Review

Ecological Intensification: Bridging the Gap between Science and Practice

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There is worldwide concern about the environmental costs of conventional intensification of agriculture. Growing evidence suggests that ecological intensification of mainstream farming can safeguard food production, with accompanying environmental benefits; however, the approach is rarely adopted by farmers. Our review of the evidence for replacing external inputs with ecosystem services shows that scientists tend to focus on processes (e.g., pollination) rather than outcomes (e.g., profits), and express benefits at spatio-temporal scales that are not always relevant to farmers. This results in mismatches in perceived benefits of ecological intensification between scientists and farmers, which hinders its uptake. We provide recommendations for overcoming these mismatches and highlight important additional factors driving uptake of nature-based management practices, such as social acceptability of farming.

Highlights

Ecological intensification aims to harness ecosystem services to sustain agricultural production while minimising adverse effects on the environment.

Ecological intensification is championed by scientists as a nature-based alternative to high-input agriculture but meets with little interest from growers.

Scientific evidence underlying ecological intensification is often unconvincing to growers, as it is based on small-scale studies of ecological processes unlinked from agricultural production.

Grower interest can be enhanced by evidence of the agronomic and economic benefits most relevant to farmers and measured at the scales of operation of farm enterprises.

In addition to concrete benefits, concerns of the general public about adverse effects of industrial farming can promote adoption of ecological intensification, both directly and indirectly, by enhancing political will to use regulatory instruments.

Ecological Intensification Shows Potential to Sustainably Safeguard Food Security . . .

Meeting the demands for agricultural products from a growing and more affluent world population through conventional intensification of agriculture is impossible without causing significant damage to the environment [1–3]. Ecological intensification has been proposed as a nature-based alternative that complements or (partially) replaces **external inputs** (see Glossary), such as agrochemicals, with production-supporting ecological processes, to sustain agricultural production while minimising adverse effects on the environment [4,5]. Ecological intensification is based on the assumption that delivery of **ecosystem services** is suboptimal in high-input agricultural systems (e.g., [6–10]), and that management of specific components of **biodiversity** can be used to either complement artificial inputs and increase agricultural productivity (ecological enhancement; Figure 1) or replace artificial inputs (ecological replacement; Figure 1), which results in reduced environmental costs without negatively impacting crop productivity [5].

Over the past few years, the evidence base underlying ecological intensification has steadily strengthened, with studies demonstrating that management can enhance the delivery of a range of regulating and supporting ecosystem services [11–14] or even produce win–win situations for agricultural production and the environment [15–18]. Scientists are therefore increasingly highlighting the benefits of ecologically intensifying agriculture through a greater reliance on biodiversity and ecosystem services. Policy makers likewise are starting to embrace ecological intensification as an environmentally friendly way towards food security [19,20] by supporting the implementation of biodiversity and ecosystem service-enhancing practices. In some regions, notably Europe and North America, this has been through considerable public expenditure (e.g., agri-environment schemes) to (partially) offset farmers' opportunity costs associated with implementation [21].

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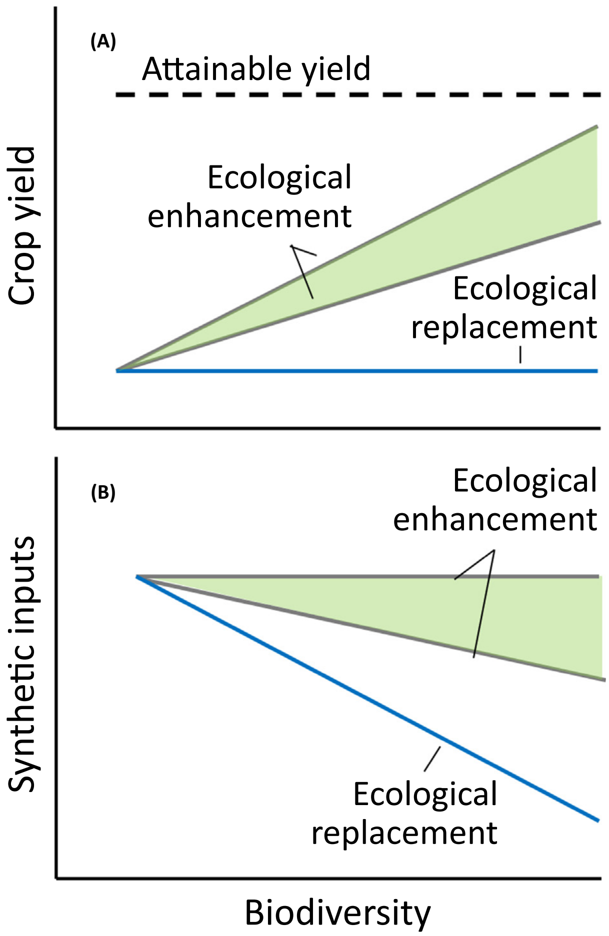


