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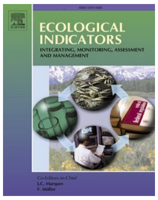

An improved indicator framework to assess and optimise ecosystem services provided by permanent grasslands

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ABSTRACT

Livestock farming systems are criticised for their environmental impacts, but they can also provide various ecosystem services to society, especially permanent grasslands. This study aimed to develop a method to assess impacts of permanent grasslands and their management on the supply of regulation and maintenance ecosystem services applicable at the field and/or farm level. To this end, an existing framework, the Ecological Focus Areas Calculator, was adapted to (i) consider attributes and location parameters of permanent grasslands and (ii) integrate impacts of permanent grassland management on the provision of ecosystem services, which yielded a score for each ecosystem service. The method developed was tested with two farms. Analysis of mapping results, which calculated a score for each ecosystem service for each permanent grassland field on each farm, highlighted the direct relation between the novel approach and the underlying ecological theory of impacts on ecosystem services. On each farm, management practices influenced ecological processes differently, which led to different changes in ecosystem service scores. Applying this novel approach directly with farmers can help them identify win–win situations and trade-offs and target their management, by identifying the fields where it may be more optimal to focus certain management practices to decrease the farm's overall impacts based on trade-offs at the individual-field scale. The novel approach combined representation of the complexity of interactions between management practices and ecological processes with the ability to provide results that are easy to use and interpret. Future development could help increase the accuracy of estimated impacts of management practices on ecosystem services, such as by adding additional practices or considering their long-term effects on ecological processes. The novel approach could also be updated to assess impacts of other types of land use, such as arable land, or management practices. The final goal of such a tool is to support decision-making to optimise the ecosystem services supplied by farming systems, which has advantages for society and for farmers.

1. Introduction

Livestock farming systems are criticised for their environmental impacts (Foley et al., 2011), but they can also provide various services to society (Rodriguez-Ortega et al., 2014) which are often overlooked, and some have rarely been quantified (Dumont et al., 2019b). The ability of herbivore systems to provide ecosystem services (ESs) (Rodriguez-Ortega et al., 2014), in particular due to their permanent grasslands, is of particular interest. Increasing the proportion of grassland area in agro-ecosystems could optimise livestock provision and also supply other ESs (Accatino et al., 2019). According to the European Union (EU) Common Agricultural Policy (CAP), permanent grasslands are "land used permanently (for five years or more) to grow herbaceous forage crops, through cultivation (sown) or naturally (self-seeded), and that is not included in the crop rotation on the holding. The land can be used for grazing or mowed for silage, hay or used for renewable energy production" (European Commission, 2014). Compared to other agricultural land uses, farming systems based on permanent grasslands have lower environmental impacts and provide more ES (Lemaire et al., 2014), but their impacts on ESs have been less studied (Bengtsson et al., 2019).

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Management of permanent grasslands influences ESs strongly (Duru et al., 2019) on these grasslands and in the landscapes around them (Neyret et al., 2021). The degree of intensification of permanent grassland management is a key driver for optimising the supply of ESs (Hao and Yu, 2018; Schils et al., 2022). Consequently, it seems essential to consider impacts of the land-use intensity of permanent grasslands on the provision of ESs (Rodríguez-Ortega et al., 2018).

Identification of drivers, such as land use and the climate, that impact the supply of ESs helps to consider interactions between ESs and optimise their overall supply (Mouchet et al., 2017). Choosing comprehensive indicators that relate these drivers to the supply of ESs is necessary to build frameworks that can analyse ESs and provide strategies to optimise their overall supply (van Oudenhoven et al., 2012). A simple and generic assessment of these impacts applicable at the field and/or farm level could help optimise the ESs provided by permanent grasslands and favour their expansion in agroecosystems, in line with results-based agri-environment schemes promoted by the EU (European Commission, 2018).

An indicator framework, the Ecological Focus Areas (EFAs) Calculator, was created for European farmers to (i) estimate current impacts of EFAs, which are farm semi-natural areas (e.g. trees, hedges or fallow land) that are beneficial for biodiversity (European Commission, 2013), and (ii) help add new EFAs that provide higher levels of ESs (Tzilivakis et al., 2016). Several other frameworks could be used to assess impacts of different land uses on ESs in agroecosystems (Michaud et al., 2020), but they (i) are more complicated because they require more input data (Allan et al., 2015), (ii) do not focus on permanent grasslands or similar land uses (Burkhard et al., 2009), (iii) are not applicable at the farm scale (Martinez-Lopez et al., 2019), (iv) are not generic because they were developed for a specific region (Farruggia et al., 2012) and/or (v) do not consider the management (i.e. land-use intensity) of permanent grasslands (Burkhard et al., 2009).

To our knowledge, no existing framework assesses effects of the complexity of relationships among ESs, permanent grasslands and management using a multicriteria approach based on land use, land cover and location in the agricultural landscape. Such a tool could help farmers adapt their management of permanent grasslands to increase the latter's environmental benefits. Such a tool for farmers or their advisers would assess impacts of permanent grasslands on ESs by considering their management, location and attributes.

This study aimed to develop a method to assess impacts of permanent grasslands on the supply of regulation and maintenance ESs applicable at the field and/or farm level, to help farmers manage permanent grasslands to increase the provision of ESs. This method must be generic and simple to use. The framework of the EFA Calculator was enhanced by adding the land use and management of permanent grasslands. The ESs studied are strongly associated with agroecosystems and directly impacted or supported by permanent grasslands (Duru et al., 2019) but are also particularly important to society (i.e. in economic value) (Tzilivakis et al., 2019). The enhanced framework was applied to two case studies of cattle farms in western France, a commercial organic dairy farm in the Brittany region and an experimental beef farm in the Poitou-Charentes region, highlighting how it could help farmers optimise the ES supplied by permanent grasslands on their farms.

2. Materials and methods

The methodological challenge was to adapt the EFA calculator framework to consider permanent grassland impacts on ESs without distorting it, thus maintaining its scientific validity, simplicity and ability to aid decision making at the European scale. The first step was to study the initial framework (section 1) to understand key challenges and the choices necessary to adapt it for permanent grasslands (section 2). Next, data were collected to relate permanent grasslands to parameters and their associated classes that impact each ES (section 3). The initial framework was then adapted to calculate impact scores (section 4) and combined with novel approaches to estimate final scores of impact of permanent grasslands and their management on the provision of ESs (section 5). Hereafter, "impact on an ES" refers to "impact on the provision of an ES". The revised framework was tested with two real farms, and then an overall approach to analyse and interpret these final scores was developed.

2.1. Functioning of the initial framework

2.1.1. Overall approach

The EFA Calculator, developed by the Agriculture and Environment Research Unit of the University of Hertfordshire, assesses ecological benefits of EFAs on a farm by estimating how different types of EFAs on the farm impact the provision of ESs and biodiversity (Tzilivakis et al., 2015). Impacts are classified according to existing impact taxonomies and classifications for biodiversity and, for ESs, the CICES classification (Haines-Young and Potschin, 2018).

2.1.2. Impacts of ecological focus areas on ecosystem services

In this framework, EFAs consist of one or more land uses (e.g. fallow land) or landscape features (e.g. hedges), each of which is described by several parameters (e.g. "ground cover" and "soil texture", for fallow land) (Table 1, Fig. 1) (Tzilivakis et al., 2016). Each parameter is associated with a range of classes (e.g. "none" and "natural regeneration", for ground cover) (Tzilivakis et al., 2016) and differ qualitatively or quantitatively from each other. For each EFA, an impact matrix is created that identifies the parameters that impact the ESs that it provides (Table 1). Then, the impact of each parameter on each ES provided by this EFA is scored on a scale of –100 to +100.

2.1.3. Impact scoring

The impact on an ES is calculated using either a qualitative or a semi-quantitative (i.e. metamodelling) approach. If the ES is not related to a quantifiable proxy, the qualitative approach is used; else, the semi-quantitative approach is used. The qualitative approach assigns a score ranging from 0 (no impact) to 100 (maximum impact) to each class, and the mean of the scores of the classes selected (for nearly all parameters) equals the "impact score" (Tzilivakis et al., 2016) (Fig. 1). The metamodelling approach uses models to calculate a score for each possible combination of parameters, which is then normalised to yield an impact score on a scale of −100 to 0 or 0 to +100. Users can map impact scores of EFAs on a farm using Geographical Information System software to easily locate those with the most impact and identify their spatial relations with other EFAs.

