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REVIEW ARTICLE

Considering farming management at the landscape scale: descriptors and trends on biodiversity. A review

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Abstract

Farming management and alterations in land cover play crucial roles in driving changes in biodiversity, ecosystem functioning, and the provision of ecosystem services. Whereas land cover corresponds to the identity of cultivated/non-cultivated ecosystems in the landscape, farming management describes all the components of farming activities within crops and grassland (i.e., farming practices, crop successions, and farming systems). Despite extensive research on the relationship between land cover and biodiversity at the landscape scale, there is a surprising scarcity of studies examining the impacts of farming management on biodiversity at the same scale. This is unexpected given the already recognized field-scale impact on biodiversity and ecosystem services, and the fact that most species move or supplement their resources in multiple patches across agricultural landscapes. We conducted a comprehensive literature review aimed at answering two fundamental questions: (1) What components of farming management are considered at the landscape scale? (2) Does farming management at the landscape scale impact biodiversity and associated ecosystem functions and services? We retrieved 133 studies through a query on the Web of Science, published from January 2005 to December 2021 addressing the broad notion of farming management at the landscape scale. The key findings are as follows: (1) The effect of farming management components at the landscape scale on biodiversity was tackled in only 41 studies that highlighted that its response was highly taxon-dependent. They reported positive effects of organic farming on pollinators, weeds, and birds, as well as positive effects of extensification of farming practices on natural enemies. (2) Most studies focused on the effect of organic farming on natural enemies and associated pests, and reported contrasting effects on these taxa. Our study underscores the challenges in quantifying farming management at the landscape scale, and yet its importance in comprehending the dynamics of biodiversity and related ecosystem services.

Keywords Agricultural practices · Organic farming · Crop succession · Natural enemies · Pollinators · Birds · Weeds · Remote sensing · Farmer survey · Farm management

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1 Introduction

For several decades, agriculture has been facing a multitude of challenges that together have led to a generalized intensification of agricultural systems around the world. Major agronomic levers, such as mechanization and the increased use of synthetic pesticides and fertilizers, have profoundly transformed agricultural landscapes by allowing farmers to specialize and reduce crop diversity, increase the size of their fields, and transform non-crop habitats (Fischer and Lindenmayer 2007). Although this economic model has dramatically improved yields and quality of life of farmers (Herrera et al. 2018), it has also led to an overall loss of biodiversity (Newbold et al. 2015) and impacted many ecosystem services (Brauman et al. 2020), such as pollination (Grab et al. 2019), pest control (Geiger et al. 2010), soil fertility (Alvarez and Steinbach 2009), or water quality regulation (Berka et al. 2001).

At the field scale, the impact of farming management* (*see Section 2.1 for definitions related to farming management considered in this review) on biodiversity has been widely studied, both in terms of direct effects (Jones et al. 2021) and the interaction of local farming management with landscape land cover (Tscharntke et al. 2012). For instance, biodiversity is impacted by farming systems, with greater diversity in organic fields than in non-organic ones (Lichtenberg et al. 2017). Many farming practices are also important drivers of biodiversity at the local scale, such as tillage, pesticide use, nitrogen fertilization, sowing date, or crop succession (Rusch et al. 2010) (Fig. 1).

Despite their tremendous impact on biodiversity observed at the field scale, the study of the effect of farming management at the landscape scale remains surprisingly anecdotal (Vasseur et al. 2013; Marrec et al. 2022). Unlike landscape ecology, agronomic sciences primarily work at the field scale, as this is the reference scale for evaluating the agricultural, technical, and environmental performance of cropping systems (Nesme et al. 2010). The stakes inherent to agronomy do not justify at first sight focusing on the landscape scale. However, for certain agronomic issues such as pest control for example, it is necessary to look beyond the field scale. Indeed, several pest species and their natural enemies have great movement capacities, and the distribution of cropping practices influences the dynamics of these organisms. Governance scenarios and simulations show that the landscape scale is the most suitable scale for preserving biodiversity while considering agricultural production objectives (Cong et al. 2014; Leventon et al. 2019; Gebhard et al. 2023). Thus, the landscape is a relevant scale to be considered for pest control if mismatches are to be avoided between ecological systems and management actions (Nesme et al. 2010; Falco et al. 2021). Indeed, given

Fig. 1 Farming management at the field scale and landscape heterogeneity are two important drivers of biodiversity in agricultural landscapes. Farming management at the landscape scale could directly impact the movement of species or indirectly by altering the heterogeneity of land cover.

(i) the already recognized impact of farming management at the local scale on biodiversity and ecosystem services (e.g., Rusch et al. 2010) and (ii) the fact that most species move, complement, or supplement their resources in multiple patches across the landscape (e.g., Dunning et al. 1992; Greenstone et al. 1987; Petit et al. 2013), it seems highly likely that farming management will have direct and indirect impacts on biodiversity at the landscape scale. In fact, farming management at the landscape scale could influence mechanisms underlying biodiversity patterns and dynamics (Tscharntke et al. 2012). For example, the disturbances generated in fields by farming practices could have an impact on the movements of species in agricultural landscapes, thus affecting relationships within meta-communities (Leibold et al. 2004). These same movements could also give rise to biodiversity concentration/dilution mechanisms (Vasseur et al. 2013; Tougeron et al. 2022), with, for example, a higher concentration of individuals in the least intensively managed fields of the landscape.

Here, we reviewed the literature, through a query on the Web of Science, that considered farming management at the landscape scale between 2005 and 2022, and followed these two steps: (i) extract the descriptors of farming management used to characterize farming management intensity at the landscape scale in retrieved studies, and (ii) analyze effect of farming management at the landscape scale on biodiversity and associated ecosystem functions and services.

2 Methods

2.1 Definition of agronomical terms

Farming management In this paper, the term farming management has been used as an umbrella term that encompasses all components and descriptors of farming activities carried out on crops and grassland intended for mowing or grazing (i.e., farming practices, crop successions, and farming systems) (Fig. 2).

