Emerging Topics in Life Sciences (2020)
https://doi.org/10.1042/ETLS20190205

PORTLAND PRESS

Review Article

Ecological intensification and diversification approaches to maintain biodiversity, ecosystem services and food production in a changing world

Claire Kremen

Institute for Resources, Environment and Sustainability, Department of Zoology, Biodiversity Research Centre, University of British Columbia, Vancouver, BC, Canada

Correspondence: Claire Kremen (claire.kremen@ubc.ca)

How do we redesign agricultural landscapes to maintain their productivity and profitability, while promoting rather than eradicating biodiversity, and regenerating rather than undermining the ecological processes that sustain food production and are vital for a liveable planet? Ecological intensification harnesses ecological processes to increase food production per area through management processes that often diversify croplands to support beneficial organisms supplying these services. By adding more diverse vegetation back into landscapes, the agricultural matrix can also become both more habitable and more permeable to biodiversity, aiding in conserving biodiversity over time. By reducing the need for costly inputs while maintaining productivity, ecological intensification methods can maintain or even enhance profitability. As shown with several examples, ecological intensification and diversification can assist in creating multifunctional landscapes that are more environmentally and economically sustainable. While single methods of ecological intensification can be incorporated into large-scale industrial farms and reduce negative impacts, complete redesign of such systems using multiple methods of ecological intensification and diversification can create truly regenerative systems with strong potential to promote food production and biodiversity. However, the broad adoption of these methods will require transformative socio-economic changes because many structural barriers continue to maintain the current agrichemical model of agriculture.

Introduction

Can agricultural landscapes be redesigned to maintain production and profitability, while promoting biodiversity, sustaining ecosystem services and human well-being, and providing resilience to climate change? Various strands of research suggest that such multifunctional designs are possible, but often are not adopted due to policy or market barriers, or lack of training and support for such designs [1,2]. Ecological intensification is defined as using natural processes to replace human-produced inputs like pesticides and fertilizers, while maintaining or increasing food production per unit area [3]. Examples include cover-cropping or intercropping with legumes to populate fields with nitrogen-fixing bacteria that improve soil fertility and increase crop yields, or planting flower-rich habitats along field edges to support the natural enemies of crop pests, reduce crop damage and reduce pesticide use [4]. These practices are an important and necessary biophysical component of the redesign of agricultural landscapes to achieve joint goals of promoting biodiversity and human well-being, although not sufficient without transformative social, political and economic changes [4]. This article explores how ecological intensification can contribute to these goals.

Ecological agricultural intensification relies on enhancing natural processes to improve yields while conventional intensification typically focuses on increased or improved inputs (such as fertilizers, pesticides and technologies) to enhance yields. While many of the practices that might be utilized in

Received: 1 June 2020
Revised: 25 July 2020
Accepted: 27 July 2020

Version of Record published:
4 September 2020

Emerging Topics in Life Sciences (2020)
https://doi.org/10.1042/ETLS20190205

ecological intensification are shared by other agricultural systems, such as agroecological, sustainable, organic, climate-smart or regenerative agriculture, ecological intensification emphasizes improving yields through the use of these techniques.

Ecological intensification practices often act by providing habitat and resources for colonizing beneficial organisms that promote crop growth. Examples of such beneficial organisms include micro-organisms that cycle and/or supply nutrients to plants, soil invertebrates that decompose organic matter and aerate soils, flower-visiting species that pollinate crops, and invertebrate and vertebrate species that prey on crop pests. In contrast, conventional farming systems frequently achieve their fertility, pollination and pest control goals through the use of purchased inputs such as synthetic fertilizers, rented honey bees and pesticides. Although generally high-yielding, conventional intensification methods often produce unintended environmental and social consequences such as nutrient runoff into streams and lakes, loss of arable soils, pesticide effects on non-target organisms and on humans, ecosystem modification and biodiversity loss, and greenhouse gas emissions [5–9].

Ecological intensification methods can achieve greater environmental sustainability in three ways: first by minimizing or eliminating negative environmental externalities from farming (i.e. negative effects that flow off the farm, affecting other people, such as pollution of waterways with fertilizers and pesticides that reduce fish catch, Table 1); second, by supporting natural processes that promote and regenerate the ecosystem services on which farmers depend [9,10]; and third, by also providing those ecosystem services, such as biodiversity conservation and good water quality, that benefit society at large [10]. Ecological intensification may also support biodiversity in two ways. First, by diversifying habitats and resources within agricultural lands, ecological intensification methods promote both the beneficial organisms they are designed to support, as well as other species [9,11,12]. Second, this diversification may also improve habitat connectivity across the landscape, either through techniques that add vegetative structure back to simplified systems (such as agroforestry), or through restoration or conservation of natural or semi-natural habitat patches that form stepping stone or continuous corridors promoting the movement of plants and animals [13–15]. Ability to disperse is thought to be critical for the long-term persistence of populations and species, allowing individuals to rescue declining populations, recolonize empty habitat patches, enhance gene flow or follow their climate niches to adapt to climate change.

Ecological intensification can contribute to economic sustainability in three ways. First, natural or semi-natural habitat patches within farming landscapes can enhance pollination or pest control services that improve yields in the surrounding landscape [16,17]. By targeting less productive areas within or bordering agricultural fields for these habitat elements, the resulting yield increases can offset yield losses due to removing lands from

Table 1. Sustainability categorization

Sustainability category	Indicator(s)
Environmental: maximize ecosystem services	*Benefits farmers* Soil quality Nutrient management Water-holding capacity Pest, weed and disease control Pollination Resistance and resilience to climate change *Benefits society* Biodiversity (habitat, connectivity) Water quality Carbon storage
Environmental: minimize externalities	GHG emissions Pollutants (nutrients, pesticides…) Land use Energy use Water use
Economic (long-term)	Production Profitability
Social equity	Intra-generational Inter-generational

