Ecological intensification: harnessing ecosystem services for food security

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Rising demands for agricultural products will increase pressure to further intensify crop production, while negative environmental impacts have to be minimized. Ecological intensification entails the environmentally friendly replacement of anthropogenic inputs and/or enhancement of crop productivity, by including regulating and supporting ecosystem services management in agricultural practices. Effective ecological intensification requires an understanding of the relations between land use at different scales and the community composition of ecosystem service-providing organisms above and below ground, and the flow, stability, contribution to yield, and management costs of the multiple services delivered by these organisms. Research efforts and investments are particularly needed to reduce existing yield gaps by integrating context-appropriate bundles of ecosystem services into crop production systems.

Meeting growing demands for agricultural products

As part of the Green Revolution, modern agriculture has simplified traditional agroecosystems and replaced biological functions, originally provided by diverse communities of organisms, with increased external inputs of energy and agrochemicals. Industrial forms of modern agriculture aim to remove limitations to plant productivity mainly by irrigation and adding inorganic nutrients, by crop breeding to improve the genetic basis for plant productivity, mechanical loosening of the soil structure that allows for better root penetration and growth, and replacing biological pest and weed control with pesticides [1].

Agricultural intensification has been successful in that it has helped meet increasing global food demands by increasing the productivity per unit area. On the downside are significant negative impacts on the environment and biodiversity that have become evident [2,3], some of which might even have negative feedbacks on sustained crop productivity [4]. In parallel, there has been an extensive conversion of land use over the past decades, with loss of natural habitat elements and simplification of the agricultural landscape [5,6]. Together with other environmental changes, such as climate change, pollution, and biotic invasions, these have degraded biodiversity to such an extent that many ecosystem services contributing to human well-being are becoming increasingly eroded [7–9].

The steady increases in agricultural productivity seen throughout the 20th century have now plateaued in many countries [10]; yet, as the human population increases, the next few decades will witness rapidly increasing demands for food, fiber, and bioenergy that will result in pressure for increased production from the same land surface [11]. Indeed, the global arable land surface has only increased by 9% since 1961 [12], and there is little scope for further increases without doing irreparable damage to vital natural ecosystems that, for instance, support biodiversity and mitigate climate change through storage of carbon (e.g., tropical forests or permanent grasslands) [13]. Furthermore, limits to productivity in major existing agricultural areas are predicted due to climate change [14] and future shortfalls of non-renewable phosphorous [15].

To meet future climatic, economic, and social challenges, agriculture needs to be made more productive, stable, and resilient while minimizing environmental impacts [16]. In this review, we present ecological intensification as an alternative approach for mainstream agriculture to meet these challenges. Ecological intensification aims to match or augment yield levels while minimizing negative impacts on the environment and ensuing negative feedbacks on agricultural productivity, by integrating the management of ecosystem services delivered by biodiversity into crop production systems [17,18]. We review current evidence and management options, and identify key knowledge gaps for achieving effective ecological intensification. Finally, we adopt a natural resource management framework of 'safe space' to illustrate how ecological intensification can sustainably enhance food security globally.

Ecological intensification with ecosystem services

Ecological intensification is based on managing service-providing organisms that make a quantifiable direct or indirect contribution to agricultural production. The supporting and regulating ecosystem services provided by these organisms can be incorporated into cropping systems, such that production is maximized while environmental impacts are minimized through the decrease, but not necessarily exclusion, of anthropogenic inputs, such as inorganic fertilizers, pesticides, energy, and irrigation [17,18].

Despite a recent surge in research on ecosystem services, actual hands-on integration of ecosystem service management into crop production systems is still missing (but see [19]). Although the acknowledged value and

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  http://dx.doi.org/10.1016/j.tree.2012.10.012 Trends in Ecology and Evolution, April 2013, Vol. 28, No. 4

Box 1. Definitions of ecosystem services

The concept of ecosystem services links ecology and society. The Millennium Ecosystem Assessment broadly defined ecosystem services as the benefits humans obtain from ecosystems, and grouped them into four categories [8]:

- Supporting services, such as nutrient cycling and soil formation.
- Regulating services, such as pest control, crop pollination, climate regulation, and water purification.
- Provisioning services, such as food, fiber, fuel, and water.
- Cultural services, such as education, recreation, and aesthetic value.

Ecosystem services have become a top research issue in ecology, natural resource management, and policy. The concept is increasingly used in different contexts where a clear definition is often not provided, which has led to considerable confusion [89]. Two main definitions of ecosystem services have emerged from the debate.