Farming practices Farming practices refer to any practice carried out by farmers on their crops and grassland with the aim of establishing and managing a crop or an intercrop cover

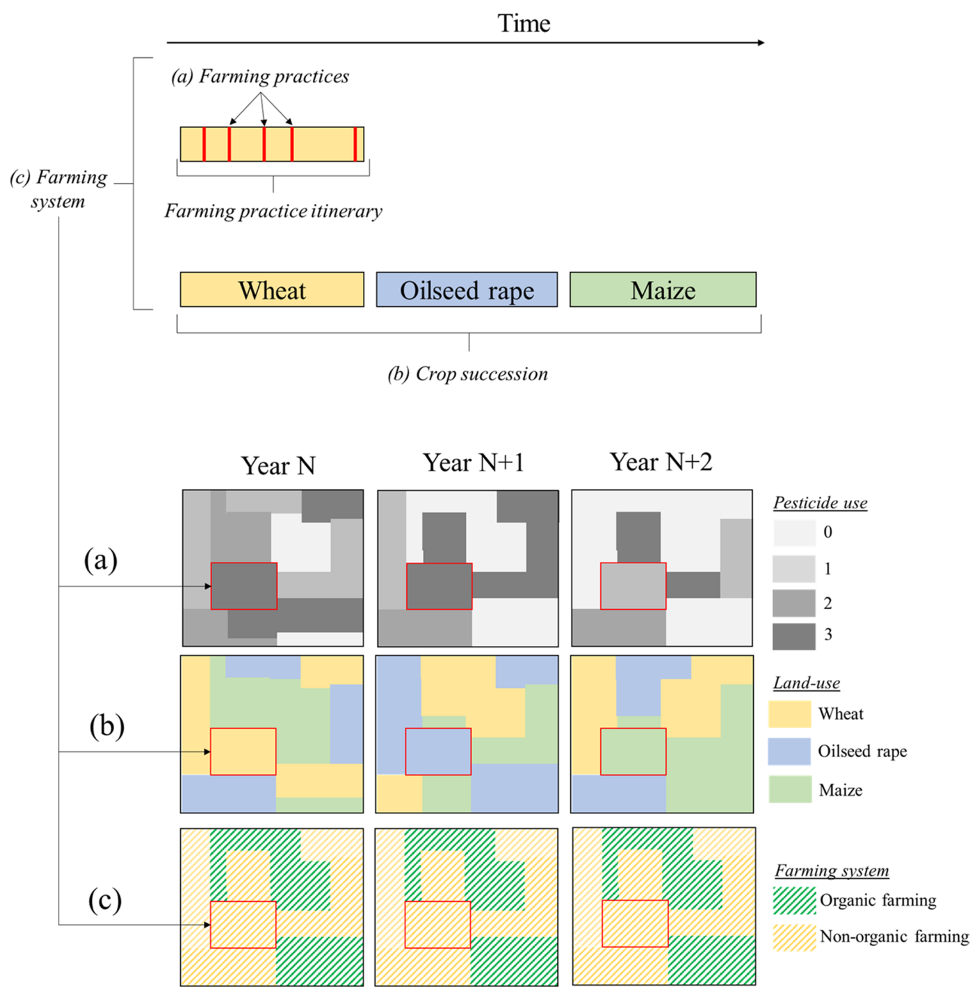

Fig. 2 The three components of farming management considered in this review—(**a**) farming practices, (**b**) crop successions, and (**c**) farming system, and examples of their representation at the landscape scale. The red square represents the local scale, while the black represents the landscape scale.

(Fig. 2a). These practices being technical operations (like nitrogen fertilization, crop protection strategy, or soil tillage) that describe a set of cultural practices referring to the same object without describing neither the way those operations are carried out nor their potential intensity. For example, the amount of nitrogen per hectare describes the total quantity of nitrogen applied in the field, without any consideration of the method used, the nature of the nitrogen applied, or the date and rates of application which is related to the cultural practices.

Crop succession We acknowledge the fact that the decision made by farmers to select a crop type on a given field—which ultimately determines the land cover/use of much of the agricultural landscape—can also be considered a farming practice. Nonetheless, the impacts of local crop type and of land cover/use at the landscape scale have already been reviewed extensively and are therefore not considered in our analysis (e.g., Estrada-Carmona et al. 2022). However, only a few studies addressed the interannual change of annual crop types at the landscape scale. We thus incorporated crop successions, defined as the successive cultivation of short-lived plant species on the same *plot* (i.e., a parcel of cultivated land), cropping season after cropping season (Fig. 2b), in our analysis. Given that crop successions were always considered independently of other components of farming management, we have chosen to consider them separately from other farming practices.

Farming systems Farming systems are defined by the way the farms are managed and organized to achieve specified agricultural objectives. It includes any agricultural system that produces livestock and/or crops (food, feed, fiber, and/or energy) that differ from each other based on intensity of farming practices, crop succession, and management of semi-natural habitats. Most often, farming systems are implicit systems in which only the main or critical elements are acknowledged and only the major or immediately relevant interrelationships are considered to define them (e.g., organic agriculture, conservation agriculture, integrated farming) (Fig. 2c).

2.2 Bibliographic research strategy

We performed a Web of Science (WoS) query on November 2, 2021, and updated on January 3, 2022, with the aim of finding all the studies considering farming management at the landscape scale (Fig. 3). We wrote a two-part equation, with the first part of the equation grouping together alternative words and expressions related to the components of farming management and selected from an agronomic Thesaurus (https://agclass.nal.usda.gov/). We focused on components of farming management that alter fields themselves (including grasslands), not semi-natural landscape features (even if they can potentially be managed by the farmers themselves). The second part of the equation referred to all the means of designating the landscape scale. In our article, landscape refers to a spatial scale, within which we study farming practices. It is for this reason that we prioritized terms such as "in the landscape" or "at the landscape scale" to target articles relevant to our study while avoiding having too many irrelevant articles which was the case by adding only "landscap*." We deliberately avoided using the vocabulary related to biodiversity because we wanted to have an overview of the methods used in all disciplines to obtain farming management and describe its intensity at the landscape scale.

We selected all studies published after January 2005 (n = 33,754 studies), as this year marked the beginning of the expansion of studies in landscape ecology (Turner 2005). Also, it was a yearlong before we began to consider the landscape as a heterogeneous mosaic—and no longer under the patch and matrix dichotomy—,an essential prerequisite for integrating farming management to characterize this heterogeneity (Marrec et al. 2022). We ranked query outputs in order of relevance (i.e., on the basis of words and expressions occurrences in title, abstract, and keywords of studies). By reading titles and abstracts, we selected articles that referred to farming management at the landscape scale. We stopped searching for articles when the number of retained abstracts per WoS page (50 articles per page) fell to a relevance threshold of <2 % (Fig. S1). We then read the 'materials and methods' section of the 280 selected studies and excluded all remaining irrelevant studies (i.e., studies that only considered land cover or long-term land-cover change) (n = 124 retained studies). Finally, an additional search with the "Connected papers" tool (https://www.connectedpapers.com) allowed us to retrieve 9 additional studies not listed in the articles retained from the WoS query (n total = 133 studies).