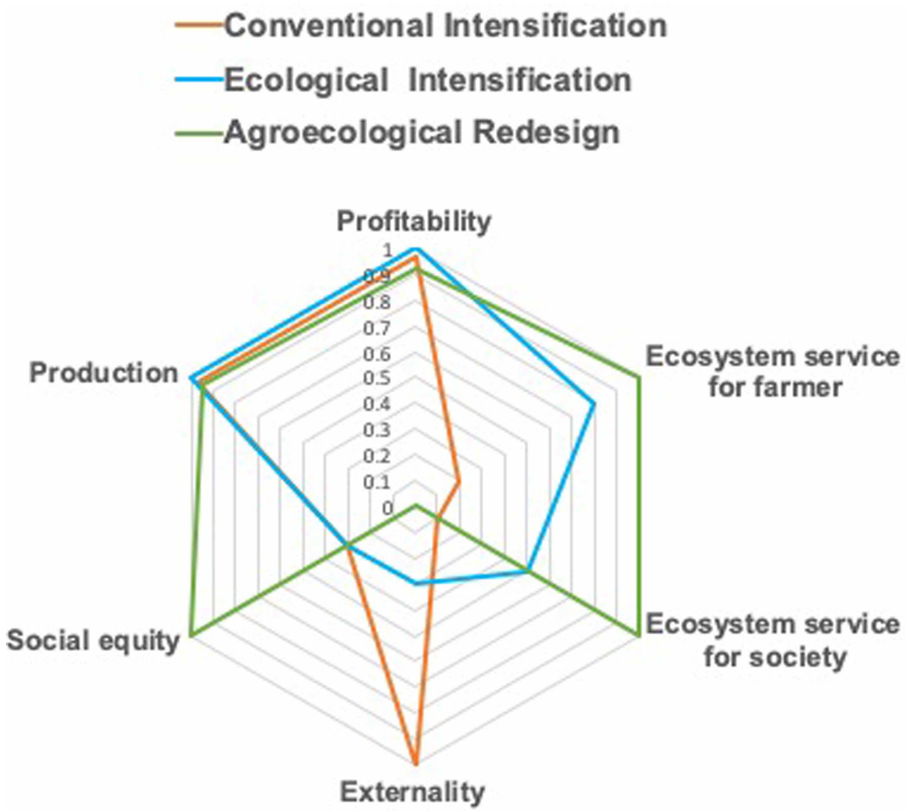

Figure 1. Conceptual figure depicting hypothetical relationships between the sustainability indicators of Table 1.
Three different agricultural systems are depicted: conventional intensification (reliance on agrichemicals for soil fertility and pest control; managed bees for pollination; and irrigation for water); ecological intensification (one or more management practices used to stimulate ecological processes in place of purchased inputs, such as use of complex crop rotations to reduce crop pests/diseases and enhance soil fertility); agroecological re-design (replacement of the original system based on ecological principles, using multiple ecological intensification techniques to achieve a regenerative, diversified farming system)[1].

production, even leading to net gains [18]. Second, ecological intensification can achieve greater profitability, through the combined effects of reducing input use (such as pesticides) while maintaining or enhancing yields [19–21]. Reduced reliance on purchased inputs such as seeds and agrochemicals can also enhance farmer agency and sovereignty. Finally, ecological intensification measures can confer resistance and/or resilience to climate extremes, such as droughts and hurricane damage, promoting economic recovery for farmers as well as maintaining food production [22,23].

To visualize and compare the multifunctionality and sustainability of ecologically versus conventionally intensified systems, one can use spider diagrams that portray sustainability indicators (Figure 1). Here, environmental sustainability is categorized as either maximizing ecosystem services or minimizing externalities (Table 1), recognizing that relationships and overlaps exist within and between these categories, as described below. Within environmental sustainability, ecosystem services are further characterized as those that benefit farmers directly and contribute to the long-term sustainability of the farm, versus those that benefit society at large by contributing to the sustainability of the planet [10]. One of the latter type of services is biodiversity itself [24]. Biodiversity in turn includes both species that are essential for providing ecosystem services to farmers [25], and other species that utilize farmlands for resources, habitat or movement but do not supply services, including pest species and wildlife that conflict with humans (disservices). Maximizing ecosystem services and minimizing externalities can be two sides of a coin: for example, promoting water-holding capacity, a soil-

[1]Photo permission and higher resolution photographs is currently being solicited for photos in Figures 3 and 4. For Figure 2, it has already been granted. High resolution files of graphics will be made available once the paper is accepted.

Emerging Topics in Life Sciences (2020)
https://doi.org/10.1042/ETLS20190205

based ecosystem service, may simultaneously reduce water use, an externality. Furthermore, many of the externalities listed in Table 1 may be inter-correlated. Production, included here as a component of economic sustainability, is also considered a provisioning ecosystem service. Just as some ecosystem services benefit farmers directly while others benefit society, similarly, profitability, another economic sustainability indicator, matters most to a farmer, while production can be a societal goal (i.e. 'feeding the world'). Social equity is the third axis of sustainability and critical for food system transformation [26]; while included in the table it does not appear in these figures because ecological intensification alone is not sufficient for food system transformation [4,27].

Case studies

A range of case studies are presented to demonstrate how ecological intensification methods may support and restore biodiversity in agricultural landscapes, while enhancing environmental and economic sustainability, using the visualization framework of Figure 1. Two of the case studies involve the adoption of a single practice within a conventional intensified system (Figure 1, blue, ecological intensification) while the third case demonstrates an entire transformation of the agricultural system (Figure 1, green, agroecological redesign). These two levels correspond to Gliessman's [27] Level 2 and Level 3 in the use of agroecological techniques for food system transformation.

Planting field edges with native perennial vegetation in California

Adding plantings of non-crop vegetation around field edges, whether annual or perennial, native or non-native, is a common diversification technique used around the world to promote beneficial organisms that provide pollination or pest control services; it serves as an ecological intensification technique when it also reduces the need to use pesticides or import managed bees [18,19,21]. The technique can be appealing to farmers because it removes no land from production, while potentially providing a range of benefits. In California, farmers planting native perennial vegetation on field margins (hereafter, 'hedgerows') did so because of perceived benefits, including, in order of importance to them: bees, natural enemies, esthetics, wildlife, erosion control, water and soil quality, weed control, windbreak and air quality, carbon storage, profit and shade [28]. However, non-adopters listed some of the same items as concerns (e.g. weeds, cost, competition with the crop for bees [28]). Farmers utilizing hedgerows in California vary from conventional growers with single crops in large fields (ca. 30 acres) to organic farmers growing many different types of crops on small fields, showing that diversification and ecological intensification techniques can apply across farming sizes and styles [4].

Detailed studies of Californian hedgerows surrounding single-crop conventional fields showed substantial benefits for bee and bird biodiversity (Figure 2). Relative to unplanted field edges (which were typically bare or weedy edges that were mowed or left unmanaged, respectively), hedgerows supported greater species richness and functional diversity of native bee species, year to year persistence and colonization, especially by more specialized bees, and abundance of less common species [29–31]. Hedgerows and remnant riparian vegetation similarly enhanced diversity and abundance of bird species, including several threatened or special concern species [32,33]. For bees, these changes in biodiversity appeared primarily related to the increased floral diversity provided by hedgerows [34], and possibly also the availability of nest sites for above-ground nesting bees requiring woody resources for nesting [35]. A network of hedgerows increased site-to-site species turnover (beta-diversity) and regional richness relative to control sites [31]. The network enhanced connectivity, as evidenced by measurably greater persistence at hedgerow sites closer to more other hedgerows [36].