Table 1

Example of the impact matrix for the fallow land ecological focus area, showing which parameters (checkmarks) influence its impact scores on four ecosystem services in the EFA Calculator.

Parameter	Mass stabilisation and control of soil erosion	Maintenance of chemical condition of freshwaters*	Pest and disease control	Pollination and seed dispersal
Adjacent vegetation structure			√	√
Adjacent wildlife corridors			√	√
Mean annual rainfall	√	√		
Field size			√	
Ground cover	√	√	√	√
Slope	√			
Soil texture	√	√		

*: the nitrate leaching sub-class of this ecosystem service.

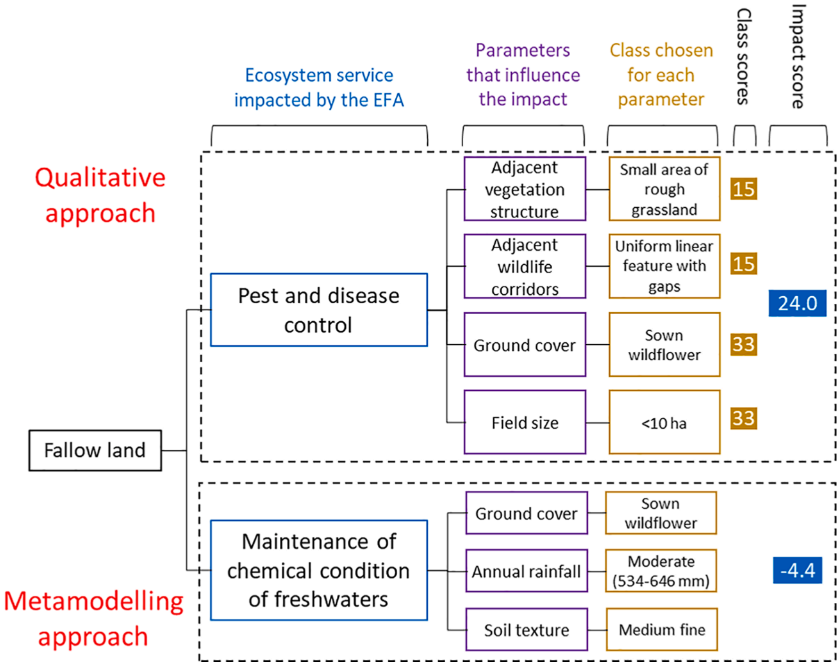

Fig. 1. Example of calculating impact scores of the fallow land ecological focus area (EFA) on ecosystem services in the EFA Calculator using the qualitative approach (for pest and disease control) or metamodelling approach (for the nitrate leaching sub-class of maintenance of chemical conditions of freshwaters).

2.2. Challenges of and choices made when adding permanent grasslands to the initial framework

The initial framework of the EFA Calculator focuses on EFAs, which unlike permanent grasslands, are rarely part of farm production strategies (Tzilivakis et al., 2016). Although several methods have been developed and applied to assess the influence of permanent grasslands on biodiversity (Nicod et al., 2019), as an initial step, only impacts of permanent grasslands on ESs were considered (i.e. not biodiversity). Adapting the initial framework for this objective presented the challenges of representing (i) permanent grasslands themselves, which are not an EFA but impact ES strongly (Kleijn et al., 2009; Dumont et al., 2019b; Duru et al., 2019), and (ii) the management of permanent grasslands.

Based on the initial framework, spatial and ecological parameters were used to estimate permanent grasslands' scores of impacts on ESs. Novel approaches were then developed to estimate impacts of management. Data were collected using a literature review and expert judgement. The latter helped to organise data to identify parameters of permanent grasslands and their associated classes that contributed to impacts on the ES. Finally, the approaches of the initial framework were combined with the novel approaches to estimate impacts of permanent grasslands on five regulation and maintenance ESs. According to CICES nomenclature (Haines-Young and Potschin, 2018), these were global climate regulation by reduction of greenhouse gas (GHG) concentrations, maintenance of chemical condition of freshwaters, mass stabilisation and control of erosion rates, pollination and seed dispersal, and pest and disease control (hereafter, GHG mitigation, water-quality maintenance, erosion control, pollination, and pest control, respectively).

As the framework focuses on ecological benefits of farming systems, it emphasises regulation and maintenance ESs. These five ESs were selected due to (i) the strong relationship between their provision and permanent grasslands and their management (Duru et al., 2019), (ii) related societal and economic issues (Tzilivakis et al., 2019) and (iii) the fact that the initial framework already considers them, thus maintaining consistency with it and enabling comparison of the impacts of permanent grasslands to those of EFAs.

2.3. Data collection

The literature was reviewed and compiled into a database to understand impacts of grasslands and their management on ESs (Table S1). This was further supplemented and refined with the expert judgement of five internationally renowned authorities collected during interviews. These scientists, who were specialists in livestock science and/or agronomy, had knowledge of research topics related to permanent grasslands (e.g. permanent grassland ecology, impacts of livestock and grassland management on permanent grasslands) (Table S2). The experts helped to relate scientific evidence to parameters and quantify the relative influence of each parameter and its classes. Experts also helped to relate impacts on biodiversity mentioned in the literature (Allan et al., 2015) to impacts on ESs, especially pest control, whose relationship to permanent grassland parameters was not clearly described and always passed through the intermediary of biodiversity (e.g. habitat, food supply).

The literature review and expert judgement were used to collect data to identify an indicator to use as a proxy for each of the five ESs and then to estimate the impacts of permanent grasslands on these proxies. As permanent grasslands can partially compensate for GHG emissions by sequestering carbon (Rumpel, 2011; Soussana and Lemaire, 2014), the annual rate of carbon sequestration was used as proxy for GHG mitigation. As nitrate leaching has one of the largest impacts on water quality in agroecosystems (Scherer-Lorenzen et al., 2003; Vertès et al., 2007), nitrate leached was used as proxy for water-quality maintenance. A potential amount of soil loss was used as a proxy for erosion control (Tzilivakis et al., 2016). Finally, the capacity to host robust populations of pollinators or natural pest enemies was used as a proxy for pollination and pest control, respectively (Scohier and Dumont, 2012; Allan et al., 2015; Bengtsson et al., 2019).

2.4. Development of parameters and parameter classes

Key parameters that influence impacts of permanent grasslands and their management on ES were identified by the literature review, expert judgement and analysis of the fallow land EFA, which is similar to permanent grasslands and already assessed in the initial framework.

Parameters contribute directly or indirectly to impacts on ESs by influencing the functional composition or landscape integration of permanent grasslands (Duru et al., 2019). The parameters (and their classes) of some EFAs that have impacts on the five ESs like those of permanent grasslands (e.g. influence of adjacent areas) were re-used for permanent grasslands. The 20 parameters defined that contribute to impacts of permanent grasslands on ES (Table 2) fall into three categories:

- Location: global (climate context) and farm-specific (adjacent area) locations of permanent grassland fields
- Grassland attributes: characteristics of permanent grasslands (e.g. floristic diversity, cover heterogeneity, soil texture)
- Management: agricultural practices on permanent grassland fields (i.e. fertilisation, grazing and mowing)

The same approach as in the initial framework was used to define parameter classes (Tzilivakis et al., 2016). Classes were chosen to specify degrees of each parameter's impact on a given ES, either quantitative (e.g. amount of nitrogen (N) applied) or qualitative (e.g. heterogeneity of grassland cover) depending on the parameter (Tables S3-S6).

2.5. *Impact assessment*

2.5.1. *Impact matrix*

As in the initial framework, an impact matrix (Table 2) was

Table 2

Impact matrix indicating which location, attribute and management parameters (checkmarks) are used to estimate the provision of ecosystem services for permanent grasslands in the modified EFA Calculator. GHG = greenhouse gas.