Ecosystem services can be defined as the benefits that humans obtain from ecosystems [90]. This is a categorization with emphasis on the provisioning or cultural services linked to the goods and benefits that are extracted from ecosystems and are thereby largely a societal issue. These can also be called 'final services'.

Alternatively, ecosystem services can be defined as processes or conditions that lead to benefits for humans [91], thereby putting the emphasis on the ecological and physical supporting and regulating processes that underpin the final benefits derived from ecosystems [78]. These can also be called 'intermediate services'.

Either definition can be effective in its respective context, and it is important to make the distinction between services as extracted goods and benefits, or as underpinning processes [92]. In the context of integrating ecosystem services with farming, it makes sense to focus on intermediate services that support the final service of crop yield. For ecological intensification, the primary interest is in managing the processes and conditions that mediate yield levels. Farmers and society have to have a clear idea of what these processes are, and the benefits and costs that are associated with using ecosystem services to enhance crop yields.

general understanding of provisioning ecosystem services (food, fiber, and energy) is high, the importance of supporting (e.g., soil fertility) and regulating (e.g., pest control and crop pollination) services remains grossly undervalued (Box 1). However, as our review shows, even intensively cultivated crop production systems depend heavily on supporting and regulating services that determine the share of primary production that can be harvested. One or several of these services can limit production and, even if all other services are optimized, no or little additional output will be attained until this ecosystem service shortfall is addressed.

To enable the practical integration of ecosystem services into crop production systems while matching or increasing yields of current intensive agriculture, we briefly review the services that are provided, or modulated, by biodiversity and that underpin agricultural production, with a focus on crop production. Below, we describe their main function and contribution to agriculture, current status and threats, management options, and key knowledge gaps.

Relation between yield and supporting and regulating ecosystem services

Crop yield has been defined as a provisioning ecosystem service, but the yield that is harvested in a given location depends largely on several supporting and regulating services (Box 1; Figures 1 and 2a,b) [8,9]. Attainable or potential yield level (Figure 1) of a locally adapted crop

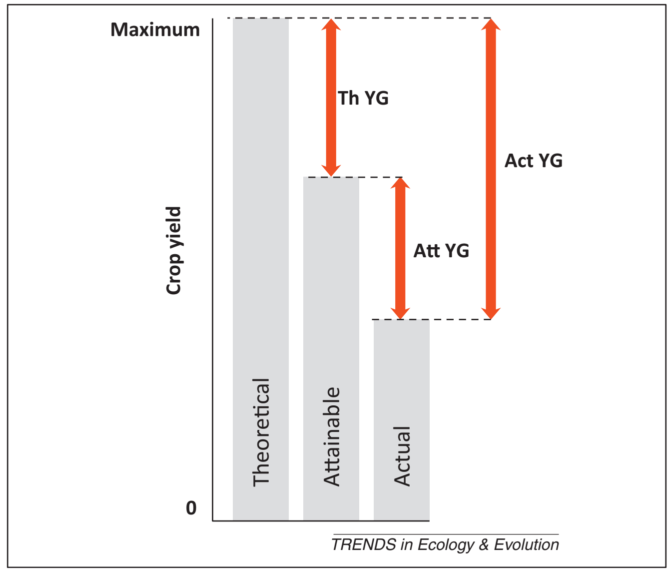

Figure 1. Conceptualization of yield gaps. Abbreviations: Th YG, theoretical yield gap that is unavoidable; Att YG, attainable yield gap that is avoidable; and Act YG, actual yield gap (i.e., Th YG + Att YG).

cultivar depends ultimately on available solar radiation and temperature. The difference between this and the actual yield that a farmer obtains represents the yield gap, which is widened by lack of water, lack or imbalance of nutrients, pest damage, weed competition, and lack of pollination; factors that, to a large extent, are modulated by ecosystem services. The necessary investment to close the yield gap increases when regulating and supporting ecosystem services are degraded and as the yield potential is approached. Further efforts to close the gap typically become non-economical when yields reach 80% of the yield potential [17]. Thus, the ability of a farmer to close this exploitable yield gap ultimately depends on either increased conventional intensification with known negative externalities and a possible long-term decline in productivity or, alternatively, the integrity and extent of several natural supporting and regulating services, such as pest control, water retention, and nutrient cycling.

In many developed countries, agricultural productivity is near maximum levels, but depends on unsustainably high levels of external inputs, where increasing energy costs, pesticide resistance, and reduced soil carbon have become threats to stable and resilient production. Here, the challenge for ecological intensification would be to replace the reliance on external inputs by re-establishment of ecosystem services generated in the soil and the landscape surrounding the cultivated field, while maintaining high, stable productivity levels (Figure 2c).

