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One Earth

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Review

Protecting crops with plant diversity: Agroecological promises, socioeconomic lock-in, and political levers

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SUMMARY

Plant diversification at field, farm, and landscape scales is a key strategy for protecting crops from pests. But its level of adoption remains confidential, while the overall negative impacts of pesticides are now well established. To understand the obstacles to this adoption, we conducted an extensive review of literature in life and socio-economic sciences. We found that all diversification practices are largely effective in pest control, achieving satisfactory yields and many ecological cobenefits, although context dependent. Plant diversification does not appear solely as an alternative to pesticide-based pest control but as a transformative approach to achieve sustainable agrifood systems. However, its adoption is currently strongly hindered by socioeconomic barriers, including low short-term profitability, rigid agricultural sectors, and limited support from public policies. The most beneficial practices, agroforestry and diversified landscapes, face the greatest obstacles. In contrast, cultivar mixtures, while easier to implement, offer limited cobenefits. Collaboration between scientists, policymakers, and local stakeholders seems essential to scale up plant diversification.

INTRODUCTION

Synthetic fertilizers and pesticides have freed farm production from many environmental (e.g., limited availability of nutrients in the soil, presence of crop pests) and some production constraints (e.g., animal manure availability, labor force), raising yields and profitability of major crops in most agroclimatic contexts. While this has had a major impact on the agricultural sector and its profitability, the environmental and health impacts of this dominant production model and its relationship with fundamental global changes (climate change, biodiversity loss, changes in land use) act as a treadmill of production.[1–4] These impacts have repercussions for agricultural production, including driving declines in biodiversity and the simplification of agroecosystems that further exacerbate problems of pest regulation.[5] The evolution of pests that are resistant to pesticides underscores the need to protect crops using alternative strategies.[6] This urgency of this need is heightened by the systematic withdrawal of pesticide molecules from the market that are harmful to human or the environment.[7]

Halving or even stopping, synthetic pesticide use will require a profound rethinking of current agrifood systems.[8–10] Evidence collected over the last three decades documented how plant diversity at different spatiotemporal scales has the potential to reduce pest infestations[11–15] and pesticide use.[16] Plant diversification, that is the process of using a greater variety of plant species and their spatial and temporal arrangement, is a determining factor in the capacity of the agricultural ecosystem to provide services to farmers and society such as natural pest control, carbon storage, and regulation of water quality.[17] Plant diversification concerns crops and uncultivated plants. For pest control, it is a key component of several approaches to managing agriculture: agroecological crop protection (ACP[18]), area-wide integrated pest management (IPM),[19] organic farming,[20] regenerative agriculture,[21] and permaculture.[22] The plant diversification complements pest control methodologies, such as the use of resistant or more tolerant varieties, sex pheromone, plant vaccination, trapping, or biological pesticides. Plant diversification also offers a wide range of potential benefits. Bottom-up processes[23–26] that increase the spatial and/or temporal diversity of plants can dilute the pest's host plants in the canopy or landscape ("hide-and-seek" principle for pathogens or animal pests) or generate periods in time where there are few resources for the pest, and/or create a more competitive environment for weed pests. Providing more resources and habitats for the natural enemies of pests (mainly predators and parasitoids), by increasing plant diversity, fosters benefits through top-down processes.[23–26] But we still lack an overall view of the efficacy of plant diversification to control pests and to provide other agroecological benefits.

Reducing the use of pesticides is increasingly considered as a target in public policy, such as in the initial ambitions of the European *Green Deal*, expressed in the strategies for agriculture ("Farm to Fork") and biodiversity.[27] Management options that improve multiple ecosystem services including pest control with no or low pesticide use are still largely underemployed by farmers. Pesticide use is still increasing at the global scale[28] as well as in developed countries,[29] and alternative crop protection strategies based on bottom-up and top-down plant diversification are not widely used by farmers in developed countries. The high yields of commodity crops permitted by conventional plant protection practices have acted as a limitation to the adoption of alternative practices. But, as yields on conventional systems have stagnated since the 1990s,[30–32] and the risks of pest outbreak have increased, there is now a much more favorable economic and agronomic context for the adoption of alternative practices. Designing favorable socio-economic and political frameworks for the future adoption of plant diversification strategies for the control of pests requires some understanding of the reasons for past failure of adoption: Was the failure linked to a lack of knowledge among farmers, the effectiveness of diversification options, or to constraints in their operational implementation? Are the difficulties technical, social, economic and/or political?

To meet the challenge of answering these questions, a multidisciplinary committee of 31 scientific experts from complementary disciplines (e.g., ecology, economics, agronomy, genetics, management sciences, law) reviewed a total of 1,193 scientific articles. We considered nine plant agrobiodiversity-based management options for pest control, which we henceforth term "diversification options." These options used are (1) varietal mixtures (i.e., sowing mixed varieties in a field), (2) intercropping (i.e., concomitant mixtures of crop species in the field, including cash crop and cover crops), (3) agroforestry (mixing trees and crops), (4) diversified crop rotations where the sequence of cash crops and/or covercrops in the field is diversified, (5) a reduced share of a given crop in the landscape, (6) a diversified crop mosaic in the landscape, (7) a reduced field size, (8) an increased distance between fields with the same crops, and (9) an increased share of semi-natural elements in the landscape, including hedgerows, meadows, forests, and edges. All spatiotemporal scales were considered, from within the field to the landscape and within-season to pluri-annual (Figure 1). Pest control was considered in its broadest sense. This included limiting or reducing the presence, absolute or relative abundance and prevalence of pests, as well as reducing the occurrence or severity of damages, injuries, or yields losses. All crops, whether from temperate or tropical environments, were considered, as the geographic areas of developed countries cover all latitudes (as in Oceania and Middle East, and for European overseas regions). The study focused on categories of pests typically managed through chemical control (excluding, for example, large herbivorous mammals), resulting in 11 main pest categories of weeds, pathogens, and insects in the aerial and soil compartments and nematodes, as detailed in Table 1. Effects of diversification on pests and on natural enemies were both considered. The links between diversification and other ecosystem services were also taken into account, drawing on two recent meta-syntheses and additional meta-analyses. The socioeconomic challenges of implementing plant diversification at large scale as a mean of crop protection differ significantly between developed and developing countries, due to differences in their value chains and high production intensity. We therefore inventoried and analyzed the technical, socio-economic and policy factors that impede or foster the adoption of diversification by farmers, focusing only on industrialized countries. Finally, we identify key knowledge gaps and propose research avenues to support the wide deployment of plant diversification.

RESULTS: MAIN MESSAGES FROM LITERATURE ANALYSIS

Our review discovered six key messages that synthesize the multiple benefits of plant diversification for pest control and how diversification can be promoted in developed countries.

Crop protection can be achieved by plant diversification across spatiotemporal scales

Articles considering the effect of one diversification option on one main pest category (each single cell in Table 2) predominantly show effective control (green dots). Each main pest category is controlled by at least one diversification option, with there being at least one positive effect per column (Table 2, green dots). This result allows certain groups of species to be considered together (the multi-species scale), and points

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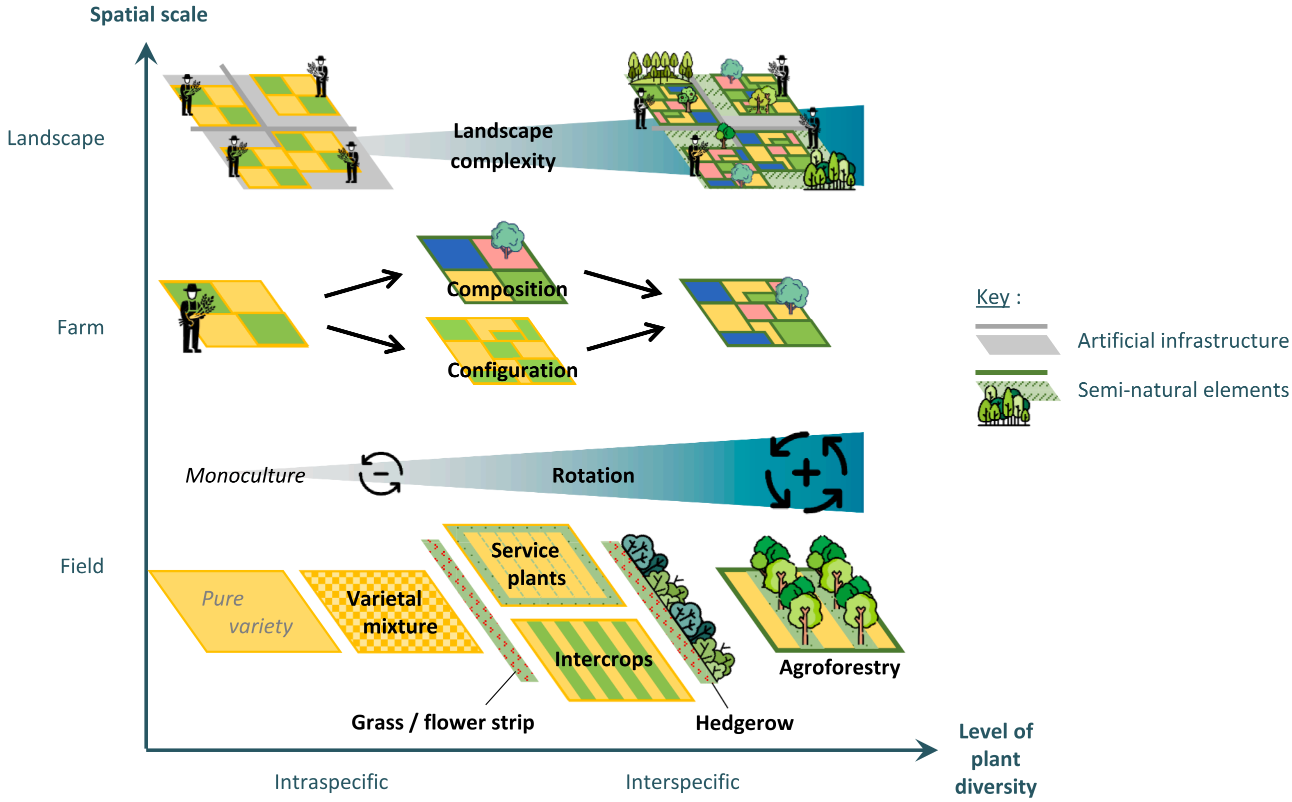


Figure 1. The plant diversification options considered in the review
Nine diversification options for pest control are presented across spatiotemporal scales (from the field to the landscape and within-season to pluri-annual): (1) varietal mixtures, (2) intercropping (i.e., concomitant mixtures of plants in the field, including cash crop mixtures and with service plants), (3) agroforestry, (4) diversified crop rotations (i.e., the succession of cash crops and also covercrops in the field), (5) reducing the share of a given crop in the landscape (composition), (6) diversifying crop mosaic in the landscape (composition), (7) reducing field size (configuration), (8) increasing the distance between fields with the same crops (configuration), and (9) increasing the share of semi-natural elements in the landscape (mainly hedgerows, meadows, forests and edges). The landscape complexity is the result of all the components at the infra-scales.

toward a rethinking of the effective diversification options that should be selected for a given pest problem. These effective options can be linked to the general life traits of the major categories of pests. From the literature review, the experts have structured pest life history traits in seven types of functional traits (which concern both pests and their natural enemies) at work in the effects of pest control through plant diversification: specialization traits (specialist, generalist), dispersal traits (active, passive, short vs. long distance), perception and communication traits (signals used to identify the host plant, or to initiate an action such as sporulation, dispersal, emergence), demographic traits (opportunistic or equilibrium species), stress resistance traits (forms of resistance: diapause, quiescence, etc.), development traits (simple or complex cycles), and effect traits (resource thieves, biomass reducers, senescence accelerators and those that affect the survival, physiology and reproduction of

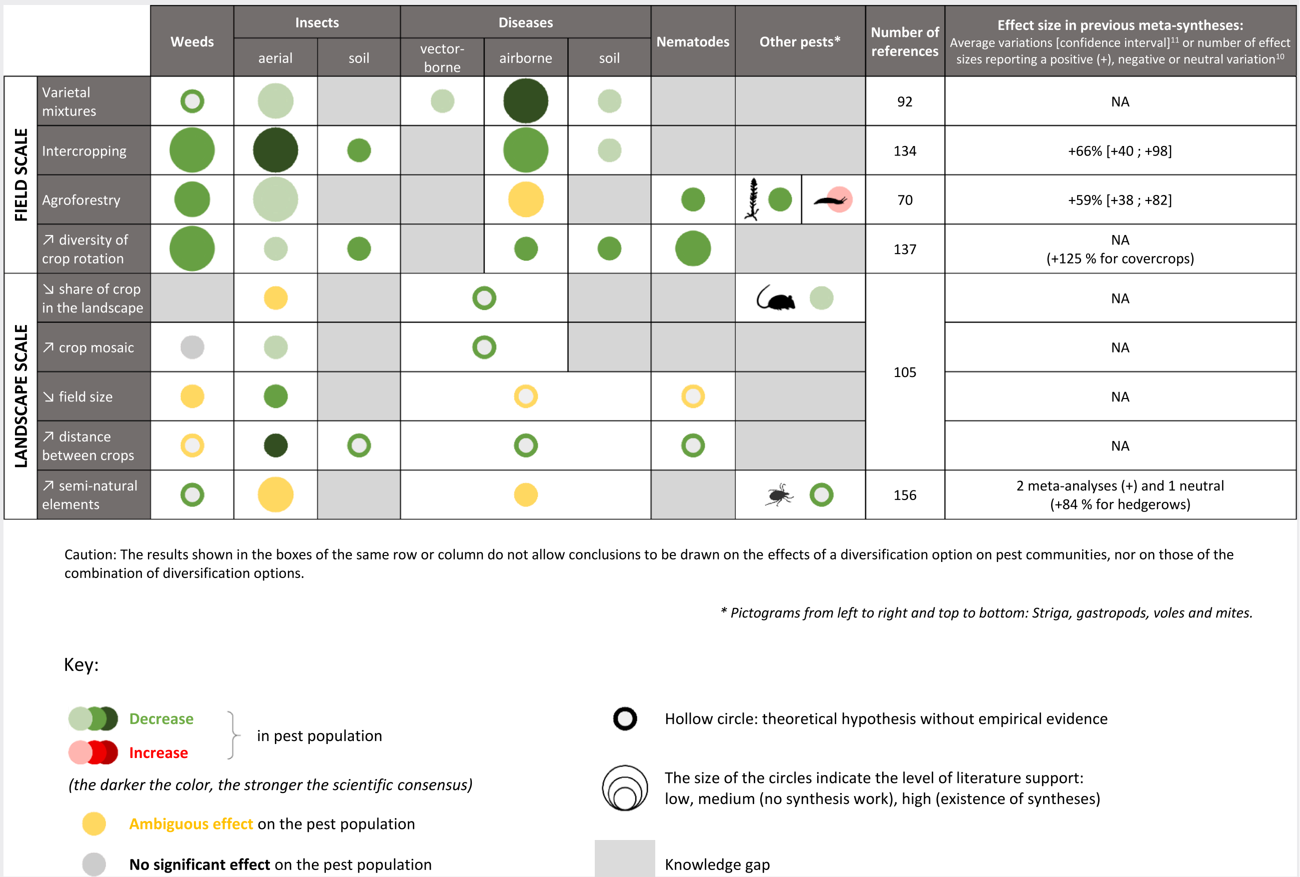
Table 1. Some characteristics of the bibliographical corpus: number of references considered for each issue, proportion of articles, syntheses, books and public reports, and primary studies used in syntheses and then indirectly taken into account here

Issue	No. of references	% articles	% of syntheses	Primary studies in syntheses	% books	% public reports
Effects of plant diversity on pest control	907	95	19	17,046	3	0
Links between plant diversity and the provision of other ecosystem services	30	90	60	2,099	2	7
Socio-economic conditions for the adoption of crop protection strategies based on plant diversification	276	82	13	4,430	7	3
Total	1,213	92	19	–	4	1

We used the presence count method: a primary study was counted only once in an issue, even if it is associated with several syntheses cited in this issue.
*The total shown includes the 20 references shared by the 3 main issues.