Parameter		Classes			Ecosystem services				
		Definition	Number	Range	Direct impact on			Support for	
					GHG mitigation	Water-quality maintenance	Erosion control	Pollination	Pest control
Location	Mean annual rainfall	Mean annual rainfall (mm yr^{-1})	5	from <451 to more than 765		√	√		
	Adjacent wildlife corridors	Type of adjacent wildlife corridors	3	from no linear features to diverse and complete linear features				√	√
	Adjacent vegetation structure	Type of land use on the adjacent area	4	from large areas of bare ground to large area of rough grassland, scrub, hedges or woodland				√	√
Attribute	Field size	Field size (ha)	2	less than or more than 10				√	√
	Age	Age (years)	2	less than or more than 20	√			√	√
	Previous land cover	Type of land cover planted before	4	arable land or 1 of 3 permanent grassland classes	√				
	Cover heterogeneity	Species and height diversity among patches of cover	3	from homogenous cover to patches of vegetation with different species composition and height				√	√
	Floristic diversity[1]	Qualitative assessment of plant diversity	3	from low to high		√		√	√
	Species richness[2]	Number of species in the cover	3	from <4 to more than 16		√			
	Legume content	% of legumes in the cover	3	from <10 % to more than 20 %		√			
	Soil texture	Soil particle size	5	from very fine to coarse		√	√		
	Slope	Slope	3	from flat to steep			√		
Management	Fertilisation intensity	Amount of nitrogen applied (kg N ha^{-1} yr^{-1})	6	from 0 to more than 200	√	√		√	√
	Fertiliser application period	Season	4	from spring to winter		√			
	Type of fertiliser	Type of fertiliser applied	4	from compost to chemical fertiliser		√			
	Grazing intensity	Overall stocking rate (livestock unit. day ha^{-1} yr^{-1})	5	from 0 to more than 510	√	√		√	√
	Grazing intensity during the critical erosion period	Mean winter stocking rate (livestock unit ha^{-1})	4	from 0 to more than 1.2			√		
	Mixed grazing	Different grazing species	2	yes or no				√	√
	Grazing period	Considering natural enemies or not, and early or late	4	combination of natural enemies and precocity				√	√
	Mowing period							√	√

[1] Floristic diversity is a qualitative assessment (low, medium, or high) of the diversity of plant species in the grassland. It is not based on a diversity index (e.g. Shannon) but on an observer's or farmer's estimate of the diversity of plants on the grassland assessed. It is used in the qualitative approach to assess impacts of grassland plant biodiversity on pollination and pest control.

[2] Species richness is a semi-quantitative assessment of the number of species in the permanent grassland and is used to calculate the impact score of maintenance of chemical condition of freshwaters using a metamodeling approach.

developed by transforming the collected data into parameters. The carbon sequestration rate of permanent grasslands is influenced by their age and previous land cover (Lemaire et al., 2014; Pellerin et al., 2019). Management parameters that influence the microbial cycle and growth of grassland vegetation cover (e.g. fertilisation and grazing intensities) also influence this rate (Rumpel, 2011). Water-quality maintenance is influenced by (i) soil and climate parameters that influence nitrate leaching (i.e. soil texture and mean annual rainfall), (ii) the ability of grassland vegetation to take up nitrate (i.e. species richness and legume content) (Scherer-Lorenzen et al., 2003), (iii) the amount of nitrate available to leach (i.e., fertiliser application period and type of fertiliser) (Ledgard et al., 2011) and (iv) the amount of N supplied (i.e. fertilisation and/or manure deposition during grazing) (Vertès et al., 2007). Erosion control is influenced by soil and climate parameters that influence the potential amount of soil loss (i.e. mean annual rainfall, soil texture and slope) (Knijff et al., 2000) and by management, which can decrease grassland cover and degrade soil structure (e.g. grazing intensity during the critical erosion period) (Decaëns and Lavelle, 2011).

Pollination is influenced by (i) the diversity of cover (i.e. cover heterogeneity and floristic diversity) (Table 2) and thus those of habitats and food supplies; (ii) the place of permanent grasslands in the farming landscape (i.e. field size, adjacent wildlife corridors and types of land use on adjacent areas) (Sabatier et al., 2014); (iii) the management, which influences cover heterogeneity directly and the diversity of habitats and food supplies indirectly (i.e. fertilisation and grazing intensity, grazing and mowing period) (Huguenin-Elie et al., 2018) and (iv) the life cycle of pollinators (i.e. grazing and mowing period) (Sabatier et al., 2015). Pest control is influenced by the same parameters as pollination, but with different intensities, which reflect the parameters' relative weights estimated by expert judgement.

2.5.2. *Impact score based on location and attribute parameters*

The same approaches as in the initial framework (i.e. qualitative approach for pollination and pest control; metamodelling for the other three ESs (section 2.1.3)) were used to calculate an impact score based on the attribute and location parameters (Table 3). Associated scores of classes or combinations of classes were determined based on the literature review, expert judgement and/or analysis of EFAs that had impacts on the five ESs like those of permanent grasslands (Tables S3-S6).

The metamodelling approach used for GHG mitigation, water-quality maintenance and erosion control estimated the ES's proxy, which was influenced differently depending on the combination of parameters, and subsequently considered as the impact on the ES (Table 5). The carbon sequestration rate (t carbon ha^{-1} yr^{-1}) was estimated from a permanent grassland's age, previous land cover and age of that land cover if also a permanent grassland, using reference data of Pellerin et al. (2019) and an equation of Poeplau et al. (2011) (Table S4). This carbon sequestration rate was then normalised into the impact score of GHG mitigation (range: 0–13.3) by dividing it by the maximum amount of carbon sequestration over 25 years estimated for EFAs (206 t ha^{-1}). Nitrate leaching (kg N ha^{-1} yr^{-1}) was estimated by modifying the metamodelling approach of Tzilivakis et al. (2015) for the fallow land EFA by adding the influence of cover heterogeneity (i.e. legume content and floristic diversity) (Scherer-Lorenzen et al., 2003). This nitrate leaching was then considered as the impact score of water-quality maintenance (range: −40 to 0) (Table S5). The potential amount of soil loss (t ha^{-1} yr^{-1} loss) was estimated using the metamodelling approach of Tzilivakis et al. (2015) for the fallow land EFA by applying a factor for land-cover of permanent grasslands (Knijff et al., 2000). This potential soil loss was then normalised into the impact score of erosion control by dividing it by two, like for the EFAs in the initial framework (range: −9.2 to 0) (Table S6).

Table 3
Approaches used to calculate impact scores (from the initial framework) and final scores (added in this study) and to normalise final scores to estimate impacts of permanent grasslands on ecosystem services in the EFA Calculator. Metamodelling: calculated from the parameter classes selected. Qualitative: mean of scores of the parameter classes selected. Coefficient: mean of mid-scores of the parameter classes selected. Equation: equations used to calculate fertilisation intensity and grazing intensity scores. GHG = greenhouse gas.

Ecosystem service	Impact score approach	Scoring method before normalisation	Normalisation to obtain final score
GHG mitigation	Metamodelling	Coefficient	None needed (impact score already normalised)
Water-quality maintenance	Metamodelling	Equation	Based on the maximum sum of scores used in equation approaches (200)
Erosion control	Metamodelling	Coefficient	None needed (no normalisation)
Pollination	Qualitative	Coefficient	Based on the maximum mean of the mid-scores (143.9)
Pest control	Qualitative	Coefficient	Based on the maximum mean of the mid-scores (139.6)

2.5.3. *Novel approaches to consider impacts of permanent grassland management on ES*

Management impacts, the main innovation added to the framework, were represented using either an equation (for water-quality maintenance) or a coefficient approach (for the other ESs) that estimated the influence of management on the impact score of the given ES (Table 5).

2.5.3.1. Coefficient approach. The coefficient approach represents the combined effects of multiple management practices that impact each ES by using combinations of management parameters related to fertilisation, mowing and grazing of permanent grasslands (Table 2). The influence of each management parameter on the impact score (IS) is first calculated as a mid-score (MS), by multiplying a class coefficient (CC) (maximum range: −1 to 1) of the class chosen by the absolute value of the impact score and then adding it to the impact score, as follows:

$$MS_i = CC_i \times |IS| + IS \tag{1}$$

where i is the parameter class.

Management parameters are then combined by calculating the mean of their mid-scores.

