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Classification of agricultural land management systems for global modeling of biodiversity and ecosystem services

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ABSTRACT

Global models of biodiversity and ecosystem services base their calculations on land use classifications, where agricultural land is only divided into a few categories of management intensity. These land use classifications were not developed to underpin biodiversity models. This is why crop diversity and the presence of non-crop plants or livestock in agricultural land are not considered in these classifications, despite the effect they have on agrobiodiversity and the supply of ecosystem services. Therefore, the use of these classifications in models results in neglecting current diversified agricultural systems and the effect of diversification practices on biodiversity and ecosystem services. In this paper, we present a new global classification of agricultural land management systems organized as a matrix of diversity and intensity ranges. The classification is based on a literature review and expert interviews and is illustrated by examples of agricultural systems around the world. This classification is a first step to build land use and land cover maps that consider diversified agricultural systems, which could then be used by global biodiversity and ecosystem services models. The matrix structure of the classification makes it flexible and adjustable to use for different purposes, such as exploring the potential of preserving biodiversity in agricultural land through land-use scenarios or assessing trade-offs between intensity and diversity.

1. Introduction

Biodiversity loss and degradation of ecosystems are major threats to human wellbeing, as the provision of ecosystem services depends on the condition of ecosystems and biodiversity (IPBES, 2019a). The main drivers of terrestrial biodiversity loss and ecosystem degradation are land use and agricultural intensification (Gibbs et al., 2009; Geiger et al., 2010; IPBES, 2019b; Schipper et al., 2020). By 2050 the world's population is expected to reach 9.7 billion people (United Nations, 2019). This and the continuing economic growth will increase the demand for food and other materials, leading to further intensification and expansion of agricultural land.

Global models of biodiversity and ecosystem services (GBESMs) were developed to project the impact of human activities on the future status of biodiversity and ecosystem services (Rosa et al., 2020; Kim et al., 2018). In GBESMs, the impacts of agricultural land use on biodiversity are assessed based on global land use and land cover datasets with classifications of agricultural land, including grasslands and cropland (Alkemade et al., 2022). Agricultural land classifications used to date in GBESMs are based on an industrial agriculture standpoint. As such, these classifications take an industrial standpoint regarding intensity (broadly defined here as the type and amount of agricultural inputs) and diversity (defined in this study as the mixture of crop and non-crop species in agricultural land). In other words, current agricultural classifications comprise intensive and specialized agriculture, characterized by the use of high amounts of synthetic inputs in monocultures or simple crop rotations (Erb et al., 2013; Levers et al., 2016).

Intensive and specialized agriculture often go hand in hand (de Roest et al., 2018). Opposed to the intensive-specialized combination, diversity in agriculture is often associated with extensive practices (i.e. low or no use of agricultural inputs, especially of synthetic composition). However, these associations do not always apply, as intensification and specialization are decoupled in some agricultural systems (Alkemade et al., 2022).

While intensive specialized agriculture is associated with high productivity in terms of yield per area (Malek and Verburg, 2017; Erb et al., 2013; Levers et al., 2016; Chavas, 2008; de Roest et al., 2018), agricultural diversification is not opposite to high productivity (Clough

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et al., 2011; Pywell et al., 2015). In fact, recent studies found that agricultural practices promoting diversity, among them mixing crops and non-crop species, increase biodiversity and the provision of several ecosystem services without affecting yield (Tamburini et al., 2020; Beillouin et al., 2021; Li et al., 2020; Martin-Guay et al., 2018). Therefore, incorporating biodiversity into agricultural land may result in higher food security and biodiversity conservation than conventional intensification (Tscharntke et al., 2012). However, GBESMs have made little differentiation regarding management aspects associated with agrobiodiversity, specifically management intensity and diversity in agricultural land, despite their influence on biodiversity and ecosystem services (Beckmann et al., 2019; Beillouin et al., 2021; Dale and Polasky, 2007; Matson et al., 1997; Tamburini et al., 2020).

Management intensity is only coarsely differentiated in global classifications of agricultural land. Classifications are based for example on whether agriculture is irrigated or rainfed (Dixon et al., 2001; FAO, 2013; Hurtt et al., 2020; Letourneau et al., 2012; Václavík et al., 2013), the livestock density (Felipe-Lucia et al., 2020; Letourneau et al., 2012), the yield gaps (Letourneau et al., 2012; Václavík et al., 2013; van Asselen and Verburg, 2012) and less frequently the fertilization rate (Dixon et al., 2001). The use of pesticides and mechanization are seldom included in global land use classifications (FAO, 2013). Regarding biodiversity, the management practices known to have higher impacts are the use of pesticides and fertilization rates (Sánchez-Bayo and Wyckhuys, 2019), and current classifications fail to consider these two practices together.

Diversity in agricultural land is also only coarsely considered. Global land use classifications usually divide agricultural land into two main land cover categories: cropland and grassland (e.g. (Hurtt et al., 2020; Václavík et al., 2013; Hudson et al., 2014, 2017; Zanaga et al., 2021). Some authors additionally account for diversity at the landscape level by defining mosaic land systems in which a mixture of land cover types occurs in one grid cell (see van Asselen and Verburg, 2012; Letourneau et al., 2012 and Bartholomé and Belward, 2005). Considering landscape diversity is important because it is beneficial for biodiversity (Benton et al., 2003; Landis, 2017) and for the provision of ecosystem services that benefit agricultural production, such as pest control (Zhang et al., 2020). However, diversified agricultural systems in which several crops or non-crop species such as livestock, forest trees or shrubs are grown in the same field are omitted in agricultural land use classifications currently used in GBESMs. By omitting diversified systems, current classifications disregard the diversity of species these systems host, providing insufficient detail to assess how diversified systems affect species diversity and evenness.

Including diversified agricultural systems in classifications of agricultural land used in GBESMs would improve the realism of their assessments, as these systems exist and are prevalent in some world regions. Moreover, we expect diversified systems to host more biodiversity and to supply more ecosystem services than simplified systems (Rosa-Schleich et al., 2019). However, if by applying diversified systems agricultural land expands due to a possibly lower productivity, the increase in biodiversity in agricultural land could be outweighed by an overall loss of biodiversity due to a reduction of natural habitat. This depends on the combination of the level of intensity and diversity of agricultural systems, which determines their productivity, biodiversity and ecosystem services' provision capacity. By including diverse agricultural systems and landscapes in GBESMs, we could assess which combinations of intensity and diversity in agricultural land could minimize impacts on biodiversity and ecosystems while producing enough food.