To get an overview of the original studies retrieved (n = 106 among a total of 133 articles, excluding reviews and opinions papers) that consider farming management at the landscape scale, we extracted the following information: (i) the country location of study areas; (ii) the types of field studied (i.e., annual field crops, permanent crops, semi-natural habitats, other plots); (iii) the topic studied (i.e., biodiversity and ecosystem services, water and soil quality, socioeconomics); (iv) the sampling methods of biodiversity (i.e., data from a plot centered on a landscape buffer, or other method) (see Supplementary Material); and (v) the methods used to obtain landscape-scale farming management (e.g., farmer survey, remote sensing, modeling, databases) and their data source(s). Finally, considering only the original studies addressing biodiversity and associated ecosystem services of a plot centered on a landscape buffer (n = 41), we first analyzed farming management descriptors used to characterize the intensity of farming management at the landscape scale, and extracted the direction of its effect on biodiversity and ecosystem services.

Fig. 3 Bibliographic search and analyzing strategies about consideration of farming management at the landscape scale. In the first part of the search equation, the words are colored according to the farming management component to which they belong: farming practices (purple), crop succession (green), farming systems (orange). Words in black may refer to several components of farming management.

3 Descriptors of farming management components at the landscape scale

Forty-one studies, out of the 106 original studies, explicitly mentioned a characterization of farming management at the landscape scale when considering their impact on biodiversity. The farming descriptors used to quantify farming management were categorized into three components: farming practices, crop succession, and farming system (Table S1). Only 16 of the 41 studies used more than one farming descriptor at the landscape scale.

Three main strategies were used by the authors of the reviewed papers to characterize the intensity of farming management at the landscape scale (Fig. 4). The first strategy considers qualitative descriptors of each plot (i.e., parcel of cultivated land) in the landscape—i.e., descriptors which do not quantify the real differences in intensity between plots, for example, the presence or absence of the farming management component under consideration—to calculate the proportion of a given landscape area impacted by the component. Among the 41 studies, 29 studies (61 %) calculated the proportion of landscape under given farming systems, mainly using the organic/non-organic farming dichotomy. Another four studies (10 %) calculated the proportion of landscape under specific adaptations of farming practices: reduction of synthetic inputs (herbicides and nitrogen fertilization); conservation or creation of specifically managed areas for biodiversity; and support of organic

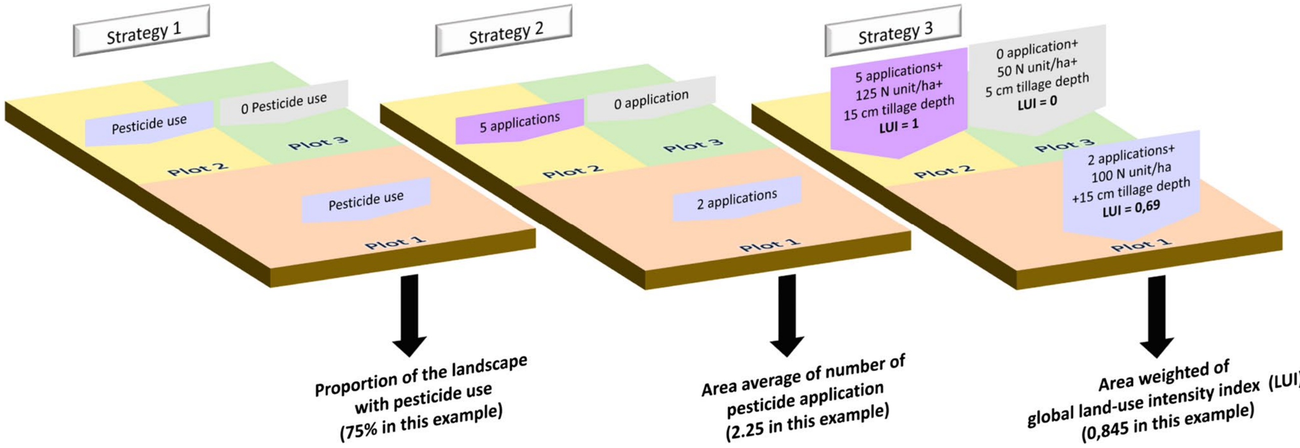

Fig. 4 Strategies found in studies to characterize farming management intensity at the landscape scale. In strategy 1, each parcel is associated with the presence/absence of a specific farming practice to calculate the proportion of the landscape under this practice. Strategy 2 quantifies the farming practice in each parcel in the landscape to calculate the area-weighted average of the farming practice at the landscape scale. Strategy 3 follows the same logic as strategy 2 but aggregates several farming practices in order to associate a global land-use intensity index (LUI) with each plot in the landscape.

farming. Only one study (2 %) used qualitative descriptors to inform individual farming practices and considered the proportion of landscape treated with neonicotinoid insecticides. Finally, five studies (12 %) characterized crop successions at the landscape scale, considering either the presence or absence of crop rotation on each plot, the alternation of crops, the nature of crops that succeed each other in the field, or the proportion of ley (i.e., sown and mown meadows) in the landscape as a proxy of the intensity of crop succession. These studies therefore calculated either the proportion of fields with crop succession, the intensity of the crop succession, or the proportion of fields by type of crop succession in the landscape.

The second strategy consists in using quantitative descriptors of each plot to calculate the area-weighted mean value of a given farming practice across the landscape. Among the 41 studies, 9 studies (22 %) described farming management using intensity indicators related to one or more farming practices, such as the amount of nitrogen or pesticides used per hectare or year, the number of tillage operations, and livestock density at the landscape scale.

The third strategy is similar to the second, except that it characterizes global land use intensity index (LUI) by considering multiple farming practices in a single index. Among the 41 studies, only one multifactor intensity index was identified in one retrieved study (2 %) (Le Féon et al. 2013), the one presented by Legendre and Legendre (1998) and adapted by Herzog et al. (2006).

