BURLEIGH DODDS SERIES IN AGRICULTURAL SCIENCE

Managing biodiversity in agricultural landscapes

Conservation, restoration and rewilding

Edited by Dr Nick Reid and Dr Rhiannon Smith, University of New England, Australia

burleigh dodds SCIENCE PUBLISHING

The impact and design of field margins in promoting biodiversity in agricultural landscapes

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1 Introduction

The transformation of agricultural landscapes involves the conversion of forests, scrub, and grasslands into fields, and pastures, as well as the expansion and amalgamation of preexisting fields to enhance farming efficiency (Tscharntke et al., 2005). More recent changes have resulted in more homogeneous agricultural landscapes with greater fragmentation of natural habitats and resulting negative effects on biodiversity. Insects and animals displaced by land-use change must find shelter in remaining fragmented patches of semi-natural land, and those that do not perish (because they do not find alternative areas) must travel further to find appropriate unoccupied habitat and food resources (Marshall and Moonen, 2002). While the trend has been to simplify agricultural production systems, heterogeneous agroecosystems with diverse and connected natural areas are potentially more resilient than simple, homogeneous landscapes (e.g. in adapting to disturbances such as more extreme weather events associated with climate change) (Tscharntke et al., 2005). As a result, the importance of uncropped natural and semi-natural areas in agricultural landscapes is better recognized. For example, the European Union Common Agricultural Policy (CAP) for 2023–2027 requires that at least

http://dx.doi.org/10.19103/AS.2024.0134.08

Chapter taken from: Reid, N. and Smith, R. (ed.), *Managing biodiversity in agricultural landscapes: Conservation, restoration and rewilding*, pp. 197–220, Burleigh Dodds Science Publishing, Cambridge, UK, 2024, (ISBN: 978 1 80146 454 3; www.bdspublishing.com)

4% of eligible land be devoted to biodiversity and landscape protection on all farms of at least 10 ha (European Commission, 2023).

A cost-effective, minimally invasive, and efficient solution is to set aside field margins, or improve existing field margins (sometimes known as buffer strips) to create a network of semi-natural vegetation across the farming landscape (Lagerlöf et al., 1992). Leaving field margins uncropped can be viewed, in some circumstances, as an advantageous trade-off for farmers, as these areas are typically less fertile and more prone to drought, shading, and lower yields than other parts of the field (Pywell et al., 2005). Nevertheless, the biodiversity supported by field margins is still only a fraction of what would have been present before agriculture.

A field margin has been defined as 'the whole of the crop edge, any margin strip present and the semi-natural habitat associated with the boundary' (Greaves and Marshall, 1987). Field margins have also been defined as linear zones of semi-natural vegetation located at arable field boundaries, usually comprising a boundary structure (Marshall and Moonen, 2002). The boundary may be a fence, line of trees, hedge, wall, terrace, track, watercourse, grass strip, or a combination of these elements. In arable landscapes, there is almost always some form of margin dividing individual fields from one another, as well as separating fields from features such as roads, tracks, and watercourses. In some situations, the boundary is simply another type of habitat (e.g. a wooded area). A variety of plant communities can occur within field margins (Marshall, 2005). Figure 1 shows the common components of an arable field margin, including the boundary structure or barrier, vegetative area or field margin strip, conservation headland (a part of the field planted with a crop but where fertilizer and pesticide application is reduced in order to promote greater floral and faunal diversity and protect the field margin) and the crop edge.

Field margins vary widely in their size, shape, composition, and level of plant diversity. These differences affect the ecosystem services these margins provide (Cirujeda et al., 2019; Pallavicini et al., 2020). Figure 2 provides several different examples of field margins in cereal agroecosystems.

Past studies have utilized simple classification systems for field margins, such as differentiating between woodland and ruderal vegetation (species that colonize uncultivated or unused land) (Marshall and Moonen, 2002). A study by Cirujeda et al. (2019) classified field margins (referred to as 'field boundaries') based on five descriptors:

- Presence of a bank;
- Width;
- Percentage cover of woody and evergreen perennials;
- Presence of a stonewall; and
- Presence of trees.