The aim of this paper is to create a global classification of agricultural land management systems centered on management aspects associated with agrobiodiversity and ecosystem services supply. Such classification can improve the global modeling of biodiversity and ecosystem services. The classification is based on management intensity and level of diversity that can be identified in agricultural systems worldwide, focusing on the intensity and diversity aspects that have a bigger influence on the biodiversity and agroecosystems' condition. The ranges of diversity and intensity were defined based on a literature review and refined through experts interviews.

2. Methods

To derive a global classification of agricultural land management systems we followed the steps described in Fig. 1. In short: literature on agricultural systems was reviewed to obtain an overview of agricultural systems that exist worldwide, and these systems were used to derive categories of diversity. At the same time, we constructed a composite indicator for management intensity based on intensity indicators commonly used in large scale studies. Then, the diversity categories were combined with the categories of intensity generating a classification. This classification was tested and adjusted by interviewing experts. Additionally, to illustrate the classification, examples of current agricultural land management systems from the literature were categorized onto the classification.

2.1. Diversity of cropland and grasslands

To identify existing agricultural systems, we collected a combination of: a) global reports by international organizations dealing with agricultural sustainability found on Google Scholar; and b) scientific literature on diversity found on Web of Science. Additional literature was collected through snowballing, i.e. reviewing the reference list of relevant publications seeking more relevant studies. We used the keywords (agriculture AND biodiversity AND global AND diversification AND "management practices" AND "ecosystem services") in Google Scholar, and the search string (("diversified farming" OR "crop diversification" OR "plant mixture" OR "agricultural diversification") AND (agroecosystems) AND (biodiversity)) applied to the title, abstract and keywords in Web of Science. The criterion for selecting literature was that it contained information about diversity in cropland and grassland, and our aim was to identify all of the types of combinations of species we could find at field level. As the information about diversity was scattered in the literature, we selected literature with, for example, agricultural systems classifications, practices promoting diversity in agricultural land or definitions of types of cropping systems or grasslands. From the identified literature, we collected types of agricultural systems based on different combinations of crop and non-crop species at field level, until no new agricultural systems were found. We then identified different diversity aspects between the agricultural systems found. The different types of combinations of crop and non-crop species found were then rearranged around these diversity aspects. For example, the combination of annual crops and livestock was identified, and the rice-fish system that had been identified was rearranged within the category "annual crops-livestock integrated systems". Similar systems in terms of diversity aspects were merged into the same diversity category, for example, crop rotations and cover crops were merged into the category "crop rotation".

We also selected literature containing classifications of grasslands at a global or continental level, as well as terms and definitions applied to grasslands to identify the different types of grasslands described in the literature. We used the search terms (grasslands AND diversity AND classification AND definition AND (global OR international)) in Google Scholar. The types of grasslands found in the literature were rearranged into categories that we expect to make a difference in terms of biodiversity. These expectations are based on the literature and experts' insights.

With the categories of cropland and grassland we created a preliminary diversity range that aimed to be: a) complete in terms of agricultural systems included; b) simple enough to be applicable in global models; c) relevant for biodiversity and ecosystem services models, i.e. expected to show differences between categories on their impact on biodiversity and ecosystem services supply; and d)

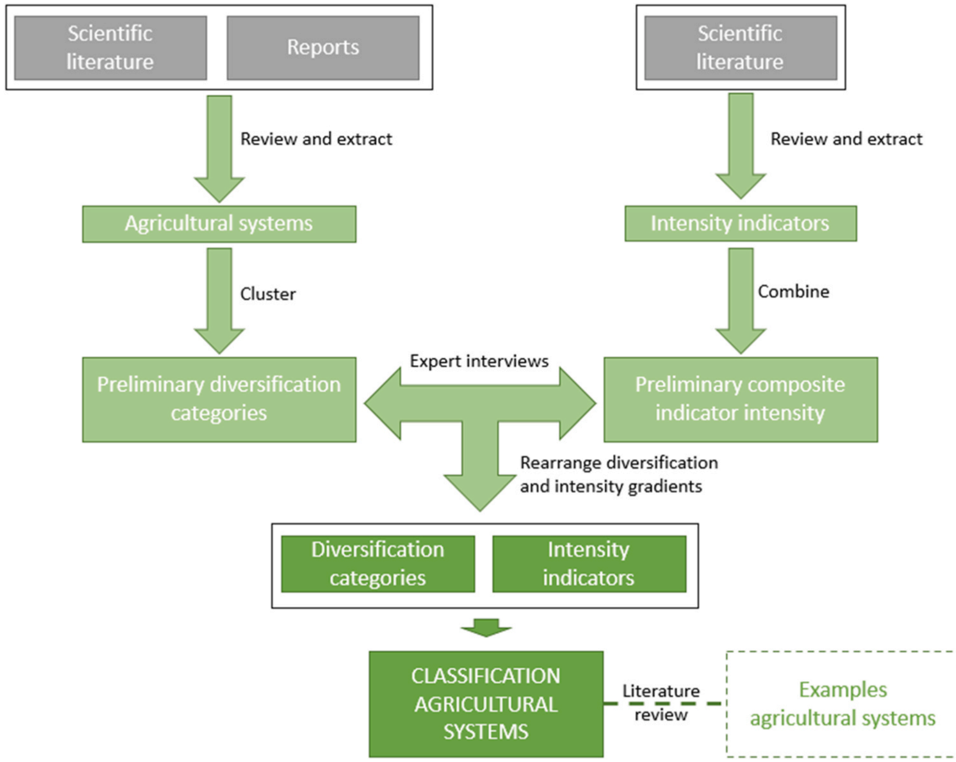

Fig. 1. Schematic overview of the methodological steps.

unambiguous, i.e. categories do not overlap (though different diversity aspects may occur within the same system e.g. crop rotation may be practiced in agroforestry). This preliminary classification was tested with experts (see Section 2.3).

2.2. *Management intensity*

Management intensity of agricultural land management systems is characterized by different aspects. We searched for indicators of agricultural intensity commonly used at large scales (i.e. global, continental or regional scale) in scientific literature for cropland and grassland, as these scientific literature has proved that these indicators can be applied at such large scales. To identify the literature, we used the search terms (land-use AND agricultur* AND intensi*) applied to the title, keywords and abstract in Web of Science. We reviewed the literature by reading title and abstract, in search for articles that had used intensity indicators to characterize agricultural land use at large spatial scales. We collected these indicators and the values for the indicators associated with different levels of intensity from the articles. The saturation principle was applied for concluding data collection (Glaser and Strauss, 1967), i.e. we stopped searching for additional literature once no new indicators were found by reviewing extra literature. We constructed intensity indicators for cropland and meadows (i.e. mown grasslands harvested for forage) differently from grazed grasslands (i.e. grasslands used for grazing livestock) due to essential differences in the way these systems are managed.