However, in large parts of the world, productivity is lower, with a wide gap between farm yields and yield potential [20–22]; here, the challenge will be to enhance productivity ecologically by optimizing ecosystem services in low-input (but not necessarily no-input) farming systems (Figure 2d). Ecological replacement and enhancement are not mutually exclusive and both processes can be combined to close the yield gap.

Large knowledge gaps exist for how to manage regulating and supporting ecosystem services efficiently for

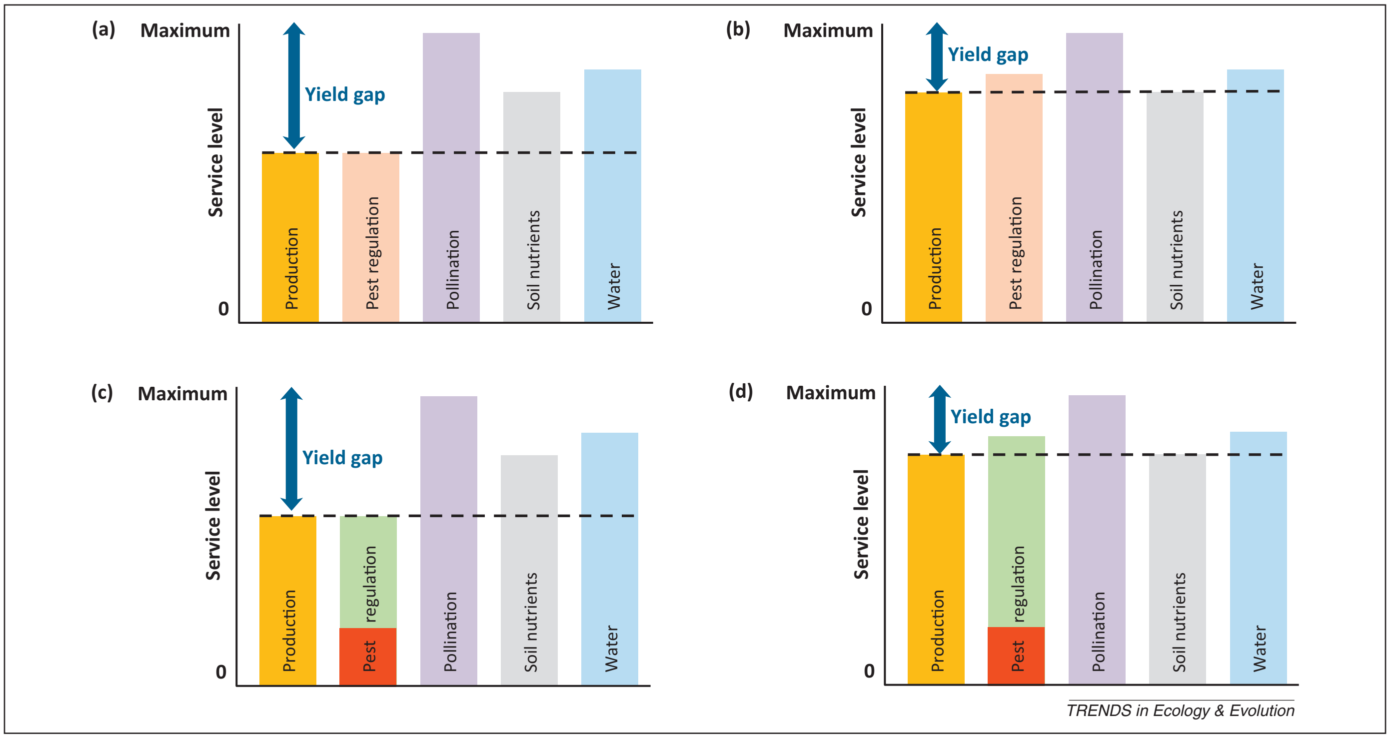

Figure 2. Conceptualization of contribution of regulating and supporting services to provisioning services (crop production). **(a)** Production can only attain a level set by the lowest underpinning regulating or supporting service, in this case pest regulation, despite other services being superoptimal. **(b)** Pest regulation is enhanced; thus, production increases and the yield gap is reduced to the level set by the next limiting service, in this case soil nutrients. **(c)** Ecological replacement is where a proportion of one (e.g., pest regulation) of several underpinning services is supplied by biodiversity (e.g., natural enemies, green bar) rather than by anthropogenic inputs (e.g., insecticides, red bar); production remains the same overall, but more of the regulating and/or supporting service(s) are provided by biodiversity. **(d)** Ecological enhancement is where the level of one (e.g., pest regulation) of several underpinning services is boosted by biodiversity (green bar) rather than by anthropogenic inputs (red bar); with the result that production increases overall.