Hedgerows provided both pest control and pollination services to several but not all of the crops studied. For field tomato, the presence of hedgerows increased pest control by invertebrate natural enemies as measured through sentinel experiments; it was also associated with lower levels of aphid pests in the field and reduced pesticide use by 4× [37]. In sunflower fields, hedgerows reduced damage to sunflower seeds from sunflower moths below the economic threshold for pesticide use without increasing damage due to pest birds [33]. However, in walnut orchards, hedgerows increased bird predator without control of codling moth, probably because walnut orchards themselves supported the presence of the two woodpecker species that controlled the moth [38]. Similarly for pollination services, hedgerows increased seed set provided by native bees for potted canola in a sentinel experiment, but had no effect on sunflower seed set at the field scale [39,40]. As in the walnut codling moth case, here the principle pollinators specialized on sunflower and tracked this resource as it was rotated across the landscape, instead of being attracted to and supported by hedgerows.

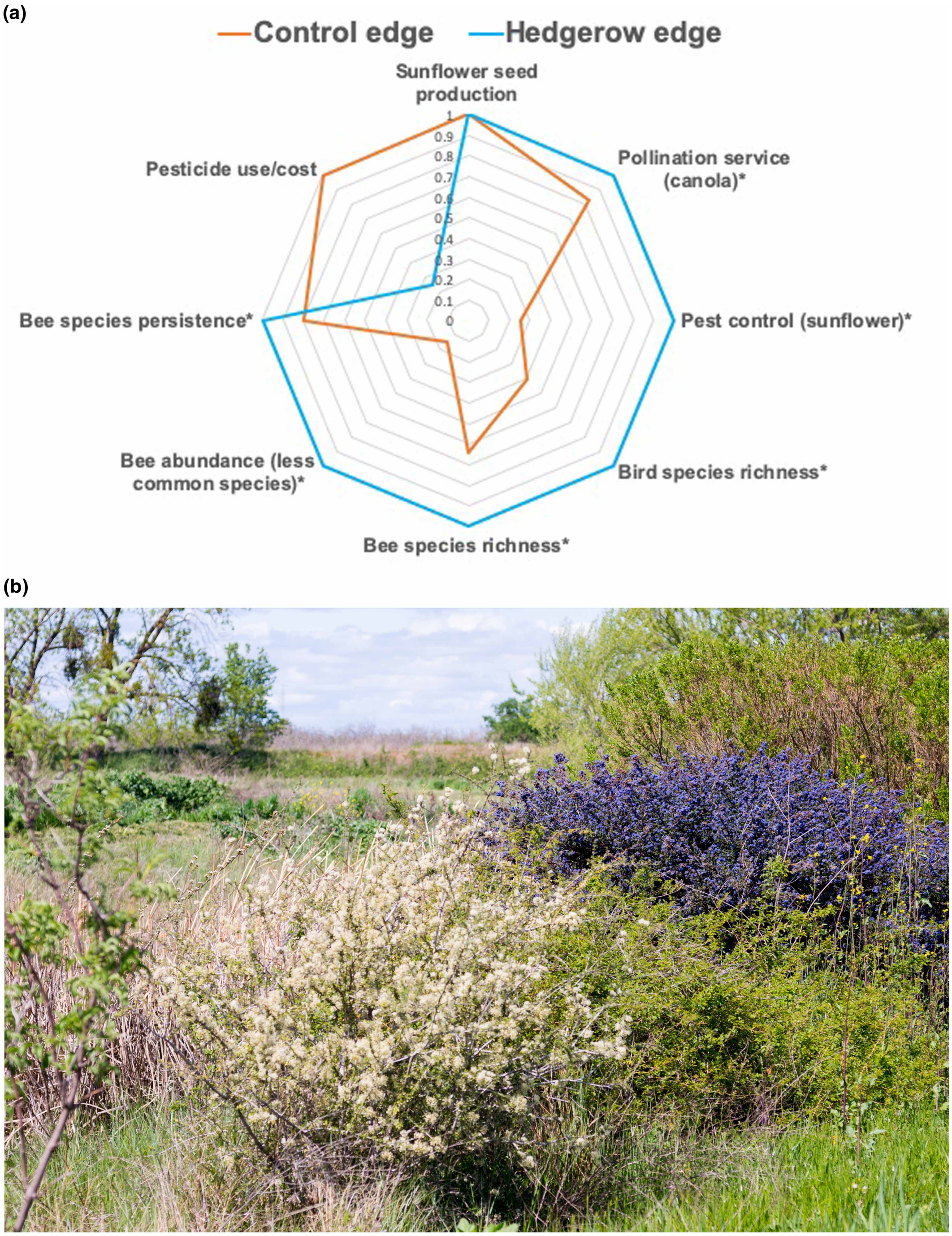

Figure 2. Hedgerow system in California.

(**A**) Spider diagram comparing control bare or weedy field edges with a native plant hedgerow edge in California (blue color denotes single ecological intensification practice). A * indicates significant difference. Details and citations are provided in the text. Hedgerows provided significant benefits for ecosystem services to farmers (pollination and pest control) and to society (bird and bee biodiversity), while reducing externalities from pesticide use. Production was not influenced by hedgerow plantings. (**B**) Two flowering shrubs (*Ceanothus* spp.) in the California native plant hedgerow that support pollinators and natural enemies of crop pests. Photo credit: Leithen M'Gonigle, Simon Fraser University.

Emerging Topics in Life Sciences (2020)
https://doi.org/10.1042/ETLS20190205

Hedgerows are expensive to install but over time, their cost could be balanced by increased yields due to enhanced pest control and pollination, and reduced use of pesticides and rented bee colonies. In California, these costs would be balanced over a period of 7 years [39], suggesting this technique would likely only be of interest to farmers that own rather than lease their land. As Figure 2 demonstrates, once implemented, they contribute substantially to the multifunctionality and environmental sustainability of the farm.

Planting prairie strips in midwestern corn and soy fields of the United States

In the midwestern United States, one of the most intensively farmed areas in the world, scientists and farmers have worked together to add strips of native prairie plants directly within the agricultural fields to mitigate the loss of soil and nutrients into freshwater habitats, while providing habitat for biodiversity. This practice removes land from production but has no impact on yields in the remaining cropped areas; thus, it is a diversification rather than an ecological intensification practice. The deep prairie roots slow down the passage of water, trap soil particles, and take up excess nutrients, leading to significantly reduced runoff (0.63×), sediment loss (0.05×) and phosphorus loss (0.23×), based on converting only 10–20% of the field to prairie strips (Figure 3). Nitrogen losses were also reduced (0.3×) although this effect was not significant. By increasing native plant richness, these prairie strips enhanced insect species richness (2.6×) (including increases in pollinator insect richness (2.4×) and abundance (3.5×) and natural enemy insect richness (2.2×)), and doubled bird species richness and abundance, including of species of conservation concern [41]. A striking element of this case study is the disproportionately large sustainability benefits achieved through a relatively small reduction in cropping area.