2.2.1. *Cropland and meadows*

In this study, we built a composite indicator to distinguish management intensities by combining intensity indicators. A composite indicator is a combination of a set of indicators into a single indicator, which helps to summarize multi-dimensional concepts (OECD, 2008). To build the composite indicator for intensity we selected the intensity indicators that are most relevant for their effects on biodiversity and productivity, and combined them into a single indicator of intensity level. The selection and combination of indicators was made in consultation with the interviewed experts. A decision tree was constructed to integrate different intensity aspects and to translate the combinations of these aspects into a composite indicator. A three category outcome (low, medium, high) was chosen for intensity because we believe that three provides the right balance between simplicity and enough differentiation for a global scale application.

2.2.2. *Grazed grasslands*

Based on the discussions with experts, we selected additional literature focusing on indicators applied only for grazed grasslands at large scales. We searched for an indicator applicable worldwide and for different types of grazing, that is, considering the natural productivity of the grasslands and the inclusion of nomadic and seasonal grazing.

2.3. *Expert interviews*

Unstructured expert interviews were carried out to review the created preliminary global classification of agricultural land management systems that emerged from the combination of diversity and intensity levels. The aim of the expert interviews was to carry out a "reality check" of the classification, following previous studies at regional levels (Malek and Verburg, 2017) and at the global level (Dixon et al., 2001). The overall question for the interviews was whether the classification sufficiently reflected the variety and intensity of existing agricultural systems, considering that the categories should be general enough to be applied worldwide. Experts were selected to cover all world regions and main types of agricultural systems. Thirteen experts were interviewed; see Annex 1 for the list of experts, their expertise and the interview questions.

Additionally to the experts interviews, examples of agricultural land management systems were found through a literature review carried out in February 2022. These examples are meant to illustrate the created matrix. For the literature review, the following search string was used in the database Web of Science: divers* NEAR/2 (farm* OR crop* OR agr*

OR practice? OR manag*) OR polycultur* AND *biodiversity AND system? NOT (marine OR aqua*) NOT (econom* OR nutriti* OR diet* OR medic*). The search was applied to title, abstract and keywords, and language-limited to English. Papers were discarded when they described experiments with a diversifying practice without mentioning that it is a common, traditional or alternative agricultural land management system practiced by farmers.

3. Results

3.1. Diversity in agricultural systems

The following studies were selected to construct the diversity range: (Beillouin et al., 2019, 2021; FAO, 2019; Kremen and Miles, 2012; Malézieux et al., 2009; Tamburini et al., 2020; Power, 2010; McSorley, 2008; Jones et al., 2021; Hufnagel et al., 2020).

The review of the literature resulted in four diversity dimensions for cropland: 1) the mixture of species in space and their spatial arrangement (e.g., planting in rows or landscape heterogeneity); 2) the mixture of species in time (i.e., crop rotation); 3) the types of species mixed (i.e., whether the species are herbaceous or woody, crops or forestry vegetation, and the presence of livestock); and 4) the number of species mixed. The combination of these dimensions was used to generate the diversity range for cropland shown as part of Table 1: monoculture, crop rotation, row/mixed intercropping, crop-livestock integrated systems, agroforestry and animal agroforestry.

The literature used to create a grassland classification is (Allen et al., 2011) and (Peeters et al., 2014). For grasslands, only these two sources were used because very little information is available about agricultural grasslands at a global level, and most publications exclude grasslands maintained for agricultural purposes (e.g. (Dixon et al., 2014; Blair et al., 2014)). The review of these two sources resulted in three main aspects affecting grasslands' biodiversity: 1) the age of the grassland; 2) the grazing management i.e. whether the grasslands are pastures (grazed) or meadows (mown); and 3) whether vegetation is sown or dominated by naturally-occurring grass communities. The combination of these aspects was used to generate a diversity range for grasslands (shown in Table 1 and Table 2).

Table 1
Classification of agricultural land management systems.

			INTENSITY		
			Low	Medium	High
DIVERSITY	Monoculture	Monoculture annual crops			
		Monoculture perennials (bare soil)			
		Monoculture perennials (with soil cover)			
	Crop rotation	Simple crop rotation (2–3 crops)			
		Complex crop rotation (4 or more crops)			
	Row/Mixed intercropping	Row/mixed intercropping annual crops			
	Crop-livestock integrated systems	Annual crops-livestock integrated systems			
		Crop trees with grazing livestock			
	Agroforestry	Sparse trees in cropland			
		Trees and herbaceous crops			
		Agroforests			
	Animal agroforestry	Agrosilvopastoral systems			
		Silvopastoralism			
	Grasslands	Temporary meadows			
		Temporary pastures			
		Permanent meadows			
		Natural or semi-natural meadows			
		Permanent pastures			
		Rangelands			

3.2. Intensity indicators for agricultural systems

The literature selected for intensity was: (Beckmann et al., 2019; Erb et al., 2013; Kuemmerle et al., 2013; Levers et al., 2016; Malek and Verburg, 2017; Tieskens et al., 2017; Weltin et al., 2018). The intensity indicators we found for grasslands are based on livestock density; these indicators are not applicable to meadows as these are mown instead of grazed. In that sense, the management of meadows is more similar to cropland. Consequently, for meadows we used the same intensity indicator as for cropland. This decision was checked with experts during the interviews.

3.2.1. Croplands and meadows

For cropland, the intensity indicator that we found most often in the literature was the fertilization amount (Beckmann et al., 2019; Malek and Verburg, 2017; Kuemmerle et al., 2013; Weltin et al., 2018), particularly nitrogen (Levers et al., 2016; Erb et al., 2013; Tieskens et al., 2017). The use of pesticide was the second most mentioned (Beckmann et al., 2019; Erb et al., 2013; Kuemmerle et al., 2013; Weltin et al., 2018). Other common indicators mentioned in the literature are yield as production per area and time (Levers et al., 2016; Erb et al., 2013; Malek and Verburg, 2017), field size (Levers et al., 2016; Malek and Verburg, 2017; Tieskens et al., 2017), use of irrigation (Malek and Verburg, 2017; Kuemmerle et al., 2013; Weltin et al., 2018) and cropping frequency (Beckmann et al., 2019; Erb et al., 2013; Kuemmerle et al., 2013). Finally, the use of machinery or the tillage practices were mentioned as indicators for intensity (Beckmann et al., 2019; Kuemmerle et al., 2013; Weltin et al., 2018).