Figure 1. An Illustration of the Relationships Assumed under Ecological Intensification in High-Input Farming Systems between Functional Biodiversity and Crop Yield and Dependence on Synthetic Inputs (Pesticides and Artificial Fertilizers) under Ecological Replacement and Ecological Enhancement. Ecological replacement hypothesises that increasing biodiversity can progressively replace synthetic inputs with ecosystem services (A), while maintaining constant crop yield levels (B). Ecological enhancement hypothesises that crop yield increases with biodiversity, through the associated ecosystem services (A), which may or may not be linked with reduced synthetic inputs (B). For simplicity, linear relationships are depicted, while in theory, saturating curves are to be expected.

. . . But Sees Little Uptake by the Agricultural Sector

Knowledge of how farmers perceive the costs and benefits of ecological intensification practices is limited [22] but European farmers generally seem to have little interest in the topic. A recent survey on farmer attitudes towards biodiversity and ecosystem service-enhancing practices in seven European countries [23] showed that farmers generally favour practices that interfere little with normal farming operations. For example, farmers appreciate relatively simple management changes targeting landscape features such as hedgerows, ditch banks, or trees (Figure 2). However, on-field management practices, such as **cover crops**, conservation headlands, or beetle banks, were consistently among the least preferred practices (Figure 2). Strikingly, the establishment of wildflower strips, the practice with the strongest evidence base for agronomic and/or economic benefits in Europe and the USA [12,16,24,25], and often eligible for subsidy support, is amongst the most disliked practices by farmers. Understanding

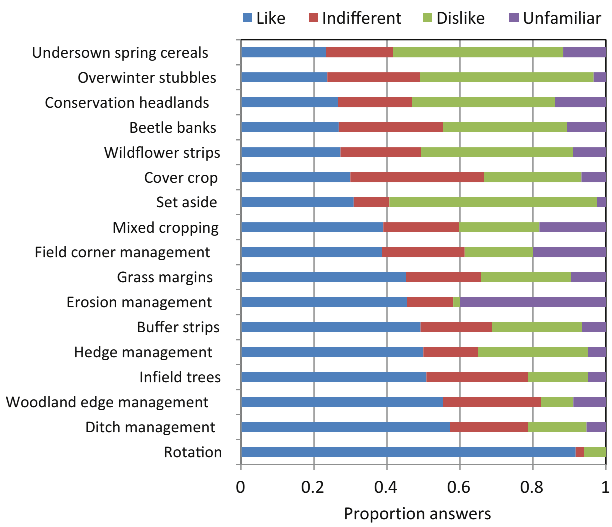


Figure 2. Preferences of Farmers from Germany, Hungary, Italy, The Netherlands, Poland, Sweden, and UK for Management Practices That May Contribute to Biodiversity Enhancement and Ecosystem Service Delivery. Number of responses per management practice ranged between 55 and 84. Based on data from [23].

why these practices are poorly adopted may explain why ecological intensification has seen little uptake to date by farmers, farmer organisations, and agricultural corporations [19,26,27].

Here, we explore why the perceptions of the costs and benefits of ecological intensification differ between scientists and farmers. We first synthesise the scientific evidence for nature-based contributions to agricultural production that underlie ecological intensification, and reflect on its relevance for farming enterprises. We consider aboveground as well as below-ground ecosystem services, as both are relevant to farming, and ecological intensification has a greater potential of delivering benefits when targeting the full range of production-enhancing ecosystem services. We then highlight key knowledge gaps and suggest ways to overcome these. Finally, we discuss the role of scientific evidence in shaping farm management, and which additional factors are important drivers of farmer behaviour. Our focus is on ecosystem service-enhancing practices rather than on farming systems (e.g., organic farming) and is mainly on **high-input farming systems** since this is where biodiversity and ecosystem services are most degraded and where enhancing such services can potentially have the most pronounced effects [28].