However, although the differences in profits were not significant between fields with and without the prairie strips, there was a net loss in yield and profit that reflected the removal of 10–20% of land from production. The loss or potential loss of revenue is a factor that prevents the adoption of this technique (Schulte-Moore, pers. comm.). In other systems, particularly those that are strongly pollinator-dependent [42,43], increased yields, due to enhancing beneficial insects that provide pollination and/or pest control services, may offset land removal, such as was observed in a wheat-legume (oilseed rape or field bean) rotation of conventional field crops in the United Kingdom [18]. Targeting lower-yielding lands within fields for restoration may further assist in minimizing or reversing profit losses from land removal, by reducing labor and input costs on the least productive areas of the farm [18,44]. In the US Midwest region where the prairie-strip technique was introduced, a large-scale analysis showed that such marginal production areas cause large losses for farmers during extreme weather events, such as occurred recently during heavy droughts. This finding strengthens the argument for targeting low productivity regions within fields for conversion to prairie strips; targeted restoration could simultaneously aid in mitigating water quality issues while stabilizing profits for farmers in response to climate change [45]. Both farm and non-farm residents noted that improving water quality is a top priority. Encouraging broader adoption of this technique, however, requires market or government-based incentive programs or policies (such as regulated water quality targets), as well as training and outreach [41]. Again, use of a single technique within a conventional, highly intensive landscape, generates surprising multifunctional benefits.

Intensive silvopastoral systems in Latin America

Intensive silvopastoral systems are based on planting locally adapted mixes of grasses, forbs, trees and shrubs at high densities to produce multiple vertical layers of forage for cattle [46]. These diverse plantings represent a system-level transformation from the monoculture pastures or pastures plus feedlot systems that predominate. Forage mixtures typically include legumes that fix nitrogen; this nitrogen source in combination with returning manure and urine from livestock and litter from vegetation, reduces or eliminates the need for additional fertilizer (synthetic or other). Cattle are rotated through the silvopasture. Forage plants may serve other uses as well, such as fuelwood and fruit production [47]. Different silvopastoral systems have been developed for diverse regions around the world [48] as a profitable and resilient solution to three major sustainability challenges posed by cattle production. First, cattle compete with wildlife for land, whether through direct competition for forage plants in semi-natural or natural habitats, or through habitat conversion to create pastures or grow grains for livestock. Reducing meat consumption in order to reduce the area of land devoted to livestock production has been identified as the single most important human behavioral change need to support biodiversity conservation [49]. Second, cattle production contributes 7–18% of global greenhouse gas emissions, principally due to methane generated from the ruminant gut. Finally, concentrated livestock operations create large

Emerging Topics in Life Sciences (2020)
https://doi.org/10.1042/ETLS20190205

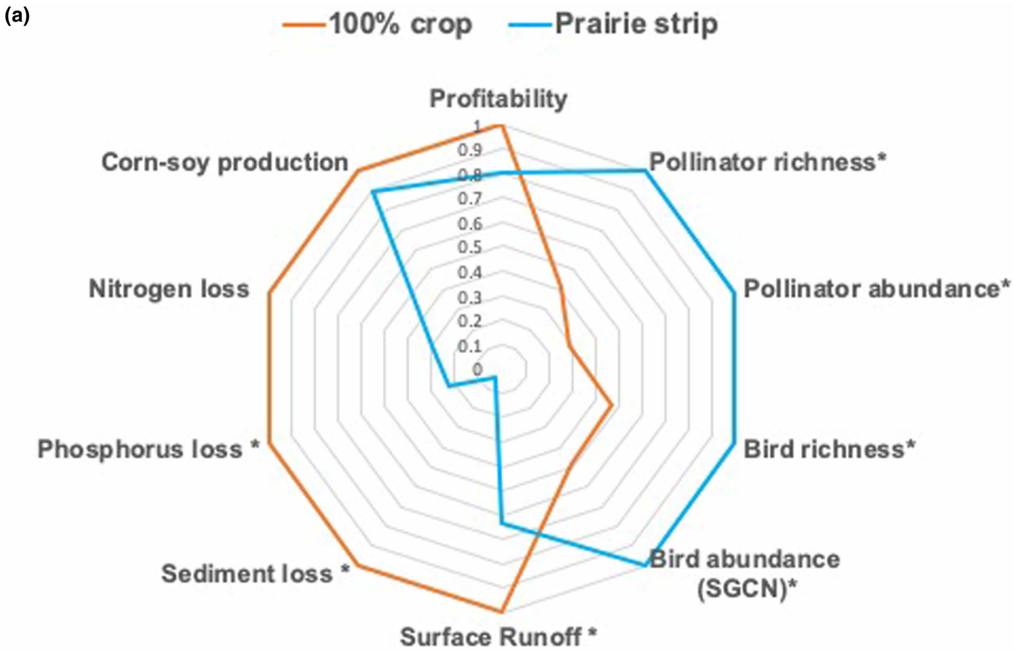

Figure 3. Prairie strip system in corn and soy agriculture in Iowa.

(**A**) Spider diagram comparing conventional corn-soy production in Iowa with the integration of 10–20% prairie strips into the corn-soy field (blue color denotes single ecological intensification practice). A * indicates significant difference, based on Supplementary Table S2 in Schulte et al. [41]. Prairie strips provided significant benefits for ecosystem services to society, including biodiversity (pollinators and birds), and reduction in negative externalities (runoff, sediment and phosphorus loss). Benefits traded-off against short-term corn and soy production and profitability (although not significantly). (**B**) Flowering prairie plants within a prairie strip in an Iowan corn field. Photo credit: STRIPS Project, University of Iowa.

