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Exploiting ecosystem services in agriculture for increased food security

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ABSTRACT

Despite contributing to economy and food security, Ecosystem Services (ES) are still not fully exploited in agriculture. Instead, external inputs have been used to boost yields, while exacting costs on public goods. Ecological intensification capitalizes on ecosystem services to enhance and stabilize production and reduce the need for external inputs, while sparing the environment. Of particular relevance are biodiversity-based ES connected to soil fertility, pest control and pollination. Ecological intensification is applicable in all regions, but for food security purposes, particular attention should be dedicated to implement it as ecological enhancement in regions with wide yield gaps, coinciding with poor food security. Diversified cropping system show promise to create win-win situations. Knowledge on ecology and socio-economy of ES will be needed, and agricultural research and innovation need to heed to resource use efficiency, production stability, minimal environmental impact, buffering of extreme events and adaptation to local conditions.

1. Food security through ecological intensification

Society needs to ensure local and global food security, i.e., availability, access and utilization of food, and stability of the former three (FAO, 2014). To support food availability, crop production has over the past decades been increased by abandoning traditional practices supporting ecosystem services (ES) and replacing them with external inputs (Tilman et al., 2001). This approach has so far been successful in meeting ever increasing global demands for food, feed and fibre, but has also exacted environmental costs. For example, leached inputs have degraded the environment, and put public goods, such as clean water, at risk. Two of the most severe effects of intensive agriculture is the large impact on Earth's biogeochemical and hydrological cycles, which have caused a cascade of effects contributing to climate change, degradation of aquatic ecosystems and human health problems (e.g. Galloway et al., 2008; Gordon et al., 2008; Bouwman et al., 2013). Even in the presence of sufficient food availability, these effects can negatively impact food security by curtailing access both to food due to reduced incomes and to food utilization from reduced availability of drinking water.

Agriculture is, furthermore, the primary cause of terrestrial biodiversity loss (Maxwell et al., 2016), mainly from agricultural expansion but also as a result of intensification (Kehoe et al., 2017). Biodiversity loss is, in turn, a major driver of ecosystem change (Hooper et al., 2012). Intensive agriculture can also negatively impact crop production itself. Grain yields have levelled off or even declined in key regions (Ray et al., 2012), partly because of cropping with few crops in short rotations (Bennett et al., 2012) and poor management of ES linked to soil fertility and plant protection (e.g. Settle et al., 1996; Foley et al., 2005). Even the mere possibility for agriculture is threatened. Soil erosion caused by intensive agriculture is a severe problem in several areas (Pimentel et al., 1995) and climate change is expected to negatively impact crop production and its stability (Challinor et al., 2014; Lobell and Tebaldi, 2014). We thus need to modify the current approaches to ensure long-term food security, locally and globally.

Here we outline how the exploitation and active management of ES can form a basis for achieving high output, low input farming that produces stably and is adaptable under changing conditions. Such stable and productive, but lean, cropping is vital for farmers with poor food security and few resources. Of particular relevance are the ES delivered by biodiversity, as many beneficial organisms and biological functions are often overlooked or poorly understood, inadequately maintained, and therefore not fully exploited for sufficient and stable crop yields. The use of biodiversity-based ES can increase the effectiveness of invested and locally available resources, thereby enhancing and stabilising yields at minimal economic cost. Further, we envisage that the approach will minimize pressure on the environment, human health and public goods that historically have been degraded in the quest for higher crop yields. We argue that to increase food security most effectively, ecologically intensified cropping systems should be

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developed and implemented in the regions where yield gaps are currently large and food security is typically low.

2. Biodiversity and ecosystem services on farmland

Given the climatic conditions on a farm and the crop genetics available, there are two main components that determine crop yield: the capture of resources to the plant and losses to pests. Both are greatly affected by living organisms below and above ground, referred to as functional biodiversity. Farmed land harbours a wealth of biota apart from the obvious crops and weeds in the fields and field borders. In the soil dwells a daunting number of species and individuals of bacteria, fungi, arthropods, protozoa, nematodes and earthworms. Hundreds of species of insects, spiders, mites and mammals fly, climb and crawl above ground. Parts of the biota are well known pests that reduce crop yields, but many, possibly most, perform activities that are beneficial for agriculture. Resource capture by the crop is enhanced by decomposers that release nutrients, and enhance soil fertility and structure. Mutualistic organisms such as nitrogen fixing bacteria, pollinators and mycorrhizal fungi feed resources that form yield (Bommarco et al., 2013). Crop losses are reduced by microbial antagonists and predatory arthropods that regulate diseases and pests, and contribute with enormous economic values (Losey and Vaughan, 2006).