Class coefficients were used to specify the relative influence of (i) parameter classes and (ii) parameters themselves on the ES. According to the literature review (for carbon sequestration (Pellerin et al., 2019)) and expert judgement (for all ESs), the influence of management on ESs was quantified and limited to a certain multiple of the impact score (Table S7). All class coefficients used are summarised in Table S9.

Three of the four ES estimated using the coefficient approach (i.e. GHG mitigation, pollination, and pest control) are influenced by more than one management parameter. To ensure that the relative influence of these management parameters equalled the parameter weights determined by expert judgement, a sensitivity analysis was performed by adjusting class coefficients for each parameter and calculating standardised regression coefficients (Bring, 1994) that quantified the relative influence of the coefficients on the mean of their mid-scores. Class coefficients were adjusted until standardised regression coefficients lay within 1% of the parameter weights determined by expert judgement (Table S8).

2.5.3.2. Equation for water-quality maintenance. For the nitrate-leaching proxy of the water-quality maintenance ES, fertilisation and grazing supply N directly to the permanent grassland, and some management parameters are interrelated (e.g. "type of fertiliser" and "spreading period"). The impact of permanent grasslands on nitrate leaching would have been too complex and difficult to estimate using the coefficient approach without modifying the structure of the initial framework greatly. Thus, two equations were developed to estimate scores for the influence of (i) fertilisation management (a combination of fertilisation intensity, fertilisation period and type of fertiliser) and (ii) grazing intensity parameters on nitrate leaching:

- Fertilisation management score: the class coefficients for the period of largest application and type of fertiliser modify that for fertilisation intensity (the amount of N applied (kg N $\text{ha}^{-1}\,\text{yr}^{-1}$)) (five classes per parameter based on expert judgement) (Table S9) to yield a score from −60 (the maximum amount of N leached (kg N $\text{ha}^{-1}\,\text{yr}^{-1}$) due to fertilisation of permanent grasslands) to 0:

$$\left[CC_{\text{Period of largest application}}\right] \times \left[CC_{\text{Type of fertiliser}}\right] \times \left|\left[CC_{\text{N applied}}\right]\right| + \left[CC_{\text{N applied}}\right] \tag{2}$$

- Grazing intensity score: nitrate leaching (kg N $\text{ha}^{-1}\,\text{yr}^{-1}$) is estimated as a function of the overall stocking rate (livestock unit (LU). day $\text{ha}^{-1}\,\text{yr}^{-1}$) to yield a score from −100 (the maximum amount of N leached (kg N $\text{ha}^{-1}\,\text{yr}^{-1}$) due to grazing of permanent grasslands) to 0 (Vertès et al., 2007):

$$8.77 \times e^{0.003\times[stockingrate]} \tag{3}$$

Then, these two scores are added to the impact score for water-quality maintenance (range: −40 to 0) to yield a maximum of −200. The maximum values of the three scores were set by expert judgement to reflect the relative importance of cover heterogeneity, fertilisation and grazing on total nitrate leaching.

2.5.4. *Impact normalisation*

To adjust the relative impact of permanent grasslands to those of the EFAs already assessed, the mean mid-scores of pollination and pest control were normalised using the largest possible value (139.57 for pest control and 143.93 for pollination) to obtain a final score in the range of 0–100, as in the initial framework (Table 5). For the same reason, the sum of the three scores for nitrate leaching (the proxy of water-quality maintenance), which ranged from −200 to 0, was normalised by dividing it by two, to obtain a final score in the range of −100 to 0. As the means of the mid-scores for carbon sequestration (the proxy of GHG mitigation) and erosion control had already been normalised from 0 to 100 and –100 to 0, respectively, their final scores did not need a second normalisation.

2.5.5. *Interpretation of final scores*

A final score of 0 indicates that permanent grasslands have no impacts on the ES. Water-quality maintenance can have a lower final score (down to −100) than erosion control (down to −9.2) because permanent grasslands influence nitrate leaching much more than they do erosion. Pollination and pest control can have a higher final score (up to 100) than GHG mitigation (up to 16.8) because permanent grasslands influence habitats and food supplies for pollinators and natural pest enemies much more than they do carbon sequestration (which eventually plateaus). Each permanent grassland field analysed has a final score for each ES, and the average of this final score weighted by the field's area yields a mean final score for the area of the farm covered by the permanent grassland fields considered.

2.5.6. *Case study application*

To illustrate the influence of a variety of parameter classes, the novel approach was applied to two case study farms, which were selected based on their diversity of management strategies and differing local contexts (Table 4, Fig. 2):

- The commercial organic farm of Trévarn, which produces cow milk, with feed self-sufficiency based exclusively on grass, in a hedgerow landscape. All the permanent grassland fields are both grazed and mowed, and some are fertilised.
- The INRAE experimental organic farm of Saint Laurent de la Prée (SLP), which produces crops and beef, with feed self-sufficiency based on producing grass, other forages and energy crops, in a marsh landscape. Most permanent grassland fields are only grazed, some of them are both grazed and mowed, and one of them is only mowed.

Table 4
Case-study farms in western France whose permanent grassland (PG) fields were assessed, with structural data and parameter classes common to all permanent grasslands of each farm.

Data	Characteristic	Trévarn	Saint Laurent de la Prée
Structural data	**Livestock production**	Organic dairy cattle	Organic beef cattle
	Mean annual livestock units	97	99
	Total area (ha)	100	160
	PG area (ha)	100	100
Parameter classes common to all PG fields	**Soil texture**	Fine	Medium-fine to fine
	Mean annual rainfall (mm)	Very high (>765)	High (647–765)
	Field size (ha)	<10	<10
	Species richness (number)	>16	>16
	Floristic diversity	High	High
	Legume content (%)	<10	<10

The approach was applied only to a set of adjacent permanent grassland fields on each farm, including one or more fields whose final scores could be increased by managing the entire set differently, as explored later. The results of applying the novel approach to the two case studies highlight its utility for estimating provision of ES on permanent grasslands. Analysing the parameters that caused these impacts led to the design and assessment of new management strategies to attempt to optimise the overall provision of ESs.

3. Results

3.1. *GHG mitigation*

The final scores for GHG mitigation under current management were 0 for all permanent grassland fields of both farms except for three at Trévarn (11.4 for 2 and 3, 14.2 for 7) (Fig. 3; Tables 5-6), which were the only ones that had arable land as the previous land use (permanent grassland >120 yr old for the others) (Table S10). Their positive final scores were due to being younger than the other permanent grasslands (<25 yr old instead of >120 yr old), as grassland age has the most influence on the rate of carbon sequestration. Field 7 had a slightly higher final score than fields 2 and 3 because it had lower grazing intensity, which has less influence than grassland age (Table S10). The overall final score of the entire set was 5.2 at Trévarn (Table 5) and 0 at SLP (Table 6).

3.2. *Water-quality maintenance*

The final scores for water-quality maintenance were negative for all permanent grassland fields on both farms (-8.6 to −48.8 at Trévarn and 0 to −20.3 at SLP) (Fig. 4; Tables 5-6), meaning that provision of the ES was degraded. At Trévarn, fields 2, 3 and 4, with the highest grazing intensity (>510 LU.day $\text{ha}^{-1}\,\text{yr}^{-1}$), had the lowest final scores (-46.5 to −48.8), whereas the other fields had higher and relatively homogenous

Fig. 2. Locations of the case-study farms in western France: the commercial organic dairy farm of Trévarn in the Brittany region and the experimental beef-cattle farm of Saint Laurent de La Prée in the Nouvelle Aquitaine region. Photographs: Lou Valence.