Evidence for Benefits of Aboveground Ecosystem Services Contributing to Agricultural Production

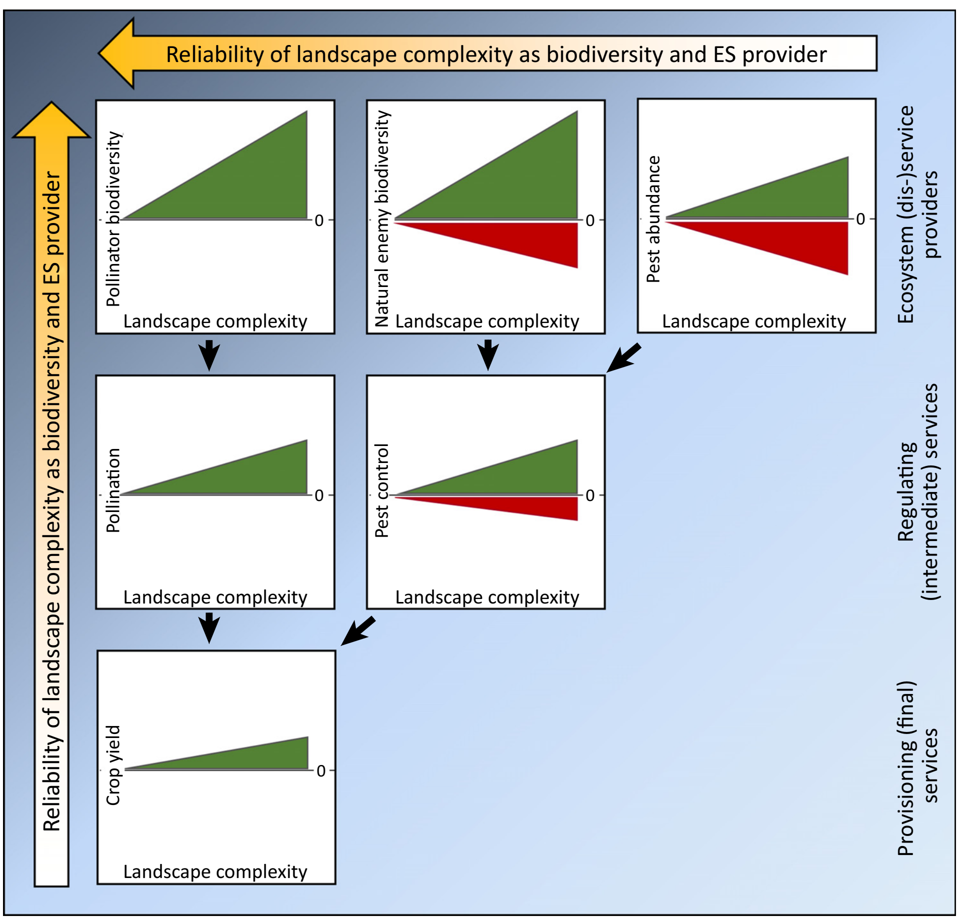
The species providing the two key aboveground ecosystem services relevant to agriculture, pollination and pest regulation, are mostly mobile organisms such as bees, hover flies, parasitoid wasps, spiders, and carabid beetles. Although agricultural fields offer them important forage and shelter resources, these often come in short-lived fluxes, and beneficial species are generally highly dependent on semi-natural habitats in the surrounding landscape [29,30]. Delivery of ecosystem services is therefore often inferred from the spatial configuration of landscape elements [31–33], with increasing **landscape complexity** (e.g., cover of semi-natural habitats, percentage non-arable land, distance to nearest semi-natural habitat, presence of wildflower strips) leading to higher **pollination service** or **pest regulation services**. A