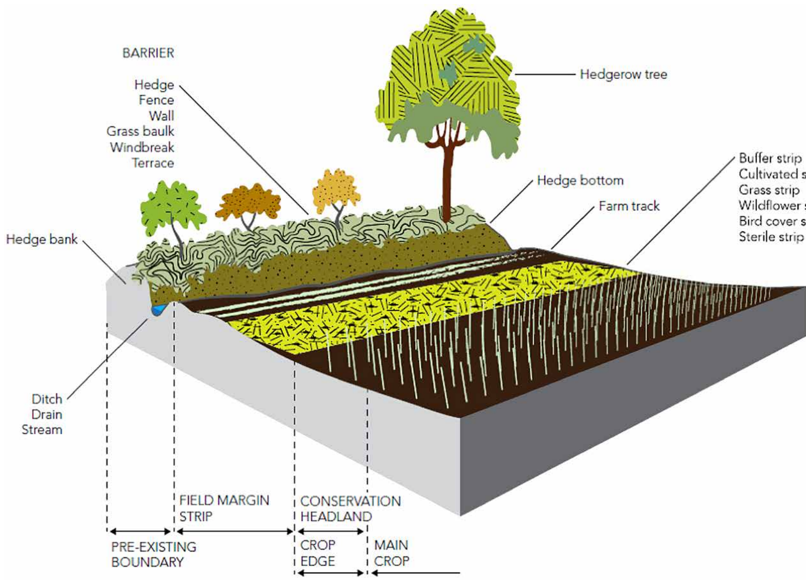


Figure 1 The common components of an arable field margin. Source: Greaves and Marshall (1987) and Marshall and Moonen (2002).

Field margins are categorized based on level of complexity, ranging from structurally simple (flat, narrow margins dominated by annual species) to structurally complex (more than 3 m wide, presence of a bank, dominated by woody and evergreen perennials) (Fig. 3).

Field margins can be permanent or temporary. Field margins comprising a diversity of annual herbaceous species, sometimes referred to as floral strips, can be a lower-investment alternative than permanent field margins comprised of perennials. These types of margins also provide a variety of ecosystem services but have been found to be less effective than perennial-dominated field margins in the delivery of some key ecosystem services (e.g. as a barrier to wind and in providing permanent habitats) (Uyttenbroeck et al., 2016). Floral strips can be rotated throughout the field, potentially as part of a larger crop rotation plan. Strips that are rotated annually may not be as effective in terms of pollinator support (McHugh et al., 2022), but may be a compromise solution when permanent land dedicated to field margins is not available. This chapter reviews the ways field margins benefit biodiversity, their design and management, enhancement with seed mixes, as well as economic aspects.

2 Beneficial impacts

This section focuses on the benefits of field margins in terms of enhancing biodiversity in agroecosystems by supporting plant diversity, increasing the

Figure 2 Examples of field margins in cereal agroecosystems (Catalonia, Spain, 2014–2016). (a) Flat margin between two cereal fields (mean width ≈4 m; ≈5% shrubs and trees). (b) Sloped, rocky margin between two cereal fields (mean width ≈4 m; only herbaceous plants). (c) Sloped margin between fallow land and a cereal field (mean width ≈5 m; ≈10% shrubs and trees). (d) Flat, rocky margin between a low-traffic road and a cereal field (mean width ≈4 m; ≈7% shrubs and trees). (e) Sloped margin between two cereal fields (mean width ≈3 m; ≈30% shrubs and trees). (f) Sloped, rocky margin between two cereal fields (mean width ≈8 m; ≈15% shrubs and trees). (g) Sloped margin between a low-traffic road and a cereal field (mean width ≈5 m; ≈30% shrubs and trees). (h) Flat margin between two cereal fields (mean width ≈3 m; only herbaceous plants). (i) Sloped, rocky margin between two cereal fields (mean width ≈4 m; ≈40% shrubs and trees).

abundance and diversity of beneficial insects, providing wildlife corridors, and contributing to landscape heterogeneity.

Field margins can enhance plant species richness, including rare species, and diversity. They are promoted as a means of increasing biodiversity in an agricultural system, offering many well-documented ecosystem services, including the provision of habitat and resources for beneficial insects (both pollinators and natural enemies of pests), acting as wildlife corridors, as well as other benefits for farming operations, environmental conservation, recreation, and rural development (Altieri, 1995; Balzan et al., 2014; Crowther et al., 2023; Dover, 2019; Hackett and Lawrence, 2014; Hannon and Sisk, 2009; Lagerlöf et al., 1992; Marshall and Moonen, 2002; Marshall, 2005; Ryszkowski, 2001; Sutter et al., 2018). The potential functions and roles of semi-natural field margins are summarized in Table 1.

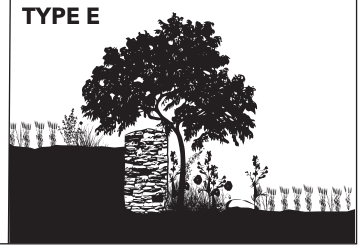
%WEP <60% / >60%	SLOPE FLAT or BANK	WIDTH <3m >3m	TREE	STONE WALL	FINAL STRUCTURE
<60%	FLAT	<3m	NO	NO	TYPE A 
<60%	BANK	<3m or>3m	NO	NO	TYPE B 
>60%	BANK	<3m or >3m	NO	NO	TYPE C 
>60%	BANK	<3m or >3m	YES	NO	TYPE D 
-	-	-	NO/YES	YES	TYPE E 

Figure 3 Field boundary categories (WEP, woody and evergreen perennials). Source: Cirujeda et al. (2019).