Table 2. Synthesis of the effects of plant diversification (nine options) on the different categories of pests

The number of references we used is indicated by diversification option. The results of previous meta-syntheses[12-13] are also recalled.



		Weeds	Insects: aerial	Insects: soil	Diseases: vector-borne	Diseases: airborne	Diseases: soil	Nematodes	Other pests*	Number of references	Effect size in previous meta-syntheses: Average variations [confidence interval][11] or number of effect sizes reporting a positive (+), negative or neutral variation[10]
FIELD SCALE	Varietal mixtures									92	NA
	Intercropping									134	+66% [+40 ; +98]
	Agroforestry									70	+59% [+38 ; +82]
	↗ diversity of crop rotation									137	NA (+125 % for covercrops)
LANDSCAPE SCALE	↘ share of crop in the landscape									105	NA
	↗ crop mosaic										NA
	↘ field size										NA
	↗ distance between crops										NA
	↗ semi-natural elements									156	2 meta-analyses (+) and 1 neutral (+84 % for hedgerows)

Caution: The results shown in the boxes of the same row or column do not allow conclusions to be drawn on the effects of a diversification option on pest communities, nor on those of the combination of diversification options.

** Pictograms from left to right and top to bottom: Striga, gastropods, voles and mites.*

Key:

Decrease / Increase } in pest population

(the darker the color, the stronger the scientific consensus)

Ambiguous effect on the pest population

No significant effect on the pest population

Hollow circle: theoretical hypothesis without empirical evidence

The size of the circles indicate the level of literature support: low, medium (no synthesis work), high (existence of syntheses)

Knowledge gap

The number of references we used is indicated by diversification option. The results of previous meta-syntheses10-11 in terms of the level of biological control of pests are also recalled. Example of how to read the table: the studies considered in our synthesis (N=7) show a positive effect of semi-natural elements on weed diversity or richness. Semi-natural elements favour certain parameters of weed communities, but the latter are then better controlled in terms of populations because they are diversified. This is why the circle is a small hallow green circle.
Caution: The results shown in the boxes of the same row or column do not allow conclusions to be drawn on the effects of a diversification option on pest communities, nor on those of the combination of diversification options.
* Pictograms from left to right and top to bottom: Striga, gastropods, voles and mites.

the host plant). These traits have an intimate role within the mechanisms of effect of plant diversification on pest control proposed by the group of experts, including: the spatial or temporal fragmentation of the pest habitat; the spatial or temporal heterogeneity of the quality of this habitat; the change in expression of plant defenses in response to signals emitted by neighboring plants; the signals emitted by the attacked plant and perceived by natural enemies; the distribution and continuity of resources for natural enemies; and, finally, the structure and dynamics of interaction networks between natural enemies and between pests.

Cases of inefficiency of pest regulation and of negative effects of some plant diversification options do exist for all the cells of Table 2, although their occurrence is generally much lower than that of positive effects (resulting in a green dot). These inefficiency or negative cases are mainly reported for aerial insects on the one hand, and for landscape diversification options on the other hand. The effects of diversification on aerial insects are dependent on their capacity and mode of dispersal, their degree of specialization to their host plant, and their mechanisms of survival during periods of resource absence.[23,24,33] The frequent reports of negative effects of diversification at landscape scales, results in equivocal trends (yellow dots) that may be explained by antagonisms between the various mechanisms that underlie the landscape scale diversification—regulation relationships, and their interactions with other agricultural practices and climatic conditions.[34] Forests support both the rapeseed beetle and its natural enemy parasitoid, which can have the effect of either improving or reducing biological control depending on the climate and the farming practices applied.[35,36] The only clear case of more negative effects (pest outbreak) than positive effects is that of agroforestry and gastropod mollusc pests in temperate regions (red dot), although the causes of these effects have been little studied.[37]

Table 2 also demonstrates that no single plant diversification option can be used to control all pests simultaneously.

The positive effect of diversification on pest control is most clearly demonstrated (solid dots) for within-field plant diversification options (varietal mixtures, intercropping, agroforestry, and diversified crop rotations), for which the greatest number of empirical articles and quantitative reviews are available. Positive effects at landscape scale are consistent with theoretical expectations for diversification (hollow dots), such as those for reducing the share of a given crop in the landscape, diversifying crop mosaic in the landscape, reducing field size, increasing the distance between fields with the same crops at the same time, and increasing the share of semi-natural elements in the landscape. Relatively few empirical works at landscape scale are present in the literature, but these include positive effect of small fields combined with semi-natural elements on pest predators.[38] Overall, the most established positive effects of diversification come from studies of intercropping and diversified crop rotation.[39,40] The effectiveness of within-field diversification has been shown for airborne diseases, weeds,[41] and, to a lesser extent, aerial insects.[42–44] The effects of agroforestry, at field scale, is still poorly studied in temperate climates, but the positive effects of tropical agroforestry were well documented, particularly for weeds and aerial insects.[13]

In collating all information related to each study, including the climatic and geographic contexts, studied crop, pest species, diversification option, involved life traits, ecological mechanisms, and other used agricultural practices, the group of experts found that, despite positive general patterns for the main pest categories, it is very difficult to build general rules to determine which plant diversification option should be implemented to control a given pest species. The strong and positive effect of varietal mixtures on disease control has predominantly been studied for wheat and barley diseases,[45,46] with relatively little research effort on other crops and diseases, much less tested in a wide range of contexts. The study of diversified crop rotations has also been based on the crop types currently in operational agriculture, and does not reflect the total number of theoretically possible rotations.[47] Another example is differential responses of pests and their natural enemies to landscape diversification with semi-natural habitats.[34] One explanation given in the literature is provided by the heterogeneous use of pesticides across the landscapes studied, which differentially impacts ecological networks and thereby pest control (prey consumption). Very few articles in the corpus dealt with the use of pesticide, which limits the possibility of testing this expectation. These articles report a reduction in the use of synthetic pesticides in diversified systems when compared with non-diversified systems,[48–50] but it is not clear whether this reduction is important.

Our work suggests that contextual knowledge is required to prioritize and adapt plant diversification options to the local situation. This local contextual situation can represent a limitation that lock-in farmer behavior and prevents them from implementing diversification strategies. The reduction of pesticides use is also cited as one of the key motivations that farmers have in implementing management options based on plant diversification.[51] Thus, a potential mechanism by which to promote adoption would be the training of farmers and advisers under the specific pedoclimatic, biogeographical, and pesticide contexts of their region, whose variability must be apprehended at different nested spatial scales (field, farm, landscape, region). Finally, we wonder whether the main issue for the adoption of diversification strategies is really to estimate the effect of plant diversification on pesticide consumption.[52,53] While this evaluation is necessary, it does not appear sufficient to trigger widescale adoption.[54] Understanding the multiple performance benefits of diversified systems would better help support their adoption, through research to demonstrate their broad contribution to societal needs, including biodiversity conservation, ecosystem services for agriculture and beyond, and the economic costs avoided by reducing the negative externalities of pesticides.

Plant diversification promotes biodiversity and provides multiple ecosystem service benefits to farmers and society

Broad spectrum chemical pesticides are easy to use and have the advantage of killing their target quickly, but they also have been found to have major drawbacks, including the emergence of pesticide resistance, loss of biodiversity, pollution, ecosystem damages, and risks to human health.[5,55–57] In contrast, using plant diversification options to protect crops are comparatively more complex to implement, introduce risk, such as those related to variable pest control, and entail management and opportunity costs. Plant diversification options have few of the drawbacks of pesticides but also offer many side benefits, both for farmers and for the whole of society.[12,38]

The various benefits of plant diversification in terms of promoting biodiversity associated with agricultural ecosystems and providing ecosystem services are well attested in the literature and summarized in recent meta-syntheses.[12,13] These meta-syntheses consider various diversification options and ecosystem services and complement each other; Tamburini et al.[12] consider semi-natural habitats in landscapes as diversification option and pollination and carbon storage as the ecosystem services outputs, while Beillouin et al.[13] considered hedgerows as the diversification option and distinguished between water quantity and quality as the ecosystem services delivered. Other recent reviews and articles that consider exceptional datasets were added to our evaluation (see list in supplemental information, Appendix A2-2), and added specific detail such as that of Sirami et al.[38] who considered the effect of field size and semi-natural elements on multi-taxa biodiversity.

The findings of these syntheses show that, on average, diversified systems host more biodiversity (a median increase of 24%) and perform better than less-diversified systems in terms of water regulation (quantity, quality, around +50%), and with higher soil quality (+11%) and carbon storage (around 10%).[13] Pollination is the least-studied ecosystem service in relation to plant diversity. The corpus that was analyzed did not make it possible to quantify the link between these two variables, but the literature tendency is toward a positive association between the level of plant diversity

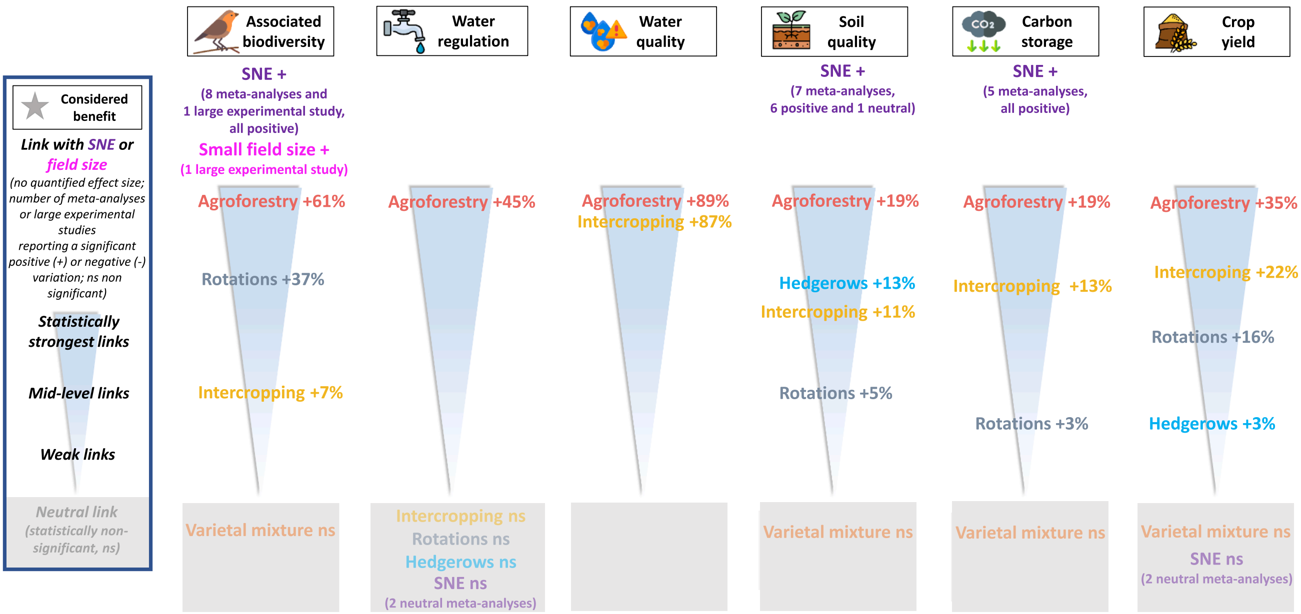


Figure 2. Classification of plant diversification options according to their links with associated biodiversity, provision of ecosystem services, and the level of crop yields

The percentages are the median variations in effect sizes between the diversified situation and the reference situation, as estimated by Beillouin et al.[13] Gradients are established relative to the strongest link situated over the widest part of the gradient. When one diversification option does not appear in a given gradient, there is no available information. For more details, notably 95% confidence interval, see supplemental information, methods 3. Adapted from Beillouin et al.,[13] Tamburini et al.,[12] and Sirami.[38]

and the provision of the pollination service.[11–32,38,58] Finally, the link between the presence of semi-natural elements and soil quality is less well documented, but identified as systematically positive in the syntheses, and quantified for hedgerows at +13% compared with the reference level of plant diversity.[13] The consistency between Beillouin et al.'s and Tamburini et al.'s results for hedgerows and semi-natural elements respectively is noteworthy, which is why we have combined these results for the purposes of the discussion. The only negative effect of diversification reported in the literature concerns increases in greenhouse gas emissions from systems involving intercropping with cover crops that are destroyed but not removed (+29%).[12] This disservice has only been evaluated for the diversification option of crop rotations, and appears to be non-significant. Using the effect sizes obtained in the meta-syntheses, agroforestry would appear the most interesting diversification option with regard to biodiversity and ecosystem services[13] (Figure 2). In contrast, varietal mixtures do not seem to be associated with significant benefits other than biological control of pathogens. The other diversification options generally yield intermediate outcomes. The presence of semi-natural vegetation in agricultural ecosystems appears to favor associated biodiversity and soil quality, but has no effect on water regulation.[12] Figure 2 illustrates that diversification options provide agronomic and ecological benefits that are different in their nature and magnitude, but appear complementary. The scientific literature thereby demonstrates that plant diversification options offer many benefits to farmers and society and are potentially effective ways of mitigating the negative environmental effects of developed agriculture, including biodiversity loss and pesticide pollution.