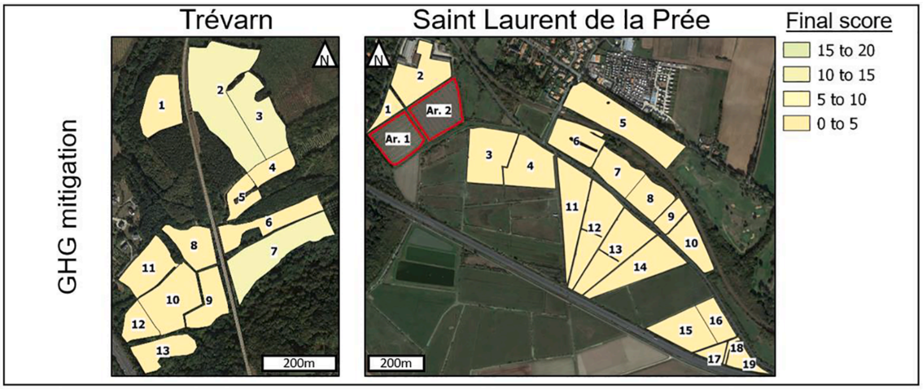

Fig. 3. Mapped final impact scores of individual permanent grassland fields on the two case-study farms for greenhouse gas (GHG) mitigation. Ar. 1 and Ar. 2 represent an arable field converted into two grassland fields in a strategy proposed to optimise the provision of ESs.

final scores (-8.6 to −10.9), with the highest final score (-8.6) for two fields lightly fertilised in spring (Tables S10-S11). At SLP, field 2, with the highest grazing intensity (290–510 LU.day ha^{-1} yr^{-1}), had the lowest final score (–20.3), whereas the other fields had higher and relatively similar final scores (−6.8 to −10.5), except for field 1, which had a score of 0 due to having no grazing (Tables 5-6). Final scores had a heterogeneous spatial distribution on both farms (Fig. 4) and the overall final score of the entire set was lower at Trévarn (–22.5) than at SLP (-8.2).

3.3. Erosion control

The final scores for erosion control ranged from −0.1 to −0.3 for all permanent grassland fields of both farms except for three at Trévarn (-7.1 for 5, −1.8 for 4 and −1.7 for 6) (Fig. 5; Tables 5-6), meaning that provision of the ES was maintained or slightly degraded overall. Nevertheless, all final scores were low, because regardless of how permanent grasslands are managed, their cover is permanent, which decreases soil loss greatly. These three fields, the only ones on either farm that were not flat, differed in their slope and grazing intensity during the critical erosion period (Tables S10-S11). Because erosion rates were influenced mainly by the slope, the overall final score of the entire set was −0.7 at Trévarn (Table 5), due to its three non-flat permanent grassland fields, and −0.1 at SLP (Table 6).

3.4. Pollination and pest control

The final scores of these two ESs covered a wider range at Trévarn than at SLP (29.2–64.3 for pollination and 33.7–60.6 for pest control at Trévarn; 46.7–55.2 for pollination and 51.2–61.2 for pest control at SLP)

Table 5

Final scores of the impact on each ecosystem service for the permanent grassland fields of the Trévarn case study according to current and new management strategies. Differences between the final scores are expressed as the percentage change (Chg.) of the new management strategy relative to the current management strategy.

Field ID	GHG mitigation			Water-quality maintenance			Erosion control			Pollination			Pest control		
	Current	New	Chg.	Current	New	Chg.	Current	New	Chg.	Current	New	Chg.	Current	New	Chg.
1	0	0	–	−10.9	−20.7	−89 %	−0.3	−0.3	–	50.5	51.2	+1%	49.0	52.3	+7%
2	11.4	15.5	+35 %	−46.5	−0.9	+98 %	−0.3	−0.3	–	29.2	30.4	+4%	33.7	35.8	+6%
3	11.4	15.5	+35 %	−46.5	−0.9	+98 %	−0.3	−0.3	–	29.2	30.4	+4%	33.7	35.8	+6%
4	0	0	–	−48.8	−10.9	+78 %	−1.8	−1.7	+3%	43.6	55.3	+27 %	43.9	54.0	+33 %
5	0	0	–	−10.9	−10.9	–	−7.1	−7.1	–	50.5	55.3	+10 %	49.0	54.0	+10 %
6	0	0	–	−10.9	−10.9	–	−1.7	−1.7	–	50.5	55.3	+10 %	49.0	54.0	+10 %
7	14.2	12.0	−16 %	−8.6	−20.7	−141 %	−0.3	−0.3	–	48.1	51.2	+6%	46.2	52.3	+13 %
8	0	0	–	−10.9	−20.7	−89 %	−0.3	−0.3	–	57.4	58.2	+1%	55.0	58.8	+7%
9	0	0	–	−8.6	−20.7	−141 %	−0.3	−0.3	–	61.3	65.1	+6%	57.2	64.7	+13 %
10	0	0	–	−10.9	−20.7	−89 %	−0.3	−0.3	–	57.4	58.2	+1%	55.0	58.5	+7%
11	0	0	–	−10.9	−20.7	−89 %	−0.3	−0.3	–	50.5	51.2	+1%	49.0	52.3	+7%
12	0	0	–	−10.9	−20.7	−89 %	−0.3	−0.3	–	57.4	58.2	+1%	55.0	58.8	+7%
13	0	0	–	−10.9	−20.7	−89 %	−0.3	−0.3	–	64.3	65.1	+1%	60.6	64.7	+7%
Overall score (ha^{-1})	**5.2**	**6.1**	**+18 %**	**–22.5**	**−13.5**	**+40 %**	**−0.7**	**−0.7**	**+1%**	**46.2**	**48.4**	**+5%**	**46.1**	**50.2**	**+9%**

Table 6

Final scores of the impact on each ecosystem service of the permanent grassland fields of the Saint Laurent de la Prée case study according to current and new management strategies. Differences between the final scores are expressed as the percentage change (Chg.) of the new management strategy relative to the current management strategy. NA: not applicable.

Field ID	GHG mitigation		Water-quality maintenance			Erosion control			Pollination			Pest control		
	Current	New	Current	New	Chg.	Current	New	Chg.	Current	New	Chg.	Current	New	Chg.
1	0	0	0	0	–	−0.2	−0.2	–	46.7	46.7	–	51.2	51.2	–
2	0	0	−20.3	−6.8	+67 %	−0.2	−0.2	–	46.7	54.3	+16 %	51.7	61.7	+19 %
3	0	0	−6.8	−6.8	–	−0.1	−0.1	–	55.2	55.2	–	62.0	62.0	–
4	0	0	−6.8	−6.8	–	−0.1	−0.1	–	51.0	51.0	–	58.8	58.8	–
5	0	0	−10.5	−6.8	+35 %	−0.2	−0.2	–	50.5	54.3	+7%	53.3	61.7	+16 %
6	0	0	−10.5	−6.8	+35 %	−0.2	−0.2	–	47.5	51.0	+7%	50.9	58.8	+16 %
7	0	0	−10.5	−6.8	+35 %	−0.2	−0.2	–	47.5	51.0	+7%	50.9	58.8	+16 %
8	0	0	−10.5	−6.8	+35 %	−0.2	−0.2	–	47.5	51.0	+7%	50.9	58.8	+16 %
9	0	0	−10.5	−6.8	+35 %	−0.2	−0.2	–	47.5	51.0	+7%	50.9	58.8	+16 %
10	0	0	−10.5	−6.8	+35 %	−0.2	−0.2	–	47.5	51.0	+7%	50.9	58.8	+16 %
11	0	0	−10.5	−6.8	+35 %	−0.1	−0.1	–	47.5	51.0	+7%	50.9	58.8	+16 %
12	0	0	−6.8	−6.8	–	−0.1	−0.1	–	55.2	55.2	–	62.0	62.0	–
13	0	0	−6.8	−6.8	–	−0.1	−0.1	–	55.2	55.2	–	62.0	62.0	–
14	0	0	−6.8	−6.8	–	−0.1	−0.1	–	55.2	55.2	–	62.0	62.0	–
15	0	0	−6.8	−6.8	–	−0.1	−0.1	–	55.2	55.2	–	62.0	62.0	–
16	0	0	−10.5	−6.8	+35 %	−0.1	−0.1	–	47.5	51.0	+7%	50.9	58.8	+16 %
17	0	0	−6.8	−6.8	–	−0.1	−0.1	–	51.0	51.0	–	58.8	58.8	–
18	0	0	−6.8	−6.8	–	−0.1	−0.1	–	51.0	51.0	–	58.8	58.8	–
19	0	0	−6.8	−6.8	–	−0.1	−0.1	–	51.0	51.0	–	58.8	58.8	–
Ar. 1(1)	NA	15.0	NA	−7.3	NA	NA	−0.2	NA	NA	35.6	NA	NA	45.4	NA
Ar. 2(1)	NA	15.0	NA	−7.3	NA	NA	−0.2	NA	NA	35.6	NA	NA	45.4	NA
Overall score (ha^{-1})	**0**	**1.6**	**−8.2**	**−6.7**	**+18 %**	**−0.1**	**−0.2**	**−17 %**	**45.6**	**51.3**	**+12 %**	**50.2**	**58.8**	**+17 %**

(1) Arable land was converted to grassland to become future permanent grassland in the new management strategy.