Glossary

Biodiversity: the variety of all forms of life, from genes to species and ecosystems.
Conservation tillage: the practice of reducing tillage intensity and retaining crop residues to conserve soil, water, and energy.
Cover crop: crop grown between two cash crops to suppress weeds, improve soil fertility, and reduce pest pressure, and that is generally not harvested.
Crop rotation: the practice of growing different crops in succession on the same land to maintain soil productivity and control weeds, pests, and diseases.
Ecosystem service: benefits obtained by people from ecosystems.
External inputs: non-renewable or industrially made resources, such as fertilizers or pesticides used by growers to increase yield or avoid yield loss.
Functional biodiversity: the part of all biodiversity that makes a direct contribution to agricultural production.
High-input farming systems: farming systems in which crop production is primarily based on external inputs such as fuel, fertilisers, and pesticides.
Landscape complexity: the extent to which a landscape is covered by a variety of semi-natural, non-crop habitats.
Mixed cropping: the practice of growing multiple crops simultaneously in the same field to enhance overall yield and reduce pressure of pests, weeds, and diseases.
Natural enemies: the naturally occurring predators and parasitoids of crop pests.
Pest regulation service: control of herbivore pests of (crop) plants by wild predators such as beetles, spiders, parasitoid wasps, and birds.
Pollination service: pollination of crop and wild plants by wild pollinators such as bees, hoverflies, and bats.

wealth of studies have examined the relationship between the diversity and abundance of service-providing species and landscape complexity and, on average, find positive relationships (Figure 3) [30,34–37]. However, there are notable exceptions, for example, because pollinators do not always relate positively to landscape complexity [38,39]. Also, **natural enemies** of crop pests are a taxonomically varied group of organisms, not necessarily all of which depend on semi-natural habitats and that may even be negatively related to the cover of semi-natural habitats [40] (Figure 3). Moreover, landscape complexity can also be related to delivery of disservices, in the form of pests, but this relationship is highly variable and unresolved [37].

The relationship between landscape complexity and the diversity of service-providing arthropods has led many scientists to conclude that delivery of ecosystem services can be influenced by maintaining or enhancing landscape complexity [41–43]. However, the relationship between landscape complexity and the actual delivery of the pollination and pest regulation services is less pronounced and more variable than that between the service providing taxa and landscape complexity [14,34,44–48]. Furthermore, the relationship between landscape complexity and



Trends in Ecology & Evolution

Figure 3. A Graphical Synthesis of the Variation in Relationships, Observed in Empirical Studies, between Landscape Complexity and Biodiversity and Delivery of Ecosystem Services (ES) Relevant to Agriculture. Green indicates positive and red indicates negative relationships.

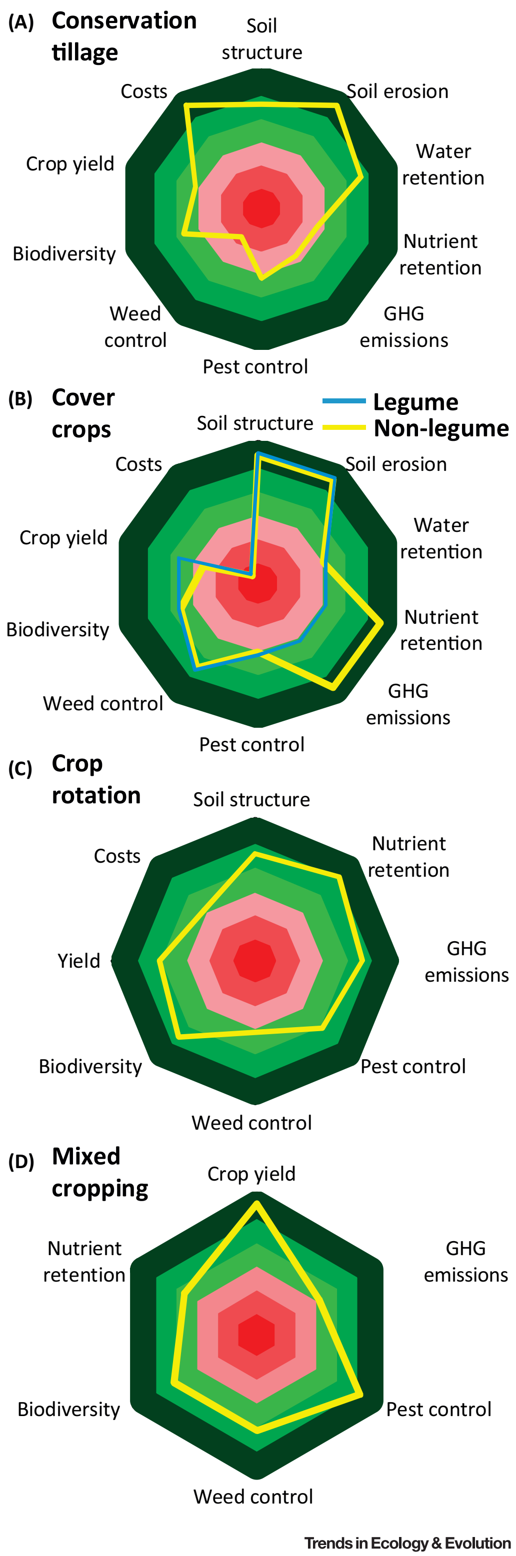
crop yield, the main variable the agricultural sector is interested in, is even weaker and often absent [13,42,49–53]. The difference in focus on the main response variable may well contribute to the difference in perceptions by scientists and farmers of the ecosystem service benefits that can be obtained by manipulating landscape complexity (Figure 3).