Plant diversification supports crop productivity

Questions about the negative effects of some diversification options on the production level are often raised, such as concerns about yield-gaps in organic farming.[59,60]

We would argue that yield gains per hectare should be weighed against the change in the surface area dedicated to agricultural production resulting from the deployment of plant diversification, a knowledge gap in the literature that we analyzed in our review. Indeed, the implementation of some diversification options leads to a reduction in the area that is cultivated, as is the case with the introduction of semi-natural elements within fields. Some other options may allow a gain of land production, as computed with the Land Equivalent Ratio, such as the production of the equivalent of 1 ha of crop in a mixture as soya-maize requires 1.4 ha of a pure crops stand.[61,62] Yield estimates also do not take into account co-products associated with semi-natural elements or agroforestry (e.g., firewood, fruit).

Our review shows that diversified systems have higher yields on average than less diversified systems (Figure 2), based upon studies from a wide variety of geographical and agronomic context.[11,12] These yield gains are small for varietal mixtures and the use of cover crops amounting to a few percent of total yield, but can be substantial for crop rotations and intercropping (on the order of +15% to 20%), and agroforestry can has a wide range of yield gain variations for the latter, given the diversity of systems included in this category).[13] It appears, however, that few studies have examined the crop productivity of diversified systems in developed countries, but these provide evidence in support of yield gain in low-input production systems, particularly in organic farming.[11,12] These studies concern intercropping, varietal mixtures with farmer's seeds, and, to a lesser extent, rotations. They show that yields are maintained or even improved, and in some cases their variability is reduced. Yield is a composite result of a set of biotic interactions such as pests and abiotic factors. Both spatial and temporal plant diversity may stem from effects of complexity per se and from identify effects. For example, diversified rotations may be associated with increased use of nitrogen-fixating crops that promote the growth of the cereals (e.g., Smith et al.[63]).

Finally, our comprehensive review of the literature suggests room for yield increase in diversified systems. First, most studies rely on crop varieties originally bred for pure stand performance under high chemical input conditions; conducting such studies with varieties specifically selected for enhanced pest resistance or good performance in diversified agroecosystems would probably give even better results. It should be noted that, in addition to crop genetics, diversified farming systems have not benefited from the same research efforts in agronomy as intensive farming systems. Similarly, most evaluations take place in fields and landscapes where the use of synthetic pesticides is dominant. Consequently, local biodiversity is strongly declining accordingly to these conditions of exposure to pesticides,[5] and, under the action of the treadmill of production, the ecosystem services that support production under diversified conditions are reduced. Studies of our corpus are therefore often comparing yields of agrosystems that have been optimized for over 60 years with those of diversified situations that are often sub-optimal and that could be improved.

Overall, the production of diversified systems appears promising, especially as (1) yields from conventional crops have plateaued for the last 30 years[30–32] and (2) yields of diversified systems can be more stable in the face of annual climatic variation, suggesting at a greater resilience of diversified systems to climate change.[58,64,65] The three previous messages demonstrate that most crop diversification options protect crops against pests, provide multiple ecosystem services to farmers and society, and support crop productivity in low chemical input systems. The question is therefore "why are these options still under-utilized by farmers?" In the following sections, we present key findings concerning the locked-in socio-technical decision-making at the root of the lack of adoption, and possible approaches to foster their increased adoption and deployment.

Profitability gaps between diversified and conventional systems could be mitigated by other benefits

Given the importance of the economic dimension in farmers' choices,[66,67] and decision making, the profitability of diversified systems is one of the key drivers of their adoption, even as other drivers also affect this choice,[68] including individual values of farmers for environmental or health concerns.[69–71] Few studies have evaluated the economic impact, for farms, of adopting plant diversification options to protect crops.[13]

The economic impact of intercropping is the most extensively studied of the diversification options. Intercropping has been shown to be profitable despite the additional costs associated with agricultural equipment for harvesting and sorting[72–74] (Table 3), and contribute to reduce market risks,[75] as well as providing the benefit from ecosystem services benefits.[76] The adoption of varietal mixtures does not appear to significantly affect the profitability of farms but tends to stabilize income.[77,78] Despite being associated with lower yields, traditional landraces or composite populations managed on farm can still be profitable when farmers adopt a niche strategy and control the distribution of the production.[77,78] Diversifying crop rotations by introducing additional crops into existing rotations induces highly variable results, with some positive, some negative, and often neutral outcomes. Rotations may be used to control weeds,[79] but we found no systematic evidence that this is a profitable strategy in all cases. The lack of profitability typically arises because the newly introduced crops are often less profitable than those already selected by the farmer (either because of low yields of the crop itself or because the farmer is still learning, because efficient outlets are lacking, etc.). Introducing an additional crop could be profitable when the pest pressure is very high (significantly jeopardizing the profit from the main crops)[80] or when the new crop is introduced mainly for another purpose[81] in which case crop protection is usually an auxiliary objective.[82] Similarly, incorporating semi-natural elements (including semi-natural grasslands) to protect crops in intensive production areas is not deemed profitable without subsidies, at least in the short term, and semi-natural elements are even often perceived as a source of pests.[83]

Overall, economic studies conclude that the potential gains of diversification compared with a conventional production system are generally insufficient to motivate farmers to confront the non-economic costs of diversification.[82,84] This includes overcoming individual cognitive lock-ins[85] and obstacles associated with the socio-technical organization of agricultural supply chains and the potential coordination costs related to implementing diversification at a landscape scale with other agents.

Providing a clear assessment of the profitability of various plant diversification options is challenging because they impact profitability through multiple avenues (such as yield, input utilization, workload, product value, and market access), all of which are highly dependent on the context.[86] Moreover, crop diversification frequently coincides with other agroecological practices, such as employing stimulators of plant defense or biological control, all of which can further influence profitability.[86,87] The literature, however, highlights certain contextual factors that can enhance the profitability of diversification. Plant diversification options tend to exhibit improved economic performance in environments with high pest pressure, as well as in low-input systems, especially in organic farming.[74,88,89] Economic profitability is further bolstered in economic contexts characterized by either low production prices, which mitigate the impacts of any yield loss, or high input costs, which amplify the benefits of input savings.[90]

The literature also underscores the expectation that the goals of plant diversification are a number of positive economic externalities that reach beyond the farm's limits. For instance, diversification implemented on a farm can contribute to regulating pests on a landscape scale.[91] These benefits are not solely confined to pest regulation; they also encompass the provision of ecosystem services that benefit all society. As such, profitability should be assessed at multiple scales, explicitly embracing economic externalities that account for these broader benefits.[91–97] Following the same logic, when comparing the profitability of diversified farming systems with those that are non-diversified, the evaluation should be adjusted to account for all the socio-economic costs they incur, including the environmental and health impacts associated with chemical crop protection strategies.[97,98]

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Table 3. Synthesis of the technical, social, economic, and institutional specificities of current sociotechnical systems favoring or hampering the deployment of the nine plant diversification options

plant diversification option	Lock-ins	technical (equipment)	advise, technical references	workload and operational organization	upstream agricultural sector: varietal selection	downstream agricultural sector	economic profitability (farm level, short term)	spatial coordination of actors	Institutional
variety mixtures	mix of certified varieties	~	-	~	--	-	~ (with stabilizing effect)	lit. gap	~ (a lock in the past)
	farmers' and traditional varierties	~	-	lit. Gap (increase on-farm processing?)	--	-- on main markets / + Niche market	- conventional / + Low-imput / niche market	lit. gap	Inconsistent with the Distinctness, Uniformity, and Stability criteria
intercropping	mixture of cash crops	--	-	- (delayed harvesting and sorting)	--	-- on main markets / + Niche market	++	Pooling of production for market access	lit. gap
	service plants	--	--	lit. gap	-	~	+/-	lit. gap	lit. gap
agroforestry		--	--	- tree planting	lit. Gap (availability of seedling?)	uncertain vlaue of wood production	lit. gap	lit. gap	legal status
rotations	New crops in rotations	-	--	Increased mental workload, but work potentially spread over time	--	-- on main markets / Niche market for market gardening / Niche market or feed for main crops	less profitable, but potential positive intertemporal and product range effects	lit. gap	Legal barrier to product exchange between farmers
	cover crops	~	lit. gap	- destruction of cover crop	-	non relevant	+/-	lit. gap	promotted to limit erosion and water pollution
% of a crop in landscape diversified crop mosaic in landscape		lit. gap	lit. gap	lit. gap	-	--	lit. gap	-	+ CAP
reduced field size increased distance between same crops		-	non relevant	-	non relevant	non relevant	lit. gap	-	~ (a lock in the past)
semi-natural elements		-	-	-	-	-	- / + with subsidies	-	+/-
Observed current ways to bypass locks in developped countries		Equipment self-construction or sharing, and outsourcing services	experimen-tations on farm, farmer networks, decision tools		investment in seed selection effort, participative approaches of ideotyping, seed exchange	labeling, direct selling, on-farm processing, local industrial initiatives	subsidy to diversification, increase of chemical inputs costs, payments for environmental services, consumers willingness-to-pay	collective eco-certification or payments for environmental services, local outlets (collective catering...)	direct support (subsidies to diversification) and indirect support (pesticide use regulation)

Legend

+	current lever to adoption
-	current lock to adoption
+/-	ambiguous effect (no consensus)
~	current neutral effect
lit. gap	Literature gap
(crossed box)	non relevant

Finally, given both that ecological mechanisms may require time to yield results (up to several years in the case of landscape diversification, rotation, and semi-natural vegetation) and that the agroecological benefits of plant diversification are often recurrent (e.g., inter-annual yield stabilization), it is crucial for any profitability assessment to adopt a long-term perspective. This temporal aspect of the profitability of farming practices and diversification has often been overlooked in the literature,[99] however.

Accounting for the various hidden costs of conventional production methods and the societal benefits derived from plant diversification strategy[98] over the long term would help deduce or even reverse the gap between their respective profitability levels.

Redesigning agrifood systems is imperative for the large-scale deployment of crop protection strategies based on plant diversification

Conventional production systems based on the use of synthetic inputs are the result of a convergent evolution of needs, knowledge, practices, and organizations within the agricultural sector over the last 70 years. These systems have become increasingly specialized, generating economies of scale at farm level with the predominance of only the most profitable crops, and within the industry through the concentration of R&D and consulting efforts on a few crop species and a standardization of agrifood processes.[100–102] Productivist public policies have reinforced this trend, leading to systemic locked-in decision-making that now hinders diversification efforts.[49,84] Our systematic review shows that none of the individual plant diversification options, when used in isolation, is capable of controlling all pests encountered on a farm. Alternative pest control will therefore require a combination of several plant diversification options and possibly other approaches such as biocontrol, which we refer to here collectively as "crop protection strategies based on plant diversification." The deployment of such strategies are complex because they cover various spatial and temporal scales and concern more stakeholders than farmers alone. This calls for a systemic, upstream and downstream redesign of the agrifood system for agricultural production, as well as for the relationship between the farmer and other stakeholders.[74–76]

Upstream of the farm, the limited availability of seeds and seedlings tailored to diversified systems stands out as one of the most commonly cited factors limiting the adoption of diversification[59] (Table 2). Research investment for breeding is highly driven by market size.[103,104] Diversifying rotation requires the introduction of minor crops for which R&D is small, all along the seed supply chain, because of small market size.[105] In addition, varieties are generally evaluated and selected for their performance when grown pure, whereas intra-field diversification would require selection for performance in combination (intra- or inter-specific). Beyond the necessary investment in crop breeding, fostering the sharing of experiences and facilitating exchange of seeds between farmers could help to alleviate this obstacle.[106] This might be further improved with co-development approaches such as participatory crop breeding involving both researchers and farmers. The supply of specific equipment adapted to manage diversified crop systems is also a potential limitation for the same reasons as for seeds (small market size). This is particularly the case for sowing and harvesting intercrops or certain niche crops, for sorting intercrops after harvest, and for the upkeep of semi-natural elements such as cover crops.[107] To address the equipment challenge, unlocking potential solutions extend beyond the individual farm level: shared equipment initiatives (such as collective purchases or service provision) are recognized as effective measures, yet they necessitate coordination among users.[108] Self-building or adaptation of equipment by farmers is also a lever for reducing equipment costs[109] even if it tends to increase working time (for coordination or building). Moreover, the literature often mentions a lack of knowledge to manage new crops (among both farmers and advisors),[110] as well as a lack of technical and economic references for diversified systems.[111–113] To fill such knowledge gaps, in addition to increase in R&D and consulting, a number of levers are mentioned in the literature, among which research has a role to play: on-farm experimentation, joining farmers' networks, having access to decision-making tools, and more comprehensive evaluations of the effects of diversification practices (particularly their effectiveness against pests) are ways to foster the adoption of diversified production systems.[114,115] More fundamentally, alternative research funding mechanisms are necessary to attenuate the effect of market size (e.g., cross-subsidization among crops, setting up contest as for other emerging market[116]).