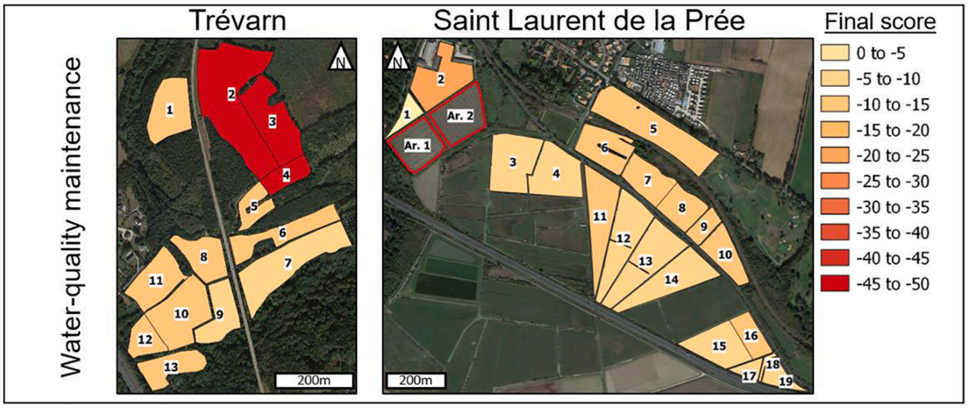

Fig. 4. Mapped final impact scores of individual permanent grassland fields on the two case-study farms for water-quality maintenance. Ar. 1 and Ar. 2 represent an arable field converted into two grassland fields in a strategy proposed to optimise the provision of ES.

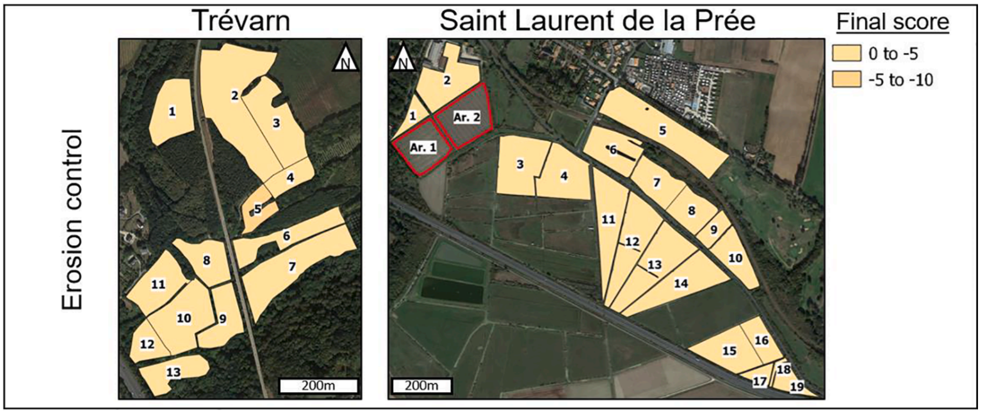

Fig. 5. Mapped final impact scores of individual permanent grassland fields on the two case-study farms for erosion control. Ar. 1 and Ar. 2 represent an arable field converted into two grassland fields in a strategy proposed to optimise the provision of ES.

(Figs. 6-7; Tables 5-6). Thus, provision of the ESs was high. At Trévarn, fields 2 and 3 had the lowest final scores (29.2 for pollination and 33.7 for pest control) due to their high grazing intensity (>510 LU.day ha^{-1} yr^{-1}) and young age (<20 years old), whereas fields 9 and 13 had the highest final scores (61.3 and 64.3, respectively, for pollination and 57.2 and 60.6, respectively, for pest control) because they were more than 20 years old and composed of patches of vegetation with different species composition and height (Table S10). At SLP, the final scores were more homogenous, with a highest positive impact for the fields 15 and 3 (55.2 for pollination and 62.0 for pest control) due to their low grazing intensity (1–145 LU.day ha^{-1} yr^{-1}) and late mowing period (Table S11). However, differing combinations of floristic diversity, grazing and mowing management on the other fields also led to differing final scores for these ES at SLP (Table S10). Trévarn had a more heterogeneous spatial distribution of final scores than SLP (Figs. 6-7). Provision of pollination and pest control were high due to attribute and location parameters of permanent grasslands (e.g. cover heterogeneity, floristic diversity), which are influenced by management only in the medium-to-long term (i.e. several years), but also due to grazing, mowing and fertilisation (in decreasing order of importance), which produce effects within a single year. At Trévarn, the overall final score of the entire set for pollination (46.2) was nearly the same as that for pest control (46.1), but at SLP, the overall final score for pollination (45.6) was lower than that for pest control (50.2) (Tables 5-6).

3.5. *Strategies to optimise the provision of ES*

Several final scores of impacts on ESs were related to attribute and location parameters of permanent grasslands that are not influenced by management (e.g. age, slope, cover heterogeneity). Management parameters also influenced some of the final scores strongly. Management parameters were modified to optimise the provision of ESs while considering constraints of the farms and trying to maintain the same levels of production.

3.5.1. *New management strategies at Trévarn*

At Trévarn, grazing intensity seemed too high on specific permanent grassland fields (2–4, with a total of 6.9 ha) and sometimes during specific periods (i.e. for the moderately steep field 4 grazed during winter) (Table S10). As a potential management strategy, it was decided to distribute this high grazing intensity among all the permanent grassland fields, while maintaining the same mean stocking rate, to continue grazing the same number of animals. In addition, because all permanent grasslands were fertilised with 30 kg N ha^{-1} yr^{-1} (Table S10), fertilisation of the permanent grasslands that had high grazing intensity was stopped. Finally, the early mowing date, which was necessary for producing wrapped bales, had negative impacts on pollination and pest control. To decrease this impact without modifying the winter feed based on wrapped bales, it was decided to concentrate mowing in a smaller area that was fertilised more and completely separated from grazing.

The new management strategy separated mowing and grazing of permanent grassland fields: fields 2 and 3 (4.9 ha) were no longer grazed (leaving only mowing for wrapped bales), and their fertilisation was increased (from 30 to 70 kg N ha^{-1} yr^{-1}) to maintain grass yield. The remaining permanent grassland fields (16.3 ha) were no longer mowed

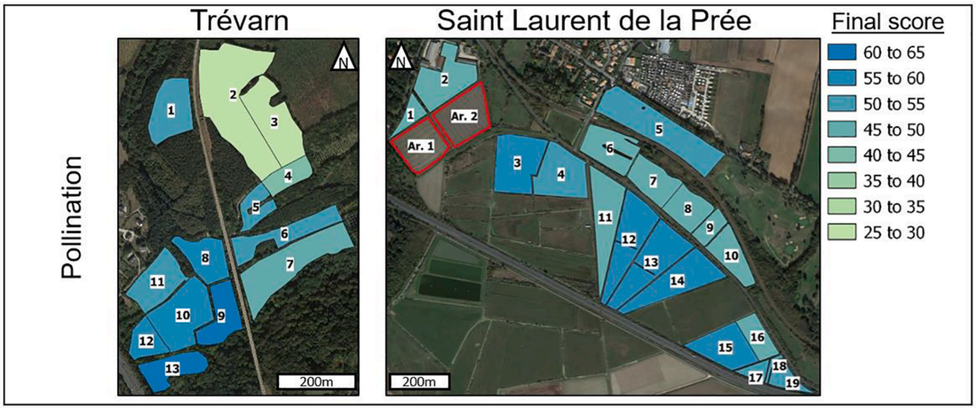

Fig. 6. Mapped final impact scores of individual permanent grassland fields on the two case-study farms for pollination. Ar. 1 and Ar. 2 represent an arable field converted into two grassland fields in a strategy proposed to optimise the provision of ES.