To date, only a few studies have convincingly demonstrated that management -enhancing pollination and pest regulation produces net agronomic or economic benefits. These studies have in common the examination of effects of establishing vegetation or wildflower strips on or next to arable fields. Such measures invariably boost densities of pollinators and natural enemies locally [54,55] and can enhance crop pollination and pest regulation [56,57] as well as a number of other ecosystem services (e.g., reduce water runoff, increase soil and phosphorus retention [58]). However, only three of these studies suggest that yield increases were sufficient to compensate for the opportunity costs (i.e., loss of cropped area) of establishing these new landscape elements [12,24,25]. Only two studies show that, in time, yield increases were larger than both establishment and opportunity costs, so that farmers benefit economically from enhancing flower-rich habitats for pollinators [16,25]. Further studies, across a range of crops and localities, are desperately needed. With increasing demands for agricultural products and tight economic margins, farmers may require more than just a proof of concept before they risk adopting ecological intensification as a viable alternative or complementary approach to external input-based practices.

Evidence for Benefits of Belowground Ecosystem Services Contributing to Agricultural Production

The belowground communities present in agricultural soils provide important ecosystem services, such as enhancing nutrient availability, prevention of pests and diseases, carbon storage, and improvement of soil structure and water holding capacity [59]. Soils contain a wealth of biodiversity of microbes, invertebrates, and some vertebrates, which can add up to thousands of species per square metre of soil surface [60]. Recent studies suggest that soil biodiversity can be engineered to specifically enhance the beneficial soil biota providing multiple ecosystem services [61,62]. In addition to the engineering approaches that often focus on introducing specific organisms, such as for nutrient provision or plant protection, a more holistic approach has shown how the stability of soil food webs depends on its structure [63]. Whereas individual groups of soil biota correlate with specific ecosystem services [64], the connectedness of the entire soil community corresponds with, for example, increased efficiency of carbon uptake by the soil food web [65]. Organic matter may promote belowground biodiversity and ecosystem processes, and can even influence aboveground–belowground interactions by, for example, enhancing aboveground abundance of natural enemies [66]. Worldwide agriculture is causing loss of soil organic matter, except in areas with intensive animal farming [67] and under certain no-till conditions [68]. The question is how ecological intensification can make use of these novel insights into the relationship between soil organic matter, belowground biodiversity, and soil functioning to improve crop production.

Key on-field practices that can improve the delivery of agriculturally relevant belowground ecosystem services are **conservation tillage**, the use of cover crops, increasing the diversity of the number of crops in a rotation, or **mixed cropping** [62]. Figure 4 shows the impact of these practices and suggests that on average, and across all examined services, they have considerable positive effects. However, Figure 4 also highlights that none of these practices consistently enhances all ecosystem services considered here. For example, conservation tillage invariably reduces soil erosion and saves farmers tilling costs but has less consistent positive effects on soil structure, water retention, and biodiversity [8,69,70], and has overall