4 Effects of landscape-scale farming management on biodiversity and associated ecosystem services

Our literature review revealed variable effects of farming management at the landscape scale, depending on the taxa (Fig. 5). Abundance and diversity of weeds, pollinators, and birds seem in most cases positively impacted by the proportion of organic farming in the landscape. On the other hand, studies suggest that it has little impact on natural enemies and insect pests, either through their diversity or the predation/parasitism service they provide. In addition, the effect of crop rotation at the landscape scale on biodiversity has been little studied, which makes it difficult to draw conclusions about this component of farming management. Finally, the effect of the extensivity of farming practices at the landscape scale was studied only on natural enemies and pollinators, with positive and mixed effects, respectively.

4.1 Effects of farming systems in the landscape

Twenty-five studies compared the effect of organic farming (OF) to non-organic farming systems on biodiversity. The results obtained on this restricted basis suggest that the effect of OF in the landscape depends on the taxon considered, with positive effects dominating in the case of weeds, pollinators, and birds (Fig. 5a).

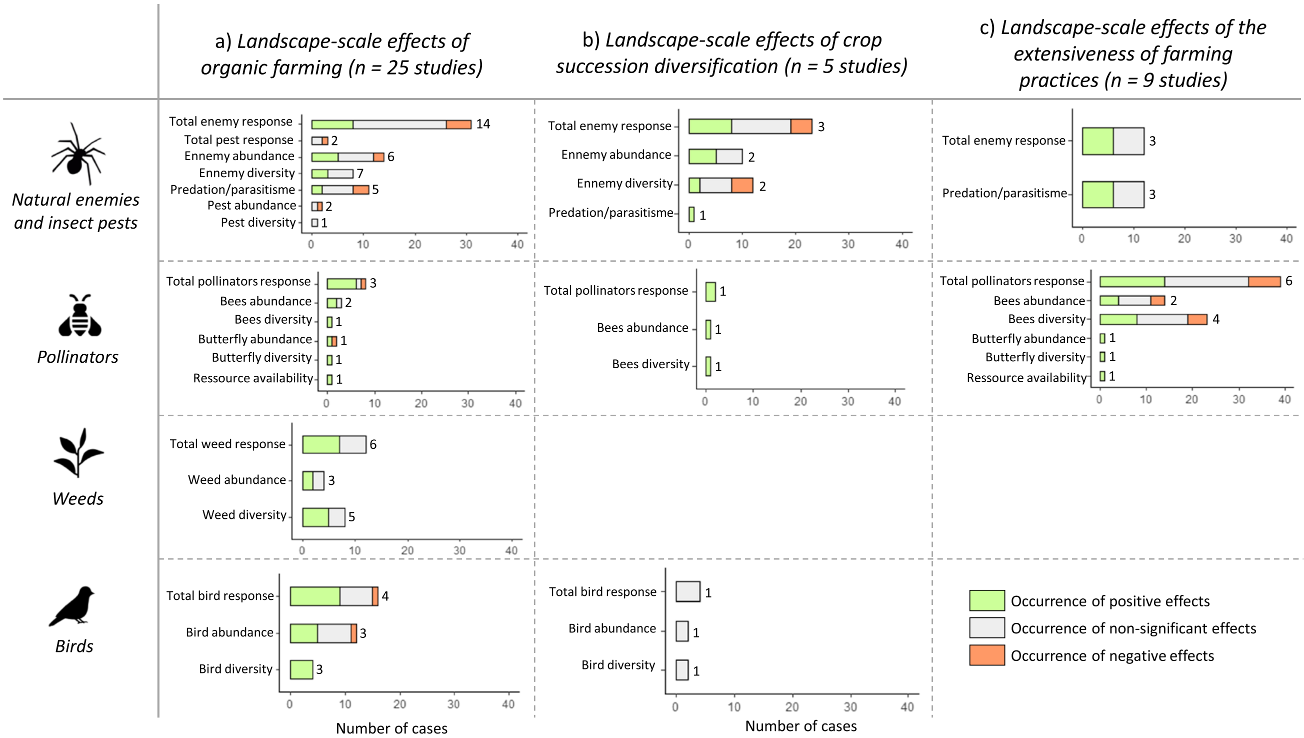

Fig. 5 Reported effects of landscape-scale farming management components on biodiversity. We distinguished the effect of organic farming, diversification of crop succession, and extensiveness of farming practices on the four most studied taxa/groups: natural enemies and insect pests, pollinators, weeds, and birds. Each bar plot represents the number of times the relationship between the farming management component and the response variable was examined. The number indicated at the end of each bar represents the number of studies reviewed that investigated the relationship.

4.1.1 Weeds

Six studies investigated the effect of OF at the landscape scale on weeds, including 24 relationships studied with OF at the landscape scale. OF increases significantly weed species richness and/or abundance in 58 % of the relationships and has no significant effects in 42 % of the relationships.

At the landscape scale, OF impacted weed communities inhabiting both organic and non-organic fields in several studies (Henckel et al. 2015; Petit et al. 2016). Indeed, Petit et al. (2016) showed that the proportion of OF within 1000 m around the sample plot exceeded the effect of local farming management. The same result is observed in Henckel et al. (2015) but only on field margin, while the effect of local practices dominates within the field. On the other hand, Gosme et al. (2012) reported no landscape-scale effect of OF on weed diversity and density.

4.1.2 Pollinators

Three studies investigated the effect of OF at the landscape scale on pollinators, which include 16 relationships studied with OF at the landscape scale. In these studies, pollinators and the service of pollination respond positively to the presence of OF in the landscape in 75 % of relationships, while negative or non-significant effects were each found in 12.5 % of relationships.

The magnitude of pollinator responses was relative to the proportion of OF in the landscape. For example, according to Holzschuh et al. (2008), an increase in the total amount of OF from 5 to 20 % in the landscape enhanced bee species richness in fallow strips by 50 %, density of solitary bees by 60 %, and of bumblebees by 150 %.

Incorporating OF fields into intensive agricultural landscapes can provide the food resources needed to sustain greater pollinator species richness, particularly during periods of resource scarcity (Wintermantel et al. 2019). These positive effects of the OF area are relative to the non-OF area in the same landscape. Indeed, Rundlöf et al. (2008) demonstrated that fields in landscapes dominated by OF had more abundant and diverse butterfly communities than those in non-OF landscape. However, this positive effect depended on the spatial distribution of OF fields in the landscape. Thus, in a landscape characterized by a majority of fields under non-OF, the OF fields favored butterfly communities in the nearby non-OF fields, whereas in landscapes characterized by a majority of OF fields, the butterfly communities were equivalent in all fields, regardless of how they are managed (Rundlöf et al. 2008).