Downstream of the value chain, the lack of markets and outlets for the products of diversified systems is a recurring problem.[84] Transformation processes used in the agroindustry impose certain standards (e.g., varietal purity for milling) that cannot be achieved with varietal mixtures, traditional or farmers' varieties or through intercropping[112] (Table 2). Products produced in market gardening and arboriculture must also meet strict standards of quality (size, appearance, cultivars) or production volume at given dates to enter some large industrial or retail markets.[117] Moreover, as fruit and vegetables are largely eaten fresh, the harvest date is a key element of the commercial quality. Diversification options in combination with a reduction of pesticide use can lead to visual defects on fruits and vegetables, or affect cropping calendars. These obstacles can be overcome by exploiting the specific product characteristics obtained in diversified systems such as low pesticide use and protection of the environment in local supply chains and/or through labeling, to achieve higher sale prices.[118,119] The lack of an outlet can also be circumvented by a transition to an on-farm processing business model (e.g., flour for cereals, preserves for fruit and vegetables), albeit with higher workloads. If short marketing channels or on-farm solutions may offer outlets for niche productions, alternative marketing outlets need to be found in long channels to deploy extensively crop diversification options. Such a large scale change will require to coordinate a diversity of stakeholders[120] and even changing consumer practices.[98] A few large-scale initiatives led by cooperatives[121] or food industry[122] were analyzed. Introducing semi-natural elements into the farm presents challenges in exploiting the wood produced by hedges or rows of trees in agroforestry systems, necessitating entry into sectors often unfamiliar to farmers.[92,123,124] The integration of grassland into cropping plans is also limited due to regional specialization, with few livestock farmers available to utilize the products of grassland locally, or which requires farm diversification at a high cost in money, labor and know-how.[125]

Territorial coordination is needed to deploy plant diversification at the landscape scale (spatial organization of crops, installation of semi-natural vegetation grids), or to scale up plant diversification options to ensure their economic viability (e.g., to reach a critical level of production for minor crops), agronomic sustainability,[126] or ecological effectiveness (for instance, wildlife friendly farming generates positive spatial spillovers between organic farms, resulting in a reduction of pesticide use[127]). Plant diversification options that involve a wide range of stakeholders, including farmers, agricultural advisors, agrifood firms, cooperatives, water managers, non-agricultural associations, and local authorities, are beginning to emerge, but remain rare.[128] The literature emphasizes the methodological difficulties of both implementing and studying pest management strategies at a landscape scale, due to the multiplicity of spatial and temporal scales to be considered, and the diversity of actors involved.[129] To overcome these difficulties, one possibility is to develop participatory research with the involved stakeholders, enabling the emergence of solutions acceptable to all.[130] Three levers have been identified to ease the adoption of such collective solutions.[131]

(1) Identifying actions that generate a collective gain (e.g., eco-certification of local production or collective payments for environmental services at a landscape scale—e.g., for water protection or biodiversity conservation).[132]
(2) Establishing collective organizations to manage agricultural territories (e.g., local collective institutions such as cooperative societies) and centralized planning and incentives by public authorities).[133]
(3) Building on the certification of products, farms and landscapes, enabling more commercial outlets (e.g., markets).[134,135]

These obstacles and mechanisms are rarely specific to a particular diversification option but are context dependent. The literature, however, does not allow us to rank the weight of each of them in the adoption of different diversification practices.

Overall, we have shown here that the adoption of plant diversification options does not depend solely on the goodwill of farmers, but requires redesigning agrifood systems to deploy plant diversification strategies, with the support of public policies.[136]

Public policies are a major leverage for the deployment of plant diversification strategies

The societal demand for alternative production methods to the input-intensive conventional systems is reflected in some European (Green Deal [https://food.ec.europa.eu/horizontal-topics/farm-fork-strategy_en], Common Agricultural Policy [https://agriculture.ec.europa.eu/sustainability/environmental-sustainability/low-input-farming/pesticides_en]) and national public policies (e.g., French Law on the Future of Agriculture, Food and Forestry [https://agriculture.gouv.fr/sites/default/files/plaqmingb72_0.pdf]). These policies set targets for reducing pesticide use and, more generally, promote a shift toward more diversified farming systems that place biodiversity and ecological processes at the forefront of production factors.[137] However, despite the growing recognition of environmental issues in public policies, the shift toward low-pesticide cropping systems is far from being sufficiently advanced to meet these targets.[138,139]

Breaking the systemic lock-ins of industrial agriculture requires ambitious policies.[51] The past and current role of EU's public policies in shaping farming practices shows that the common agricultural policy (CAP) measures are not sufficiently restrictive to promote the development of plant diversification at different spatiotemporal scales[140–142] (Table 3). Several rationales are made in the literature to advocate for public policies in favor of plant diversification. Firstly, as highlighted in key message 2, the benefits of plant diversification for biodiversity and ecosystem services justify support for their adoption through subsidies. Policies favoring diversification could be an additional approach for biodiversity conservation, on top of the usual policies that have not really been successful so far.[143] Secondly, the use of chemical pesticides incurs societal costs of pollution and human health impacts,[144] justifying their regulation or taxation.[145] Such policies would help narrow the profitability gap between conventional practices and diversification strategies, as discussed in key message 4. Lastly, the adoption of pest management strategies based on landscape-scale plant diversification, involving all stakeholders along the value chain, represents an organizational innovation[146] that is unlikely to be achieved without strong public policy support to foster its early stages.[147] While there have been some large-scale diversification projects driven by major food industries (e.g., the Harmony program of Mondelez or the development of a sustainable supply chain for Barilla[122]), such bottom-up initiatives are exceptions and will not generalize more widely without support from public policies. Public policies will also not succeed without the involvement of all relevant stakeholders.

DISCUSSION

Using the results derived from our in-depth review, we can compare the agroecological benefits (provision of services including pest control, support for associated biodiversity, and yield) expected from the different plant diversification options with the degree of transformation necessary for existing systems for their implementation (Figure 3). We show that, while all diversification practices offer agronomic and ecological advantages, their benefits are not uniform in magnitude. The most advantageous practices often face the most significant obstacles. While varietal mixtures offer modest benefits compared with other options, their adoption requires minimal adjustments both at the farm and at the upstream/downstream chain levels, which explains their recent and fast increase in different European countries (near +20% in France[148]). Integrating trees into farms as a productive element (diversification options as agroforestry and semi-natural elements), by contrast, will require a fundamental redesign of the farming system and the farmer's role. The literature highlights the requirement for specialized agricultural equipment such as spreaders, the need to integrate forestry markets into the farm business, and the coherence of public policies, particularly between environmental and agricultural objectives. While the efficacy of agroforestry in pest regulation requires further validation in temperate environments, abundant research on (sub)tropical agroforestry underscores the benefits of these complex canopies in biodiversity conservation and the provision of many ecosystem services.[149,150] Diversification options linked to the organization of fields in landscapes (field size, crop mosaic, distance between crops, share of a given crop in the landscape) require coordination between farmers, the organization of which needs to be considered in relation to other local stakeholders. In particular, this requires a shared vision between different agricultural sectors. The other diversification options are positioned in between these two extremes. The diversification of rotations by introducing new crops offers interesting potential for the provision of ecosystem services but comes up against a number of obstacles at farm level (knowledge of growing a new crop, the need for new equipment), in upstream channels (lack of variety breeding, advice and research for minor crops) and in downstream channels to overcome the lack of outlets. Although intercropping presents technical challenges and higher production costs related to sowing, harvesting, and sorting, it remains one of the most profitable diversification strategies. This is due to its potential for higher yields and a favorable land-equivalent ratio, making it a viable option even under the current economic conditions in the agricultural sectors.

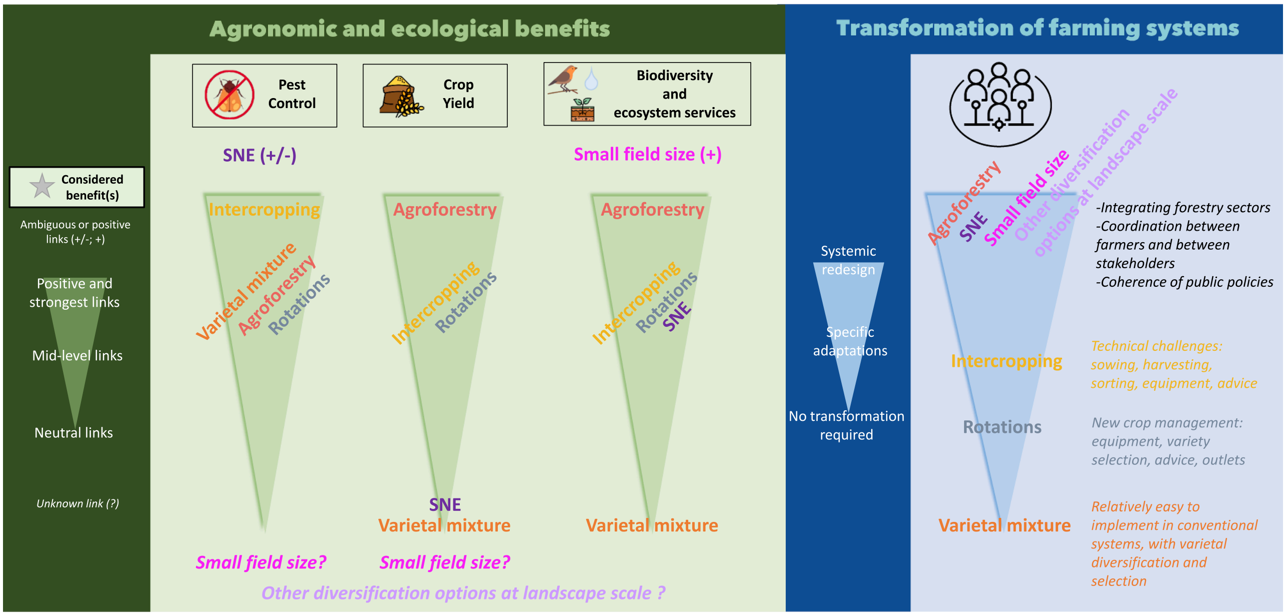

Figure 3. Classification of the nine different plant diversification strategies according to (1) the agronomic and ecological benefits (pest control, crop yield, biodiversity and ecosystem services) and (2) the level of transformation of farming system required for their adoption (the lower in the figure, the higher the benefits or the required transformations)

The diversification options presented here are those for which all the ecological and technical/socio-economic information is available in the literature.

Few references consider the implementation of a combination of plant diversification options or study their effect on the joint control of several pests.[48] The potential of plant diversification to simultaneously control multiple pests therefore remains to be assessed, in particular by considering the traits of the organisms involved (plants as well as pests), in order to estimate their compatibility or synergy. However, farms that implemented multiple diversification strategies for various purposes than biological control clearly had more win-win socio-environmental outcomes.[111] The conditions for adopting multiple diversification options are also an area of research.

Including local agronomic constraints (pedoclimatic, biogeographical) and social organizations (local outlets, regional policies) at the territorial scale appears to be most appropriate scale at which system redesign for crop protection strategies based on plant diversification should be considered.[18,53] International strategies, such as the CAP and national policies (e.g., how CAP is implemented) can be downscaled for regional implementation. However, the implementation of plant diversification at a landscape scale represents an economic risk for stakeholders in the current food system. The spatial and temporal scales involved renders the cost of researching and studying territorial solutions very high. Innovation at national and multinational scales is required, however, due to competition on international markets for major products (e.g., cereals).

Finally, implementing the transition through landscape solutions involves building territorial projects that go beyond the management of each individual pest-crop problem separately. Our synthesis shows that plant diversification should not be promoted as a toolbox for devising alternative methods to specifically replace all chemical pesticides, but as a holistic approach changing the overall logic of crop production in light of all the benefits that plant diversity provides. In addition to ambitious agricultural policies, a widespread transition in agricultural production methods toward agroecological systems requires proactive food policies to ensure more environmentally friendly agricultural products and sustainable diets integrating the diversity of produced crops, particularly grain legumes. These policies cannot be designed independently of each other,[138] whether at European or national level.

OUTLOOK AND FUTURE RESEARCH NEEDS

Our review highlights several gaps of knowledge. While agroecological literature on the regulatory effects of plant diversity is large, the research effort is not evenly distributed between pest categories and plant diversification options. Soil-dwelling insects, vector-borne diseases, nematodes, gastropods, mites, and parasitic plants are poorly documented. The potential offered by the diversity of crop rotations and semi-natural elements (dissociating types of elements as hedgerows, meadows, woods, etc.) in the landscape also needs to be further explored. In addition, cropping systems are much more extensively studied than vegetable cropping or market gardening, limiting the knowledge available to design the deployment of plant diversification in horticulture systems that are currently among the highest consumers of pesticides per unit.[16] In addition, there is a lack of research on the assessment of the effects of combinations of plant diversification options on the regulation of multiple pests. Anticipating these effects requires a deeper understanding of the ecological mechanisms underpinning natural regulation. Process-based modeling approaches provide a conceptual framework for formalizing and gathering knowledge of the ecological mechanisms involved and then predicting their combined effects on pest and disease regulation, productivity, and the provision of ecosystem services. In addressing issues of this level of complexity, modeling could also prove valuable where there are too many combinations of options to be evaluated experimentally[18,151].

Filling these knowledge gaps requires a paradigm shift in the study of the effects of plant diversity. Instead of an ad hoc comparison of different levels of landscape simplification on pest control, we need to explicitly assess the effects of diversification through large-scale experiments to restore plant diversity, i.e., the design of experiments on the scale of agroecological territories.[152] The aim is to capture large-scale ecological processes and attribute causation. Such experiments are at a scale beyond that currently conducted in agroecology, would enable us to document the dependence of natural pest control on local conditions and its ability to respond and adapt to global changes, such as climate change. This need would be complementary to the evidence gathered in this synthesis and would answer some of the limitations we have identified.

Estimating the socio-economic performance of diversified systems requires a reassessment of the notions of pest regulation thresholds, damage and economic profitability (e.g., at which pest-level damages become harms or economic losses). These are currently defined with reference to the norms and standards associated with conventional systems, and do not sufficiently consider the negative externalities of pesticides or conversely the positive externalities of plant diversification. Benefits from plant diversification should be assessed with respect to all dimensions of performance, including environmental and social benefits.[153] The development of outlets and markets for products from diversified systems calls for research into the distribution of value and risk within value chains, and into consumer attitudes toward particular production methods and/or products that do not meet conventional standards. The study of the diffusion dynamics of innovations such as plant diversification also remains an active scientific question, demanding work on the role of social networks, behavioral economics, and the spread of these new practices in local areas.

Finally, we advocate for a need to examine the role of livestock in diversified cropping systems as an approach to crop diversification and an outlet for crop production.[154] In their review,[155] Maillet et al. highlight some validated effects of animal grazing in orchard protection but also the lack of studies on the topic. Here again, territorial experiments could be a mean to meeting these research needs at all scales of socio-economic organization.