The intensity indicators we selected to define intensity levels for cropland and mown grasslands are: the use of pesticides, the amount of fertilizer applied (kg N ha^{-1} yr^{-1}), the type of fertilization (organic or mineral) and whether the system is irrigated or rainfed. We combined these indicators through a decision tree into three levels of intensity (Fig. 2).

The main agricultural practice driving biodiversity loss is pesticide use (Sánchez-Bayo and Wyckhuys, 2019; Newton, 2004; Gilburn et al., 2015; Wickramasinghe et al., 2004), therefore we selected pesticide use as the most important criterium in the decision tree. We differentiated two categories for pesticide use depending on whether pesticides were used or not. Other pest management strategies could have been considered as intermediate levels of pesticide use, for example organic agriculture in which only some pesticides are allowed or Integrated Pest Management in which pesticides are used only after a threshold damage level is reached. However, these strategies were not included because

Table 2
Grasslands classification based on management practices affecting biodiversity.

Grasslands	Temporary (<10 years)	Meadows (cut)	Temporary meadows
		Pastures (grazed)	Temporary pastures
	Permanent (>10 years)	Meadows (cut)	Permanent meadows
			Natural or semi-natural meadows
		Pastures (grazed)	Permanent pastures
			Rangelands

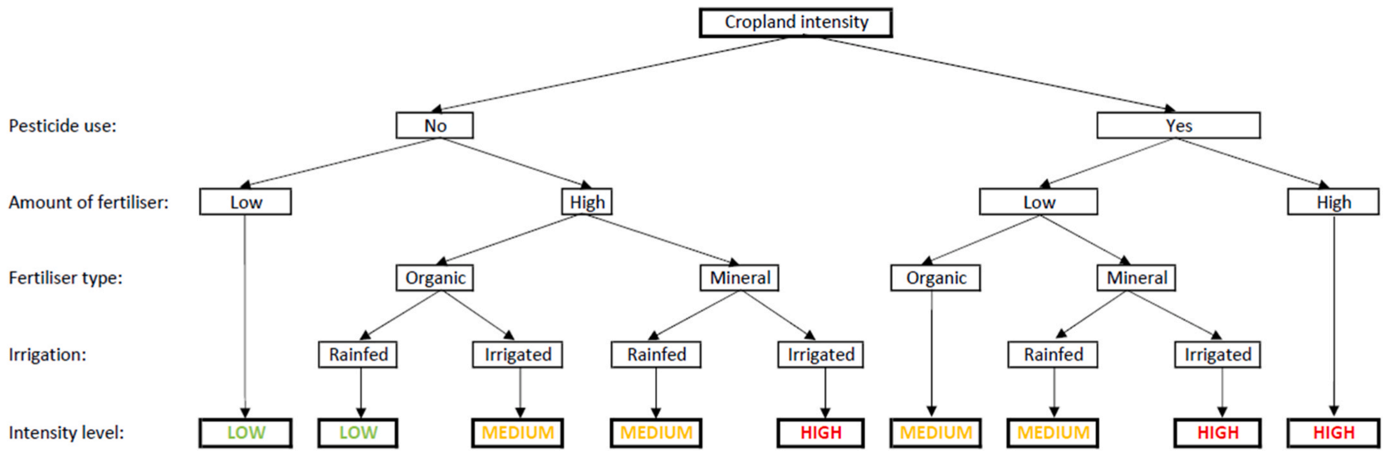

Fig. 2. Decision tree for levels of cropland and meadows intensity. Amount of fertilizer is considered low between 0 and 100 kg N ha^{-1} yr^{-1} for cropland and between 0 and 30 kg N ha^{-1} yr^{-1} for meadows; and high when more than 100 kg N ha^{-1} yr^{-1} and 30 kg N ha^{-1} yr^{-1} are applied to croplands and meadows respectively (Kleijn et al., 2009). Note that organic fertilization includes the combination of organic and mineral fertilizers. N amendments include atmospheric N deposition, where applicable.

their scope goes beyond pesticide use, including the use of trap plants and fertilization practices, which are considered separately in this classification.

Overfertilization is damaging for biodiversity regardless of the type of fertilizer applied (Klimek et al., 2008; Tscharntke et al., 2021), hence the amount of fertilizer is another important criterion in the decision tree. The identified papers differ in the ranges of fertilizer application that define intensity levels (Supplementary information), these ranges are however not tied to impacts on biodiversity or ecosystem services supply (Temme and Verburg, 2011; Tieskens et al., 2017). For our purpose, we decided to apply the thresholds identified in a study relating N application and farmland biodiversity (Kleijn et al., 2009). Based on (Kleijn et al., 2009), the fertilizer ranges were considered low between 0 and 100 kg N ha^{-1} yr^{-1} for cropland and between 0 and 30 kg N ha^{-1} yr^{-1} for meadows; and high above 100 kg N ha^{-1} yr^{-1} for cropland and above 30 kg N ha^{-1} yr^{-1} for meadows.

Organic fertilization applied in right amounts is often considered a measure that helps to preserve soil biodiversity (Jiang et al., 2021; Tamburini et al., 2020). Therefore, we decided to consider organic fertilization, as well as the combination of organic and mineral fertilizers, as less intensive than mineral fertilization. Finally, the use of irrigation is important in terms of productivity per area in many world regions (Siebert and Döll, 2010), and rainfed systems were considered less intensive than irrigated systems (Bruinsma, 2003).

3.2.2. *Grazed grasslands*

For grazed grasslands (i.e. pastures), we identified livestock density (see (Faria and Morales, 2020; Kuemmerle et al., 2013; Malek and Verburg, 2017; Tieskens et al., 2017)) as the most common intensity indicator. Other intensity indicators found in the literature are defoliation frequency (see (Faria and Morales, 2020; Schils et al., 2022), N input and grass renewal (see (Schils et al., 2022)). Experts pointed out that livestock density has the disadvantage of disregarding differences in natural productivity of the grasslands. To overcome this disadvantage we applied a grazing intensity indicator that quantifies the relationship between the biomass consumed by herbivores and the climatic specific net primary production of a grassland (Abdalla et al., 2018; Aryal, 2022; Petz et al., 2014). This grazing intensity indicator combines livestock density and defoliation frequency (Aryal, 2022), which allows to account for nomadic systems and seasonal grazing.