4.1.3 Natural enemies and associated crop pests

Fourteen studies focused on natural enemies, crop pests, and/or the associated biological control service, and investigated relationships with OF at the landscape scale. In most cases, non-significant effects of OF on the potential of the biological control service were reported (59 %), while positive and negative effects accounted for 27 % and 14 % of the relationships, respectively.

While at the local level, organically grown vineyards showed higher biocontrol activity against a variety of pests, the study of Muneret et al. (2019) did not provide evidence that biocontrol was greater in landscapes composed of organically grown vineyards compared to those composed of non-organically grown vineyards (except for weed seed removal). An increase in the proportion of OF fields in the landscape may therefore not increase pest occurrence, at least in low pest pressure contexts (Gosme et al. 2012). Increasing OF area has been reported to have a neutral effect on pest infestations, such as in vineyards (Muneret et al. 2018). On the other hand—and this is an important distinction—it appears that the biological control service may decrease when the share of non-organically farmed fields in the landscape increases. Maalouly et al. (2013) showed that codling moth parasitism rates were significantly higher in organic than in non-organic orchards, but at the landscape scale, they also showed that parasitism rates were higher in orchards surrounded by a small proportion of non-organic orchards. The same conclusion was reached in a study of codling moth predation rates, which decreased when the proportion of surrounding non-organic orchards increased (Monteiro et al. 2013).

For both predatory arthropods and parasitoids, positive effects of OF in the landscape have been observed on their abundance, their species richness, or directly on the biological control function provided. For example, the diversity of tachinid parasitoids was higher in landscapes with higher proportions of organically managed land, with an especially significant effect in arable fields, compared to grasslands (Inclán et al. 2015). The abundance of the spider *Cheiracanthium mildei* increased when the number of organic orchards within a radius of 50 m increased (Lefebvre et al. 2016). For carabids, Djoudi et al. (2018) showed that the proportion of organic fields in the landscape had a positive effect on their species richness.

It is also interesting to observe that the proportion of organic/non-organic farming in the landscape can affect biodiversity differently depending on whether the sampled field is farmed in organic or non-organic farming. Increasing the amount of OF in the landscape had a positive effect on spider abundance-activity in organic fields, but a negative effect in non-organic fields (Muneret et al. 2019). Moreover, the proportion of OF benefited the abundance-activity of spiders even more in landscapes with a low proportion of semi-natural habitats than in landscapes with a high proportion of semi-natural habitats (Muneret et al. 2019). In a non-organic agricultural landscape, locally organically managed fields may help promote biodiversity and associated ecosystem functions (Diekötter et al. 2010). These authors showed that abundance-activity of the granivorous carabid *Harpalus affinis* was 3.5 times higher in organic wheat fields compared to non-organically managed fields if these were surrounded by non-organic fields. The presence of organic fields in the landscape reduced the number of aphids in organic and non-organic fields and decreased leaf blotch densities, but only in non-organic fields (Gosme et al. 2012). These results illustrate the existing interactions between local farming practices and the context of the agricultural landscape and could refer to the intermediate hypothesis of landscape complexity (Tscharntke et al. 2012).

4.1.4 Birds

Four studies investigated the effect of OF at the landscape scale on birds, which include 32 studied relationships with OF at the landscape scale. Significant positive effects were observed in 56 % of relationships, non-significant and negative effects in 38 % and 6 % of relationships, respectively.

Studies showed that the proportion of fields managed in OF in the landscape increases community diversity (Hiron et al. 2013; Katayama et al. 2019) and abundance of birds (Katayama et al. 2019). These effects were accentuated in simplified and intensive landscapes, i.e., with large fields, undiversified crop successions, and few semi-natural habitats (Wrbka et al. 2008; Hiron et al. 2013). Furthermore, the effects of OF seemed to be stronger for farmland specialist bird species, in particular ground-nesting species such as skylark (*Alauda arvensis*) or lapwing (*Vanellus vanellus*) (Piha et al. 2007).

4.1.5 How can the effects of organic farming be explained?

The OF certification prohibits the use of synthetic pesticides and fertilizers (Seufert and Ramankutty 2017), substances that can have a direct negative impact on farmland biodiversity (Geiger et al. 2010; Sánchez-Bayo and Wyckhuys 2019), as for example, non-target taxa such as certain plants (Marshall 2002; Boutin et al. 2014) and arthropods (Sánchez-Bayo and Wyckhuys 2019). In the case of wild plants, the insertion of OF plots in the landscape could therefore benefit them by an overall reduction in herbicide pressure (Gaba et al. 2016). Thus, landscapes with high OF densities may allow the maintenance of less frequent species through a metacommunity effect, with fields under OF providing habitats for biodiversity. OF fields in the landscape represent habitats with higher floral diversity and abundance than non-organic fields (Holzschuh et al. 2008). As previously explained, this may be due to higher weed abundance and richness in response to reduced herbicide use as well as, in some cases, longer crop successions with temporary grasslands (Barbieri et al. 2017). Increasing weeds and floral resources through OF in the landscape can thus in turn improve bee populations and pollination service (Woodard and Jha 2017; Alignier et al. 2023). Indeed, as most solitary bee species have foraging distances of less than 1000 m, the presence of food resources near nesting sites is a critical parameter for the maintenance of solitary bee communities (Zurbuchen et al. 2010). Moreover, as insecticide use has direct effects on pollinators (Brittain et al. 2010), low insecticide pressure in landscapes with a high proportion of OF may also explain the greater diversity of pollinators. For birds, some studies point to limitations and highlight some discrepancies in the observed effects. For example, studies indicate that the positive landscape-scale effects of OF on birds can be explained by increased food availability (i.e., abundance and diversity of plants and invertebrates) that benefit both granivorous and insectivorous bird species (Katayama et al. 2019; Piha et al. 2007). Yet, if OF generally provides more resources in the landscape, it can also favor species that can act as pest, such as corvids, that attack crops after sowing as well as nests of other species (Gabriel et al. 2010), leading to questioning the cost-benefit balance in terms of species conservation.

