, indicators could only assess ecosystem processes that were related to the botanical composition of the grassland. But as many ecosystem processes (e.g., biomass production) are dependent on climate conditions and management, ESs emanating from them (e.g., forage provisioning) result from the interaction between the flora, the environment, and the management. In this case, these SE indicators could be viewed only as a potential of ESs (the potential allowed by the flora). It is one reason why the indicators constructed in our methodology are only scores and not predictive values, such as yield for example. Indeed, the yield depends not only on the flora present on the grassland but was impacted by the pedoclimatic condition and the management of the plot. This means that a high indicator score can lead to high or low performance, but a low score can only lead to poor performance. This validation was proposed by Bockstaller and Girardin (2003) and used in Dumont et al. (2022). In our case, the indicators constructed were validated at the level of the final score, but some intermediate scores were validated on the basis of field measurements. For example, some of the forage provisioning indicators (quantity and quality of forage) were validated (Poisse, 2019).

Nevertheless, the indicator creation methodology cannot be used for all categories of ESs, which limits the approach via the bundles of ESs provided by grasslands (Dumont et al., 2019). Indeed, some ESs are not only related to biodiversity and, for some such as climate regulation, TATALE is not adapted. For example, the climate regulation ES integrates processes that have a positive effect on climate regulation (carbon storage in the soil) and others that have a negative effect (methane emission from livestock or soil) (Assouma et al., 2018). The net ESs from these counteracting effects is so strongly decided by the balance between positive and negative effects that the outcome cannot be assessed using TATALE.

Another limitation arises from the calculation of the vegetation criterion. For example, to calculate the criterion based on functional traits, we used the TRY database (Kattge et al., 2020). However, in such a global database, even if extensive curation is carried out by the contributors, certain "errors" or "missing values" are present, which increases the uncertainty associated with the calculated criterion. For some traits (SLA, vegetative height), we had to deal with missing data using imputation methods, which led to inaccuracies (Taugourdeau et al., 2014). Furthermore, if the trait value varies within a species (Albert et al., 2010), the trait value in the database is not fully representative of the value that would be measured in the field (Albert et al., 2012). This results in some inaccuracies in the calculation of certain criteria. Finally, we were unable to calculate the pollination indicator due to a lack of available/usable data.

A methodology allowing to assess SE trade-off

Our study focuses on six major ESs provided by grasslands, for which we have constructed six indicators based solely on data from vegetation surveys. If ES indicators for grasslands are available in the literature, most of them rely on field measurements of ecosystem functioning (Richter et al., 2021) or on land use (Villoslada et al., 2018). Other indicators combine botanical survey and complementary variables. For example, the "insect abundance and diversity" indicator from Dumont et al. (2022) combines botanical data and management practice, whereas the ES indicators of Norwegian grassland by Johansen et al. (2019) use also the adult tree cover in the plots. Beyond the simple savings in information required to implement them, indicators based only on botanical surveys present the advantage of using existing data sets, mainly easily available (Chytrý & Rafajová, 2003; Plantureux & Amiaud, 2010; Taugourdeau et al., 2019; Violle et al., 2015).

Moreover, the scores calculated for this set of indicators on large botanical data sets can be used to assess the trade-off between ESs (Lavorel & Grigulis, 2012) and to understand variability in ESs. Thus, the indicators developed by the approach developed in this study could be used to assess trade-offs between ESs. Indeed, as this methodology allows estimating ES indicators from the same data set (botanical surveys), construction biases linked to the association of multiple (or heterogeneous) data sources are minimized or nonexistent. Our approach shows many positive links between services. Plant biodiversity conservation and forage flexibility appears to be positively linked. According to Duru et al. (2010), the diversity within a grassland was generally associated with the flexibility of use. Indeed, the diversity of species generally induces species with different temporalities of production; hence, production is more evenly spread across the growth period. Nitrogen availability and forage production were also positively linked. Rich legume grasslands are associated with high nitrogen availability thanks to biological fixation. Legume species are also associated with higher protein content, and hence with a higher nutritional value (Lüscher et al., 2014). Furthermore, both services are linked to the leaf economic spectrum (Wright et al., 2004). Indeed, species with an "acquisitive" set of traits (high SLA and LNC, low LDMC) are species with high productivity and fodder quality (Duru et al., 2012; Gardarin et al., 2014; Khaled et al., 2006), but also with high litter decomposition (Freschet et al., 2012). This methodology also makes it possible to highlight neutral or negative correlations. For example, plant biodiversity conservation (and forage flexibility) and forage provisioning (and nitrogen availability) were found to be independent. Several studies have shown that forage production and species richness in grasslands are not linked (Jeangros et al., 1994). Although our indicators are not limited to yield and species richness, we found similar trends. This means that some grasslands are able to provide high forage production and good biodiversity conservation, but others are poor at both. An applied objective could be to identify the management and environmental conditions that favor the provision of these two services.