We adapted the methodology described by (Abdalla et al., 2018) to calculate the grazing intensity of grazed grasslands because their method did not include fertilized grasslands. (Abdalla et al., 2018) first calculated Net Primary Productivity (NPP) based on mean annual temperature (°C) and precipitation (mm), and then estimated that 50% of NPP is aboveground biomass (AB).

$$NPP = minimum(NPP_T; NPP_P)$$

Where: $NPP_T = 30 \times (1 + \exp(1.315 - 0.119T))$ and $NPP_P = 30 \times (1 - \exp(-0.000664P)$

$$AB = 0.5 \times NPP$$

In fertilized grasslands, we considered that aboveground biomass increases by 33.2% in comparison with unfertilized grasslands (Li et al., 2022).

$$AB_{fert} = 1.332 \times 0.5 \times NPP$$

Next the carrying capacity (CC) was calculated considering the Animal Unit Months (AUM) that can be supported by the grassland with its aboveground biomass (following Abdalla et al., 2018). AUM considers for how long the animals are grazing, so this method is also suitable to calculate the feed demand of nomadic and seasonal grazing systems.

$$CC = ABfert/0.350AUM$$

Finally, the grazing intensity (GI) is the ratio between actual AUM and carrying capacity (Abdalla et al., 2018).

$$GI = Actual \quad AUM/CC$$

The intensity was considered low for a grazing intensity between 0 and 0.33 GI; medium between 0.33 and 0.66GI; and high above 0.66GI (following (Abdalla et al., 2018)).

3.3. *Expert interviews results*

The classification was adjusted based on the input given by experts, and these adjustments are explained along the definitions of each category.

The interviewed experts pointed out that some systems were missing in the classification. Greenhouses and landless livestock systems were missed by some experts. Since both systems are considered built-up area in land use maps we did not include them as agricultural land. The land used to grow feed for landless livestock is considered in the classification. Moreover, in the case of greenhouses they are isolated from the environment, therefore increasing crop diversity in greenhouses would have no effect on biodiversity. We acknowledge that pollution derived from landless livestock systems and greenhouses can harm biodiversity, but this harm does not derive from land use, therefore it is accounted for as a different pressure in GBESMs.

Other missing aspects were belowground biodiversity and landscape diversity. While it would be worth considering agricultural practices targeting belowground biodiversity, not enough comprehension is available to quantify the effect of these practices on biodiversity at a global scale (Cappelli et al., 2022). Following the suggestions of experts, diversity at the landscape level was included by adding mosaic patterns of land use and cover.

3.4. Global classification of agricultural systems based on diversity and intensity

A global typology of agricultural land management systems was created by combining ranges of diversity and management intensity into a matrix structure (Table 1), including management practices affecting grasslands biodiversity (Table 2), and landscape diversity (Table 3).

In this classification, crops include annual, biennial and perennial crops for food or fiber production, cover crops, insectary plants and other service crops. Woody perennials include tree crops, forest trees, windbreaks and hedgerows. Fruit and nut trees and vineyards are considered crops in this typology as in (FAO, 2020; Einarsson et al., 2021; Bartholomé and Belward, 2005), but because of their different management tree crops are differentiated from herbaceous crops (as in Bartholomé and Belward, 2005).

3.4.1. Cropping systems

Monocultures are systems in which the same crop is cultivated in an (often large) field each consecutive growing season, without rotation with other crops (Reeves et al., 2016). Monocultures of perennial crops were included to account for orchards in which only one tree species is grown, differentiating between orchards with bare soil and orchards with soil cover, following the input of the experts.

Crop rotations are systems in which only one crop is grown at a time in a field or plot, and this crop is succeeded by a different crop, so that the same crop is not grown consecutively on the same piece of land. Crop rotations involve annual and biennial crops, but not perennials. We differentiated between simple (two or three crops) and complex rotations (four crops or more) to account for the diversity found within crop rotation.

In strip intercropping, multiple rows of the same crop are grown in a strip of land, and strips of different crops alternate (Renard and Tilman, 2021). According to experts, it is custom to practice crop rotation in strip intercropping. Consequently, when the strips are wide (18–27 m), if each strip is considered as a plot, strip intercropping would be a combination of plots in rotation, not different from small fields under crop rotation. Moreover, small fields would fall under one of the mosaic categories defined for the landscape level because the resolution applied in GBESMs is too coarse to differentiate land covers of small fields. Therefore, wide strip intercropping was included within crop rotation.

In *row and mixed intercropping systems*, multiple herbaceous crops are grown at the same time in the same field (McSorley, 2008). The crops are spatially distributed: a) in rows: in each row one crop species is grown, and adjacent rows contain different crops; b) mixed: without any organized spatial arrangement in rows or strips or c) in rows with species mixed within the rows. This last type of spatial distribution was not found in the reviewed literature, but it was identified by experts as prevalent in West Africa. Row and mixed intercropping were considered as one category after consultation with experts because of two reasons.

Table 3
Diversity categories at the landscape level.

Landscape level	
Mosaic patterns	Mosaic of agricultural patches Mosaic of diverse agricultural patches Mosaic of land use types (including natural patches)

The first reason is that it would be difficult to differentiate between mixed and row intercropping when crops are spatially arranged in rows, but species are mixed within the rows. The second reason is that the difference in spatial distribution is expected to have a negligible effect on biodiversity and ecosystem services provision.

In *crop-livestock integrated systems*, crop production is integrated with livestock in the same field (FAO, 2019). In consultation with experts, this category was subdivided depending on whether the crop is annual or perennial. In annual crop-livestock integrated systems the production of annual crops is combined with livestock in the same field, including rice-fish systems and livestock grazing on stubble in arable land after crops have been harvested or during fallows (FAO, 2019). In crop trees with grazing livestock systems, crop trees are integrated with grazing livestock in the same field (FAO, 2019).

3.4.2. Agroforestry systems

Agroforestry is a system combining two or more species, in which at least one of the plant species is a woody perennial, and at least one of the plant species is managed for forage or food production (Somarriba, 1992). Agroforestry systems are subdivided based on dominance of types of vegetation. Sparse trees in cropland is an agroforestry system combining herbaceous vegetation and woody perennials, in which the herbaceous vegetation is prevalent and is a crop, and there is low density of woody perennials. Trees and herbaceous vegetation are agroforestry systems combining trees and herbaceous vegetation, in which trees are prevalent, and either a) the trees are forest trees with a herbaceous crop or b) the trees are a combination of species of crop trees (fruit or nut trees) with herbaceous vegetation. The category trees and herbaceous vegetation includes alley cropping and sequential agroforestry (crop temporarily mixed with trees). Agroforests are a combination of crops and trees (and shrubs) that ressembles a forest in which crops, trees and shrubs have more or less equal prevalence in the system (Torquebiau, 2000).