4.2 Effects of crop succession in the landscape

Among the selected studies, only five investigated the effect of the diversification of crop successions in the landscape on biodiversity (Fig. 5b).

Three studies focused on natural enemies and crop pests, which include 46 relationships studied with crop succession at the landscape scale. In most cases (48 %), no significant effects of crop succession diversification were reported, while positive and negative effects accounted for 35 % and 17 % of cases, respectively. Bertrand et al. (2016) demonstrated that carabid abundance-activity increased with increasing temporal heterogeneity of crops, and that species with high movement capacities were favored by high spatial heterogeneity and those less mobile were positively influenced only by the temporal dynamics of crops. Rusch et al. (2014) showed that landscapes with longer and more diverse crop successions enhanced the abundance-activity of spiders and rove beetles, but not the species richness or evenness. As the authors point out, this does not necessarily imply increased levels of biological control because both positive (i.e., facilitation, mutualism) and negative (i.e., competition, intra-guild predation) interactions can occur between predator species. However, an increase in the intensity of crop successions in the landscape (i.e., shorter and less diverse crop successions) increased the within-field stability of biological control, but decreased the stability in parasitism rates of cereal aphids (Rusch et al. 2013). For pollinators, Le Féon et al. (2013) found that diversifying successions in the landscape would increase pollinator abundance and species richness and therefore pollination potential (Le Féon et al. 2013). Finally, Katayama et al. (2019) investigated the effect of crop succession in the landscape on birds and did not report significant effects on abundance and diversity.

The effect of crop successions at the landscape scale on biodiversity has been little studied, and mainly on the diversity of natural enemies and associated biological control. Crop successions drive the inter-annual spatiotemporal heterogeneity of the crop mosaic in the landscape and have significant effects on farmland biodiversity depending on species traits (Marrec et al. 2017). This is especially true for species that use crops during their life cycle or move between fields (Marrec et al. 2015). The interaction between landscape complexity and crop succession can drive the effectiveness of pest management. Indeed, Rusch et al. (2013) suggested that complex landscapes with short crop successions may increase natural pest control, while simpler landscapes associated with more diverse crop successions, including perennial crops, may decrease pest control. Species that share similar traits are likely to respond similarly to landscape features and management strategies aiming at decreasing agricultural intensification, such as OF or diversification of crop rotation (Rusch et al. 2014). However, the structural aspects of predator communities and the effectiveness of the biological control service itself would be governed by complex interactive processes between management strategies and landscape heterogeneity, which need to be considered in further ecological studies, and their relative impact assessed (Rusch et al. 2014). It is suggested that the combined management of semi-natural habitats (grasslands, hedgerows), crop successions, and other aspects of spatiotemporal landscape heterogeneity (e.g., field size) can enhance natural pest control in agricultural landscapes (Rusch et al. 2013, Montgomery et al. 2020).

4.3 Effects of farming practices in the landscape

Of the selected studies, a small number ($n = 9$) investigated the effect of farming practices in the landscape on biodiversity and reported taxa- and farming practice-dependent effects (Fig. 5c).

4.3.1 Natural enemies and associated pests

Three of these studies focused on the maintenance of biological control, which include 24 studied relationships with farming practices at the landscape scale. The extensiveness of farming practices at the landscape scale has a positive effect on the potential of biological control service in 50 % of the relationships and non-significant in 50 % of the relationships.

Concerning the intensity of pesticide use at the landscape scale, Bakker et al. (2021) found no effect on predation and parasitism rates. On the other hand, Jonsson et al. (2012) demonstrated that parasitoids were more sensitive to pesticide use and tillage at the landscape scale (associated with increased areas of annual crops), compared with their phytophagous hosts. This deleterious effect was even stronger in hyperparasitoids (fourth trophic level), suggesting an uneven response within food webs and reinforcing the idea that higher trophic levels are more sensitive to disturbances associated with land cover change. No-till in the landscape was also found as beneficial for biological control (Jonsson et al. 2014). For example, Rusch et al. (2011) found that rates of pollen beetle (*Meligethes aeneus*) parasitism by parasitoids were negatively related to the proportion of previous year's oilseed rape fields with conventional tillage at large landscape scales (radius >1.5 km). Here, the most significant effects are linked to soil tillage. In OF, soil tillage is frequently used to compensate for the absence of synthetic herbicides (Friedrich 2005). Therefore, OF and non-OF farming practices overlap considerably in this respect, and could explain why we did not observe as many significant effects of organic farming on natural enemies.

The extensiveness of farming practices (i.e., lesser use of pesticides and reduced tillage) seems to favor biological control. In fact, farming practices, such as ploughing and pesticide use, are known to have negative effects on natural enemies (e.g., Pekár 2012; Shearin et al. 2007). Thus, reducing the intensiveness of these practices at the landscape scale would increase the diversity of natural enemies and consequently the biological control.

4.3.2 Pollinators

Six studies investigated the effects of farming practices in the landscape on pollinators, which include 79 studied relationships with farming practices at the landscape scale. In most cases, studies reported no significant or positive effects (45 % and 38 % of relationships, respectively). Negative effects were reported in 17 % of relationships. The intensive use of pesticides at the landscape scale has a negative impact on wild bees (Le Féon et al. 2010; Basu et al. 2016) but this impact can be counterbalanced by semi-natural habitats playing the role of refuge habitats and providing alternative resources (Le Féon et al. 2010). More specifically, Carrié et al. (2017) demonstrated that a low intensity of farming practices at the landscape scale could mitigate the negative effect of habitat loss on bee species richness and abundance-activity, and could also support a positive complementary effect of semi-natural habitats and crops in promoting rich wild bee communities. This finding reinforces the recommendations of Bloom et al. (2021) who highlighted the need for changes in pesticide use at large spatial scales to reduce dependence on honeybees and maximize wild bee visitation to pollinator-dependent crops. Moreover, these results are in line with the effects of organic farming on pollinators since the ban on synthetic pesticides is one of the only criteria for organic farming certification.