Emerging Topics in Life Sciences (2020)
https://doi.org/10.1042/ETLS20190205

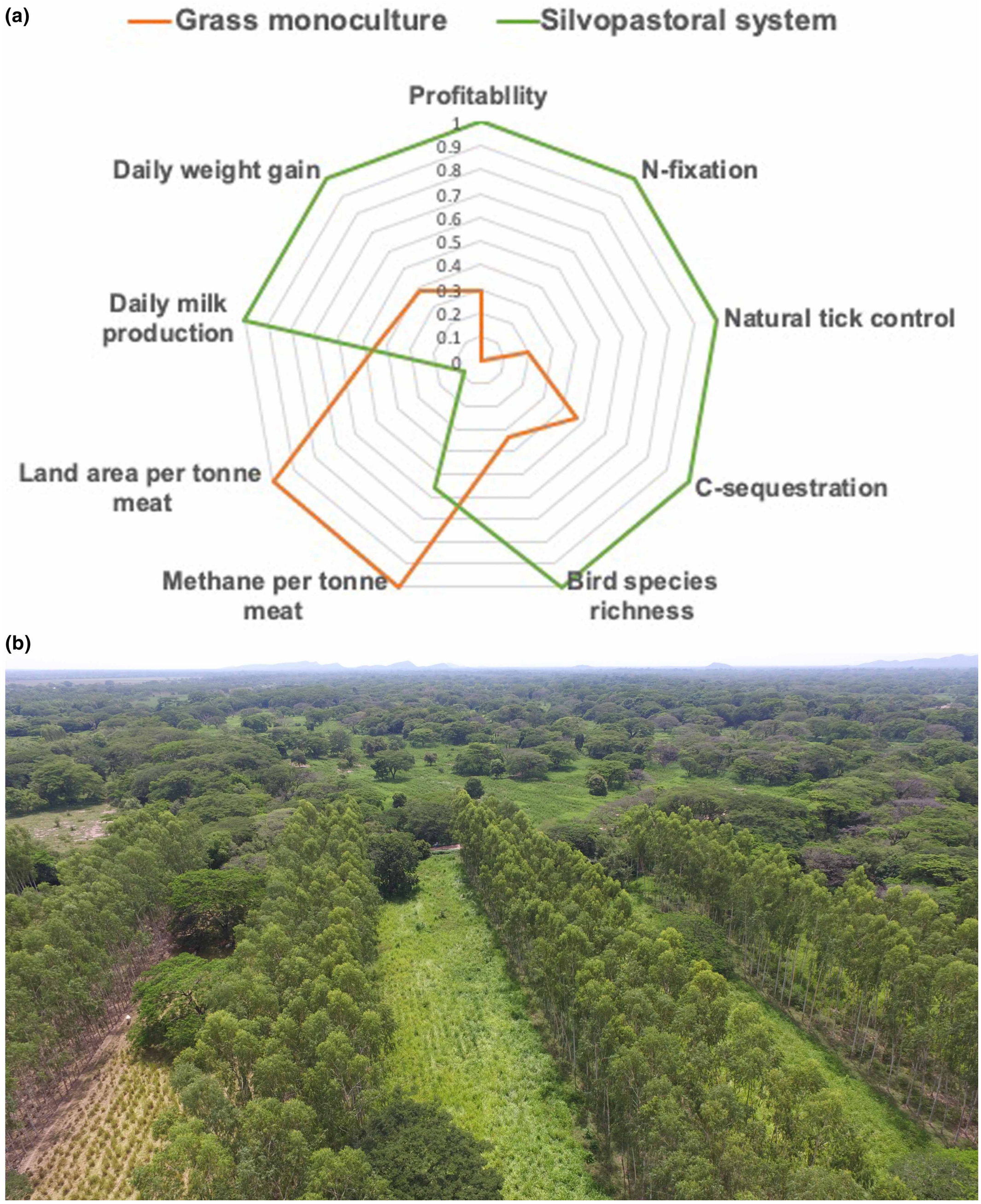

Figure 4. Intensive silvopastoral system in Colombia.

(**A**) Spider diagram comparing conventional grass pasture with intensive silvopasture in Colombia (green color indicates agroecological redesign to create diversified farming system). Details and citations are provided in the text. Intensive silvopasture provided important ecosystem services benefiting farmers (nitrogen fixation and tick control) and also society (carbon-sequestration, bird biodiversity). Intensive silvopasture reduced methane production and land use — two major negative externalities of beef and dairy production. Due to the whole system redesign, no negative trade-offs were observed. Production and profitability are also superior in this system. (**B**) Planted intensive silvopasture in Colombia (Finca La Luisa) with grasses, *Eucalyptus* and *Leucaena leucocephala* in the foreground, and seeded grasses with native tree species in the background. Photo Credit: Fernando Uribe, CIPAV.

quantities of manure and other pollutants (such as antibiotics) that pollute the environment [50]. Intensive silvopastoral systems produce cattle more efficiently and sustainably, in ways that reduce these sustainability issues substantially.

For example, in Latin American countries including Argentina, Brazil, Colombia, Mexico, Nicaragua and Panama, intensive silvopastoral systems are being used to create productive, profitable and resilient livestock operations, restore fertility to exhausted agricultural lands, provide habitat for biodiversity and/or re-establish connectivity across large landscapes [46,47]. These systems often include the nitrogen-fixing forage shrub *Leucaena leucocephala* which fixes 150 kg N/ha/yr; these fast-growing trees can recuperate fertility of exhausted agricultural soils over the short to medium term. Manure and leaf litter returning to the soil enhance soil fertility and structure and support soil biodiversity, while permanent maintenance of vegetative cover protects soils from erosion. Deep roots of trees and shrubs promote the infiltration of water and the storage of carbon in soils, promoting resilience to drought [48]. Trees and shrubs store carbon and provide shade, which can reduce temperatures by 4–8°C. Shaded microclimates promote animal welfare, improve forage quality, stabilize grass forage production across the season and increase meat and milk production, especially during droughts [47]. Multiple vegetative strata provide habitats for other organisms; at the landscape scale, the restoration of diverse tree species enhances structural connectivity and may improve animal movements [13]. Finally, by restoring soil fertility for livestock production, silvopasture also may help to arrest the cycle of soil and land degradation that causes continuous agricultural expansion into tropical forests [47].

Compared with conventional single-species grass pastures, daily meat production was enhanced 3–4× while milk production was enhanced 2–3×, even though animal stocking rates were also increased by 2–4× in silvopastures [47] (Figure 4). Due to the enhanced per animal production and increased stocking rates, two important externalities were reduced: the amount of methane (a potent greenhouse gas) dropped by ~0.5× per tonne of meat produced, while the amount of land used per tonne production dropped from 14.8 to 1.2 ha [48]. Simultaneously, twice as much carbon was sequestered [47], while bird species richness tripled and ant species richness increased by 1.3×, although as a caveat, some species found in forests or wetlands of the region were never found in silvopastures [48]. Paradoxically, although land use for livestock production generally poses a huge threat to biodiversity conservation [49], raising cattle through silvopastoral production appears to provide an important conservation tool in agricultural and rangelands. First, due to its land use efficiency, more meat or milk can be produced per hectare, potentially allowing more land available for wildlife. Second, adding trees and other diverse vegetation back to simplified pastures and row crops can create habitat and structural connectivity to support biodiversity at the landscape scale [13]. Third, restoring soil fertility may reduce farmers' need for continued agricultural expansion into the forest. Of course, this system, which combines elements of land-sparing and sharing [51], will only be effective in preventing expansion if coupled with policies and programs to arrest deforestation [4].