In *animal agroforestry systems*, livestock is integrated with forest trees or shrubs, and sometimes also with crops (tree crops, herbaceous crops or a combination). Animal agroforestry includes silvopastoralism and agrosilvopastoral systems. In silvopastoralism, forest trees and/or shrubs are integrated with grazing livestock in the same land (FAO, 2019). In agrosilvopastoral systems, non-crop trees and/or shrubs are grown together with crops and integrated with grazing livestock in the same field (FAO, 2019).

3.4.3. Grasslands

Grasslands are agricultural land management systems dedicated to grow grasses or other forage (self-seeded or sown and/or reseeded). Vegetation can include grasses, legumes, forb species and grass-like plants (families Cyperaceae and Juncaceae), and in self-seeded grasslands a low coverage of trees or shrubs (Dixon et al., 2014; Blair et al., 2014; Peeters et al., 2014).

The diversity range of grasslands (Table 2) is based on three aspects associated with biodiversity:

Age:

a. Permanent (>10 years): the grassland has been established for at least ten years without being completely renewed; or
b. Temporary (<10 years): the grassland has been established or completely renewed in the previous ten years (Peeters et al., 2014).

Management type:

a. Meadows: predominantly mown grasslands; or
b. Pastures: predominantly grazed grasslands (Peeters et al., 2014).

Human intervention level:

a. Cultural: grasslands are human-made with sown vegetation; or

b. Natural: grasslands are self-seeded and human interventions are limited to application of very low amounts of organic fertilizers, grazing, mowing or burning (Peeters et al., 2014; Dixon et al., 2014; Blair et al., 2014).

Temporary meadows are cultural, predominantly mown grasslands that are sown in arable land with grasses, legumes or grass-legume mixtures, and are harvested green as hay or silage (Dixon et al., 2014; Peeters et al., 2014). *Temporary pastures* are cultural, predominantly grazed grasslands that are also sown in arable land with grasses, legumes or grass-legume mixtures (Dixon et al., 2014; Peeters et al., 2014). Both temporary meadows and pastures can be integrated into a crop rotation or sown after another grassland vegetation (Peeters et al., 2014).

Permanent meadows are cultural, predominantly mown grasslands with higher fertilization rates and more frequently mown than natural and semi-natural grasslands (Dixon et al., 2014; Peeters et al., 2014). *Natural or semi-natural meadows* are permanent, predominantly-mown grasslands but they have not been substantially modified by humans (except from application of very low amounts of organic fertilizers), and are dominated by indigenous, naturally occurring grass communities (Peeters et al., 2014).

Permanent pastures are cultural, predominantly grazed grasslands that use more frequent defoliations and higher fertilization rates than natural and semi-natural grasslands (Peeters et al., 2014). Their vegetation can include grasses, legumes and forb species (Peeters et al., 2014). *Rangelands* are permanent, extensively grazed grasslands dominated by semi-natural vegetation (i.e. vegetation not planted by humans but influenced by human actions such as grazing, cutting or burning) (Allen et al., 2011; Peeters et al., 2014).

3.4.4. Diversity at the landscape level

The resolution of land use and land cover maps used in GBESMs is coarse, 10 arcsec (~300 m by 300 m at the equator) at most (Zanaga et al., 2021). Consequently, it is common to find several land use types and/or land covers in a grid cell. The grid cells that contain several of the diversity categories defined in Table 1 exhibit diversity at the landscape scale. Diversity of land use types, including patches of natural land (Tscharntke et al., 2005), and diversity of land cover (Gámez-Virués et al., 2015) at landscape scale influence biodiversity outcomes, for example, field margins benefit biodiversity by providing non-cropped habitats (Fahrig et al., 2015; Landis, 2017). According to (Fahrig et al., 2015), biodiversity in cropland depends more on land cover heterogeneity than on land use heterogeneity. Based on these findings, three mosaic systems were defined to account for diversity at the landscape level. A mosaic of agricultural patches refers to a landscape composed by different fields with a similar land cover and diversity level. A mosaic of diverse agricultural patches refer to a landscape composed by agricultural patches, but in which land cover is different (e.g. adjacent cropland and grassland) or agricultural patches contain different diversity levels (e.g. agroforestry and monoculture). Finally, a mosaic of land use types refers to a landscape composed by agricultural patches and patches of forest or natural areas. Grid cells in land use and land cover maps of agricultural land can be classified within the three defined mosaic systems when they exhibit diversity at the landscape scale. The influence of landscape diversity on biodiversity and ecosystem services provision can then be assessed based on these mosaic systems.

3.5. Examples of agricultural land management systems

Examples of agricultural land management systems found in the publications from Web of Science and pointed out by experts in the interviews are shown in Table 4. Please note that even though we did not list examples for all of the systems, according to experts all of the systems exist with the three intensity levels, even though some systems are more common than others.

4. Discussion

The global classification of agricultural land management systems proposed in this paper organizes agricultural systems within ranges of both diversity and intensity. The classification was constructed based on literature and experts interviews. The intensity and diversity ranges were combined to form a matrix structure of agricultural land management systems (Table 1). The examples presented in Section 3.5 show how agricultural systems in different world regions fit within the proposed typology, illustrating that the classification is applicable worldwide. To our knowledge, this is the first global typology of agricultural land focusing on management aspects associated with agrobiodiversity.

Previous classifications made a start on considering diversity or intensity. For example, in the classification by (Hudson et al., 2017, 2014), crop diversity is considered, though only intermingled with management practices as one of the aspects characterizing intensity. Their classification uses intensity factors relevant for biodiversity and ecosystem services models, but intermingling diversity and intensity has the disadvantage of considering only typical agricultural systems (i.e. coupling high intensity with specialization, and low intensity with diversity). Additionally, crop diversity categories in Hudson's classification are limited to mixed crops and crop rotation (Hudson et al., 2017, 2014), omitting the diversity provided by non-crop plants and livestock that benefits biodiversity and ecosystem services supply (FAO, 2019). (Malézieux et al., 2009) on the other hand, developed a range of diversity on agricultural systems and provided a basis for a diversity based classification, but they did not consider intensity. Given the impact of management intensity on biodiversity and ecosystem services (Beckmann et al., 2019; Dale and Polasky, 2007), it is important to consider intensity in a land use classification to be used in GBESMs.