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negative effects on nutrient retention, greenhouse gas emissions, and weed control [14,70]. The use of cover crops consistently improves soil structure and reduces soil erosion, however, it has less consistent positive effects on weed control and biodiversity [10,20,71]. Cover crops may improve nutrient retention and greenhouse gas emissions, depending on whether nitrogen-fixing cover crops are being used [9,17]. However, in arid systems, competition for water with the main crop generally results in yield reductions. Moreover, cover cropping requires additional sowing and sometimes killing the crop before planting the main crop, which may bring substantial costs and the use of herbicides that may have negative side effects on biodiversity. The practices of mixed cropping and increasing **crop rotation** diversity, on average, positively affect ecosystem service delivery [15,47,72–75], but for mixed cropping, key information on the costs is still missing. Whether this is considered convincing evidence to a farmer may depend on which services are enhanced and which are reduced, and probably what that means to the farm economically. In tandem with aboveground services, more studies on belowground services in different cropping systems and locations are needed in order to obtain a robust evidence base to support changes in farmer practices.

Knowledge Gaps in the Evidence Base of Ecological Intensification

To be more convincing to farmers, scientific studies on ecological intensification need to address the costs and benefits that are most relevant to farmers (see Outstanding Questions). In addition to measuring straightforward yield variables, parameters such as quality, commercial grading, whether key thresholds are met, and stability of yield should be quantified, as they also determine production value in many crops. Potential costs of ecological intensification should be an integral component of research. These include direct costs (e.g., establishment and maintenance of wildflower strips [16]), as well as opportunity costs (e.g., loss of crop production on land used to establish wildflower strips). Ideally this should be done under a range of scenarios, to account for context-dependence of the costs and benefits. For example, land prices in The Netherlands are an order of magnitude higher than in the United States (in 2009 approximately €47 000 ha^{-1} and €3700 ha^{-1}, respectively [Eurostat (2015) Agricultural prices and price indices (EU and candidate countries). http://ec.europa.eu/eurostat/web/agriculture/data] [76]) resulting in higher fixed (mortgage) costs, which necessitates greater financial benefits from ecosystem services to break even. The benefits of particular ecosystem services can also be variable over time, as illustrated by the pest regulation services provided by bats to cotton production in south-western United States. These benefits declined by 79% between 1990 and 2008 due to falling global cotton prices and the widespread adoption of genetically modified Bt cotton [77]. Furthermore, when multiple services are considered, the cost–benefit analysis is complicated because different ecosystem services are usually expressed in different units, making it difficult to assess whether a decline in one service is compensated by an increase in another. Cost–benefit analyses should additionally distinguish between private benefits and public goods delivered by ecological intensification. Public goods, such as reduced greenhouse gas emissions or wildlife conservation, can benefit society at large but represent little or no direct benefit to individual farmers. For example, non-nitrogen-fixing cover crops clearly outperform nitrogen-fixing cover crops in terms of reducing greenhouse gas

Figure 4. Radar Plots Graphically Summarising the Effects of the Most Frequently Implemented Management Practices to Increase Sustainability of Farming on Multiple Ecosystem Services. Dark green/red: consistent positive/negative effects found in meta-analyses, reviews, and individual studies. Intermediate green/red: positive/negative effects dominate but some studies show no effects. Light green/red: positive/negative effects dominate but many studies show no effect and some even negative effects. Effects based on references [14,69,70,104] for conservation tillage; [3,9,10,17,18,20,71,105,106] for cover crops; [10,15,73,106–110] for crop rotation; and [74,75,111–115] for mixed cropping. Abbreviation: GHG, greenhouse gas.

emissions and nutrient leaching (Figure 4). However, leguminous cover crops are preferred by many farmers because they can result in higher yields in follow-on crops [17].