Silvopastoral systems can be more profitable due to enhanced meat and milk production and reduced chemical inputs [19,48]. Farmers do not need to purchase fertilizers due to the recycling of manure and litter in the system [46]. They also no longer need to apply pesticides to control ticks since other organisms in the environment reduce tick incidence and tick-borne disease on livestock [48]. Reduced chemical usage minimizes the potential for pollutants to leak into the surrounding environment. Silvopastoral systems can provide benefits for farmworkers, such as more interesting or stable employment [48]. However, they require training and knowledge to implement as well as up-front investments. While these systems can be used to restore exhausted agricultural soils that have lost fertility, it takes some time for them to become productive. Similar to the hedgerow restoration described above, the up-front costs and knowledge barriers can be prohibitive for adoption [46]. As a method that enhances diversity from plot to field to landscape scale, intensive silvopasture represents an agroecological redesign to a fully diversified farming system [52]. If adopted at a larger scale, which is happening in some regions of Colombia under the auspices of governmental incentive programs and alliances of farmers and NGOs [e.g. 46], such farm-scale transformations may begin to create significant positive effects for biodiversity through improving habitat and connectivity of the agricultural matrix.

Conclusions

Each of the described case studies provides evidence for the multifunctional benefits of ecological intensification and diversification practices, but each also points to similar challenges in encouraging broader uptake. For each practice, the initial economic cost can be prohibitive, even if ultimately the technique provides economic benefits as well as the potential for greater resilience to environmental shocks. In all three cases, a time component

Emerging Topics in Life Sciences (2020)
https://doi.org/10.1042/ETLS20190205

exists for the ecological practices and sustainability enhancements to translate to economic gain — for example, in the hedgerow case, 7 years to eliminate the initial installation costs ([39], see also [53]). All cases note the need for outreach and training to promote these novel interventions [28,41,46]. Two of these cases (hedgerows and prairie strips) represent single practice shifts within conventional farming systems that reduce negative environmental externalities within the context of the existing farming approach (Level 2 in Gliessman's [27] classification of food system change), whereas the intensive silvopastoral system represents a full-scale (i.e. Level 3) transformation from a conventional system to a regenerative, diversified farming system [52].

While a wide variety of possible tools and institutional arrangements exist to encourage investment in ecological intensification practices and provide the implementation knowledge [4,13], successful use of these tools requires an enabling policy and governance context. An impressive example comes from the Altiplano region of Andalusia Spain. Here, after decades of conventional, industrial agriculture for large-scale commodity cropping, water, soils and biodiversity were depleted, many farms abandoned, and rural infrastructure crumbled. However, an agroecological social movement, working together with provincial government and researchers, redesigned the farming system from the ground up, employing techniques of ecological intensification and diversification to create an integrated system for co-producing almond, native trees, sheep and bees, with joint processing and local marketing of a variety of products. Through ups and downs of political support, this strong movement, which integrates farmers, scientists, civil society and government, has persisted across a broad region, leading to restored soil fertility, improved water and biodiversity, and creation of robust and diverse local supply chains ([54], Level 5 in Gliessman's [27] classification of food system change).

As shown in this last example, ecological intensification can provide practices to improve environmental and economic sustainability; however, a broader socio-economic transformation is required to provide nutritious, culturally appropriate food for all people equitably, while sustaining Earth's biodiversity and life support systems. Agroecology provides a broad and promising socio-ecological framework to accomplish such sweeping food system transformations [54]. Agroecology encompasses a suite of agricultural practices, a science and a social movement [55]. Agroecological practices include the ecological intensification and diversification practices described here. Farming practices and systems are identified, tested and adapted by farmers and scientists working together through a participative and transdisciplinary agroecological science. Lastly, the agroecological social movement works towards the societal transformations needed to promote not only uptake of agroecological practices but also a food system that is sustainable along environmental, economic and social equity axes [26,27]. Agroecology can be a major tool for promoting land uses in working lands that are compatible with biodiversity conservation [56].

Summary

- It is vital to develop agricultural systems that are sustainable yet productive.
- Ecological intensification and diversification are promising techniques for creating agricultural systems that are environmentally and economically sustainable while enhancing agricultural landscapes for biodiversity.
- A broader socio-economic transformation, such as that provided by the agroecology framework, is needed to promote broad uptake of ecological intensification and diversification methods, and to create a food system providing equitable access to nutritious food for all people.

Competing Interests

The author declares that there are no competing interests associated with this manuscript.

Open Access

Open access for this article was enabled by the participation of the University of British Columbia in an all-inclusive *Read & Publish* pilot with Portland Press and the Biochemical Society.

Author Contribution

C.K. wrote the manuscript.

Acknowledgements

The author declares no conflicts of interest.