ecological replacement or enhancement in agriculture (Box 2). Current understanding of ecological interdependencies between land use, biodiversity, and ecosystem services needs to be improved. Measurements of the contribution to yield formation from single and combined services are lacking, together with cost–benefit estimates for management interventions targeted at manipulating services. Research and technological efforts to increase crop productivity have mainly focused on areas with prime agricultural soils, plenty of water, and developed infrastructures. However, much agriculture occurs in areas with poorer resource conditions and there is a need to develop approaches to close the yield gap based on the available resource base [23].

Supporting services

Soil formation and nutrient cycling

Ecosystem services linked to agricultural soils are crucial for yield formation and are provided by several interrelated processes that govern decomposition, soil formation, structure, moisture, and cycling of mineral nutrients and carbon. Soil services provide global resources, such as water storage and purification, and carbon storage and gas regulation that mitigates climate change. Indeed, more than one-fifth of the global soil carbon pool is stored in agricultural soils [24], which is substantial given that 80% of global terrestrial carbon is stored in agricultural and non-agricultural soils. Soil services that promote plant growth include pest and disease regulation, nutrient flow, and soil formation and structure that allow for root penetration, gas exchange, water retention, and erosion control. These processes are mediated by an immense, diverse, and largely unexplored biological community of mainly bacteria and fungi, but also protozoa, nematodes, arthropods, and earthworms [25,26].

Until recently, soil ecological research was hampered by difficulties in the taxonomic identification of especially microbial soil organisms. Although problems remain, new molecular techniques have allowed for more studies on relations between soil biodiversity and functioning [27]. These suggest that species richness *per se* is often not important and redundancy is large, at least for broad functions, such as carbon cycling and nutrient mineralization. Instead, species identity, number of trophic levels present, community abundance composition, and functional dissimilarities appear to determine these processes [28–30]. It has also been argued that soil biodiversity is best considered by focusing on the groups of soil organism that play major roles in ecosystem functioning (i.e., microsymbionts, decomposers, elemental transformers, engineers such as earthworms, pests, and their natural enemies) when exploring links with the provision of ecosystem services; it is proposed that activity measurements provide a better understanding of soil biological function than do inventories of soil organisms or measurements of biomass [31]. However, more specific processes provided by a few specialized taxa, such as nitrification, symbiotic nitrogen fixation, or decomposition of specific compounds, are probably susceptible to species losses or shifts in community composition [32–34].

Box 2. Knowledge gaps

Successful ecological intensification requires basic insights into how biodiversity contributes to ecosystem services and the quantification of links between community composition and the stocks and flows of ecosystem services. In particular, more needs to be known about the dynamics of service-providing communities over time and how this affects the stability and resilience of services and crop productivity. This remains to be assessed for many ecosystem services [79].

Nearly all studies to date have examined a single service process in isolation and the effects of combinations of processes are implicitly considered to be additive or stacked. It has never been tested whether suites of below- and aboveground services contribute synergistically, or trade off, in their contribution to crop yield and quality [93–95] (see also Box 3). This has important implications for decision making and for developing management interventions that can boost the limiting service(s), but without negatively affecting other services.

For successful management of multiple services, more information is needed about how land use and other environmental factors affect the distribution, abundance, and community composition of organisms that contribute to crop production. Intermediate services are being produced by a wide range of contrasting organism groups and are generated at varying spatial and temporal scales. To be able to promote synergies and avoid trade-offs, one needs to know which service-providing communities need to be managed at what spatial scale and by what form of management, and how interventions aimed at enhancing one target service affect the stock and flows of other services.

For ecosystem services to be become an integral part of farming, estimates are needed of the economic benefits and costs associated with ecological intensification. Although still lacking for most of the major world crops, more studies are becoming available that demonstrate the economic benefits of supporting and regulating services to agricultural production (e.g., [62,96,97]). The real challenge is, however, to quantify the costs of ecosystem service-targeted management options in relation to the potential net increases in profitability.

Agricultural landscapes deliver more services besides crop production, such as climate regulation, water regulation, and biodiversity conservation, many of which give benefits at regional or global scales. 'Multifunctional agriculture' is emerging an important research topic to quantify these benefits and propose strategies to encourage farmers and land managers to support them [98]. Strategies benefiting ecological intensification might also benefit other services and *vice versa*, but many of these relations remain poorly understood.