2.1 Plant diversity

Declining plant biodiversity is a widespread phenomenon occurring in different habitats and geographic regions across the world (Eichenberg et al., 2020). Transforming an undisturbed landscape into an agroecosystem displaces naturally occurring plants in that landscape (Dorado and López-Fando, 2006; Mas et al., 2007; Romero et al., 2008). Once a species is removed from a landscape, it is possible that it either takes many years to re-establish or

Table 1 Potential functions and roles of field margins (Altieri, 1995; Balzan et al., 2014; Crowther et al., 2023; Dover, 2019; Hackett and Lawrence, 2014; Hannon and Sisk, 2009; Lagerlöf et al., 1992; Marshall and Moonen, 2002; Marshall, 2005; Ryszkowski, 2001; Sutter et al., 2018)

Function	Role
Agronomy	To define the field edge
	To increase water retention in the field (reduce run-off)
	To promote ecological stability in crops
	To provide shelter for crops, particularly as windbreaks
	To reduce soil erosion by wind or water
	To enhance crop pollination services
	To facilitate biological pest control and reduce crop damage
	To create microclimates
	To provide organic matter and improve soil health
	To optimize crop nutrition (by helping to retain fertilizers in the field)
	To increase crop yields
	To keep animals (or trespassers) in or out
	To provide shelter for animals
	To provide a source of fruits or wood
Environment	To promote biodiversity and farm wildlife conservation
	To act as a refuge or corridor for beneficial plants and animals
	To support the biodiversity of soil microorganisms
	To buffer pesticide drift
	To reduce pesticide use (by facilitating biological pest control)
	To reduce the movement of fertilizer and other pollutants, especially in run-off (i.e. reducing eutrophication)
	To maintain landscape diversity
	To improve soil carbon sequestration
Recreation and rural development	To provide access (i.e. walking or driving paths)
	To promote populations of game species and facilitate hunting activities
	To enhance landscape aesthetics

never becomes re-established at all (Firbank, 1999). Field margins provide an opportunity for threatened wild plant species to persist across the agricultural landscape (Fried et al., 2009). Field margins may often harbor naturally occurring plants that can play a significant role in supporting local biodiversity and ecosystem services (Norris and Kogan, 2005).

2.2 Supporting beneficial insects: pollinator and pest predator species

Intensively managed agriculture has had negative effects on beneficial insects, including pollinators and natural enemies of pests, due to loss of habitat and food resources, increased agrochemical use, and introduction of alien species (Hopwood, 2008; Koh et al., 2016). Field margins potentially provide nesting habitats for beneficial insect species, continuity and diversity of floral resources as a food source, and can act as a potential refuge from pesticides and other agrochemicals (Nicholls and Altieri, 2013; Requier et al., 2015).

We are currently experiencing a 'global pollinator crisis' – a marked reduction in the diversity, density, and distribution of pollinators around the world (Shivanna et al., 2020). Maintaining diverse and abundant communities of effective pollinators is crucial for successful agricultural production and sustaining native plant diversity (Balzan et al., 2014).

In many circumstances, wild pollinators are key for stable crop pollination or are an important supplement to managed honeybees. For example, buzz-pollinated crops, which include species from 65 families and comprise tomatoes and potatoes, cannot be pollinated by honeybees and rely on certain wild bee species with the ability to use vibration to extract pollen from the anthers (De Luca and Vallejo-Marín, 2013). For seed production, specialist bees or bees with preferred diets may be required, such as *Megachile rotundata*, which is used extensively to pollinate alfalfa (Goettel et al., 1991). In addition, because of the instability of honeybee colonies in recent decades as a result of *Varroa* mites, the spread of viruses, and colony collapse disorder, the importance of wild pollinators for stable crop pollination has become increasingly evident (Drummond, 2012; Buchmann, 2022). Field research with a range of crops (e.g. coffee and watermelon) has suggested that abundant and diverse native bee communities can compensate for declining honeybee populations (Klein et al., 2003; Winfree et al., 2007). However, compared to honeybees, solitary bees do not travel nearly as far and have inherent survival challenges in agricultural landscapes, such as reduced spatial flexibility and recolonization ability, and are not able to forage for resources at larger spatial scales (Tscharntke et al., 2005).

The negative effects of agriculture on wild bees and other pollinator populations have been well documented (Koh et al., 2016; Le Féon et al., 2010). Several entomologists and ecologists have hypothesized that an increased separation from critical floral and nesting resources is likely the main cause of wild bee declines and, consequently, reduced pollination services (Nicholls and Altieri, 2013). Monocultures, fields of a single variety of a single species often grown on a large scale (Cooper et al., 2007), have resulted in loss of habitat and reduced floral resources (i.e. lower floral diversity with greater fragmentation)

(Kline and Joshi, 2020). Monocultures of flowering crops usually provide only a few weeks of abundant food for wild pollinators (Nicholls and Altieri, 2013), and in some countries, the expansion of agricultural land devoted to wind-pollinated grain crops has greatly reduced forage options (e.g. the 'corn belt' in the Midwestern USA) (Cane and Tepedino, 2001).