Regarding cropland intensity, the indicators applied in land use classifications are either too simple or inappropriate for the purposes of our classification. Some classifications base cropland intensity levels on only one aspect, see for example (van Asselen and Verburg, 2012) and (Ellis and Ramankutty, 2008). While there are global classifications considering a combination of intensity factors, these often include yield gaps (Letourneau et al., 2012; Václavík et al., 2013). Yield has been widely used as an indicator for intensity, but it is not appropriate as a base for modeling ecosystem services and biodiversity. The use of external inputs has historically helped to produce high yields, thus systems with high inputs are considered to be highly productive. Nonetheless, the role of ecosystem services supporting yield has been widely discussed in the literature, and recent studies have found that diversified systems with abundant provision of ecosystem services can also achieve high yields (Beillouin et al., 2021; Tamburini et al., 2020). Therefore, using yield as an indicator for intensity would mask whether yield is supported by external inputs, ecosystem services, or both. As such, the use of external inputs applied in the presented classification is a more appropriate intensity indicator for modeling ecosystem services and biodiversity. For example, this classification could be applied to model the effect of different levels of external inputs on biodiversity and on the provision of different ecosystem services. By including the most impactful inputs in a separable manner, this classification also allows to isolate the effects of the inputs, which is particularly useful to model ecosystem services that are expected to be most affected by that input. For example, pesticide use could be isolated to model pollination or pest control services.

Classifications considering grasslands intensity aspects related to biodiversity or ecosystem services are scarce, despite the fact that grasslands occupy ~70% of the global agricultural area (Klein Goldewijk et al., 2007). In the global land use classification proposed by (Hudson et al., 2014), pastures are divided into three intensity levels based on a combination of stock density and the use of fertilizers and pesticides (Hudson et al., 2014). (Felipe-Lucia et al., 2020) studied the relationship between biodiversity, the provision of ecosystem services and grasslands intensity, and used as intensity indicators mowing

Table 4
Examples of agricultural land management systems in the diversity-intensity matrix. *Intensity information not enough to classify according to our criteria (intensity allocation based on papers description); "/"means "or"; and "-" separates crops in ro rotation. Numbers correspond to sources (Supplementary information).

		Intensity		
		Low	Medium	High
Monoculture	Monoculture annual crops	Millet monoculture (Africa)*[1]	Wheat monoculture (Finland)*[2] Araq papas monoculture (Peru)*[3]	Maize monoculture (Mexico) *[4] Wheat monoculture (Finland) *[2] Potato/peanut/cabbage/cereals/cotton/paddy (China) *[5] Triple rice system (Vietnam)[6]
	Monoculture perennials (bare soil)			Sun-grown coffee plantations (Mexico and Colombia)*[7&8]
	Monoculture perennials (with soil cover)	Unshaded organic coffee plantations[9]	Rubber (Thailand)*[10] Cacao and Citrus monocultures (Colombia) *[11]	Sun-grown coffee plantations (Mexico and Colombia)[12]
Crop rotation	Simple crop rotation (2–3crops)	Kutirpa system-Potato, oca and mashua (Peru)*[3] Deepwater rice systems-legumes/oilseeds (South Asia)1,33	Organic cereals-lupine/peas/alfalfa (Northern Europe)*[13]	Irrigated horticulture (Australia)[14] Wheat-Turnip-Wheat-Barley (Finland)*[2] Wheat-Potato (Italy)[15] Wheat-Maize (China)*[5]
	Complex crop rotation (4 or more crops)		Wheat-Turnip-Barley-Pea (Finland)*[2]	Irrigated horticulture (Australia)[14] Cover crops-maize-wheat-rapeseed-wheat (France)[16]
Row/Mixed intercropping	Row/mixed intercropping annual crops	(Multiple) Milpa (Mexico) or "Three sisters"*[1,4,17,18&19] Mixed intercropping-Araq papas, maize, beans and possibly other crops (Peru)*[3] Sorghum and peas (West Africa)*[1]	Organic cereals intercropped with rows of potatoes/sunflower/buckweit (Northern Europe)*[13] Tropical gardens (Haiti)*[1] Wheat, mustard & a legume (India&Pakistan)*[1]	
Crop-livestock integrated systems	Annual crops-livestock integrated systems	Livestock grazing on stubble (West Africa)*[1]		
	Crop trees with grazing livestock		Cattle under coconut trees*[1] Oil palm grazing systems*[1]	
Agroforestry	Trees and herbaceous crops	Diversified home orchards (Mexico)*[18]	Pecan trees with peanut and/or red sage (China)*[20] Alley cropping-Apples and herbaceous crops organic (UK)*[21] Cacao, banana, fruit trees (Costa Rica)*[22] Fruit orchards-Apple,pear,apricot&plum, sometimes potatoes,carrots and onions (China)*[5]	Alley cropping-Apples and herbaceous crops (UK)*[21] Walnut and chrisanthemum (China)*[5]
	Trees in agricultural soil, low density		Bocage (France)*[1] Wheat, soybean and maize with trees (China)*[1]	Flax, soybean and trees (China)*[1]
	Agroforests	Semi-forest coffee (Ethiopia)*[23] Semi-plantation coffee (Ethiopia)*[23] Traditional rustic or "Mountain" coffee system (Mexico)*[7] Traditional polyculture or coffee garden (Mexico)*[7] Traditional rustic cocoa agroforestry (Mexico)*[24] Jungle rubber system (Thailand)*[10] Enset based home garden (Ethiopia)[25]	Commercial/diverse coffee polyculture (Mexico and Colombia)*[7,8&26] Plantation coffee (Ethiopia)*[23] Te'lom (Mexico)*[19] Rubber, fruit trees & vegetables (Thailand) *[10]	Shaded coffee monoculture (Colombia and Mexico)*[7,8&26] Simple polyculture coffee plantations (Mexico)*[26&27]
Animal agroforestry	Agrosilvopastoral systems	Parkland (Senegal)*[1&28]	Dehesa: oak trees, pigs and wheat (Spain)*[1]	
	Silvopastoralism	Low-intensity silvopastoral system (Argentina)*[29]	Intermediate-intensity silvopastoral system (Argentina and Mexico)*[29&32]	
Grasslands	Temporary meadows			Lucerne and grasses (North Eastern USA)*[1] Alfalfa (Utah)*[1]
	Temporary pastures		C4 grasses (Southern USA)*[1]	Monoculture of Indiangrass with cattle (USA)*[30] Exotic bermudagrass and tall fescue with cattle (USA)*[30]
	Permanent meadows			Kentucky bluegrass, clover, forbs (North Eastern USA)*[1]
	Natural or semi-natural meadows	Mountain pastoral system (Portugal)*[31]		Native warm-season grass mixture without cattle (USA) *[30]
	Permanent pastures		Pasture (Mexico)*[32]	
	Rangelands	Rangelands (Nepal)*1,34	Native warm-season grass mixture with cattle (USA)*[30]	C3 grasses and forbs (Utah)*[1]