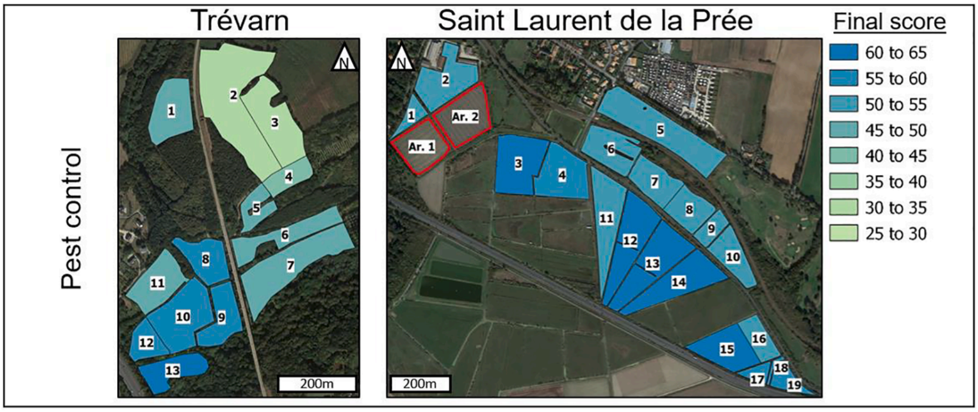

Fig. 7. Mapped final impact scores of individual permanent grassland fields on the two case-study farms for pest control. Ar. 1 and Ar. 2 represent an arable field converted into two grassland fields in a strategy proposed to optimise the provision of ES.

(leaving only grazing). The high grazing intensity on fields 2, 3 and 4 (>510 LU.day ha^{-1} yr^{-1}) in the current situation was spread among all the remaining fields to obtain a grazing intensity of 290–510 LU.day ha^{-1} yr^{-1} on the flat fields (1 and 7–13) and 145–290 LU.day ha^{-1} yr^{-1} on the sloping fields (4, 5 and 6) (Table S10).

3.5.2. *New management strategies at SLP*

As the permanent grassland fields at SLP differed little in management, it was difficult to identify a new management strategy that would not change the production system greatly. Thus, a more extreme strategy was developed, in which grazing intensity was decreased in fields where it was high and kept low in the other fields to achieve an overall lower grazing intensity (<145 LU.day ha^{-1} yr^{-1}) in the entire set, by converting 4.3 ha of arable land (fields Ar. 1 and Ar. 2; Fig. 3) to grasslands sown with a homogenous cover with lower species richness (4–16 species) and higher legume content (10–20 %) than those of the current permanent grasslands (Table S11). Although these grasslands were too young to meet the CAP definition of permanent grasslands, they were assessed as such because they were planned to become permanent grasslands. To maintain the same amount of grass production, fertilisation and mowing were not changed (Table S11).

3.5.3. *Results with the new management strategies*

3.5.3.1. Separating grazing and mowing at Trévarn. The strategy tested for Trévarn improved GHG mitigation overall (+0.9 points in the overall final score), with no change on most fields, an increase of 4.1 points on the permanent grasslands <20 years old that were no longer grazed but fertilised more (fields 2 and 3) and a decrease of 2.2 points on the field that was grazed more intensively and no longer fertilised (field 7) (Tables 5 and S10). This strategy degraded water-quality maintenance of fields in which the grazing intensity increased (with a final score more than twice as negative) but improved or maintained it in the fields where grazing stopped (with a final score close to 0 for fields 2 and 3). At the whole-farm level, the degradation was not apparent, as water-quality maintenance improved (+9 points in the overall final score) (Tables 5 and S10). It generally maintained erosion control (the overall final score was nearly the same) with a slight improvement on the moderately sloping field (field 4) that was no longer grazed during the critical erosion period (Tables 5 and S10). It improved pollination and pest control of permanent grassland fields (+2.2 and +4.1 points in the overall final scores, respectively), especially those in which grazing intensity was reduced and mowing and fertilisation were stopped (+11.7 points for pollination and +10.1 points for pest control for field 4). On the other fields, where grazing intensity increased and mowing and fertilisation stopped, or where grazing stopped and fertilisation increased, the improvement was smaller (+0.7 to +4.8 points for pollination and +2.1 to +6.1 points for pest control) (Table 5 and Table S10).

3.5.3.2. Increasing the grassland area at SLP. The strategy tested for SLP resulted in no change in GHG mitigation on the older permanent grasslands and yielded a score of 15 for the two new grasslands, improved water-quality maintenance by 0–13.5 points, pollination by 0–8 points and pest control by 0–10 points, while maintaining erosion control (Table 6). On the newly sown grasslands (Ar. 1 and Ar. 2), water-quality, pollination and pest control scores were lower than those of the older permanent grassland fields due to their lower species richness and higher legume content, but GHG mitigation was higher due to their young age (Table 6). By considering the older permanent grasslands and two new grasslands, the overall score improved for GHG mitigation (+1.6 points), water-quality maintenance (+1.5 points), pollination (+5.7 points) and pest control (+8.6 points) and barely changed for erosion control (−0.2 points) This more extreme modification of the overall production system, however, decreased provisioning ESs (e.g. agricultural production) by decreasing the arable area.

4. Discussion

Livestock production systems, especially their permanent grasslands, directly influence provision of ESs, which in turn influence these systems in feedback loops (Rodriguez-Ortega et al., 2014). However, the ESs that these systems provide and the influence of permanent grasslands on them are difficult to assess and quantify (Dumont et al., 2019a), and few operational methods that can be used by stakeholders exist to do so. The present study tested one such tool to address this issue by adapting an existing framework to include grasslands and their most influential management practices (Tzilivakis et al., 2016), while maintaining its transparency and simplicity of use. Applying the tool to two grass-based livestock farms (Trévarn and SLP) identified different localised impacts of permanent grasslands on five ESs as a function of grassland attributes and management, and the new management strategies tested highlighted the ability to change the overall impact of permanent grasslands on the ESs.

4.1. *Analysis of the new management strategies*

The novel approach developed for the management strategies considered was related directly to underlying ecological theory of impacts on ES provision. All ESs are provided by a combination of ecological processes that are impacted differently by management practices (Duru et al., 2019). The overall score of ESs thus summarises interactions among ecological processes and management practices on the entire area assessed to provide an overview of ES provision.

For the new strategies explored for Trévarn, in the grassland fields where grazing intensity increased (fields 1 and 7–13), the water-quality maintenance score decreased due to an increased risk of nitrate leaching caused by grazing cattle depositing more manure (Vertès et al., 2007). In contrast, the pollination and pest control scores remained stable or increased slightly due to maintaining the ability to host key arthropods for these ESs, with the higher grazing intensity compensated by stopping mowing, because mowing negatively impacts pollinating arthropods both directly and indirectly (by modifying their habitats) (Kovacs-Hostyanszki et al., 2017). In fields where grazing stopped and fertilisation increased (fields 2 and 3), (i) the water-quality maintenance score increased due to a decreased risk of nitrate leaching caused by moderate fertilisation instead of high grazing intensity (Vertès et al., 2007), and (ii) the pollination and pest control scores increased due to stopping grazing, which increased the grasslands' ability to host biodiversity (Sabatier et al., 2015). The GHG mitigation score changed only on the young permanent grasslands (fields 2, 3 and 7), as the older grasslands had already reached equilibrium carbon stocks (Poeplau et al., 2011), and the increase (fields 2 and 3) or decrease (field 7) in score was due only to the difference in grazing intensity, which must be moderate to maintain enough grass growth to sequester carbon (Soussana and Lemaire, 2014). As the erosion control score is related mainly to the amount of permanent cover, the grazing during the critical erosion period in fields 2, 3 and 4, which could have degraded the permanent cover (Donovan and Monaghan, 2021), decreased in intensity, which increased the scores of these fields but had little effect on that of the entire set of permanent grasslands.