Pollinators require nearby nesting areas and floral resources that bloom before and after the main crop (Nicholls and Altieri, 2013). Numerous studies have shown that field margins help to preserve both pollinator abundance and diversity within agroecosystems, and pollination services in general (Pywell et al., 2005; Carvell et al., 2007; Hannon and Sisk, 2009; Marini et al., 2012; Morandin and Kremen, 2013). Field margins with diverse plant species offer several ecosystem services to support pollinators. Firstly, they have the potential to provide continuous nesting and floral resources. A diversity of flowering plants provides pollinators with a stable supply of pollen, nectar, and floral oils (Hannon and Sisk, 2009). A consistent floral supply is especially critical early and late in the year and when the main crop is not in bloom. For example, most solitary bee species hibernate over winter and need food sources immediately after emerging in the spring. Bumblebee queens also require late-season floral resources to build up their reserves before hibernating (Nicholls and Altieri, 2013). Because different pollinator species have different floral preferences, a high diversity of plant species, preferably flowering all year long depending on the climate, is required to support a high diversity of pollinator species (Nicholls and Altieri, 2013). Field margins indirectly support crop pollination services. Since bees return to fixed nest sites after foraging, the proximity of nesting habitats to agricultural fields is critical for pollinating crops (Ricketts et al., 2006). Indeed, wild bee pollination services have been shown to have a negative relationship with distance from the natural habitat (Kwaiser and Hendrix, 2008). For example, Kremen et al. (2004) found that pollination services from native bees were positively related to the proportion of upland natural habitat in the vicinity of farm sites in California. A model based on the data determined that if farmers were to rely entirely on native bee communities for pollination, their farms would need to be situated in areas containing at least 40% natural habitat within a 2.4 km radius or at least 30% within a 1.2 km radius.

Natural enemies, including parasitoids and predators, can help regulate insect pest populations to levels that minimize plant damage (Coppel and Mertins, 1977). Integrated pest management strategies attempt to increase plant diversity to subsequently increase the abundance of natural enemies (Harvey and Eubanks, 2005). In addition to helping to conserve pollinators, naturally occurring plants in field margins provide hibernation services for natural enemies of pests (Altieri, 1995). By conserving wild plants in field margins, populations of these beneficial insects can be maintained or enhanced by providing shelter, breeding sites, and food, either directly (i.e. with plant matter, pollen, or nectar) or by hosting their preferred insect food sources (Norris and Kogan, 2005). These plants also provide continual shelter during times of the year when the crop is absent or not able to support insects (e.g. during the early stages of growth). For example, a study by Ndakidemi et al. (2022) found that natural enemies (i.e. lady beetles, assassin bugs, hoverflies, and lacewings) benefited from field margin plants in smallholder bean farming systems in sub-Saharan Africa. They observed that certain plant species were preferred by different natural enemy groups since they provided different benefits.

2.3 Wildlife corridors

Field boundaries provide habitat for many species. In addition to plants and beneficial insects, field margins may also support a diverse fauna, including other invertebrates, mammals, and birds (Marshall and Moonen, 2002). Unfortunately, suitable habitats have become more fragmented due to field amalgamation, resulting in large gaps and discontinuous networks (Barr and Gillespie, 2000).

In addressing this problem, another benefit of field margins is that they can act as wildlife corridors, connecting otherwise isolated patches of suitable habitat (Rosenberg et al., 1997). A network of linear field margins can facilitate the movement of fauna and flora throughout the landscape. They can link patches of fragmented habitats to provide sufficient territory for animals to maintain population integrity or facilitate recolonization of a habitat after local extinction (Marshall and Moonen, 2002; Cirujeda and Pardo, 2020). For example, wood mice move out of fields and into woodlands after harvest. A network of field margins would help them to move and disperse safely (Feber and Macdonald, 2013).

Ideally, margins should link to each other and link other habitats across the farm. Increasing these linkages will help to maximize their effectiveness as movement corridors for wildlife around the farm and across the landscape (Feber and Macdonald, 2013). The likelihood of a field margin functioning as a wildlife corridor is dependent on having larger remnant patches in the network. Without the remnant patches, the role of field margins acting as wildlife corridors is greatly diminished (Marshall and Moonen, 2002; Bennett, 2003). It is also important to note that the corridor function provided by field margins may not be equally beneficial for all species. Specific benefits have not been quantified for the majority of species (Marshall and Moonen, 2002), and a corridor for one species may be a barrier for another (Dover and Settele, 2009). Corridors can also have unintended negative effects. Five categories of potential negative ecological effects on native biodiversity have been identified (Haddad et al., 2014):

- Dispersal of species antagonistic to species that are conservation targets (predators or pathogens; e.g. increased rates of seed predation by small mammals);
- Creation of negative edge effects (e.g. a change in corridor habitat leading to an increase in parasitic brown-headed cowbirds *Molothrus ater*);
- Spread and increased abundance of invasive species;
- Spread of disturbances (e.g. fire); and
- Synchronization of population dynamics (because connecting patches increases the likelihood of simultaneous extinction).