References

1 S. Parmentier, (2014) Scaling-up agroecological approaches: what, why and how? Oxfam-Solidarity, Belgium. http://www.oxfamsol.be
2 IPES-Food (2016) From Uniformity to Diversity: a paradigm shift from industrial agriculture to diversified agroecological systems, International Panel of Experts on Sustainable Food Systems. https://doi.org/IPES-Food
3 Bommarco, R., Kleijn, D. and Potts, S.G. (2013) Ecological intensification: harnessing ecosystem services for food security. *Trends Ecol. Evol.* **28**, 230–238 https://doi.org/10.1016/j.tree.2012.10.012
4 Garibaldi, L.A., Pérez-Méndez, N., Garratt, M.P.D., Gemmill-Herren, B., Miguez, F.E. and Dicks, L.V. (2019) Policies for ecological intensification of crop production. *Trends Ecol. Evol.* **34**, 282–286 https://doi.org/10.1016/j.tree.2019.01.003
5 Ramankutty, N., Mehrabi, Z., Waha, K., Jarvis, L., Kremen, C., Herrero, M. et al. (2018) Trends in global agricultural land use: implications for environmental health and food security. *Annu. Rev. Plant Biol.* **69**, 789–815 https://doi.org/10.1146/annurev-arplant-042817-040256
6 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
7 Evans, A.E., Mateo-Sagasta, J., Qadir, M., Boelee, E. and Ippolito, A. (2019) Agricultural water pollution: key knowledge gaps and research needs. *Curr. Opin. Environ. Sustain.* **36**, 20–27 https://doi.org/10.1016/j.cosust.2018.10.003
8 Nicolopoulou-Stamati, P., Maipas, S., Kotampasi, C., Stamatis, P. and Hens, L. (2016) Chemical pesticides and human health: the urgent need for a new concept in agriculture. *Front. Public Heal.* **4**, 148 https://doi.org/10.3389/fpubh.2016.00148
9 Kremen, C. and Miles, A. (2012) Ecosystem services in biologically diversified versus conventional farming systems: benefits, externalities, and trade-offs. *Ecol. Soc.* **17**, 40 https://doi.org/10.5751/ES-05035-170440
10 Zhang, W., Ricketts, T.H., Kremen, C., Carney, K. and Swinton, S.M. (2007) Ecosystem services and dis-services to agriculture. *Ecol. Econ.* **64**, 253–260 https://doi.org/10.1016/j.ecolecon.2007.02.024
11 Kovács-Hostyánszki, A., Espíndola, A., Vanbergen, A.J., Settele, J., Kremen, C. and Dicks, L.V. (2017) Ecological intensification to mitigate impacts of conventional intensive land use on pollinators and pollination. *Ecol. Lett.* **20**, 673–689 https://doi.org/10.1111/ele.12762
12 Garibaldi, L.A., Carvalheiro, L.G., Leonhardt, S.D., Aizen, M.A., Blaauw, B.R., Isaacs, R. et al. (2014) From research to action: enhancing crop yield through wild pollinators. *Front. Ecol. Environ.* **12**, 439–447 https://doi.org/10.1890/130330
13 Kremen, C. and Merenlender, A.M. (2018) Landscapes that work for biodiversity and people. *Science* **362** https://doi.org/10.1126/science.aau6020
14 DeClerck, F.A.J., Chazdon, R., Holl, K.D., Milder, J.C., Finegan, B., Martinez-Salinas, A. et al. (2010) Biodiversity conservation in human-modified landscapes of Mesoamerica: past, present and future. *Biol. Conserv.* **143**, 2301–2313 https://doi.org/10.1016/j.biocon.2010.03.026
15 Mendenhall, C.D., Shields-Estrada, A., Krishnaswami, A.J. and Daily, G.C. (2016) Quantifying and sustaining biodiversity in tropical agricultural landscapes. *Proc. Natl. Acad. Sci. U.S.A.* **113**, 14544–14551 https://doi.org/10.1073/pnas.1604981113
16 Kremen, C., Williams, N.M., Bugg, R.L., Fay, J.P. and Thorp, R.W. (2004) The area requirements of an ecosystem service: crop pollination by native bee communities in California. *Ecol. Lett.* **7**, 1109–1119 https://doi.org/10.1111/j.1461-0248.2004.00662.x
17 Chaplin-Kramer, R., de Valpine, P., Mills, N.J. and Kremen, C. (2013) Detecting pest control services across spatial and temporal scales. *Agric. Ecosyst. Environ.* **181**, 206–212 https://doi.org/10.1016/j.agee.2013.10.007
18 Pywell, R.F., Heard, M.S., Woodcock, B.A., Hinsley, S., Ridding, L., Nowakowski, M. et al. (2015) Wildlife-friendly farming increases crop yield: evidence for ecological intensification. *Proc. Biol. Sci.* **282**, 20151740 https://doi.org/10.1098/rspb.2015.1740
19 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
20 Davis, A.S., Hill, J.D., a Chase, C., 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
21 Gurr, G.M., Lu, Z., Zheng, X., Xu, H., Zhu, P. and Chen, G. (2016) Multi-country evidence that crop diversification promotes ecological intensification of agriculture. *Nat. Plants* **2**, 16014 https://doi.org/10.1038/nplants.2016.14
22 Holt-Gimenez, E. (2002) Measuring farmers' agroecological resistance after Hurricane Mitch in Nicaragua: a case study in participatory, sustainable land management impact monitoring. *Agric. Ecosyst. Environ.* **93**, 87–105 https://doi.org/10.1016/S0167-8809(02)00006-3
23 Bowles, T.M., Mooshammer, M., Socolar, Y., Calderón, F., Cavigelli, M.A., Culman, S.W. et al. (2020) Long-term evidence shows that crop-rotation diversification increases agricultural resilience to adverse growing conditions in North America. *One Earth* **2**, 284–293 https://doi.org/10.1016/j.oneear.2020.02.007
24 Mace, G.M. (2014) Whose conservation? *Science* **345**, 1558–1560 https://doi.org/10.1126/science.1254704
25 Kremen, C. (2005) Managing ecosystem services: what do we need to know about their ecology? *Ecol. Lett.* **8**, 468–479 https://doi.org/10.1111/j.1461-0248.2005.00751.x
26 Loos, J., Abson, D.J., Chappell, J.M., Hanspach, J., Mikulcak, F., Tichit, M. et al. (2014) Putting meaning back into "sustainable intensification". *Front. Ecol. Environ.* **12**, 356–361 https://doi.org/10.1890/130157
27 Gliessman, S. (2016) Transforming food systems with agroecology. *Agroecol. Sustain. Food Syst.* **40**, 187–189 https://doi.org/10.1080/21683565.2015.1130765
28 Garbach, K. and Long, R.F. (2017) Determinants of field edge habitat restoration on farms in California's Sacramento Valley. *J. Environ. Manage.* **189**, 134–141 https://doi.org/10.1016/j.jenvman.2016.12.036
29 Morandin, L.A. and Kremen, C. (2013) Hedgerow restoration promotes pollinator populations and exports native bees to adjacent fields. *Ecol. Appl.* **23**, 829–839 https://doi.org/10.1890/12-1051.1
30 M'Gonigle, L.K., Ponisio, L.C., Cutler, K. and Kremen, C. (2015) Habitat restoration promotes pollinator persistence and colonization in intensively managed agriculture. *Ecol. Appl.* **25**, 1557–1565 https://doi.org/10.1890/14-1863.1

Emerging Topics in Life Sciences (2020)
https://doi.org/10.1042/ETLS20190205

31 Ponisio, L.C., M'Gonigle, L.K. and Kremen, C. (2016) On-farm habitat restoration counters biotic homogenization in intensively managed agriculture. *Glob. Chang. Biol.* **22**, 704–715 https://doi.org/10.1111/gcb.13117

32 Heath, S.K., Soykan, C.U., Velas, K.L., Kelsey, R. and Kross, S.M. (2017) A bustle in the hedgerow: woody field margins boost on farm avian diversity and abundance in an intensive agricultural landscape. *Biol. Conserv.* **212**, 153–161 https://doi.org/10.1016/j.biocon.2017.05.031