For the new strategies explored for SLP, the main change in management was to decrease grazing intensity in permanent grassland fields 2, 5–11 and 16, which increased the scores for water-quality maintenance, pollination and pest control due to the same ecological processes as at Trévarn (i.e. lower grazing intensity decreased manure deposition and thus the risk of nitrate leaching for water-quality maintenance but maintained the ability to host key arthropods for pollination and pest control). This strategy required converting two arable fields into grasslands, which increased the carbon sequestration rate because the arable land had a lower soil carbon content than grasslands (Poeplau et al., 2011).

The overall scores highlighted the ability of the new strategies to decrease nitrate leaching, increase the ability to host biodiversity and maintain carbon sequestration (albeit at a low level), which are the main ecological processes that permanent grasslands can impact and which influence provision of ESs on this key land use of livestock systems (Duru et al., 2019). The new strategies maintained agricultural production at Trévarn and decreased it slightly at SLP. On each farm, management practices influenced ecological processes differently, which led to different changes in ES scores, thus highlighting win–win situations between ESs (e.g. both pollination and pest control improved in permanent grasslands at Trévarn when grazing intensity increased and mowing stopped) and trade-offs among them (e.g. although pollination and pest control improved in these grasslands, water-quality maintenance worsened). Finally, trade-offs between the ESs assessed and provisioning ESs are also highlighted, such as when converting arable land to future permanent grasslands at SLP. In this way, the novel approach can help identify and manage these win–win situations and trade-offs. In general, analysis and interpretation of these relations among ESs are based on deep understanding of farming systems, with analysis at the field scale combined with analysis at the farm or plot scale, which highlights the need to work with farmers.

4.2. Utility for assessing impacts on the provision of ESs

Analysis of the two case studies and their proposed new management strategies highlighted five strengths of the novel approach, which:

- Represents the strong relationships among a permanent grassland's attributes, location and management (Duru et al., 2019).
- Translates effects of each management practice precisely, by considering impacts of management intensity, and transparently, by detailing the practices that influence these impacts.
- Differentiates parameters that users cannot change (attributes and location) from those that they can change (management), which increases users' understanding.
- Highlights win–win situations or trade-offs among ESs for a given farm, which can help users attempt to optimise ESs of the entire farm.
- Identifies hotspots (of positive and negative impacts) due to its fine spatial scale and helps farmers target their management by identifying the fields where it may be more optimal to focus certain management practices in order to decrease the farm's overall impacts based on trade-offs at the individual-field scale.

The novel approach also remains consistent with the initial framework, which can be applied throughout the EU (Tzilivakis et al., 2016), is easy to use and combines advantages of other ES assessment tools (Burkhard et al., 2009; Farruggia et al., 2012; Michaud et al., 2020).

4.3. Limitations

One limitation of the novel approach is that it assesses only five regulation and maintenance ESs; however, they are the main ESs supplied by permanent grasslands, and provisioning ESs can be considered separately through a farm's agricultural production. The subjectivity of cultural ESs depending on the context of the assessment (Zoeller et al., 2022) makes it difficult to assess them in a generic method such as this one. Among the ESs assessed, erosion control was influenced little by grassland management, but it was important to include it to emphasise the strong influence that permanent grasslands have on soil stability in agricultural landscapes (Dumont et al., 2019b).

A second limitation of the study was that only five experts were consulted to help develop more robust relations between scientific evidence and the influence of parameters and classes on the ESs. Engaging with more experts could have enhanced the approach further (albeit with potentially diminishing returns as the number of experts increases). Nevertheless, the five experts consulted helped us to assess the evidence needed to adapt the framework and had generally similar judgements for each ES.

To expand upon the eight management parameters currently included, it may be interesting to include mowing intensity and overseeding due to their influence on species richness (Zechmeister et al., 2003) and thus on ESs, but they may be too complex to represent (e.g. need for more data, difficulty in choosing classes and their thresholds), and they have less influence than the current management parameters. However, this raises the issue of the relation between management parameters and attribute parameters, as in the middle-to-long term, management can modify the floristic diversity and thus the provision of ESs on permanent grasslands (Sanderson et al., 2007). Therefore, it is important to recall that the framework assesses a single moment and does not consider long-term effects of current management on attribute parameters. Finally, it would be interesting to apply the novel approach to a wider range of case studies to explore its generality and the weights assigned to its parameters. The novel approach is incorporated in the current framework, which allows users to adapt parameter weights without modifying its overall structure.

4.4. Wider perspectives

The novel approach has been integrated into a new software application based on the EFA Calculator that is being developed as part of the EU H2020 project FRAMEWork (2022) to use clusters of farmers to manage agrobiodiversity across ecosystems. It aims to "develop and promote biodiversity-sensitive farming to conserve native biodiversity, support [ES] provision and maintain reliable agricultural output…in Europe" with "the integration of diversity into farming practices and incentives for wider biodiversity management including native biodiversity" (AERU, 2022). This new software application will combine ES calculations with biodiversity monitoring data and routines to assess habitat suitability, connectivity and zones of influence to provide a tool that facilitates holistic landscape management to deliver ES and biodiversity benefits.

The CAP has established policies and mechanisms to decrease environmental impacts and increase the provision of ESs of farming systems, and permanent grasslands are a key land use to which they are applied. The CAP's financial incentives, such as payment for ESs (Reed et al., 2014), could even be based on using such tools and methods, which partner farmers have considered help them adapt their management to increase ES provision as much as possible. Beyond the CAP's financial incentives, considering EFAs and permanent grasslands together could help farmers understand grassland interactions and manage their farms to increase ecosystem interactions and ecological processes on them to drive their agroecological transition. To consider an entire farm, the framework could be modified to assess impacts of arable fields and their management on ESs, using the same structure of attribute and management parameters as in the novel approach. Indeed, nearly all farms contain arable land, which also influences ES provision but has wider ranges of practices and intensities than permanent grasslands (Casagrande et al., 2017), which implies more complex modelling. Considering the relative impacts of EFAs, permanent grasslands and arable land together would thus assess the provision of ESs of an entire farm.

Assessing ESs is useful for considering the environmental performance of permanent grasslands because ESs combine the concepts of biodiversity and ecological impacts (Tzilivakis et al., 2016). Although the novel approach does not assess the status of biodiversity on a farm's permanent grasslands directly, it does so indirectly due to biodiversity's strong influence on ESs (Balvanera et al., 2006). Direct assessment of short- and long-term effects of grassland management practices on biodiversity could be added to the novel approach to create a parallel with the initial framework, which assesses impacts of EFAs on both ESs and biodiversity.

5. Conclusion

Addressing ESs provided by farms requires considering interactions between nature and human management in farming landscapes. Doing so can help reconcile agriculture and ecosystem well-being by enhancing ES provision and move towards agroecological systems based more on ecological processes (Altieri and Nicholls, 2012), especially in key land uses such as permanent grasslands. Some relations between management practices and ecological processes behind ESs are relatively well documented, but tools that assess relative impacts of management practices on ESs and highlight how to optimise trade-offs between them are needed to increase the provision of ES by farms.

One difficulty in developing such tools is capturing the complexity of interactions between management practices and ecological processes while remaining easy to use, as well as producing results that are sufficiently easy for farmers to interpret that they can help them adapt their management strategies. Here, a novel approach that combined expert judgement and metamodelling was used as such a tool to assess relations between management practices and ESs on permanent grasslands. Results of applying the approach to case-study farms were consistent with the data used to model interactions between management practices and ecological processes. Nevertheless, future development could help increase the accuracy of estimated impacts of management practices on ESs, such as by adding additional practices or considering their long-term effects on ecological processes. The tool could also be updated to assess impacts of other types of land use, such as arable land, or management practices. The final goal of such a tool is to support decision-making to optimise the ESs supplied by farming systems, which will benefit both farmers and the wider society.

CRediT authorship contribution statement

A. Mondière: Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft, Writing – review & editing. **J. Tzilivakis:** Conceptualization, Methodology, Software, Resources, Formal analysis, Writing – original draft, Writing – review & editing. **D. J. Warner:** Conceptualization, Methodology, Resources, Writing – original draft, Writing – review & editing. **H.M.G. van der Werf:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **A. Farruggia:** Validation, Writing – review & editing. **O. Glinec:** Validation. **M.S. Corson:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing.

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.

Data availability

Additional data are available in the document "Supplementary material - Mondière et al. 2022".

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Appendix A. Supplementary data

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