However, a literature review and meta-analysis by Haddad et al. (2014) to evaluate the prevalence of negative effects of habitat corridors concluded that any negative effects were relatively small and manageable compared to the large positive effects. For example, they found no evidence that corridors increased non-native species invasion, although they noted that this had not been well studied.

2.4 Ecosystem service multifunctionality

In addition to supporting plant diversity, increasing the abundance and diversity of beneficial insects, and providing wildlife corridors, field margins can provide numerous other ecosystem services within agroecosystems (Table 1). When assessing the impact of field margins in an agroecosystem, it is important to consider the combined contribution of multiple ecosystem services, rather than focusing on a single ecosystem service. The ability of a management strategy to simultaneously provide multiple ecosystem services is referred to as ecosystem service multifunctionality (Manning et al., 2018). This is an important consideration when calculating the return on investment of implementing or restoring field margins.

2.5 Contribution to landscape heterogeneity

It is important to recognize the overarching importance of biodiversity in restoring complexity to landscapes simplified by more intensive, monocultural forms of agricultural production (Tscharntke et al., 2005; Morrison et al., 2017). Field margins should be one component in a wider set of measures to restore heterogeneity. Other measures include permanent set-aside land where natural vegetation can recover (toward the state represented by climax vegetation in uncleared areas), which can then be connected by field margins, as well as practices such as more frequent rotations involving a wider range of crops flowering at differing times, or introducing greater diversity through intercropping and the use of cover crops (Cirujeda and Pardo, 2020).

It is important to be aware that setting aside new field margins may not always be the most appropriate conservation solution. In general, more diverse field margins support more diverse pollinator communities (Brittain et al., 2022). However, less benefit is seen in landscapes that are already heterogeneous (Scheper et al., 2013; Morrison et al., 2017; Wix et al., 2019). In these landscapes, conservation efforts focused on maintaining the quality of existing natural areas may be best (Carvell et al., 2011). More generally, the role of field margins and other practices promoting biodiversity in farming landscapes can be viewed in the context of the wider debate about the relative benefits for biodiversity of a 'land sparing' strategy (increasing efforts to preserve or restore natural landscapes while concentrating farming in a smaller area and focusing on improving productivity) versus a 'land sharing' strategy (where farming practices are modified to accommodate greater biodiversity). At a global level, a significant body of research seems to favor the benefits of land-sparing over land-sharing, though some argue that the two approaches need not be mutually exclusive, with land-sharing practices ensuring greater connectivity between conservation areas separated by farmland, for instance (Grass et al., 2019; Balmford, 2021).

3 Design and management

As noted, field margins come in all shapes and sizes. Some are carefully designed, constructed and maintained by intentionally seeding carefully selected mixes of diverse plant species, adding boundary or other features, and with periodic mowing to control dominant species and maintain floral diversity. Other marginal areas are simply left undisturbed. In general, a one-size-fits-all conservation approach is not an efficient way of spending the limited funds available for preserving biodiversity on farms. The ideal approach should be adapted to the landscape context and local flora, as well as any species groups being targeted (Batáry et al., 2011). Field margins should not compete with the crop for light, moisture, or nutrients, and they should not harbor weeds, pests, or diseases (Marshall and Moonen, 2002).

3.1 Protecting field margins

It is important that field margins be protected from agrochemicals applied to crops in the main field area. Long and Krupke (2016) found that dust or spray drift from pesticides could accumulate in margins, settling on and contaminating flowers and their pollen – potentially poisoning insects (Nicholls and Altieri, 2013). Pesticides making their way to field boundaries can also cause changes in plant communities, with resistant species becoming more dominant (Ryszkowski, 2001), the disappearance of vulnerable species (Schmitz et al., 2014) and overall lower plant species richness (Marshall, 2004).