Large knowledge gaps remain as to the drivers of belowground community structure and soil processes for agricultural soils. Attention has been given to catastrophic degradation of soil quality through processes such as salinization, acidification, and erosion, often occurring as a result of unsustainable agricultural practices. Despite being a potentially huge threat to food security, less is known about long-term negative influences of intensive cropping on soil quality on prime agricultural land. Longer-term intensive forms of agriculture, particularly those that rely strongly on external inputs, lead to diminished microbial biomass. This is probably explained by well-documented declines in soil organic matter (SOM) that fuel microbial communities [35]. Functions are not lost at the same rate, indicating that microbial communities provide functional redundancy [36]. However, particularly functions that are supported by species-poor functional groups run a disproportionate risk of being lost when critical SOM thresholds are reached [25,37].

Because SOM content correlates with the flow of services, agricultural scientists often use this as a proxy for soil services [38]. Enhancing SOM content is also an important part of traditional farming because it enhances soil fertility mediated by soil organisms. SOM generally mitigates soil compaction, reduces soil erosion, and surface crusting, and increases workability, water-holding capacity, and pest control. It also supports a continuous nutrient supply, because nearly all plant nutrients are part of, or bound to, SOM, thereby allowing uptake at the most demanding crop growth stage, preventing lodging, and reducing the margin for error in the management of inorganic nitrogen fertilizers. Overall, more intensively managed agricultural fields appear to become less efficient in functioning, mainly because of reduced flow of soil services at decreased SOM, with consequences for yield level and stability [39]; however, the ecological processes underlying these effects remain largely to be explored. Use of new cultivation techniques and increased, more precisely applied, inputs might also mask negative effects on yields and the true extent of the problem of declining SOM [40].

Based on current understanding, two general management strategies appear to sustain or enhance soil services: increasing SOM and diversified crop rotation. Negative trends of SOM can be reversed with addition of manure, residue management, reduced tillage, and inclusion of perennial grasses and legumes in the crop rotation [35]. There is a worldwide trend to shorten rotations and grow monoculture crop sequences, but these usually lead to lower yields. For instance, at least 10% of the yield is lost each year during the first 2 years of wheat after wheat [41]. The underlying ecological mechanisms are not known, but soil organisms are thought to play a major role, especially through a build up of soil-borne pathogens and pests [41], degraded soil fertility [42], and water-use efficiency [43]. Different crop species are not equally efficient as the break crop [44], possibly because they enhance components of soil biodiversity that regulate pests and enhance fertility differently [45]. Such predominantly plant species-specific effects are also often observed in plant diversification experiments (e.g., [46,47]). Major research challenges will be to quantify the consequences for yield level and stability of increased soil diversity and SOM, and to explore the substitutability or potential combined benefits of natural and artificial inputs.

Regulating services

Biological pest control

Losses to weeds and animal pests have been estimated to be approximately 30% in maize and 14–35% in wheat, despite control efforts, and yield losses worldwide are not decreasing despite increased use of pesticides [48]. Not long after the large-scale introduction of pesticides during the 1940s, their overuse and landscape changes led to secondary pests, pest resurgence, and, in some cases, a complete collapse of crop production systems due to eroded natural pest regulation [49–51]. These and several other examples show that natural control of pests can enhance and stabilize yields and resilience in the crop production system. This contribution must also be recognized in crop production systems that rely on pesticides for pest control.

Each pest species has a large number of natural enemies pertaining to different guilds (e.g., specialist and generalist predators), which often have a pervasive negative effect on pest population growth in the agricultural field [49,52]. A meta-analysis showed that, in general, natural enemy diversity enhances pest herbivore suppression in agricultural systems, although the strength of this relation varied substantially among studies and was often even negative [53]. Weak or negative effects can result from strengthened intraguild or cannibalistic interactions among predators as new species are added to the food web [54]. Recent studies also highlight the importance of considering both abundance composition and species numbers for understanding how communities of natural enemies affect pest populations [55]. Currently, there is a lack of information on how environmental conditions, species identity, and relative abundances affect the way in which communities of natural enemies modulate pest regulation [56].