33 Kross, S.M., Martinico, B.L., Bourbour, R.P., Townsend, J.M., McColl, C. and Kelsey, T.R. (2020) Effects of field and landscape scale habitat on insect and bird damage to sunflowers. *Front. Sustain. Food Syst.* **4**, 1–11 https://doi.org/10.3389/fsufs.2020.00040

34 Kremen, C., M'Gonigle, L.K. and Ponisio, L.C. (2018) Pollinator community assembly tracks changes in floral resources as restored hedgerows mature in agricultural landscapes. *Front. Ecol. Evol.* **6** https://doi.org/:10.3389/fevo.2018.00170

35 Kremen, C. and M'Gonigle, L.K. (2015) Small-scale restoration in intensive agricultural landscapes supports more specialized and less mobile pollinator species. *J. Appl. Ecol.* **52**, 602–610 https://doi.org/10.1111/1365-2664.12418

36 Ponisio, L.C., de Valpine, P., M'Gonigle, L.K. and Kremen, C. (2019) Proximity of restored hedgerows interacts with local floral diversity and species' traits to shape long-term pollinator metacommunity dynamics. *Ecol. Lett.* **22**, 1048–1060 https://doi.org/10.1111/ele.13257

37 Morandin, L.A., Long, R.F. and Kremen, C. (2014) Hedgerows enhance beneficial insects on adjacent tomato fields in an intensive agricultural landscape. *Agric. Ecosyst. Environ.* **189**, 164–170 https://doi.org/10.1016/j.agee.2014.03.030

38 Heath, S.K. and Long, R.F. (2019) Multiscale habitat mediates pest reduction by birds in an intensive agricultural region. *Ecosphere* **10**, e02884 https://doi.org/10.1002/ecs2.2884

39 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

40 Sardiñas, H.S. and Kremen, C. (2015) Pollination services from field-scale agricultural diversification may be context-dependent. *Agric. Ecosyst. Environ.* **207**, 17–25 https://doi.org/10.1016/j.agee.2015.03.020

41 Schulte, L.A., Niemi, J., Helmers, M.J., Liebman, M., Arbuckle, J.G., James, D.E. et al. (2017) Prairie strips improve biodiversity and the delivery of multiple ecosystem services from corn–soybean croplands. *Proc. Natl. Acad. Sci. U.S.A.* **114**, 11247–11252 https://doi.org/10.1073/pnas.1620229114

42 Garibaldi, L.A., Carvalheiro, L.G., Vaissière, B.E., Gemmill-herren, B., Hipólito, J., Freitas, B.M. et al. (2016) Mutually beneficial pollinator diversity and crop yield outcomes in small and large farms. *Science* **351**, 388–391 https://doi.org/10.1126/science.aac7287

43 Klein, A.M., Vaissière, B., Cane, J.H., Steffan-Dewenter, I., Cunningham, S.A., Kremen, C. et al. (2007) Importance of crop pollinators in changing landscapes for world crops. *Proc. R. Soc. London Ser. B-Biol. Sci.* **274**, 303–313 https://doi.org/10.1098/rspb.2006.3721

44 Brandes, E., McNunn, G.S., Schulte, L.A., Muth, D.J., VanLoocke, A. and Heaton, E.A. (2017) Targeted subfield switchgrass integration could improve the farm economy, water quality, and bioenergy feedstock production. *GCB Bioenergy* **10**, 199–212 https://doi.org/10.1111/gcbb.12481

45 Brandes, E., McNunn, G.S., Schulte, L.A., Bonner, I.J., Muth, D.J., Babcock, B.A. et al. (2016) Sub field profitability analysis reveals an economic case for cropland diversification. *Environ. Res. Lett.* **11**, 14009 https://doi.org/10.1088/1748-9326/11/1/014009

46 Murgueitio, E., Calle, Z., Uribe, F., Calle, A. and Solorio, B. (2011) Native trees and shrubs for the productive rehabilitation of tropical cattle ranching lands. *For. Ecol. Manage.* **261**, 1654–1663 https://doi.org/10.1016/j.foreco.2010.09.027

47 Solorio, S., Wright, J., Franco, M., Basu, S., Sarabia, S., Ramirez, L. et al. (2017) Silvopastoral systems: best agroecological practice for resilient production systems under dryland and drought conditions. In *Quantification of Climate Variability, Adaptation and Mitigation for Agricultural Sustainability* (Ahmed, M. and Stockle C.O. eds.), pp. 235–250, Springer, Springer International Publishing AG Switzerland

48 Broom, D.M., Galindo, F.A. and Murgueitio, E. (2013) Sustainable, efficient livestock production with high biodiversity and good welfare for animals. *Proc. R. Soc. B.* **280**, 20132025 https://doi.org/10.1098/rspb.2013.2025

49 Machovina, B., Feeley, K.J. and Ripple, W.J. (2015) Biodiversity conservation: The key is reducing meat consumption. *Sci. Total Environ.* **536**, 419–431 https://doi.org/10.1016/j.scitotenv.2015.07.022

50 Burkholder, J.A., Libra, B., Weyer, P., Heathcote, S., Kolpin, D., Thorne, P.S. et al. (2007) Impacts of waste from concentrated animal feeding operations on water quality. *Environ. Health Perspect.* **115**, 308–312 https://doi.org/10.1289/ehp.8839

51 Kremen, C. (2015) Reframing the land-sparing/land-sharing debate for biodiversity conservation. *Ann. N. Y. Acad. Sci.* **1355**, 52–76 https://doi.org/10.1111/nyas.12845

52 Kremen, C., Iles, A. and Bacon, C. (2012) Diversified farming systems: an agroecological, systems-based alternative to modern industrial agriculture. *Ecol. Soc.* **17**, 44 https://doi.org/10.5751/ES-05103-170444

53 Blaauw, B.R. and Isaacs, R. (2014) Flower plantings increase wild bee abundance and the pollination services provided to a pollination-dependent crop. *J. Appl. Ecol.* **51**, 890–898 https://doi.org/10.1111/1365-2664.12257

54 IPES-Food (2018) BREAKING AWAY FROM INDUSTRIAL FOOD AND FARMING SYSTEMS: seven case studies of agroecological transition, International Panel of Experts on Sustainable Food Systems. www.ipes-food.org

55 Wezel, A., Bellon, S., Dore, T., Francis, C., Vallod, D. and David, C. (2009) Agroecology as a science, a movement and a practice. A review. *Agron. Sustain. Dev.* **29**, 503–515 https://doi.org/10.1051/agro/2009004

56 Wanger, T.C., DeClerck, F., Garibaldi, L.A., Ghazoul, J., Kleijn, D., Klein, A.-M. et al. (2020) Integrating agroecological production in a robust post-2020 global biodiversity framework. *Nat. Ecol. Evol.* 8–10 https://doi.org/10.1038/s41559-020-1262-y