CONCLUSION

Our review of the available evidence shows that plant diversification strategies provide significant agronomic and environmental benefits and underscores their value to farmers and wider society. Few of the results we analyzed were from pesticide-free cultivation systems, but there is evidence that all ecosystems including those supposedly free of pesticide have been affected by the widespread use of pesticides in recent decades.[20] Studies suggest that the lower the use of pesticide in a system, the greater the benefits of plant diversification.[53,156] We find that to reduce pesticide use, plant diversification is an important approach. We therefore formulate the hypothesis that the reduction or elimination of pesticide use in agriculture by following reduced-pesticide frameworks such as IPM, ACP, or regenerative agriculture, would amplify the effects of plant diversification for regulating pests, improving biodiversity preservation but also providing other ecosystem services and crop production. As we clearly show that the most beneficial diversification options are the most complex to deploy in current conventional systems, and that the simplest options to implement provide limited benefits, changes in farming practices need to be thought from a systemic perspective.[136] To initiate this virtuous cycle, our study supports the idea of an agricultural transition at territorial scale. This scale is at the nexus of local agronomic and ecological constraints (pedoclimatic, biogeographical), and agricultural socio-economic issues (local outlets, farm cooperatives, regional policies). The territorial scale appears essential to facilitating change across all five dimensions we explored for the deployment of plant diversification: (1) context-dependent crop protection by natural pest control, (2) biodiversity preservation and ecosystem service provision, (3) good crop yields, (4) economic issues at farm and agricultural sectors, and (5) adapted and adaptative use of general public policies. Study at the territorial scale is certainly entering into policy. The Sharm-el-Sheikh protocol signed at COP27 envisions regional climate change solutions that are adapted to the needs of local societies and the EU has enshrined regional thinking in the HORIZON MISSION initiatives, envisioning the future climate change adaptation will increasingly become the responsibility of regional governments around the EU. This is therefore a valuable scale at which legislation, management and the needs of stakeholders should come together to foster robust change in agricultural practices. This ambitious and complex goal implies the co-design of interdependent, multi-level (field, farm, sector) and transdisciplinary (agronomic, environmental, social, economic, scientific) action to prevent the transformation of one part of the system being limited or retarded by any other.

METHODS

Literature search

This review was carried out following the approach of the Collective Scientific Assessment (CSA), an institutional assessment activity developed by the French National Research Institute for Agriculture, Food and the Environment (INRAE) in the early 2000s. Conducted in compliance with principles that guarantee the robustness of their conclusions, i.e., competence and plurality of the scientific expert committee, impartiality, transparency of the method, and traceability of the work process implemented, CSA provides a critical review of the international scientific literature. Based on queries from bibliographic databases, the analysis was carried out in three independent stages. First, a query was conducted to assess the effectiveness of the nine plant diversification options to control pests. Then, the links between diversification options and biodiversity or other ecosystem services provision were evaluated based mainly on recent syntheses.[12,13] Finally, the committee conducted a second query to assess the technical, socio-economic, and policy factors impeding or fostering the adoption of the diversification options by farmers in developed countries.

Strategy for building bibliographic corpuses

First, to analyze the effects of plant diversity on pest control, we built Web of Science (WoS) queries for each of the diversification options, combining keywords describing the notions of plant diversification, pests OR natural enemies and agricultural environment (detailed in the supplemental information, methods 1, section A1).

These queries were interdisciplinary, i.e., they combined plant pathology, weed science, entomology, agronomy, soil science, evolutionary ecology, functional ecology, and landscape ecology. No restrictions have been applied in the WoS, except the type of references limited to scientific articles, syntheses (reviews and meta-analyses), books, and book chapters. Each of the queries thus constituted made it possible to collect several hundred scientific articles, which the experts first sorted based on reading the titles and abstracts. A more detailed reading of the articles retained in the first sorting step led to further articles being eliminated.

Given the abundance of literature collected, comprising about 5,200 references, the committee adopted a three-stage analysis strategy leading to the detailed analysis of 490 articles. The stages were as follows:

(1) first, works of synthesis such as reviews, meta-analyses, and large-scale analyses considering multi-site experiments or experiments along landscape gradients, were analyzed to extract the trends and general findings as the main message in the literature. These syntheses were focused on a specific diversification option and its effects for crop protection, and generally also focused on specific geographic areas as Europe or Asia.
(2) Second, additional insights were gained through the review of articles (often more recent) that did not fall into the previous category.
(3) Finally, where necessary, some "case study" articles from the primary bibliography of the synthesis works were analyzed to provide more details about certain effects, including the ecological mechanisms underlying the effects of plant diversification.

To ensure the maximum coverage of the literature, we added specific articles to the corpus that were not captured by systematic interrogation of WoS. This was done, for several reasons. Most of our queries required that keywords describing plant diversification practices appear in the title or among the keywords of the articles (to limit the noise caused by articles mentioning diversification only as a contextual or perspective element without making it the central object of their analysis), which led to the elimination of articles that mentioned diversification only in their abstract. Our queries only targeted articles that explicitly mentioned pest management, thereby excluding important but more general articles that dealt with the agroecological effects of plant diversification that did not specifically mention pest management in their title, abstract, or keywords. Some articles were from journals that are not referenced in the WoS, such as for some volumes of *Advances in Ecological Research*, or were papers where the object of study was beyond the precise limits of the WoS queries, including dealing with the plant resource requirements of certain natural enemies without studying their direct biological control effects. Finally, a large number of papers that were added ($n = 119$) dealt with the mechanistic effects of intra- and inter-specific diversity of cultivated and non-cultivated plants, due to their organization at different spatial and temporal scales, their intra-field arrangement (in rows, mixtures, strips, etc.), and the diversity of strata among cover crops, etc., which give information on observed effects due to the life traits of the different pest species and their environment. A total of 417 articles were added to the 490 previously collected. The lists of requested references and those added by the experts are in supplemental information, methods 2, section A2.1.

To analyze the links between plant diversity and the provision of other ecosystem services, our review is based on existing synthesis works, with priority given to quantitative ones that, taken together, provide a matrix of links between different diversification options and associated biodiversity, a range of ecosystem services and agricultural production. This analysis proceeded by

(1) conducting an in-depth analysis of the results of two recent meta-syntheses[12,13] (meta-analyses of meta-analyses, each one synthetizing about 5,000 primary studies) that cover with unprecedented breadth the scientific literature on the links between plant diversity, biodiversity, and ecosystem services, and provide elements on the correlation between plant diversity and level of crop production.
(2) Querying the WoS to identify relevant meta-analyses not included in the two meta-syntheses (either because there were not enough focused on a given plant diversification option to summarize their results, or because the ecosystem services or plant diversification options considered in these meta-analyses were outside the scope of the meta-syntheses, supplemental information, methods 1, section A1.2). This additional bibliographical interrogation also enabled us to collect non-quantitative synthesis articles such as reviews that could contribute to the discussion, especially for those concerning ecosystem services that were not covered by the two meta-syntheses. This step led to the analysis of 30 additional synthesis articles (list in supplemental information, methods 2, section A2.2).

An analysis of the socio-economic conditions for the adoption of plant diversification for crop protection was performed using systematic WoS and Scopus databases interrogations combining keywords describing plant diversification, crop protection, socio-economic factors, and agriculture as detailed in the supplemental information, methods 1, section A1.3.

This subject is difficult to reduce to a set of keywords for query construction, which results in either too large or too restrictive article corpora, the precise cropping techniques of a study are more rarely mentioned in the social science literature than they are for life science. No restrictions were applied in either WoS or Scopus, apart from specifying the type of references that was limited to scientific articles, reviews, books, and book chapters. These queries together collected about 2,100 scientific articles. After sorting them by reading the titles and abstracts, only about 160 articles addressing the theme of interest and dealing with agricultural and socio-economic contexts similar to that of continental Europe were selected for analysis. This restriction was required because we hypothesized that the socio-economic conditions of adoption are very different in developed countries with intensive production, high yields, and well-established value chains than in other socio economic and political contexts. A total of 116 other articles not referenced in the online database, including from unreferenced scientific journals, institutional reports, and legislative texts, were subsequently added by the experts, giving a corpus of 276 references for analysis. The lists of references from the database search and those added by the experts are presented in supplemental information, methods 2, section A2.3.

Characteristics of the bibliographical corpus

Of the 1,193 references in the corpus, 19% are reviews or meta-analyses (Table 1). The processed information aggregates the results of approximately 23,000 primary studies. The bibliographical corpus supplemented studies found using systematic requests in databases with references added by experts, and our study therefore represents a scientific hybrid form between a systematic map and a narrative review. These are robust and complementary methods of analysis that allow us to explore the effects of all plant diversification strategies to control all major pests (weeds, pathogens, and insects in the aerial and soil compartments, nematodes) of all crops in all agronomic systems under all soil and climatic conditions.[157]

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AUTHOR CONTRIBUTIONS

Conceptualization, A.V., V.M., and A.T.; methodology, A.V., V.M., and A.T.; article screening, all authors; data coding and extraction, all authors; formal analysis, all authors; writing – original draft, all authors.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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REFERENCES

1. IPBES (2019). Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (Zenodo). https://zenodo.org/record/3831673.
2. IPCC (2022). Summary for Policymakers. In Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, and V. Möller, et al., eds. (Cambridge University Press), pp. 3–33. https://doi.org/10.1017/9781009325844.001.
3. Hallmann, C.A., Sorg, M., Jongejans, E., Siepel, H., Hofland, N., Schwan, H., Stenmans, W., Müller, A., Sumser, H., Hörren, T., et al. (2017). More than 75 percent decline over 27 years in total flying insect biomass in protected areas. PLoS One *12*, e0185809. https://doi.org/10.1371/journal.pone.0185809.
4. Blüthgen, N., Dicks, L.V., Forister, M.L., Outhwaite, C.L., and Slade, E.M. (2023). Insect declines in the Anthropocene. Nat. Rev. Earth Environ. *4*, 683–686. https://doi.org/10.1038/s43017-023-00478-x.
5. Ziesche, T.M., Ordon, F., Schliephake, E., and Will, T. (2023). Long-term data in agricultural landscapes indicate that insect decline promotes pests well adapted to environmental changes. J. Pest. Sci. *97*, 1281–1297. https://doi.org/10.1007/s10340-023-01698-2.
6. Deguine, J.P., Aubertot, J.N., Flor, R.J., Lescourret, F., Wyckhuys, K.A. G., and Ratnadass, A. (2021). Integrated pest management: good intentions, hard realities. Agron. Sustain. Dev. *41*, 38. https://doi.org/10.1007/s13593-021-00689-w.
7. Candel, J., Pe'er, G., and Finger, R. (2023). Science calls for ambitious European pesticide policies. Nat. Food *4*, 272. https://doi.org/10.1038/s43016-023-00727-8.
8. Hill, S.B., and MacRae, R.J. (1996). Conceptual framework for the transition from conventional to sustainable agriculture. J. Sustain. Agric. *7*, 81–87. https://doi.org/10.1300/J064v07n01_07.
9. Nandillon, R., Guinet, M., and Munier-Jolain, N. (2024). Crop management strategy redesign enables a reduction in reliance on pesticides: A diachronic approach based on a diversity of French commercial farms. Agric. Ecosyst. Environ. *366*, 108949. https://doi.org/10.1016/j.agee.2024.108949.
10. Jacquet, F., Jeuffroy, M.H., Jouan, J., Le Cadre, E., Litrico, I., Malausa, T., Reboud, X., and Huyghe, C. (2022). Pesticide-free agriculture as a new paradigm for research. Agron. Sustain. Dev. *42*, 8. https://doi.org/10.1007/s13593-021-00742-8.
11. Rosa-Schleich, J., Loos, J., Mußhoff, O., and Tscharntke, T. (2019). Ecological-economic trade-offs of Diversified Farming Systems - A review. Ecol. Econ. *160*, 251–263. https://doi.org/10.1016/j.ecolecon.2019.03.002.
12. Tamburini, G., Bommarco, R., Wanger, T.C., Kremen, C., van der Heijden, M.G.A., Liebman, M., and Hallin, S. (2020). Agricultural diversification promotes multiple ecosystem services without compromising yield. Sci. Adv. *6*, eaba1715. https://doi.org/10.1126/sciadv.aba1715.
13. Beillouin, D., Ben-Ari, T., Malezieux, E., Seufert, V., and Makowski, D. (2021). Positive but variable effects of crop diversification on biodiversity and ecosystem services. Glob. Change Biol. *27*, 4697–4710. https://doi.org/10.1111/gcb.15747.
14. Garibaldi, L.A., Oddi, F.J., Miguez, F.E., Bartomeus, I., Orr, M.C., Jobbágy, E.G., Kremen, C., Schulte, L.A., Hughes, A.C., Bagnato, C., et al. (2021). Working landscapes need at least 20% native habitat. Conserv. Lett. *14*, e12773. https://doi.org/10.1111/conl.12773.
15. Gurr, G.M., Lu, Z., Zheng, X., Xu, H., Zhu, P., Chen, G., Yao, X., Cheng, J., Zhu, Z., Catindig, J.L., et al. (2016). Multi-country evidence that crop diversification promotes ecological intensification of agriculture. Nat. Plants *2*, 16014. https://doi.org/10.1038/nplants.2016.14.
16. Larsen, A.E., and Noack, F. (2017). Identifying the landscape drivers of agricultural insecticide use leveraging evidence from 100,000 fields. Proc. Natl. Acad. Sci. USA *114*, 5473–5478. https://doi.org/10.1073/pnas.1620674114.
17. Ratnadass, A., Avelino, J., Fernandes, P., Letourmy, P., Babin, R., Deberdt, P., Deguine, J.P., Grechi, I., Naudin, K., Rhino, B., et al. (2021). Synergies and tradeoffs in natural regulation of crop pests and diseases under plant species diversification. Crop Prot. *146*, 105658. https://doi.org/10.1016/j.cropro.2021.105658.
18. Deguine, J.-P., Aubertot, J.-N., Bellon, S., Côte, F., Lauri, P.-E., Lescourret, F., Ratnadass, A., Scopel, E., Andrieu, N., Bàrberi, P., et al. (2023). Chapter One - Agroecological crop protection for sustainable agriculture. In Advances in Agronomy, D.L. Sparks, ed. (Academic Press), pp. 1–59. https://doi.org/10.1016/bs.agron.2022.11.002.
19. Stenberg, J.A. (2017). A Conceptual Framework for Integrated Pest Management. Trends Plant Sci. *22*, 759–769. https://doi.org/10.1016/j.tplants.2017.06.010.
20. Muneret, L., Mitchell, M., Seufert, V., Aviron, S., Djoudi, E.A., Pétillon, J., Plantegenest, M., Thiéry, D., and Rusch, A. (2018). Evidence that organic farming promotes pest control. Nat. Sustain. *1*, 361–368. https://doi.org/10.1038/s41893-018-0102-4.