frequency, amount of nitrogen fertilization and livestock density. While the indicators proposed by (Felipe-Lucia et al., 2020 and Hudson et al., 2014) are relevant for biodiversity, as one of the interviewed experts pointed out, it is important to consider the climatic specific productivity of the grassland to determine impacts of stocking density. In that sense, the indicator grazing intensity used in this classification has the advantage of considering the climatic specific productivity of the grassland, including the effects of nitrogen fertilization when applied, as well as the stock density and the duration of herbivory. By considering climatic effects on productivity, our classification is more appropriate for modeling grasslands at a global scale.

Our classification adds to the existing ones the fact that it is: complete, simple, relevant for biodiversity and ecosystem services modeling, flexible and unambiguous. The classification is complete because it considers different aspects of intensity and all the existing diversity categories, including landscape level. At the same time, it is simple, as agricultural systems identified in the literature were simplified to create categories with similar diversity levels. It is relevant for biodiversity and ecosystem services provision as it considers all of the aspects expected to have a big influence on them. The classification is flexible, as the design of the intensity decision tree and the matrix structure provide flexibility to include or remove intensity indicators as needed to evaluate different ecosystem services in combination with the diversity range. Additionally, the diversity range is arranged in levels of detail, which also provides flexibility to apply a different level of detail depending on data availability. For example for crop rotation, one could select the maximum level of detail, differentiating by the number of crops in rotation, and when data to such level of detail are unavailable, one could still select the category 'crop rotation'. This increases the applicability of the classification, making it adjustable to data availability and spatial scope, as data at regional level is often more detailed than at global level. Finally, the classification is unambiguous, as all existing systems belong only to one category of intensity and diversity.

It is important to note that even though the diversity categories were defined to be unambiguous, different diversification practices may occur simultaneously in an agricultural system, for example, in an agroforest, crop rotation or row/mixed intercropping may be practiced. In that case, the classification presents a limitation and the user of the classification would have to decide how to proceed depending on the application. If one of the diversity categories is less important for the application, the user could choose one diversity category that would supersede the other diversification practice. However, if both diversity aspects are important for the application, the user may create new (sub)categories combining the two diversity practices so that all combinations are represented.

While the nomenclature used in the classification was derived from the literature, it should be noted that nomenclature may be a source of confusion. For example, mixing woody perennials with herbaceous crops is defined as agroforestry in the literature, whereas it can also be found as intercropping (see (David, 1995; Jama and Getahun, 1991; Jefwa et al., 2006). Also, according to (Peeters et al., 2014) ten years is the time needed to reach levels of plant and soil biodiversity typical of long-term permanent grasslands, while some experts used the term permanent grasslands five years after establishment. Finally, levels of intensity and what they entail vary between authors and world regions. The nomenclature confusion is unavoidable, as this is a global classification and there is no universal nomenclature. To prevent nomenclature misinterpretations when applying this classification, it is key to keep in mind the definitions of the systems during data collection.

Data availability at a global scale is one of the limitations of this classification. For grasslands diversity, for example, only two literature sources were found defining different types of grasslands. This shortage of literature is a limitation because even though we used a triangulation of methods by also interviewing experts, we may still have missed some grassland types. Data are also not available to include practices aiming at increasing soil biodiversity in the classification.

Regarding the applicability of the classification, another important limitation is the lack of information about how prevalent each agricultural system is, and what its geographical distribution is. Assumptions could be made based on general trends in some regions, though these assumptions would represent a simplification of reality. For example, intensive monocultures or simple rotations could be associated with industrialized countries in North America based on the dominance of intensive monocultures or simple crop rotations in the US Corn Belt (Roesch-McNally et al., 2018). Nonetheless, in many world regions the picture is more complex, for example, agroforestry is widespread in Indonesia (Shin et al., 2020), but perennial monocultures of palm oil are also common and expanding in the country (Wicke et al., 2011). This limitation can be overcome by applying the classification for modeling based on assumptions or scenarios. However, we recommend the collection of more information about the extent and geographical distribution of the agricultural systems.

A natural progression of this work is to build land use and land cover maps based on our classification that could be used in GBESMs. Data to map the composite indicator for intensity can be obtained from existing publications, such as (Maggi et al., 2019) for pesticide use, (Potter et al., 2010) for use of organic and mineral fertilizers, and (Siebert et al., 2013) for irrigation. Mapping the diversity categories is challenging, but the combination of remote sensing and data driven approaches enables georeferencing some combinations of diversity aspects, such as the tree cover in cropland (Zomer et al., 2022), the crop diversity (Aramburu Merlos and Hijmans, 2022) and the presence of livestock (Gilbert et al., 2018). The combination of all of these data would result in a global map of agricultural systems with information about diversity and intensity. This map would build on existing approaches that combine multiple datasets (e.g. (Letourneau et al., 2012; Václavík et al., 2013)). However, it would include a more accurate representation of the existing range of agricultural land management systems than the maps currently used, as unlike current maps it would not seek for recurrent patterns (Václavík et al., 2013) and similarities (Letourneau et al., 2012). The map would allow to model current biodiversity and ecosystem services of agricultural systems, creating a reference baseline for scenario studies.

In addition, our classification can be applied as a framework for collecting data about biodiversity and ecosystem services associated with the diversity and intensity of agricultural systems. The structure of the classification allows to analyze trade-offs between intensity and diversity. By characterizing the agricultural systems in the classification in terms of associated biodiversity and ecosystem services, including productivity, we could improve the modeling of biodiversity and ecosystem services (Daily, 2001; Alkemade et al., 2022). Consequently, the classification has the potential to be used to inform agricultural and environmental policy makers about which systems should be implemented to achieve production and environmental targets. Thus, this classification sets the base to evaluate a range of conservation options that go beyond protecting natural areas and explore the potential of preserving biodiversity in agricultural land (Alkemade et al., 2022).

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

No data was used for the research described in the article.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2023.108795.

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