Understanding determinants for predator community composition and management of biological control services requires a landscape perspective. Both the pest and its enemies are often highly mobile and regulated at a much larger spatial scale than at the level of the field, because they often require multiple resources, such as alternate food, hosts, and winter refuges to complete their life cycles [57,58]. Therefore, communities of natural enemies are often found to be more abundant and species rich in structurally complex landscapes, but few studies have estimated how the landscape context and farming practice affect the biological control service that they deliver [52,59]. Existing studies often, but not always, show that the contribution of biological control to yield depends on a combination of local cultivation practice and the landscape in which the agricultural field is embedded [60,61].

Thus, interventions to enhance biological control potentially include landscape-level diversification by creation or conservation of natural and resource-rich habitat, combined with directed or diversified crop rotation, and decreased pesticide pressure at both the field and landscape levels. However, implementation of such management options is impeded by a lack of cost–benefit estimates. In particular, the contribution of naturally occurring communities of pest enemies to biological control, and the type, amount, and spatial distribution of interventions needed to attain a desired level of the service have not been systematically explored for most crops (but see [62]).

Crop pollination

Globally, 75% of food crops are dependent, at least in part, on insect pollination, with bees being the main pollinators [63]. Although many staple crops, such as wheat, maize, and rice, are wind pollinated, a high proportion of fruit crops and some vegetables rely on insect pollination, generating large economic values [64] and contributing significantly to certain vitamins and micronutrients in the human diet [65].

Honeybees remain the most commonly managed pollinators used by farmers and often dominate pollinator communities in crops [63]. Although the number of honeybee colonies might be increasing worldwide, the area of flowering crops needing insect pollination is increasing at a greater rate, so that the demand for pollination services is outstripping the supply [66]. Reliance on a single species also poses a high risk, should that species decrease or vary markedly spatially or temporally in abundance. Diverse wild pollinator communities can provide insurance in terms of stability of service delivery under environmental change [67]. Increases in crop yield, quality, and profit, as well as the stability of these through time and space, have been found to be positively related to pollination rate and pollinator diversity [68,69]. A deficit of pollination services is compounded by observed losses of both wild pollinators [70,71] and honeybees (e.g., [3]). The causes are multifactorial, with increasing evidence of combined roles of habitat loss and fragmentation, agrochemicals, pests and pathogens, climate change, and social economic drivers [3,72]. However, the relative importance of single or combinations of drivers remains poorly understood.

Research has suggested that pollinators can be promoted at the field or farm scale by enhancing floral resources and nesting sites (e.g., [73]), thereby potentially reducing the part of a yield gap caused by pollination deficits. However, studies relating pollination services to these interventions are lacking. At the landscape scale, protection of seminatural habitats can facilitate the spill-over of pollinators from these landscape elements into crops [69]. Similarly, other practices, such as low tillage [74], provisioning of nesting resources [75], and diversified flowering crops through rotations or mixed cropping are tools that could enhance wild pollinators [76]. These approaches are longer-term sustainable strategies to maintain healthy pollinator communities in production systems and can be used on their own, or in conjunction with, introduced managed pollinators to ensure that yield gaps are minimized.

Biodiversity conservation and ecosystem services

An often held, but not universally true, assumption of the ecosystem services concept is that service delivery increases with the level of intactness, complexity, and/or species richness of ecosystems [77]. Originally, evidence of the importance of biodiversity for ecosystem services came from experimental studies of biodiversity function, which examined communities whose structures often differed markedly from those providing services in real landscapes [78]. More recent studies show that species communities, formed by the multiple pressures and drivers acting in human-dominated landscapes, generally function better with increasing diversity levels [79] and demonstrate, for example, that crop yield increases with increasing pollinator diversity [68] or with diversified crop rotations [41].

The benefits (ecosystem services) that humans derive from biodiversity have therefore become an important argument for conserving biodiversity. However, the contribution of individual species to regulating or supporting ecosystem services in agriculture varies markedly and is a function of the abundance of each species and the efficiency with which it provides the service [80]. Although rare species can increase the response diversity and contribute to resilience [77,81], their role as service providers is often limited (but see [82–84]). Ecosystem service provisioning to support agricultural production is therefore not a strong argument to protect the species needing conservation most urgently and, although acknowledging the value of both, it is important to distinguish between promoting biodiversity for the services it delivers and biodiversity with inherent conservation value [85]. The differences between these 'functional' and 'cultural' services are at the very base of the recent land-sharing versus land-sparing debate. Consequently, arguments in favor of land sparing are largely based on how individual species can persist most efficiently, whereas arguments in favor of land sharing are largely based on the benefits humans can get from biodiversity [86,87]. Functional arguments for conserving biodiversity are valid and important, but cannot replace ethical arguments.