21. O'Donoghue, T., Minasny, B., and McBratney, A. (2022). Regenerative Agriculture and Its Potential to Improve Farmscape Function. Sustainability *14*, 5815. https://doi.org/10.3390/su14105815.

22. Hirschfeld, S., and Van Acker, R. (2021). Review: ecosystem services in permaculture systems. Agroecol. Sustain. Food Syst. *45*, 794–816. https://doi.org/10.1080/21683565.2021.1881862.

23. Ninkovic, V., Markovic, D., and Dahlin, I. (2016). Decoding neighbour volatiles in preparation for future competition and implications for tritrophic interactions. Perspect. Plant Ecol. Evol. Syst. *23*, 11–17. https://doi.org/10.1016/j.ppees.2016.09.005.

24. Wuest, S.E., Peter, R., and Niklaus, P.A. (2021). Ecological and evolutionary approaches to improving crop variety mixtures. Nat. Ecol. Evol. *5*, 1068–1077. https://doi.org/10.1038/s41559-021-01497-x.

25. Pelissier, R., Ballini, E., Temple, C., Ducasse, A., Colombo, M., Frouin, J., Qin, X.P., Huang, H.C., Jacques, D., Florian, F., et al. (2023). The genetic identity of neighboring plants in intraspecific mixtures modulates disease susceptibility of both wheat and rice. PLoS Biol. *21*, e3002287. https://doi.org/10.1371/journal.pbio.3002287.

26. Pélissier, R., Violle, C., and Morel, J.B. (2021). Plant immunity: Good fences make good neighbors? Curr. Opin. Plant Biol. *62*, 102045. https://doi.org/10.1016/j.pbi.2021.102045.

27. Finger, R. (2024). Europe's ambitious pesticide policy and its impact on agriculture and food systems. Agric. Econ. *55*, 265–269. https://doi.org/10.1111/agec.12817.

28. FAO (2023). Pesticides Use and Trade 1990–2021. FAOSTAT Analytical Briefs Series No. 70. Rome.

29. Guichard, L., Dedieu, F., Jeuffroy, M.-H., Meynard, J.-M., Reau, R., and Savini, I. (2017). Le plan Ecophyto de réduction d'usage des pesticides en France : décryptage d'un échec et raisons d'espérer. Cah. Agric. *26*, 14002. https://doi.org/10.1051/cagri/2017004.

30. Grassini, P., Eskridge, K.M., and Cassman, K.G. (2013). Distinguishing between yield advances and yield plateaus in historical crop production trends. Nat. Commun. *4*, 2918. https://doi.org/10.1038/ncomms3918.

31. Ray, D.K., Ramankutty, N., Mueller, N.D., West, P.C., and Foley, J.A. (2012). Recent patterns of crop yield growth and stagnation. Nat. Commun. *3*, 1293. https://doi.org/10.1038/ncomms2296.

32. Gerber, J.S., Ray, D.K., Makowski, D., Butler, E.E., Mueller, N.D., West, P.C., Johnson, J.A., Polasky, S., Samberg, L.H., Siebert, S., and Sloat, L. (2024). Global spatially explicit yield gap time trends reveal regions at risk of future crop yield stagnation. Nat. Food *5*, 125–135. https://doi.org/10.1038/s43016-023-00913-8.

33. Burdon, J.J., Barrett, L.G., Rebetzke, G., and Thrall, P.H. (2014). Guiding deployment of resistance in cereals using evolutionary principles. Evol. Appl. *7*, 609–624. https://doi.org/10.1111/eva.12175.

34. Karp, D.S., Chaplin-Kramer, R., Meehan, T.D., Martin, E.A., DeClerck, F., Grab, H., Gratton, C., Hunt, L., Larsen, A.E., Martínez-Salinas, A., et al. (2018). Crop pests and predators exhibit inconsistent responses to surrounding landscape composition. Proc. Natl. Acad. Sci. USA *115*, E7863–E7870. https://doi.org/10.1073/pnas.1800042115.

35. Rusch, A., Valantin-Morison, M., Roger-Estrade, J., and Sarthou, J.-P. (2012). Local and landscape determinants of pollen beetle abundance in overwintering habitats. Agric. For. Entomol. *14*, 37–47. https://doi.org/10.1111/j.1461-9563.2011.00547.x.

36. Thies, C., Steffan-Dewenter, I., and Tscharntke, T. (2008). Interannual landscape changes influence plant-herbivore-parasitoid interactions. Agric. Ecosyst. Environ. *125*, 266–268. https://doi.org/10.1016/j.agee.2007.12.011.

37. Staton, T., Walters, R.J., Smith, J., and Girling, R.D. (2019). Evaluating the effects of integrating trees into temperate arable systems on pest control and pollination. Agric. Syst. *176*, 102676. https://doi.org/10.1016/j.agsy.2019.102676.

38. Sirami, C., Gross, N., Baillod, A.B., Bertrand, C., Carrié, R., Hass, A., Henckel, L., Miguet, P., Vuillot, C., Alignier, A., et al. (2019). Increasing crop heterogeneity enhances multitrophic diversity across agricultural regions. Proc. Natl. Acad. Sci. USA *116*, 16442–16447. https://doi.org/10.1073/pnas.1906419116.

39. Rakotomalala, A.A.N.A., Ficiciyan, A.M., and Tscharntke, T. (2023). Intercropping enhances beneficial arthropods and controls pests: A systematic review and meta-analysis. Agric. Ecosyst. Environ. *356*, 108617. https://doi.org/10.1016/j.agee.2023.108617.

40. Guinet, M., Adeux, G., Cordeau, S., Courson, E., Nandillon, R., Zhang, Y., and Munier-Jolain, N. (2023). Fostering temporal crop diversification to reduce pesticide use. Nat. Commun. *14*, 7416. https://doi.org/10.1038/s41467-023-43234-x.

41. Boudreau, M.A. (2013). Diseases in Intercropping Systems. In Annual Review of Phytopathology, *51*, N.K. VanAlfen, ed. *(Annual Reviews), pp. 499–519. https://doi.org/10.1146/annurev-phyto-082712-102246.*

42. Tooker, J.F., and Frank, S.D. (2012). Genotypically diverse cultivar mixtures for insect pest management and increased crop yields. J. Appl. Ecol. *49*, 974–985. https://doi.org/10.1111/j.1365-2664.2012.02173.x.

43. Koricheva, J., and Hayes, D. (2018). The relative importance of plant intraspecific diversity in structuring arthropod communities: A meta-analysis. Funct. Ecol. *32*, 1704–1717. https://doi.org/10.1111/1365-2435.13062.

44. Snyder, L.D., Gomez, M.I., and Power, A.G. (2020). Crop Varietal Mixtures as a Strategy to Support Insect Pest Control, Yield, Economic, and Nutritional Services. Front. Sustain. Food Syst. *4*, 60. https://doi.org/10.3389/fsufs.2020.00060.

45. Kiaer, L.P., Skovgaard, I.M., and Ostergard, H. (2009). Grain yield increase in cereal variety mixtures: A meta-analysis of field trials. Field Crop. Res. *114*, 361–373. https://doi.org/10.1016/j.fcr.2009.09.006.

46. Borg, J., Kiaer, L.P., Lecarpentier, C., Goldringer, I., Gauffreteau, A., Saint-Jean, S., Barot, S., and Enjalbert, J. (2018). Unfolding the potential of wheat cultivar mixtures: A meta-analysis perspective and identification of knowledge gaps. Field Crop. Res. *221*, 298–313. https://doi.org/10.1016/j.fcr.2017.09.006.

47. Bohan, D.A., Schmucki, R., Abay, A.T., Termansen, M., Bane, M., Charalabidis, A., Cong, R.G., Derocles, S.A.P., Dorner, Z., Forster, M., et al. (2021). Designing farmer-acceptable rotations that assure ecosystem service provision in the face of climate change. In Future of Agricultural Landscapes, Pt Iii, D.A. Bohan, A.J. Dumbrell, and A.J. Vanbergen, eds. (Elsevier Academic Press Inc), pp. 169–244. https://doi.org/10.1016/bs.aecr.2021.01.002.

48. Martin, E.A., Seo, B., Park, C.R., Reineking, B., and Steffan-Dewenter, I. (2016). Scale-dependent effects of landscape composition and configuration on natural enemy diversity, crop herbivory, and yields. Ecol. Appl. *26*, 448–462. https://doi.org/10.1890/15-0856.

49. Meynard, J.M., Charrier, F., Fares, M., Le Bail, M., Magrini, M.B., Charlier, A., and Messéan, A. (2018). Socio-technical lock-in hinders crop diversification in France. Agron. Sustain. Dev. *38*, 54. https://doi.org/10.1007/s13593-018-0535-1.

50. Vialatte, A., Tibi, A., Alignier, A., Angeon, V., Bedoussac, L., Bohan, D.A., Bougherara, D., Carpentier, A., Castagneyrol, B., Cordeau, S., et al. (2021). Promoting crop pest control by plant diversification in agricultural landscapes: A conceptual framework for analysing feedback loops between agro-ecological and socio-economic effects. In Future of Agricultural Landscapes, Pt Iii, D.A. Bohan, A.J. Dumbrell, and A.J. Vanbergen, eds. (Elsevier Academic Press Inc), pp. 133–165. https://doi.org/10.1016/bs.aecr.2021.10.004.

51. Galli, F., Prosperi, P., Favilli, E., D'Amico, S., Bartolini, F., and Brunori, G. (2020). How can policy processes remove barriers to sustainable food systems in Europe? Contributing to a policy framework for agri-food transitions. Food Policy *96*, 101871. https://doi.org/10.1016/j.foodpol.2020.101871.

52. Garnault, M., Barbu, C., Aulagnier, A., Bockstaller, C., Kudsk, P., Labeyrie, B., Le Bellec, F., Richard, F.-J., Gallien, M., Grimonprez, B., et al. (2024). Evaluation of two indicators according to the objectives of the Sustainable Use of pesticides Directive (SUD). A French case study, https://hal.science/hal-04564733v2.

53. Tscharntke, T., Grass, I., Wanger, T.C., Westphal, C., and Batáry, P. (2022). Restoring biodiversity needs more than reducing pesticides. Trends Ecol. Evol. *37*, 115–116. https://doi.org/10.1016/j.tree.2021.11.009.

54. Yan, E., Munier-Jolain, N., Martin, P., and Carozzi, M. (2024). Intercropping on French farms: Reducing pesticide and N fertiliser use while maintaining gross margins. Eur. J. Agron. *152*, 127036. https://doi.org/10.1016/j.eja.2023.127036.

55. Yamamuro, M., Komuro, T., Kamiya, H., Kato, T., Hasegawa, H., and Kameda, Y. (2019). Neonicotinoids disrupt aquatic food webs and decrease fishery yields. Science *366*, 620–623. https://doi.org/10.1126/science.aax3442.

56. Paul, K.C., Krolewski, R.C., Lucumi Moreno, E., Blank, J., Holton, K.M., Ahfeldt, T., Furlong, M., Yu, Y., Cockburn, M., Thompson, L.K., et al. (2023). A pesticide and iPSC dopaminergic neuron screen identifies and classifies Parkinson-relevant pesticides. Nat. Commun. *14*, 2803. https://doi.org/10.1038/s41467-023-38215-z.

57. Willetts, L., Comeau, L., Vora, N., Horn, O., Studer, M., Martin, K., Lem, M., Pétrin-Desrosiers, C., Grant, L., and Webb, K. (2023). Health in global biodiversity governance: what is next? Lancet *401*, 533–536. https://doi.org/10.1016/s0140-6736(23)00130-7.

58. Redhead, J.W., Oliver, T.H., Woodcock, B.A., and Pywell, R.F. (2020). The influence of landscape composition and configuration on crop yield resilience. J. Appl. Ecol. *57*, 2180–2190. https://doi.org/10.1111/1365-2664.13722.

59. Knapp, S., and van der Heijden, M.G.A. (2018). A global meta-analysis of yield stability in organic and conservation agriculture. Nat. Commun. *9*, 3632. https://doi.org/10.1038/s41467-018-05956-1.

60. Meemken, E.M., and Qaim, M. (2018). Organic Agriculture, Food Security, and the Environment. In Annual Review of Resource Economics, *10*, G.C. Rausser and D. Zilberman, eds. *(Annual Reviews), pp. 39–63. https://doi.org/10.1146/annurev-resource-100517-023252.*

61. Li, C., Stomph, T.J., Makowski, D., Li, H., Zhang, C., Zhang, F., and van der Werf, W. (2023). The productive performance of intercropping. Proc. Natl. Acad. Sci. USA *120*, e2201886120. https://doi.org/10.1073/pnas.2201886120.

62. Van der Werf, W., Zhang, L.Z., Li, C.J., Chen, P., Feng, C., Xu, Z., Zhang, C.C., Gu, C.F., Bastiaans, L., Makowski, D., and Stomph, T. (2021). Comparing performance of crop species mixtures and pure stands. Front. Agric. Sci. Eng. *8*, 481–489. https://doi.org/10.15302/j-fase-2021413.

63. Smith, M.E., Vico, G., Costa, A., Bowles, T., Gaudin, A.C.M., Hallin, S., Watson, C.A., Alarcòn, R., Berti, A., Blecharczyk, A., et al. (2023). Increasing crop rotational diversity can enhance cereal yields. Commun. Earth Environ. *4*, 89. https://doi.org/10.1038/s43247-023-00746-0.

64. Reiss, E.R., and Drinkwater, L.E. (2018). Cultivar mixtures: a meta-analysis of the effect of intraspecific diversity on crop yield. Ecol. Appl. *28*, 62–77. https://doi.org/10.1002/eap.1629.