This can be attributed to the damaging effects of pesticides on the natural plant community, such as flower suppression, reduced seed production, and reduced growth affecting plant fitness and competitive ability (Schmitz et al., 2014). Schippers and Joenje (2002) showed that excessive nutrients such as nitrogen in field boundaries, resulting from spray drift during fertilizer application, had a negative effect on plant species diversity as well as on surrounding water bodies. Fertilizers can favor plants with high nutrient uptake (e.g. tall grasses) and decrease the frequency of small and subordinate species, which are replaced by fast-growing species and species with large leaf canopies (Schmitz et al., 2014). Fertilizers can also have a particularly adverse effect on rare wild plants (Ryszkowski, 2001). Other types of disturbances can be inadvertent, as a result of adjacent cultivation, or intentional (e.g. from tilling or cutting practices) (Ryszkowski, 2001). Margins should be minimally tilled and ideally left *in situ* over multiple years (Fried et al., 2009; McHugh et al., 2022).

Enlarging margins (to at least 2 m in width) is one solution to reduce disturbances, agrochemical drift, and edge effects, as well as setting aside a spray-free zone or conservation headland in the adjacent field (Lagerlöf et al., 1992; Haddad et al., 2014). Moonen and Marshall (2001) found that sown grass strips along the edge of margins protected margin flora and facilitated greater species richness by providing extra distance from farming operations. Gove et al. (2007) found that the impacts of pesticide drift on non-target plants in woodland margins in the United Kingdom were sufficient to affect community structure, but only within the first few meters of the woodland edge. They determined that a 5 m no-spray buffer zone would be very likely to render spray drift and fertilizer overspread impacts negligible and would protect the majority of woodland species from the impacts of agrochemicals applied to adjacent land. They also found that a 2 m buffer would still have considerable benefits but recommended a precautionary approach (5 m buffer) to give valuable sites as much protection as reasonably possible.

3.2 Configuration

In order for beneficial insects and other wildlife to thrive in agroecosystems, they require suitable nesting sites and materials (e.g. vegetation, tree cavities, soil substrates), sufficient and continuous floral resources within their flight range (e.g. pollen, nectar, and floral oils) and, if necessary, suitable sites for overwintering (Hannon and Sisk, 2009; Le Féon et al., 2016). Common substrates found in margins (e.g. bare ground, dry branches, hollow logs, and earth banks) provide ideal nesting sites for various pollinator species (Nicholls and Altieri, 2013).

Boundary structure, such as width and the presence or absence of a bank, has been found to drive plant community composition (Hovd and Skogen, 2005; Schippers and Joenje, 2002). Features such as banks also help to reduce disturbances from farming practices (Cirujeda et al., 2019). Wider margins have been found to host more diverse plant communities than narrower margins (Pallavicini et al., 2020; Schippers and Joenje, 2002). This is not just because wide margins buffer against agrochemical drift (one of the major causes of diversity decline and margin homogenization) but also because species richness tends to increase with increasing area (Schippers and Joenje, 2002). Studies have found that wider field margins better support wild pollinator abundance and diversity (e.g. Rands and Whitney, 2010; Häussler et al., 2016; Morrison et al., 2017).

3.3 Weed control

One common concern of farmers is that margins may encourage pernicious weeds, which can spread into the crop (Marshall and Moonen, 2002). This reflects a wider concern amongst some farmers that field margins are sources of competing species (e.g. competing with the crop for water, nutrients, and light) as well as a potential source of pests (Cirujeda and Pardo, 2020). Such concerns could result, for example, in the application of herbicides to margins, resulting in the perpetuation of species-poor plant communities with negative impacts on species biodiversity, as well as the need for ongoing management (Feber et al., 1996).

Marshall (2004) claimed that the perception of weed species in field margins invading crops is misguided and that the amount of important weed species that originate in margins is limited. However, this is not always the case (Cirujeda et al., 2013). What has become clear is that whether or not weeds thrive in the field margin depends on the level of disturbance and margin width (Cirujeda et al., 2019). High levels of disturbance from machinery or agrochemical drift tend to promote more annual species (often weeds) and impede the growth of perennial species (De Cauwer et al., 2008; Marshall, 2009; Schippers and Joenje, 2002). Cirujeda et al. (2019) found that structurally simple, flat, and narrow field boundaries contained high abundances of many of the weed species found in the center of the adjacent field. They also found that more complex and wider field boundaries with a slope and high percentages of woody and evergreen perennials had a lower probability of hosting the main weeds present throughout adjacent fields.

Marshall (2004) found that, when winter annuals dominate boundary flora, field margins may have a more significant influence on the presence of weed flora in adjacent fields. In these circumstances, specialized margin management strategies should be applied, such as sowing non-invasive perennial species to help provide a barrier against the spread of weeds from the field edge into the crop, or having a grassy strip beside the margin (Marshall and Moonen, 2002).

Removal or mowing of noxious weeds in field margins may be necessary in some cases.