Using PCA analysis, we showed that certain services were opposed (Figure 5). Plant community robustness to extreme events was negatively related to forage provisioning and nitrogen availability. This could mean that highly productive grasslands may be less robust. It can be explained by the presence of highly competitive species in productive cover, which express their growth potential under optimal conditions but which are weakened under conditions of water stress, for example, Zwicke et al. (2015). This result may have important consequences for assessing the biomass produced in the long term in a warming climate where extreme weather events are more frequent. In this sense, the production of integrated indicators of ESs provided by grasslands, based on the construction of decision trees and botanical data, could be a first step toward removing one of the obstacles identified by Stokes et al. (2023), namely, better assessing the link between the ecological indicators describing the functional characteristics of the ecosystem and the final ESs; see also Birkhofer et al. (2015).

Exploring temporal and spatial change in ESs

The botanical surveys used in this study come mainly from the e-FLORA-sys database. The 2000 or so surveys available (particularly in eastern France) were carried out over four decades (1970s, 1980s, 2000s, and 2010s). The data set was obtained from various research projects. The surveys are not temporal replications carried out in the same place but on four different dates, which means that the data from each decade do not cover exactly the same geographical area. This is not, however, a limitation of our analysis, as we seek to assess the trajectories of services across the data set as a whole. Moreover, the data were well distributed enough to be used for spatiotemporal studies.

Two services showed temporal trends in this region: a decrease in biodiversity conservation and an increase in nitrogen availability (Figure 6). Different factors can explain these changes: intensification of grassland management or abandonment (Hilpold et al., 2018). Intensification is generally associated with higher nitrogen inputs and higher defoliation frequency. These two factors are known to have a negative impact on the species richness of grasslands (Gaujour et al., 2012) as well as on the values of functional traits (Louault et al., 2017). Intensification generally selects species with higher growth and nutrient acquisition. With regard to abandonment, some grasslands studied in the 1970s or 1980s are currently no longer grasslands but have begun a succession toward forest (Odum, 1969). The negative effects of abandonment on grassland diversity (species richness, but also functional diversity) are well known (Cramer et al., 2008; Peco et al., 2012; Uchida & Ushimaru, 2014; Wehn et al., 2017). These few examples show the interest of the indicators developed in this study to better study the relationships between management practices and ESs in agroecosystems, which remains a major knowledge gap (Stokes et al., 2023). Our methods, based on the mobilization of botanical inventories, also make it possible to address the problem of the data needed to make progress in our understanding of the relationships between management practices and ESs in grasslands.

CONCLUSIONS

In this paper, we presented a set of indicators for grassland ESs (forage production, forage flexibility, resilience to extreme events, conservation of biodiversity, nitrogen inputs to the vegetation) that relied only on botanical surveys. The indicators can thus be used on large data sets of botanical surveys, especially historical surveys. Thus, the temporal dynamics of ESs can be studied, and also trade-offs between ESs. The indicators were developed based on expert knowledge combined with an indicator tool. One of the merits of expert knowledge was to reach a consensus on the relations existing between biodiversity and ESs. Furthermore, this approach was also interesting for identifying knowledge gaps. The methodology could be used to develop indicators for other services linked to biodiversity, such as medicine, food, wood, energy provision, or carbon sequestration. The indicators were only developed and tested for temperate permanent grasslands in Europe. It would be interesting to test and evaluate the indicators on other types of grassland in other parts of the world.

AUTHOR CONTRIBUTIONS

Simon Taugourdeau: Conceptualization; data curation; funding acquisition; methodology; project administration; software; visualization; writing—original draft. **Frédérique Louault**: Conceptualization; formal analysis; investigation; methodology; writing—review and editing. **Alice Michelot-Antalik**: Conceptualization; investigation; methodology; writing—review and editing. **Samir Messad**: Data curation; formal analysis; software. **François Munoz**: Methodology; writing—review and editing. **Denis Bastianelli**: Methodology; writing—review and editing. **Pascal Carrère**: Conceptualization; formal analysis; funding acquisition; methodology; writing—review and editing. **Sylvain Plantureux**: Conceptualization; methodology; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The different vegetation criteria used in the different indicators are available in CSV format (one per indicator) in the Supporting Information. The TATALE functions and the scripts to obtain (one per indicator) the different scores are available in the Supporting Information.

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