3. Ecological intensification of agriculture with ecosystem services

Ecological intensification in farming - i.e., the enhancement of productivity or replacement of anthropogenic inputs by enhancing ES - has been suggested as a strategy to overcome the combined challenges of feeding the world while sparing the environment and public goods. The concept was promoted by Cassman (1999), who focused on how enhancing soil fertility in combination with technological advances can increase crop yields in high-producing areas through improved capture and reduced leakage of resources. The concept has since been expanded to include other ES, such as biological pest control, soil services and crop pollination (Bommarco et al., 2013).

Examples of how production and environmental goals can be met with ecological intensification are emerging. Setting aside arable land for wildlife habitat creation rendered ES that increased yield per unit area so that the overall crop production from the field was maintained (Pywell et al., 2015). Agricultural intensification without biodiversity loss was observed in grasslands, although conservation and production could not be maximized simultaneously at the landscape level (Simons and Weisser, 2017). In managed forest ecosystems, a negative effect of biodiversity loss on forest productivity and the benefits from the transition of monocultures to mixed-species stands in forestry practices were recently demonstrated (Liang et al., 2016). Ecological intensification in agriculture is now moving towards explicitly considering and capitalizing on the organisms whose activities prevent yield losses, and enhance soil fertility and resource capture (e.g. Kennedy et al., 2013, Bender et al., 2016). A recent review shows a predominance of win-win situations from ecologically intensified cropping, as compared with conventional farming, in terms of maintaining or increasing both yields and public goods (Garbach et al., 2017). Nevertheless, more efforts are needed to identify underpinning mechanisms and design farming systems that result in such win-win multi-functional outcomes.

Ecological intensification has potential to contribute to long-term food security globally, by reducing i) the yield gap - i.e., the difference between what is actually produced on farms in a region and the potential primary production, given the climatic and edaphic conditions at that location, and with no losses to pests (van Ittersum and Rabbinge, 1997), and ii) the resource use efficiency gap - i.e., enhancing the output in relation to the input (van Noordwijk and Brussaard, 2014). It has been suggested, but not yet verified, that ecological intensification supports a more stable and resilient crop production (Bommarco et al., 2013). This might be as important for long-term food security as for yield levels in the face of future, more variable, climatic conditions (Challinor et al., 2014; Lobell and Tebaldi, 2014). For example, if a severe drought event such as the Dust Bowl crisis in the 1930's should occur today, it would result in a 40% loss in maize and soy yield and a 30% decline in wheat yield in the U.S. due to low resilience (Glotter and Elliot, 2016). Diverse agricultural systems emerge as more resilient to climate variability and climate change (Altieri and Nicholls, 2017), but the mechanisms remain largely unexplored (Gil et al., 2017; Di Falco, 2012b). Promoting resilience will likely require moving away from input-intensive agriculture and rethinking the current model of how we manage agroecosystems.

4. Contrasting goals depending on local food security

Ecological intensification would need to be implemented with somewhat contrasting (but not mutually exclusive) goals depending on the food security situation and production level in a specific region. In high-producing regions, which typically depend on high levels of external inputs, the yield gap is small, but the environmental impacts are often large. In this case, the focus should be to reduce negative impacts on the environment and public goods rather than towards further closing the yield gap. Of special concern is to mitigate climate change by exploiting ES that minimize greenhouse gas emissions and increase carbon sequestration (Philippot and Hallin, 2011). For example, there are research-based solutions for curbing nitrogen-related greenhouse gas emissions in China without adventuring food security (Zhang et al., 2013). The main challenge in high-producing regions would be to, at least partly, replace the reliance on external inputs, by restoring ES to maintain reasonably high and stable crop production levels (Bommarco et al., 2013).

Globally, food security will be effectively strengthened if crop production is increased in regions with large yield gaps (van Ittersum et al., 2013; Lobell et al., 2009, www.yieldgap.org), where food security is typically poor (Mueller et al., 2012). In these regions, efforts to enhance food security shall therefore primarily be directed towards increasing yield level and, importantly, crop yield stability. The food security of poor consumers is largely affected by price shifts as they spend a large proportion of their income on food (Hertela et al., 2010). Increasing and stabilizing crop production by closing the yield gap locally in these areas will reduce the dependency on the larger market, create a basis for a vital local economy, and increase food security (FAO, 2011). Means to close yield gaps that were used in the Green Revolution are likely to be inadequate and potentially counterproductive in these regions and have been shown to be ineffective and often poorly adapted to the biophysical and socio-economic conditions in, for instance, sub-Saharan Africa (Tittonell and Griffin, 2013). Green Revolution intensification based on mineral fertilizers and improved genetics of a crop (e.g. maize) do raise yields (Denning et al., 2009), but is costly and require subsidies to farmers that put substantial pressure on government spending and allocation in a low income country (Chirwa and Dorward, 2013). In contrast, diverse agriculture including multiple crops and enhanced biodiversity-based functions that increase the effectiveness of moderate amounts of mineral fertilizers, includes legumes that fixate nitrogen, has been demonstrated to increase farmers profitability, match farmers' preferences and enhance food security in sub-Saharan Africa (Snapp et al., 2010). Ecological intensification through ecological enhancement to close yield gaps, emerges as a more suitable and very effective alternative.