65. Di Falco, S., and Chavas, J.-P. (2008). Rainfall shocks, resilience, and the effects of crop biodiversity on agroecosystem productivity. Land Econ. *84*, 83–96. https://doi.org/10.3368/le.84.1.83.

66. Chavas, J.P., Chambers, R.G., and Pope, R.D. (2010). Production economics and farm management: A century of contributions. Am. J. Agric. Econ. *92*, 356–375. https://doi.org/10.1093/ajae/aaq004.

67. Di Bene, C., Gomez-Lopez, M.D., Francaviglia, R., Farina, R., Blasi, E., Martinez-Granados, D., and Calatrava, J. (2022). Barriers and Opportunities for Sustainable Farming Practices and Crop Diversification Strategies in Mediterranean Cereal-Based Systems. Front. Environ. Sci. *10*, 861225. https://doi.org/10.3389/fenvs.2022.861225.

68. Dessart, F.J., Barreiro-Hurlé, J., and van Bavel, R. (2019). Behavioural factors affecting the adoption of sustainable farming practices: a policy-oriented review. Eur. Rev. Agric. Econ. *46*, 417–471. https://doi.org/10.1093/erae/jbz019.

69. Dupraz, P., Vermersch, D., De Frahan, B.H., and Delvaux, L. (2003). The environmental supply of farm households - A flexible willingness to accept model. Environ. Resour. Econ. *25*, 171–189. https://doi.org/10.1023/a:1023910720219.

70. Howley, P., Buckley, C., O Donoghue, C., and Ryan, M. (2015). Explaining the economic 'irrationality' of farmers' land use behaviour: The role of productivist attitudes and non-pecuniary benefits. Ecol. Econ. *109*, 186–193. https://doi.org/10.1016/j.ecolecon.2014.11.015.

71. Lohr, L., Park, T., and Higley, L. (1999). Farmer risk assessment for voluntary insecticide reduction. Ecol. Econ. *30*, 121–130. https://doi.org/10.1016/s0921-8009(98)00103-7.

72. Dowling, A., Sadras, V.O., Roberts, P., Doolette, A., Zhou, Y., and Denton, M.D. (2021). Legume-Oilseed Intercropping in Mechanised Broadacre Agriculture - a review. Field Crop. Res. *260*, 107980. https://doi.org/10.1016/j.fcr.2020.107980.

73. Exner, D.N., Davidson, D.G., Ghaffarzadeh, M., and Cruse, R.M. (2009). Yields and returns from strip intercropping on six Iowa farms. Am. J. Alt. Ag. *14*, 69–77. https://doi.org/10.1017/S0889189300008092.

74. Pelzer, E., Bazot, M., Makowski, D., Corre-Hellou, G., Naudin, C., Al Rifaï, M., Baranger, E., Bedoussac, L., Biarnès, V., Boucheny, P., et al. (2012). Pea-wheat intercrops in low-input conditions combine high economic performances and low environmental impacts. Eur. J. Agron. *40*, 39–53. https://doi.org/10.1016/j.eja.2012.01.010.

75. Martin-Gorriz, B., Zabala, J.A., Sánchez-Navarro, V., Gallego-Elvira, B., Martínez-García, V., Alcon, F., and Maestre-Valero, J.F. (2022). Intercropping Practices in Mediterranean Mandarin Orchards from an Environmental and Economic Perspective. Agriculture-Basel *12*, 574. https://doi.org/10.3390/agriculture12050574.

76. Alcon, F., Marín-Miñano, C., Zabala, J.A., De-Miguel, M.D., and Martínez-Paz, J.M. (2020). Valuing diversification benefits through intercropping in Mediterranean agroecosystems: A choice experiment approach. Ecol. Econ. *171*, 106593. https://doi.org/10.1016/j.ecolecon.2020.106593.

77. Dedeurwaerdere, T., and Hannachi, M. (2019). Socio-economic drivers of coexistence of landraces and modern crop varieties in agro-biodiversity rich Yunnan rice fields. Ecol. Econ. *159*, 177–188. https://doi.org/10.1016/j.ecolecon.2019.01.026.

78. Baniszewski, J., Burton, A., Kemanian, A.R., Roth, G., and Tooker, J. (2021). Wheat intraspecific diversity suppressed diseases with subdued yield, economic return and arthropod predation services. Agric. Ecosyst. Environ. *315*, 107438. https://doi.org/10.1016/j.agee.2021.107438.

79. Ratnadass, A., Fernandes, P., Avelino, J., and Habib, R. (2012). Plant species diversity for sustainable management of crop pests and diseases in agroecosystems: a review. Agron. Sustain. Dev. *32*, 273–303. https://doi.org/10.1007/s13593-011-0022-4.

80. Pacilly, F.C.A., Groot, J.C.J., Hofstede, G.J., Schaap, B.F., and van Bueren, E.T.L. (2016). Analysing potato late blight control as a social-ecological system using fuzzy cognitive mapping. Agron. Sustain. Dev. *36*, 35. https://doi.org/10.1007/s13593-016-0370-1.

81. Mawois, M., Vidal, A., Revoyron, E., Casagrande, M., Jeuffroy, M.-H., and Le Bail, M. (2019). Transition to legume-based farming systems requires stable outlets, learning, and peer-networking. Agron. Sustain. Dev. *39*, 14. https://doi.org/10.1007/s13593-019-0559-1.

82. Vanloqueren, G., and Baret, P.V. (2008). Why are ecological, low-input, multi-resistant wheat cultivars slow to develop commercially? A Belgian agricultural 'lock-in' case study. Ecol. Econ. *66*, 436–446. https://doi.org/10.1016/j.ecolecon.2007.10.007.

83. Salliou, N., Vialatte, A., Monteil, C., and Barnaud, C. (2019). First use of participatory Bayesian modeling to study habitat management at multiple scales for biological pest control. Agron. Sustain. Dev. *39*, 7. https://doi.org/10.1007/s13593-018-0553-z.

84. Magrini, M.-B., Anton, M., Cholez, C., Corre-Hellou, G., Duc, G., Jeuffroy, M.-H., Meynard, J.-M., Pelzer, E., Voisin, A.-S., and Walrand, S. (2016). Why are grain-legumes rarely present in cropping systems despite their environmental and nutritional benefits? Analyzing lock-in in the French agrifood system. Ecol. Econ. *126*, 152–162. https://doi.org/10.1016/j.ecolecon.2016.03.024.

85. Weituschat, C.S., Pascucci, S., Materia, V.C., Tamas, P., de Jong, R., and Trienekens, J. (2022). Goal frames and sustainability transitions: how cognitive lock-ins can impede crop diversification. Sustain. Sci. *17*, 2203–2219. https://doi.org/10.1007/s11625-022-01156-5.

86. Davis, A.S., Hill, J.D., Chase, C.A., Johanns, A.M., and Liebman, M. (2012). Increasing Cropping System Diversity Balances Productivity, Profitability and Environmental Health. PLoS One *7*, e47149. https://doi.org/10.1371/journal.pone.0047149.

87. Chantre, E., and Cardona, A. (2014). Trajectories of French Field Crop Farmers Moving Toward Sustainable Farming Practices: Change, Learning, and Links with the Advisory Services. Agroecol. Sustain. Food Syst. *38*, 573–602. https://doi.org/10.1080/21683565.2013.876483.

88. Bedoussac, L., Journet, E.-P., Hauggaard-Nielsen, H., Naudin, C., Corre-Hellou, G., Jensen, E.S., Prieur, L., and Justes, E. (2015). Ecological principles underlying the increase of productivity achieved by cereal-grain legume intercrops in organic farming. Agron. Sustain. Dev. *35*, 911–935. https://doi.org/10.1007/s13593-014-0277-7.

89. Delbridge, T.A., Fernholz, C., King, R.P., and Lazarus, W. (2013). A whole-farm profitability analysis of organic and conventional cropping systems. Agric. Syst. *122*, 1–10. https://doi.org/10.1016/j.agsy.2013.07.007.

90. Michuda, A., Goodhue, R., Klonsky, K., Baird, G., Toyama, L., Zavatta, M., Muramoto, J., and Shennan, C. (2019). The economic viability of suppressive crop rotations for the control of verticillium wilt in organic strawberry production. Agroecol. Sustain. Food Syst. *43*, 984–1008. https://doi.org/10.1080/21683565.2018.1552228.

91. Grogan, K.A., and Goodhue, R.E. (2012). Spatial Externalities of Pest Control Decisions in the California Citrus Industry. J. Agric. Resour. Econ. 37, 156–179.

92. Alam, M., Olivier, A., Paquette, A., Dupras, J., Revéret, J.P., and Messier, C. (2014). A general framework for the quantification and valuation of ecosystem services of tree-based intercropping systems. Agrofor. Syst. *88*, 679–691. https://doi.org/10.1007/s10457-014-9681-x.

93. Barot, S., Allard, V., Cantarel, A., Enjalbert, J., Gauffreteau, A., Goldringer, I., Lata, J.C., Le Roux, X., Niboyet, A., and Porcher, E. (2017). Designing mixtures of varieties for multifunctional agriculture with the help of ecology. Agron. Sustain. Dev. *37*, 13. Artn 13. https://doi.org/10.1007/s13593-017-0418-x.

94. Garcia, L., Celette, F., Gary, C., Ripoche, A., Valdés-Gómez, H., and Metay, A. (2018). Management of service crops for the provision of

ecosystem services in vineyards: A review. Agric. Ecosyst. Environ. *251*, 158–170. https://doi.org/10.1016/j.agee.2017.09.030.