Safeguarding food security with ecological intensification

It remains an outstanding challenge to ensure simultaneously stock, stability, and resilience in food production and balance this with minimal impacts on the environment, biodiversity, and all the other benefits that agricultural landscapes provide. To illustrate how ecological intensification can be implemented while avoiding potential negative trade-offs, we use an adaptation of the natural resource management framework of 'safe space' presented by Beddington *et al.* [88]. This scheme depicts how different strategies allow one to navigate into, or widen, a safe area where global food demands are met while environmental impacts are minimized (Figure 3). A priority for agricultural scientists, ecologists, and other researchers will be to combine expertise to identify the boundary conditions for this space at global and regional scales, and to develop viable options for management of multiple ecosystem services (Box 2). To meet increasing demands for food, ecological intensification has to be combined with other measures that dampen demands, such as reducing food loss across the supply chain and by stepping down the food chain in global consumption (Figure 3). Ecological intensification provides a strategy based on local management interventions that can move crop production into the safe space globally. This framework is potentially portable to address similar food security issues in the livestock, forestry, and fishery sectors.

Concluding remarks

Our review demonstrates that modern agriculture will benefit from a more explicit consideration of ecological processes, where ecological intensification has potential to ensure productive and environmentally friendly agriculture globally. Multidisciplinary research approaches will be necessary to address critical knowledge gaps (Box 2). Understanding underpinning ecological processes and addressing how one can harness functional biodiversity to secure food production without damaging the wider environment emerge as research priorities.

Furthermore, farmers and land managers need to be provided with concrete options for how to close the yield gap, with the support of clearly defined ecosystem services and based on a much improved understanding of economic opportunities and consequences. This includes the identification of service deficits that limit yields in different crop production systems, and of the type, amount, cost, and benefit of interventions needed to enhance services and meet sustainable food production goals.

Our review shows that, although major knowledge gaps remain, a growing evidence base already provides several on- and off-field management options that can be