To summarize, the majority of studies considered OF as the only means of characterizing the intensity of farming management, eclipsing the components of farming practices and crop succession. However, some studies reviewed here showed that integrating farming management into landscape-scale planning strategies could make landscapes more sustainable for biodiversity and ecosystem services. For example, increasing the proportion of landscape area without tillage can improve parasitoid diversity and biological regulation (Jonsson et al. 2012; Rusch et al. 2011). Nevertheless, some studies suggested that farming management needs to be strategically planned spatially (i.e., cooperation between farmers) to ensure that landscape-scale management can benefit biodiversity and amplify its positive effects at the local scale (Diekötter et al. 2010; Caro et al. 2016). For example, it is estimated that there is always an increase in total profits through landscape-scale management (i.e., farming management resulting from a cooperation between farmers) compared to farm-scale management when yield is dependent on ecosystem services provided by biodiversity (Cong et al. 2014).

5 Research perspectives for an improved consideration of farm management on a landscape scale

The articles we have identified and reviewed are still few in number, but show promising results as regard the effect of farming management at the landscape scale on biodiversity. Despite this, few studies have so far attempted to integrate farming management at this scale. In this section, we develop two possible limitations to explain the lack of studies, and potential solutions: (1) the difficulty of choosing relevant landscape metrics synthesizing farming management information and (2) the challenge of gathering farming management information at large scales. Last, we develop new research perspectives that would benefit from the consideration of farming management at the landscape scale.

5.1 The choice of relevant farming management metrics

In order to conduct this type of research involving consideration of farming management on a landscape scale, choosing the right farming management metrics to explain biodiversity patterns and processes can prove challenging. To date, the proportion of organic farming (OF) in the landscape has been the most widely used metric in studies and appears to be a good metric for explaining plant and pollinator patterns.

However, natural enemies and crop pests appear to be less affected by the amount of OF in the landscape, highlighting that characterizing farming management intensity only by farming system may not be as relevant for all taxa. This dichotomy between organic and non-organic farming is based on the principle that the overall intensity of farming management is lower in organic than in non-organic farming: more diversified successions, lesser use of chemical inputs, and more practice planning such as the use of crop residues or late sowing (Gosme et al. 2012; Baudron et al. 2015; Katayama et al. 2019). However, it has been shown that the opposition between organic and non-organic farming does not always make sense because of the diversity of farming practices used in each farming system (Gosme et al. 2012; Puech et al. 2014). In addition, the presence of OF in agricultural landscapes is often correlated with landscape heterogeneity (i.e., land cover diversity and average field size) (Levin 2007), and is more likely to occur in areas with low agricultural value (i.e., high proportion of semi-natural habitats) (Gabriel et al. 2009). These factors of "visible" heterogeneity are widely recognized as drivers of biodiversity (Estrada-Carmona et al. 2022). Thus, it seems possible to consider "visible" heterogeneity as a potential confounding factor, influencing both the implementation of organic farming in the landscape and biodiversity. It is important to note that only two selected studies compared the weight of landscape-scale farming management variables to traditional land cover variables (Gabriel et al. 2010; Puech et al. 2015). The first one showed that biodiversity was determined by location in the field (on average 35 % of the fixed effects fit depends on this factor), region (34 %), farm management (15 %), crop type (14 %), and landscape-scale management (10 %) (Gabriel et al. 2010). The second study mentioned that land cover (here, the proportion of semi-natural habitats) was a more important factor in explaining the diversity of natural enemies than OF, although the heterogeneity of OF indirectly benefited natural enemies through improved local habitat quality (Puech et al. 2015). These results are in line with the arguments of Tscharntke et al. (2021), who explained that OF has limited biodiversity benefits compared to land cover measures (i.e., increasing the proportion of semi-natural habitats, increasing crop diversity, and decreasing field size). However, additional studies would make it possible to reinforce this hypothesis and to approach the potential indirect effects of farming management, as pointed out by Puech et al. (2015). Another potential confounder is the possibility of spillover effects from non-organic fields to organic fields, and vice versa. For example, pesticides used in non-organic fields can drift to neighboring organic fields, potentially affecting their crops (Hanson et al. 2004).

These limitations of OF show the importance of considering farming practices and crop succession as such, and moreover, of using integrative and flexible methods to estimate the intensity of these farming practices. However, we then face difficulties in converting practice data into meaningful landscape metrics as soon as we wish to integrate more than one practice variable at a time. The most used method is the one of Herzog et al. (2006), adapted from Legendre and Legendre 1998) for estimating the intensity of a plot based on pre-selected farming practice variables (e.g., Le Féon et al. 2010). Nevertheless, this approach is not without its limitations, not least because it does not allow us to consider a large number of practice variables, especially if they are correlated with each other. To avoid a preliminary—and often subjective—selection of farming practice variables, using a principal component analysis (PCA) approach has been shown to offer the possibility of statistical and objective selection of variables at the plot scale (Armengot et al. 2011; Büchi et al. 2019), and can be extended for a landscape-scale consideration. This method enables the consideration of the interrelation among the farming practices, thereby allowing the integration of an unlimited number of variables. It provides the adaptability researchers require to estimate intensity indices for different hypotheses on the relationship between landscape intensity and some taxa and ecosystem services, involving potentially very different combinations of variables. In any case, care must be taken that the retained farming practice variables are consistent with hypotheses on the life cycle of the taxon under study. In addition, one must be cautious not to miss some components of farming management that would potentially impact the taxon under study and would therefore be relevant to consider in some study areas. However, agronomic and environmental contexts change from one study area to another, so the conclusions reached in one study may not be generalizable to all areas.

5.2 The challenge of collecting farming management data

Our findings revealed that farming management at the landscape scale has a significant impact on biodiversity. Despite this, few studies have so far attempted to integrate farming management at this scale. The challenge of gathering farming management information at large scales may explain the limited number of studies in this area and is discussed in this section.

Among the selected studies, farming surveys are the most widely used method for obtaining landscape-scale farming management information (34 %, $n = 36$ studies; see detailed results in Supplementary Material), although the method of information acquisition was missing in 20 % of the studies ($n = 21$ studies). We argue that farming surveys are indeed an effective way for providing accurate and comprehensive information on all farming practices, with a high level of description. Nevertheless, the approach is not without its caveats. The researchers in charge of the survey-based research we reviewed were only able to provide information on farming management for an average of half of the utilized agricultural area studied. Although the authors never mentioned the reasons why they were unable to survey the entire area, we recognize that collecting this information requires a great deal of effort.