A second set of knowledge gaps concern the limited spatio-temporal scope of the evidence for ecosystem service benefits that is currently available (see Outstanding Questions). To date, most studies examine service delivery in a single crop at the field level in 1 or 2 years only [11–13,47,49,56,57,78]. Studies that consider the spatio-temporal dimensions most relevant to farmers are rare. The key issues that need to be addressed are, first, that the populations of service-providing species often need to build up before measurable effects can be established, resulting in a time lag between implementation of ecological intensification and manifestation of ecosystem service benefits. Such time lags [79] may range from 2 or more years for pollination [16,80] to one or several decades for soil services [81]. Especially in farming systems where economic margins are low, farmers may not be willing to invest in practices of which they do not know when they will reap the benefits. Second, there is little information on pollination and pest regulation benefits across the crop rotation in annual cropping systems. The benefits of ecological intensification generally improve with increased targeting of the specific species groups providing the bulk of the services to a particular crop [12]. However, annual farming systems often rotate crops on individual fields. Ecological intensification should produce benefits across all crops in the rotation to be attractive to farmers. Third, information is lacking on benefits from ecological intensification at the farm scale, arguably the most relevant scale from the perspective of a farmer. In many countries, farms do not consist of a contiguous block of land, and fields can be scattered throughout the landscape. Most of the species providing pollination or pest regulation services are mobile and can be influenced by semi-natural habitats or crops up to several kilometres away from the target location [29,38,47,57,78]. Their foraging ranges therefore generally supersede the size of individual farms [82]. The net farm-level benefits of enhancing pollination or pest regulation are difficult to predict, as they depend on the implementation of nature-based management on the focal farm and on neighbouring farms, and on biodiversity-supporting habitat on public land such as protected areas, roadside verges, and railway embankments [83]. Finally, although ecological theory predicts that service delivery becomes more stable with increasing biodiversity [84], this has only been empirically demonstrated in small-scale studies using experimental plant communities [85]. Variability in the profitability of farms as a result of adverse effects of inclement weather conditions on crop growth and yield is of major concern to farmers. Evidence of improved yield stability could be a powerful argument to interest farmers in ecological intensification.

Can Scientific Evidence of the Benefits of Ecological Intensification Increase Its Uptake?

Studies of farmer behaviour consistently show that short-term economic benefits enhance the adoption of novel biodiversity-enhancing practices [26,86,87]. However, proven benefits alone do not guarantee uptake of management practices [88]. For example, conservation tillage in wheat has met with large-scale adoption in south Asia due to a 15–16% cost saving, but has met with limited uptake in Mexico and Southern Africa despite evidence of higher and more stable yields both for maize and wheat [89]. Farmers may decide not to follow scientific evidence because they are unsure about the relevance of generic recommendations from scientific studies for their specific farms and conditions. For example, a farm may be located on a different soil type than the study or bad weather can change the response of a crop to a management practice [90]. Apart from economic considerations, key decisions by farmers and land managers are based on previous experience, familiarity with technologies, interactions with peers and advisors, labour requirements, and perceived risks [26,91]. Currently, advice to farmers often comes from advisors or sales representatives from agro-chemical companies that may sell both seeds and pesticides, and have financial incentives to promote their products [92]. By contrast, advice on nature-based management coming from parties such as independent extension services, non-governmental organisations, and scientists may not reach as many farmers as this is not always a well-resourced core part of their business. Furthermore, agro-chemical applications offer quick, highly visible, short-term solutions to perceived problems. Rate and method of application are readily available as label instructions or otherwise provided by the manufacturers, and effects can be easily observed. Ecological intensification tends to offer longer-term solutions. However, it relies on complex networks of service-providing communities, and management has mostly indirect effects that are rarely clear-cut and easily observed. For example, the relationship between semi-natural habitat or wildflowers in the wider countryside and pest regulation or fruit set may not be obvious to a farmer. Even with clear evidence of the benefits, using ecosystem services requires more knowledge and initiative from farmers than spraying pesticides or adding honey bees at recommended rates. For some farmers, this alone may be an argument not to adopt ecological intensification practices. Finally, there is a general lack of practical, on the ground information to help farmers adopt nature-based management practices. We still have very little information on where, how much of, and what kind of measures should be implemented to achieve a certain effect. This is because the proof of concept for ecological intensification has only recently been established and the amount of research on the topic is still small compared with the long-term and wide-ranging research on conventional farming practices [93]. Even today, conventional farming still receives not only the majority of the governmental funding but also almost all of the research investments by the private sector [94].