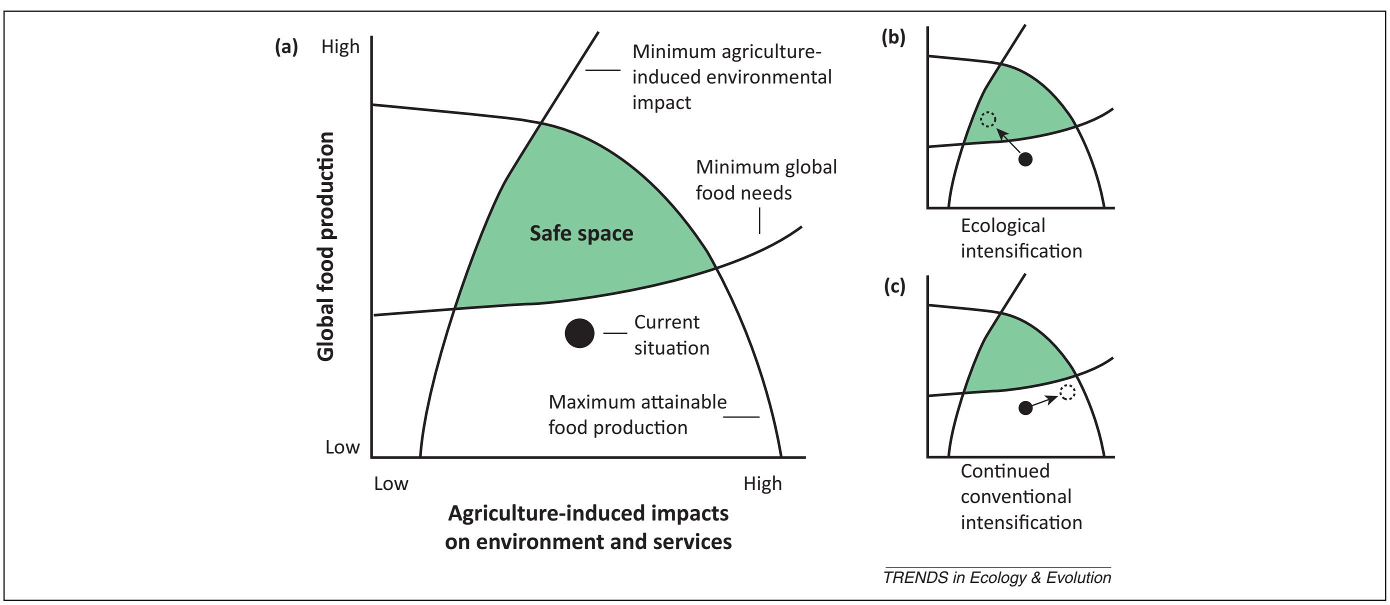

Figure 3. Illustration of limits and alternatives for global food security with a safe area (green) where global food demands are met **(a)**. **(b,c)** show alternative scenarios of ecological (b) and continued conventional (c) intensification. Conventional intensification is expected to move systems towards the right, with increased impacts on ecosystems services and the environment. Even if conventional intensification moved systems into safe space above minimum global food needs, there remains little room for maneuver close to maximum attainable yields, posing increased risks under further environmental change. As systems move towards the right-hand boundary of the safe space, maximum attainable food production is expected to decrease due to degraded ecosystem services. Furthermore, negative impacts on the environment, biodiversity, and other benefits are expected to increase in this direction. A complementary strategy is to widen safe space by dampening demands for food products, such that minimum global needs for agricultural products are lowered. Adapted from [88].

Box 3. Management strategies for multiple ecosystem service delivery

A key issue of ecological intensification is to devise management interventions that boost the limiting (suboptimal) service(s) without negatively affecting other services. A major challenge is that different ecosystem services need to be managed at contrasting spatial and temporal scales. Management practices that affect soil services and biological weed control include mixed cropping, conservation tillage, diversification of the crop rotation, or the use of cover crops (e.g., [12,41]). Most of these practices are implemented at the field level. Supporting services, such as pollination or biological pest control, can also be affected by on-field management, such as integrated pest management (IPM) or conservation tillage, but additionally these are strongly governed by the quantity and spatial configuration of non-agricultural land and agricultural practices in the surrounding landscape (e.g., [58,60,99]; Table I).

Management aimed at enhancing one ecosystem service may negatively affect other ecosystem services. For example, effective biological weed control reduces cover of weeds on which many pollinators and natural enemies rely on for food and, therefore, can reduce pollination and pest control services. However, trade-offs between management interventions for different services seem to be limited, possibly because most interventions diversify cropping systems with positive consequences for many natural processes [19]. There are potentially many possibilities for synergies between management options targeting different ecosystem services, but few have been studied. For example, diversified crop rotations can improve soil structure and reduce disease and weed pressure, and if animal pollinated crops are included, also enhance pollination. Which overall management strategy optimizes multiple ecosystem service delivery depends upon the locality of the farm, the cropping system, soil type, and landscape structure. Adoption of ecological intensification strategies by the farming community depends on the consequences of management interventions for yield and, ultimately, the economic costs and benefits. This final aspect is particularly poorly unexplored in any systematic manner and, as such, is probably an important reason why management of multiple ecosystem services has rarely been put into practice.

Table I. Examples of general relations between service-providing processes and a non-exhaustive selection of commonly adopted on-field and off-field management options for ecological intensification[a]

Management option	Pollination	Biological pest control	Biological weed control	Soil formation and nutrient cycling
On-field				
IPM	0 (+)	++	+	(+)
Conservation tillage	0 (+)	+	–	+
Manure and residue addition	0	+	+	++
Mixed cropping	0 (+)	+	++	++
Diversified crop rotation and cover crops	0 (+)	+	++	++
Set-aside or fallow	++	+	+	++
Off-field				
Increasing quantity of seminatural habitats	++	++	0	0
Increasing quality of seminatural habitats	++	++	0	0

[a]'–' indicates overall negative impact; '0' indicates no impact; '+' indicates moderate positive impact; and '++' indicates strong positive impact; '(+)' indicates likely but unproven positive impacts. To be useful as a menu of options for farmers and land managers to choose from, research will have to complement the Table with yield gain estimates, management costs, and the effects of an intervention on other services.

implemented for ecological intensification (Box 3). We suggest that these and emerging management options should be gathered in geographically explicit public information systems for easy access.

Public spending on agricultural research also needs to be increased. Ecological intensification with replacement emerges as a priority strategy in countries where agricultural production is already approaching maximum exploitable yields, with the principal aim being to reduce environmental costs and erosion of ecosystem services that are now under pressure. However, a main priority for supporting food security should be directed at closing existing yield gaps around the world with ecological enhancement.

Acknowledgments
We thank Henrik G. Smith, Claire Kremen, and an anonymous reviewer for constructive comments. The contribution by R.B., D.K., and S.G.P. was made in the framework of the European Union (EU) FP7 projects LIBERATION (grant 311781) and STEP (grant 244090). In addition, R.B. was funded by the Swedish Research Council for Environmental, Agricultural Sciences and Spatial Planning (FORMAS).

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