4 Enhancement: sowing with seed mixes

Margins that are simply allowed to regenerate naturally are more cost-effective and involve lower maintenance for farmers. In some situations, maintaining natural field margins may be sufficient to support a robust wildlife community (Williams et al., 2015). However, plant species richness tends to be lower in more intensively managed agricultural areas (Görzen et al., 2021). The impoverished flora persisting in arable lands typically comprises species that can tolerate intensive farming practices, and these species often do not provide suitable forage resources for bees or other pollinators (Pywell et al., 2005). In highly degraded agricultural landscapes, floral density, richness, and specific floral traits can be increased by supplementing naturally occurring vegetation with sown plant species.

Many studies have found that sowing field margins with carefully selected wildflower mixtures increases the abundance of pollinators within intensively farmed agricultural landscapes (Feber et al., 1996; Pywell et al., 2005). For example, Pywell et al. (2005), in the UK, observed that sowing field margins with wildlife seed mixtures had the potential to provide the best foraging habitat for bumblebees. They found that all bumblebee species except one were significantly more abundant on the margins sown with the wildlife seed mixtures (mean of 28.6 ± 6.6 bumblebees per 100 m) compared with conventional cereal field margins (mean of 0.3 ± 0.1). However, they emphasized the importance of including preferred forage species for the target species in the mixture (in this case, *Trifolium pratense*, *Lotus corniculatus*, and *Borago officinalis*). Plant species differ in their potential contribution to ecosystem services, so increasing the diversity of species enhances the ability of the floral margin community to deliver a range of ecosystem services (Tscharntke et al., 2005). Sowing field margins with flowering plants, particularly native species, can help to increase the abundance and diversity of pollinators (Hopwood, 2008; McHugh et al., 2022).

Many seed mixtures marketed for bee or pollinator conservation are available for purchase, some of which contain specific host plants for the larval stages of butterflies, moths and beetles (Tscharntke et al., 2005). However, some studies have found that flowers planted in dense clumps have a stronger attractive potential for pollinators compared to those that are highly intermingled, as is the case with seed mixtures (e.g. Ohashi and Yahara, 1999; Grindeland et al., 2005; Barbir et al., 2014; Morrison et al., 2021). A higher density of species increases the probability that insects detect specific flowers from a distance (e.g. via visual or olfactory cues) while also increasing the ease of travel from one plant to another (Morrison et al., 2021). These results indicate that it would be more beneficial, in terms of attracting pollinators, to sow single species in clusters. However, the relationship between pollinator visitation and floral density is complex. Some studies have found no or even negative effects of high floral density on pollinator visitation rates to flowers (Essenberg, 2012).

According to Carreck and Williams (1997), the practical requirements for a sown floral mixture are that it should establish well, require minimum seedbed preparation, be able to compete with arable weed species, not require agrochemicals (e.g. fertilizers), and be affordable. The established plant system should also be self-sustaining and resilient. When considering which plant species to sow and in what proportion, it is important to consider providing not just overall species diversity, but functional diversity, that is, a high distribution of functional traits within the field margin community (Navas, 2012). Increased biodiversity enhances ecosystem functioning if new species add unique and complementary traits to the overall floral community (Tscharntke et al., 2005). Functional traits include flowering time and duration, floral display size and color, nectar and pollen content, leaf area, and root structure, all of which can be important in supporting insects and other species (Creswell et al., 2019). A community with both functional trait diversity and redundancy (i.e. the presence of multiple species with a similar effect on a given ecosystem function) is more stable and able to reorganize more effectively after a disturbance (de Bello et al., 2021).

In general, a variety of floral colors and shapes will attract a diverse community of beneficial insects (Tscharntke et al., 2005). However, the species composition of a community of beneficial insects is highly affected by fine-scale habitat variations (e.g. the presence or absence of a particular flower species) (Hannon and Sisk, 2009). Flowering plant species possess particular morphological and physiological characteristics that attract certain groups of floral visitors over others (Bosch et al., 1997). The choice of plant species to sow should thus be context specific. Margins can be sown with plant species known to support specific beneficial insects or wildlife species that are important within an agroecosystem, or those in need of conservation (Norris and Kogan, 2005).

The floral rewards offered by particular species are important in determining how flower-visiting insects partition themselves among available flowering plants (Bosch et al., 1997). In order to examine the capacity of certain flower species to attract particular beneficial insects, it is essential to consider which floral traits are important. Hegland and Totland (2005) pointed out that flower-visiting insects do not choose a flower species based on any one floral trait. Their research shows that flower species with similar combinations of traits have a comparable attractiveness to insect visitors, indicating that several floral traits can affect the flower choice of insects. Nectar (for carbohydrates) and pollen (for protein, vitamins, and minerals)

(Sammataro and Yoder, 2011) are usually considered the ultimate attractions driving insect visitors, while color, odor, and shape act more like 'cues' to help insects discriminate between the variety of reward sources available (Real, 2012).