95. Morandin, L.A., Long, R.F., and Kremen, C. (2016). Pest Control and Pollination Cost-Benefit Analysis of Hedgerow Restoration in a Simplified Agricultural Landscape. J. Econ. Entomol. *109*, 1020–1027. https://doi.org/10.1093/jee/tow086.
96. Snyder, L.D., Gomez, M.,I., Mudrak, E.L., and Power, A.G. (2021). Landscape-dependent effects of varietal mixtures on insect pest control and implications for farmer profits. Ecol. Appl. *31*, e02246. https://doi.org/10.1002/eap.2246.
97. Zilberman, D., and Millock, K. (1997). Pesticide Use and Regulation: Making Economic Sense Out of an Externality and Regulation Nightmare. J. Agric. Resour. Econ. 22, 321–332.
98. Latvala, T., Regina, K., and Lehtonen, H. (2021). Evaluating Non-Market Values of Agroecological and Socio-Cultural Benefits of Diversified Cropping Systems. Environ. Manage. *67*, 988–999. https://doi.org/10.1007/s00267-021-01437-2.
99. Carrié, R., Smith, H.G., and Ekroos, J. (2024). Sensitivity to agricultural inputs and dispersal limitation determine the response of arable plants to time since transition to organic farming. J. Appl. Ecol. *16*. https://doi.org/10.1111/1365-2664.14650.
100. Kuokkanen, A., Mikkilä, M., Kuisma, M., Kahiluoto, H., and Linnanen, L. (2017). The need for policy to address the food system lock-in: A case study of the Finnish context. J. Clean. Prod. *140*, 933–944. https://doi.org/10.1016/j.jclepro.2016.06.171.
101. Magrini, M.-B., Anton, M., Chardigny, J.-M., Duc, G., Duru, M., Jeuffroy, M.-H., Meynard, J.-M., Micard, V., and Walrand, S. (2018). Pulses for Sustainability: Breaking Agriculture and Food Sectors Out of Lock-In. Front. Sustain. Food Syst. *2*, 1–17. 64. https://doi.org/10.3389/fsufs.2018.00064.
102. Oliver, T.H., Boyd, E., Balcombe, K., Benton, T.G., Bullock, J.M., Donovan, D., Feola, G., Heard, M., Mace, G.M., Mortimer, S.R., et al. (2018). Overcoming Undesirable Resilience in the Global Food System. 1.
103. Charlot, S., Dridi, C., and Lemarié, S. (2015). Market size and innovation: An application to the French seed market for large crops. 015 AAEA & WAEA Joint Annual Meeting, San Francisco, California 205520, Agricultural and Applied Economics Association.
104. Fuglie, K.O., and Walker, T.S. (2001). Economic Incentives and Resource Allocation in U.S. Public and Private Plant Breeding. J. Agric. Appl. Econ. 33, 459–473.
105. Fugeray-Scarbel, A., and Lemarié, S. (2024). The amplified effect of market size on innovation: A comparative analysis of pea and wheat seed value chains in France. Agric. Syst. *219*, 104051. https://doi.org/10.1016/j.agsy.2024.104051.
106. Di Falco, S., and Chavas, J.-P. (2006). Crop genetic diversity, farm productivity and the management of environmental risk in rainfed agriculture. Eur. Rev. Agric. Econ. *33*, 289–314. https://doi.org/10.1093/eurrag/jbl016.
107. Casagrande, M., Alletto, L., Naudin, C., Lenoir, A., Siah, A., and Celette, F. (2017). Enhancing planned and associated biodiversity in French farming systems. Agron. Sustain. Dev. *37*, 57. https://doi.org/10.1007/s13593-017-0463-5.
108. Lucas, V., Gasselin, P., and Van der Ploeg, J.D. (2019). Local inter-farm cooperation: A hidden potential for the agroecological transition in northern agricultures. Agroecol. Sustain. Food Syst. *43*, 145–179. https://doi.org/10.1080/21683565.2018.1509168.
109. Salembier, C., Segrestin, B., Sinoir, N., Templier, J., Weil, B., and Meynard, J.M. (2020). Design of equipment for agroecology: Coupled innovation processes led by farmer-designers. Agric. Syst. *183*, 102856. https://doi.org/10.1016/j.agsy.2020.102856.
110. Calatrava, J., Martínez-Granados, D., Zornoza, R., González-Rosado, M., Lozano-García, B., Vega-Zamora, M., and Gómez-López, M.D. (2021). Barriers and Opportunities for the Implementation of Sustainable Farming Practices in Mediterranean Tree Orchards. Agronomy-Basel *11*, 821. https://doi.org/10.3390/agronomy11050821.
111. Labarthe, P. (2009). Extension services and multifunctional agriculture: Lessons learnt from the French and Dutch contexts and approaches. J. Environ. Manage. *90*, S193–S202. https://doi.org/10.1016/j.jenvman.2008.11.021.
112. Labarthe, P., Coleno, F., Enjalbert, J., Fugeray-Scarbel, A., Hannachi, M., and Lemarie, S. (2021). Exploration, exploitation and environmental innovation in agriculture. The case of variety mixture in France and Denmark. Technol. Forecast. Soc. Change *172*, 121028. https://doi.org/10.1016/j.techfore.2021.121028.
113. Sutherland, L.-A., and Labarthe, P. (2022). Introducing 'microAKIS': a farmer-centric approach to understanding the contribution of advice to agricultural innovation. J. Agric. Educ. Ext. *28*, 525–547. https://doi.org/10.1080/1389224X.2022.2121903.
114. Wick, A.F., Haley, J., Gasch, C., Wehlander, T., Briese, L., and Samson-Liebig, S. (2019). Network-based approaches for soil health research and extension programming in North Dakota, USA. Soil Use Manag. *35*, 177–184. https://doi.org/10.1111/sum.12444.
115. Lacoste, M., Cook, S., McNee, M., Gale, D., Ingram, J., Bellon-Maurel, V., MacMillan, T., Sylvester-Bradley, R., Kindred, D., Bramley, R., et al. (2022). On-Farm Experimentation to transform global agriculture. Nat. Food *3*, 11–18. https://doi.org/10.1038/s43016-021-00424-4.
116. Liotard, I., and Revest, V. (2018). Contests as innovation policy instruments: Lessons from the US federal agencies' experience. Technol. Forecast. Soc. Change *127*, 57–69. https://doi.org/10.1016/j.techfore.2017.07.008.
117. Boulestreau, Y., Casagrande, M., and Navarrete, M. (2021). Analyzing barriers and levers for practice change: a new framework applied to vegetables' soil pest management. Agron. Sustain. Dev. *41*, 44. https://doi.org/10.1007/s13593-021-00700-4.
118. Lefèvre, A., Perrin, B., Lesur-Dumoulin, C., Salembier, C., and Navarrete, M. (2020). Challenges of complying with both food value chain specifications and agroecology principles in vegetable crop protection. Agric. Syst. *185*, 102953. https://doi.org/10.1016/j.agsy.2020.102953.
119. Marette, S. (2021). Sustainability and Consumer Willingness to Pay for Legumes: A Laboratory Study with Lentils. Sustainability *13*, 3408. https://doi.org/10.3390/su13063408.
120. Boulestreau, Y., Casagrande, M., and Navarrete, M. (2023). A method to design coupled innovations for the agroecological transition. Implementation for soil health management in Provencal sheltered vegetable systems. Agric. Syst. *212*, 103752. https://doi.org/10.1016/j.agsy.2023.103752.
121. Falco, S.D., Smale, M., and Perrings, C. (2008). The role of agricultural cooperatives in sustaining the wheat diversity and productivity: the case of southern Italy. Environ. Resour. Econ. *39*, 161–174. https://doi.org/10.1007/s10640-007-9100-0.
122. Pancino, B., Blasi, E., Rappoldt, A., Pascucci, S., Ruini, L., and Ronchi, C. (2019). Partnering for sustainability in agri-food supply chains: the case of Barilla Sustainable Farming in the Po Valley. Agric. Food Econ. *7*, 13. https://doi.org/10.1186/s40100-019-0133-9.
123. Beer, L., and Theuvsen, L. (2019). Conventional German farmers' attitudes towards agricultural wood and their willingness to plant an alley cropping system as an ecological focus area: A cluster analysis. Biomass Bioenergy *125*, 63–69. https://doi.org/10.1016/j.biombioe.2019.04.008.
124. Brodt, S.B., Fontana, N.M., and Archer, L.F. (2020). Feasibility and sustainability of agroforestry in temperate industrialized agriculture: preliminary insights from California. Renew. Agric. Food Syst. *35*, 513–521. Pii s1742170519000140. https://doi.org/10.1017/S1742170519000140.
125. Schut, A.G.T., Cooledge, E.C., Moraine, M., Van de Ven, G.W.J., Jones, D.L., and Chadwick, D.R. (2021). Reintegration of crop-livestock systems in europe: An overview. Front. Agric. Sci. Eng. *8*, 111–129. https://doi.org/10.15302/j-fase-2020373.
126. Rimbaud, L., Fabre, F., Papaix, J., Moury, B., Lannou, C., Barrett, L.G., and Thrall, P.H. (2021). Models of Plant Resistance Deployment. In Annual Review of Phytopathology, *59*, J.E. Leach and S.E. Lindow, eds. *(Annual Reviews), pp. 125–152. https://doi.org/10.1146/annurev-phyto-020620-122134.*
127. Larsen, A.E., Noack, F., and Powers, L.C. (2024). Spillover effects of organic agriculture on pesticide use on nearby fields. Science *383*, eadf2572. https://doi.org/10.1126/science.adf2572.
128. Ouin, A., Andrieu, E., Vialatte, A., Balent, G., Barbaro, L., Blanco, J., Ceschia, E., Clement, F., Fauvel, M., Gallai, N., et al. (2021). Chapter Two - Building a shared vision of the future for multifunctional agricultural landscapes. Lessons from a long term socio-ecological research site in south-western France. In Advances in Ecological Research, D.A. Bohan, A.J. Dumbrell, and A.J. Vanbergen, eds. (Academic Press), pp. 57–106. https://doi.org/10.1016/bs.aecr.2021.05.001.
129. Petit, S., Alignier, A., Allart, R., Aviron, S., Boussard, H., Franck, P., Gibert, C., Ladet, S., Lavigne, C., Lecuyer, L., et al. (2023). Building capacities for the design of agroecological landscapes: The added-value of Landscape Monitoring Networks. Agric. Ecosyst. Environ. *342*, 108263. https://doi.org/10.1016/j.agee.2022.108263.
130. Lacombe, C., Couix, N., and Hazard, L. (2018). Designing agroecological farming systems with farmers: A review. Agric. Syst. *165*, 208–220. https://doi.org/10.1016/j.agsy.2018.06.014.
131. Villamayor-Tomas, S., Sagebiel, J., Rommel, J., and Olschewski, R. (2021). Types of collective action problems and farmers' willingness to

accept agri-environmental schemes in Switzerland. Ecosyst. Serv. *50*, 101304. https://doi.org/10.1016/j.ecoser.2021.101304.

132. Villanueva, A.J., Gómez-Limón, J.a., Arriaza, M., and Rodríguez-Entrena, M. (2015). The design of agri-environmental schemes: Farmers' preferences in southern Spain. Land Use Policy *46*, 142–154. https://doi.org/10.1016/j.landusepol.2015.02.009.

133. Xu, G., Sarkar, A., and Qian, L. (2021). Does organizational participation affect farmers' behavior in adopting the joint mechanism of pest and disease control? A study of Meixian County, Shaanxi Province. Pest Manag. Sci. *77*, 1428–1443. https://doi.org/10.1002/ps.6161.

134. Edwards, D.P., and Laurance, S.G. (2012). Green labelling, sustainability and the expansion of tropical agriculture: Critical issues for certification schemes. Biol. Conserv. *151*, 60–64. https://doi.org/10.1016/j.biocon.2012.01.017.

135. Torquebiau, E., Cholet, N., Ferguson, W., and Letourmy, P. (2013). Designing an Index to Reveal the Potential of Multipurpose Landscapes in Southern Africa. Land *2*, 705–725. https://doi.org/10.3390/land2040705.

136. Morel, K., Revoyron, E., San Cristobal, M., and Baret, P.V. (2020). Innovating within or outside dominant food systems? Different challenges for contrasting crop diversification strategies in Europe. PLoS One *15*, e0229910. https://doi.org/10.1371/journal.pone.0229910.

137. Möhring, N., Ingold, K., Kudsk, P., Martin-Laurent, F., Niggli, U., Siegrist, M., Studer, B., Walter, A., and Finger, R. (2020). Pathways for advancing pesticide policies. Nat. Food *1*, 535–540. https://doi.org/10.1038/s43016-020-00141-4.

138. Guyomard, H., Bureau, J.-C., Chatellier, V., Detang-Dessendre, C., Dupraz, P., Jacquet, F., Reboud, X., Requillart, V., Soler, L.-G., and Tysebaert, M. (2020). The Green Deal and the CAP: Policy Implications to Adapt Farming Practices and to Preserve the EU's Natural Resources (AGRI committee of the European Parliament). https://www.europarl.europa.eu/thinktank/en/document/IPOL_STU(2020)629214.

139. Sauquet, A. (2023). Ex post analysis of the crop diversification measure of CAP greening in France. Eur. Rev. Agric. Econ. *50*, 717–742. https://doi.org/10.1093/erae/jbac022.

140. Recanati, F., Maughan, C., Pedrotti, M., Dembska, K., and Antonelli, M. (2019). Assessing the role of CAP for more sustainable and healthier food systems in Europe: A literature review. Sci. Total Environ. *653*, 908–919. https://doi.org/10.1016/j.scitotenv.2018.10.377.

141. Pe'er, G., Finn, J.A., Diaz, M., Birkenstock, M., Lakner, S., Roder, N., Kazakova, Y., Sumrada, T., Bezak, P., Concepcion, E.D., et al. (2022). How can the European Common Agricultural Policy help halt biodiversity loss? Recommendations by over 300 experts. Conserv. Lett. *15*, 1–12. https://doi.org/10.1111/conl.12901.

142. Pe'er, G., Zinngrebe, Y., Moreira, F., Sirami, C., Schindler, S., Müller, R., Bontzorlos, V., Clough, D., Bezák, P., Bonn, A., et al. (2019). A greener path for the EU Common Agricultural Policy. Science *365*, 449–451. https://doi.org/10.1126/science.aax3146.

143. Batáry, P., Dicks, L.V., Kleijn, D., and Sutherland, W.J. (2015). The role of agri-environment schemes in conservation and environmental management. Conserv. Biol. *29*, 1006–1016. https://doi.org/10.1111/cobi.12536.

144. Frank, E.G. (2024). The economic impacts of ecosystem disruptions: Costs from substituting biological pest control. Science *385*, eadg0344. https://doi.org/10.1126/science.adg0344.

145. Finger, R., Möhring, N., Dalhaus, T., and Böcker, T. (2017). Revisiting Pesticide Taxation Schemes. Ecol. Econ. *134*, 263–266. https://doi.org/10.1016/j.ecolecon.2016.12.001.

146. Cieslik, K., Cecchi, F., Assefa Damtew, E., Tafesse, S., Struik, P.C., Lemaga, B., and Leeuwis, C. (2021). The role of ICT in collective management of public bads: The case of potato late blight in Ethiopia. World Dev. *140*, 105366. https://doi.org/10.1016/j.worlddev.2020.105366.

147. Steingrover, E.G., Geertsema, W., and van Wingerden, W.K.R.E. (2010). Designing agricultural landscapes for natural pest control: a transdisciplinary approach in the Hoeksche Waard (The Netherlands). Landsc. Ecol. *25*, 825–838. https://doi.org/10.1007/s10980-010-9489-7.

148. Taschen, E., Dezette, D., Guillot, E., Abadie, J., Arnal, D., Plassard, C., Taudière, A., Violle, C., Enjalbert, J., Le Roux, X., and Hinsinger, P. (2024). Wheat varietal diversity modulates nitrogen-related enzymatic activities but has limited impact on arbuscular mycorrhizal fungi. Plant Soil *503*, 13–27. https://doi.org/10.1007/s11104-023-06440-6.

149. Tscharntke, T., Clough, Y., Bhagwat, S.A., Buchori, D., Faust, H., Hertel, D., Hölscher, D., Juhrbandt, J., Kessler, M., Perfecto, I., et al. (2011). Multifunctional shade-tree management in tropical agroforestry landscapes - a review. J. Appl. Ecol. *48*, 619–629. https://doi.org/10.1111/j.1365-2664.2010.01939.x.

150. Pumarino, L., Sileshi, G.W., Gripenberg, S., Kaartinen, R., Barrios, E., Muchane, M.N., Midega, C., and Jonsson, M. (2015). Effects of agroforestry on pest, disease and weed control: A meta-analysis. Basic Appl. Ecol. *16*, 573–582. https://doi.org/10.1016/j.baae.2015.08.006.

151. Zellner, M.L. (2024). Participatory modeling for collaborative landscape and environmental planning: From potential to realization. Landsc. Urban Plan. *247*, 105063. https://doi.org/10.1016/j.landurbplan.2024.105063.

152. Berthet, E.T., Bretagnolle, V., and Gaba, S. (2022). Place-based social-ecological research is crucial for designing collective management of ecosystem services. Ecosyst. Serv. *55*, 101426. https://doi.org/10.1016/j.ecoser.2022.101426.

153. Rasmussen, L.V., Grass, I., Mehrabi, Z., Smith, O.M., Bezner-Kerr, R., Blesh, J., Garibaldi, L.A., Isaac, M.E., Kennedy, C.M., Wittman, H., et al. (2024). Joint environmental and social benefits from diversified agriculture. Science *384*, 87–93. https://doi.org/10.1126/science.adj1914.

154. Wu, K., Pan, C., Zhou, S., Zhou, F., Long, G., and Wu, B. (2021). Farming ducks in a maize field: a new and potential crop-livestock system from China. Agron. Sustain. Dev. *41*, 76. https://doi.org/10.1007/s13593-021-00732-w.

155. Maillet, G., Dufils, A., Angevin, F., Ramonteu, S., Peyraud, J.-L.,J.L., and Baumont, R. (2023). Benefits and limits of farm animals to control herbage mass, pests and weeds in orchards: a review. In 29. Book of abstracts of the 74st annual meeting of the european federation of animal science held in Lyon, France, 2023-08-26 (Wageningen Academic Publishers), p. 158.

156. Adeux, G., Vieren, E., Carlesi, S., Bàrberi, P., Munier-Jolain, N., and Cordeau, S. (2019). Mitigating crop yield losses through weed diversity. Nat. Sustain. *2*, 1018–1026. https://doi.org/10.1038/s4.

157. Greenhalgh, T., Thorne, S., and Malterud, K. (2018). Time to challenge the spurious hierarchy of systematic over narrative reviews? Eur. J. Clin. Invest. *48*, e12931. https://doi.org/10.1111/eci.12931.