Nevertheless, some components of farming management can also be obtained at the landscape scale by methods other than farming surveys, especially remote sensing (Bégué et al. 2018). However, despite the potential of remote sensing to get some components of farming management over large spatial areas and recent advances, our analysis found few studies using this method compared to farmer surveys (6.6 %, $n = 7$ studies). One of the major caveats of remote sensing, however, is the extensive post-processing required to associate index values with crop types and key farming practices. In terms of data accuracy, remote sensing is sensitive to environmental parameters such as weather—aircraft and UAV are sensitive to wind speed and direction, for example, and all sensors are affected by air temperature—or cloud cover, which can block the view of satellites, but also create shadows that disrupt signal acquisition, making it more difficult to identify farming management and analyze changes in farming management from one year to the next (Pei et al. 2019).

In addition, to facilitate access to data that can readily be used for research purposes, the creation of databases that can be made available should become widespread. Despite their importance for landscape-scale studies (26.4 % of the studies reviewed used—publicly or not—already available databases; $n = 28$ studies), their development is still rare, and difficult to access when they do exist. The only easily accessible databases are those on the referencing of organic farming plots (https://cartobio.org/), which also explains the greater number of papers that have considered organic farming at the landscape scale. Our analysis revealed that the use of databases on farming practices is ubiquitous in some countries such as the USA, but anecdotal in others such as countries in the European Union (e.g., Hashemi et al. 2018). However, improvements can be made in the EU, as farmers already georeference their crop surfaces as part of the Land Parcel Acquisition System (LPIS). EU countries already monitor certain components of farming management and make them publicly available, based on individual initiatives, for instance in France, certified organic fields (https://cartobio.org/) or the amount of plant protection products purchased at the level of each municipality (https://solagro.org/nos-domaines-d-intervention/agroecologie/carte-pesticides-adonis). Other initiatives are currently being developed to generalize the secure exchange of data on farming practices, such as the French agricultural data exchange platform API-Agro (https://platform.api-agro.eu/).

5.3 Towards new research perspectives

The integration of landscape-scale farming management into studies opens up new research perspectives that deserve more attention. Both to pursue investigations of types already conducted, but also in still more innovative directions. First, there is a need to better understand how the benefits of land use management of agroecosystems, particularly the implementation of agroecological infrastructures, can be impaired by the intensity of farming management at the landscape scale. Studies have already shown that the beneficial effect of the proportion of semi-natural habitats on biodiversity can be counteracted by the intensity of certain farming practices both locally and in the landscape (Tscharntke et al. 2016; Carrié et al. 2017). Nevertheless, only three studies reviewed in this article (i.e., 7.3 % of the studies) have integrated the interaction between landscape heterogeneities due to either land cover or farming management (Carrié et al. 2017; Le Féon et al. 2010; Rusch et al. 2013). The study of the interaction between farming practices on a landscape scale and the landscape context has therefore not been sufficiently studied, and better consideration of these two factors simultaneously would make it possible to answer some essential questions, i.e., How do they covariate? How do they jointly influence biodiversity patterns? Given the importance of this hidden heterogeneity caused by practices, it seems essential to consider them in order to better understand the effects of the landscape context on biodiversity. Considering these two aspects simultaneously will inevitably lead to improved advice in terms of landscape planning, whether to ensure the efficiency of green infrastructures, or to implement a transition towards more agro-ecological farming practices.

Second, it seems important to evaluate the effect of the configuration of farming practices in the landscape in addition to their composition. To our knowledge, no study has looked at the effect of the configuration of farming practices on biodiversity—unlike land cover, for which the importance of its configuration for biodiversity is well known (Estrada-Carmona et al. 2022). Future research questions could focus on the aggregation of farming practices with each other. For example, consider whether it is more favorable for biodiversity to have plots with intense farming practices grouped together in the same geographical area or whether they should be interspersed with less intensive agricultural plots. In a context of agricultural transition, it is unlikely that all farmers in a given area will follow the same trajectory, nor that this is feasible or desirable, for example, in terms of supply chains. As a result, addressing this perspective could also enable us to better plan the spatial organization of these changes, to benefit production and biodiversity conservation.

Finally, it is crucial to explore the temporal effects of farming practices on biodiversity patterns and dynamics in the landscape in greater depth. Although one study considered in this article has explored the temporal effect of farming practices in the landscape (Rusch et al. 2011), it only briefly looked at farming practices in the previous year. Given our knowledge of the temporal effect of farming practices at the local scale, we could expect a landscape-wide effect. For instance, Marrec et al. (2015) and Bertrand et al. (2016) have highlighted the effects of crop succession and previous crop on the abundance and diversity of natural enemies. Therefore, it is essential to study how rotations impact biodiversity on a large spatial scale to improve the management of agricultural landscapes.

6 Conclusion

The small number of studies investigating the effect of farming management at the landscape scale on biodiversity does not allow for recommendations for the preservation of biodiversity and associated ecosystem services. We therefore call for greater consideration of farming management at the landscape scale by ecologist and agronomist, while recognizing the need to make farming management data available for academic research.

Our analysis reveals that when the intensity of farming management is not restricted to a few simple indicators based on the presence of a particular crop in the landscape or in crop succession at the field scale, it is generally approximated via the dichotomy between organic and non-organic farming in the landscape. However, this approach does not consider the variability of farming practices and crop successions within each farming system and may not be sufficient to explain biodiversity patterns and dynamics across certain taxa and territories. Based on the reviewed articles, the opposition between organic and non-organic farming seems thus relevant to study the impact of farming management on weeds, pollinators, and birds, with taxa-specific responses, but maybe not for pests and natural enemies. The response of the latter may in fact be more a function of parameters independent of organic farming specifications, such as tillage intensity.

The low consideration of farming management at the landscape scale is an important knowledge gap, given that it can potentially provide important levers of preservation of biodiversity and ecosystem services in agricultural landscapes. Extensification of farming management at the landscape scale could reduce the pest population and its impact on crops by enhancing abundance and diversity of natural enemies, and thus lower the need for chemical protection. To achieve a more sustainable agriculture, both in terms of productivity and environmental impact, there is a need to enforce stricter environmental regulations. Many policy makers and international organizations also support the idea that landscape-scale management and stakeholder cooperation are essential for sustainable agriculture. Despite these recommendations, to date, few actions have been implemented at the landscape scale by farmers, agronomic institutes, or agricultural advisory offices, but above all little academic research has been carried out to support the implementation scientifically.

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