The quantity and accessibility of nectar and pollen vary depending on the flower species. For example, perennials with long corollas tend to have more nectar than annuals (Nicholls and Altieri, 2013). How accessible the nectar is for the insect is based on the architecture of the flower, the concentration of the nectar, the morphology of the insect, and the mechanisms it uses to extract nectar (Wäckers, 2004). Plant height impacts the visibility of flowers to insects, particularly as many pollinating insects prefer to fly and forage at a constant height in order to conserve energy (Dafni and Potts, 2004).

Studies have shown that margins and other restored semi-natural areas with perennial plants may help to improve pollinator diversity and support less-common insect species (e.g. Morandin and Kremin, 2013; Erickson et al., 2021; McHugh et al., 2022). Cirujeda et al. (2019) found that field margins with high percentages of woody and evergreen perennials also demonstrated a lower probability of hosting crop weeds that might outcompete floral species.

Another important aspect to consider when examining the relationships between flower species and their visitors is the overlap between the flowering period of the species and the activity periods of insects (Bosch et al., 1997). In general, it is beneficial to have continuous flowering throughout the margin, choosing species with different and overlapping flowering periods without gaps. This can be further refined if a specific insect species is being targeted (i.e. sowing flower species that bloom when the insect species is active).

5 The economics of field margins

Field margins can deliver a number of financial benefits to farmers (see Table 1, Agronomy function). However, field margins also occupy space that is often limited on farms, and they require investment of capital and time for their implementation and maintenance. Farmers may be hesitant to invest in margins because of the lack of clarity concerning the economic benefits (Morandin et al., 2016) or concerns with regard to weeds or pests. The limited available research suggests that, when viewed in terms of lost revenue (from land not used for crop production) and expenditure to create and maintain them, field margins resulted in overall financial losses for most crop types (Segre et al., 2019, 2022). This research also suggests an inverse relationship between features promoting biodiversity (e.g. increasing field margin width) and the level of potential losses. This means government policies that encourage and support farmers to actively establish and manage field margins may be required. Farmers can be rewarded for implementing ecological projects or compensated for losses in income that arise as a result of sacrificing fertile land for field margins and other semi-natural areas on farms.

6 Conclusion and future trends in research

Increasing biodiversity is key for improving both productivity and resilience within agricultural systems. Field margins support biodiversity on farms, offering multiple ecosystem services simultaneously. This includes the provision of habitat and resources for beneficial insects, the creation of wildlife corridors, as well as other agronomic benefits for farmers, and contributions to landscape heterogeneity. In order to compensate for any financial losses to farmers, government policies that encourage and support farmers to actively establish and manage field margins may be required.

Future research should aim to determine the most effective and practical approaches to utilizing field margins as a means of maintaining or increasing biodiversity in agriculture. More studies are needed that focus on the characteristics of the margin and the traits of the vegetation communities that are important, based on conservation goals and the objectives of the farmer (e.g. how field margins can contribute toward soil carbon sequestration). Protocols are required to provide practical guidance to farmers on whether a new or regenerated field margin would be a wise investment for their specific context and goals, and how to achieve this (e.g. recommended sown plant species).

Region-specific studies are needed in order to determine recommended sown plant species and to optimize the capacity of plant species to thrive in given combinations of soil, climate, and altitude. The information available about many native plant species (i.e. traits, attractiveness to pollinators, and invasiveness) is limited and often out of date. In order to optimize sown plant recommendations, new open-access data are needed about a wide array of species.

Research will continue to measure the contribution and practicality of field margins in different applied scenarios. However, in order to examine the full impact of agricultural field margins (combined benefits as well as trade-offs), future research should consider amalgamated contributions of multiple ecosystem services together, rather than focusing on a single ecosystem service (Van Vooren et al., 2018).

Finally, integrating biodiversity into a productive farm is extremely challenging, partly because of increased system complexity (Petit et al., 2011). More research is needed in order to develop reliable, context-based protocols and management plans which ensure efficient farm operations and high yields while supporting optimal ecosystem health. Research is also needed to determine the best ways of imparting knowledge to farmers and encouraging their acceptance of biodiversity enhancement practices through the effective use of field margins.

7 Where to look for further information

Related scientific articles can be found in a range of journals, including *Agriculture Ecosystems and Environment*, *Biological Conservation*, *Ecological Applications*, *Ecology Letters*, and *Journal of Applied Ecology*. Some recommended recent books are *Reconciling Agricultural Production with Biodiversity Conservation* (Bàrberi and Moonen, 2020) and *The Ecology of Hedgerows and Field Margins* (Dover, 2019). Research centers studying field margins are located across the world, such as in the United Kingdom (e.g. Centre for Ecology and Hydrology, Staffordshire University, University of Bristol), Spain (e.g. Agri-Food Research and Technology Centre of Aragon, Institute for Sustainable Agriculture), Italy (e.g. Scuola Superiore Sant'Anna), the United States (e.g. University of California, Berkeley), and Canada (e.g. University of British Columbia).

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