Farmers may, however, also adopt **functional biodiversity**-enhancing practices without clear evidence of economic benefits, as human behaviour is not solely driven by economic or other rational considerations [95]. Public attitude, in particular, can have strong direct and indirect effects on uptake of nature-based management practices by farmers. Farmers with strong social motivations can be influenced directly, as adoption of ecological intensification contributes to a desired, more positive image of their own farm by society and their peers [96]. Indirectly, public attitude can influence management of a much wider range of farms. For example, concern of the general public, in many parts of Europe, about intensive farming practices such as the use of pesticides or genetically engineered crops [97,98] contributed to the EU restriction on the use of neonicotinoid pesticides in 2013. Perceptions by the general public can also adversely affect application of nature-based practices, as illustrated in the Californian fresh produce sector. After a deadly *Escherichia coli* outbreak, growers were pressured to remove nearby semi-natural vegetation and discontinue use of manure-based composts, as wildlife was implicated as a disease vector even though studies failed to reveal any evidence for this [99,100]. Uptake of ecological intensification may furthermore be influenced by conflicts of interests between farmer communities and agribusiness multinationals and governments [101]. Many agribusinesses aim to generate societal support for the implementation of industrial forms of agriculture in new territories by emphasising aspects of efficiency, productivity, economies of size, trade liberalization, free markets, and the need to feed the world [Rosset, P.M. and Martinez-Torres, M.E. (2017) La via campesina's open book: celebrating 20 years of struggle and hope (https://viacampesina.org/en/la-via-campesina-s-open-book-celebrating-20-years-of-struggle-and-hope/)]. Especially in the southern hemisphere, social movements such as La Via Campesina counter this by emphasising benefits of family-based diversified agroecological farming, such as small-scale production of healthy, local food, good stewardship of the rural environment and cultural heritages, and the peasant or family farm way of life [102]. Such agroecology movements are now also gaining interest in northern countries with more industrial farming systems [103].

Concluding Remarks

Large-scale adoption of ecological intensification requires a stronger evidence base than is currently available. To date, most research has focused on the ecological mechanisms and processes underlying ecological intensification in specific cropping systems. More knowledge is needed, particularly on the quantification of the costs and benefits of ecological intensification, using variables that are relevant to farmers (e.g., crop yield and profits at the farm level), and the effectiveness of different ecological intensification practices, alone and in combination with other practices, over longer periods of time, and in a range of crops, farming systems, and locations. The results of studies that have been carried out so far suggest that in the majority of crops and under the current economic paradigm it will be difficult for ecological intensification to achieve higher profits than under conventional intensification. However, this could change in the near future as the prices of external inputs are expected to rise, demand for more sustainably produced agricultural products is increasing, and societal acceptance of the external, environmental costs of high-input farming is waning.

We propose that there are three complementary pathways towards wide-scale adoption of ecological intensification: through market-driven processes, regulatory instruments, and through reputational concerns. Market-driven adoption will occur if a greater reliance on ecosystem services produces direct and net economic benefits [16], in which case it may simply become part of farm business models. Large-scale adoption through regulatory instruments requires political will to promote nature-based farm management, for example, through compulsory practices to support functional biodiversity linked to payments or by taxing agrochemical inputs to integrate the environmental costs associated with the use of pesticides and artificial fertilizers into their price. Making external inputs more expensive would make nature-based alternatives more attractive economically. Reputational concerns will increase adoption if a sufficiently large part of the general public is worried about adverse effects of industrial farming and intensive use of agro-chemicals. This may influence farmers directly to manage their farms in ways to promote functional biodiversity when they can do this without economic repercussions. Moreover, given the global nature of the food market, changes in consumption patterns towards more environmental-friendly products (e.g., organic food) can influence farming practices all over the world. Just as importantly, public concern can be a strong driver of the political will to promote ecological intensification directly or indirectly (i.e., the regulatory instruments pathway). Future research should therefore not only address ecological, agronomic, and economic aspects of ecological intensification but also the sociological aspects (see Outstanding Questions).

Outstanding Questions

Response variables considered:

What are the effects of ecological intensification on parameters relevant to farmers?

What are the (opportunity) costs of ecological intensification and are they balanced by the benefits?

Are there synergies or trade-offs between delivery of multiple ecosystem services?

Does ecological intensification have different effects on delivery of private benefits and public goods?

Spatio-temporal scales considered:

How long are time-lags between implementing management and delivery of benefits?

What are the pollination and pest regulation benefits across the full rotation of annual crops?

What are the farm-scale costs and benefits of ecological intensification?

Does ecological intensification reduce yield variability?

How can ecological intensification best be implemented practically (e.g., how much, where, when)?

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