5. Underutilised or poorly understood ecosystem services for food security

To enhance food security, ecological intensification needs to exploit several ES, among which some are currently underutilized or not fully understood. These mainly pertain to the spheres of ES derived from soil biota and pest control, but also pollination, as discussed next.

Soil fertility is fundamental for food security. It is ultimately determined by the geology in the area, but also greatly affected by soil management and nutrient input. Therefore, soils are central to ecological intensification (Smith et al., 2016). Fertility management and nutrient use efficiency have been at the core of good agronomy practice for decades and this is an example when agricultural, ecological and environmental thinking converge - a win-win scenario. Management of nitrogen to decrease losses without adventuring food security is a major focus in temperate agriculture and recently also in China (Cameron et al., 2013; Zhang et al., 2013, 2015). These strategies could be exploited in regions with large as well as small yield gaps and further developed to also utilise recently discovered, microbially mediated ES for mitigating soil emission of the greenhouse gas nitrous oxide (Jones et al., 2014). The next step will be promoting nitrogen retention by transferring leachable nitrate to a less mobile compound, like ammonium - a potential ES that has yet not been purposefully utilized in agriculture (Rütting et al., 2011). In severely nutrient depleted soils, integrated soil fertility management, which aims at using locally adapted practices to improve soil fertility by combining organic amendments with mineral fertilizers is gaining interest (https://ifdc.org/integrated-soil-fertility-management/). Soil fertility is intertwined with the soil biota and their associated functions (e.g. Bender et al., 2016), but the organisms that underpin the soil ES have been largely ignored when working with fertility management. Research on management of the soil biota that contribute to soil fertility and other relevant ES promoting crop production is in its infancy, especially when it comes to management aiming at fostering specific soil microorganisms (Busby et al., 2017; Hartman et al., 2018). Currently, the most promising is management of microbiota in the rhizosphere (e.g. Chaparro et al., 2012; Section 6.2).

Avoiding losses to pests is a major concern for food security. In ecologically intensified farming, pest attacks are prevented by exploiting naturally occurring enemies and antagonists to the pests (Barbosa, 1998), combined with cultural and mechanical practices. Responsive interventions against pest attacks is the exception, and then primarily with preferably cheap biological and low-toxicity agents. This concept was suggested already in the 1950s in response to the widespread unsustainable use of pesticides (Stern et al., 1959). There is, thus, a knowledge base to build on, but further research is needed to devise locally adapted practices that provide targeted support for beneficial organisms (Section 6.2), and to better understand how natural enemy communities should be composed to deliver stable and sufficient services (Tylianakis and Romo, 2010). Preventive pest control is a promising pathway for strengthening food security in regions with large yield gaps.

Two-thirds of the world's crop species are at least partly dependent on insect pollination to set seed or fruit (Klein et al., 2007), and cultivation of pollinated crops is increasing globally (Aizen and Harder, 2009). Wild insects, especially bees, are at least as important as managed honey bees to maintain crop production (Garibaldi et al., 2013), as they enhance food security by providing yield and nutrients (Gallai et al., 2009; Eilers et al., 2011; IPBES, 2016). Despite that, pollination, especially by wild insects, is still a poorly considered production factor in agriculture, particularly for partly pollination-dependent crops. Hence, managing wildlife for crop pollination provides yet unexploited opportunities to increase yields (Isaacs et al., 2017).

6. Diversified agriculture to promote ecosystem services in practice

There are several potential ways to achieve ecological enhancement in practice, but there is no single silver bullet to achieve this. Both knowledge and supporting technologies adapted to different crops, climatic, edaphic and socio-economic situations will need to be developed. An often proposed general approach to promote and better exploit ES is to diversify the farming system (Kremen and Miles, 2012). As emerging from Section 5, a number of underutilized ES hinges on diversification. Cropping systems can be diversified in many ways and at a number of spatial and temporal scales. At the field scale, diversification can be implemented by growing functionally diverse crop species or varieties mixed in a field (intercropping) or in a crop rotation, or by adding organic amendments that stimulate the soil biota, e.g. as promoted in conservation agriculture (Hobbs et al., 2008). Crop and, in general, income diversification at the farm level buffers against external disturbances, e.g. from droughts, extreme temperatures and pest outbreaks. At the landscape scale, diversification implies mixed cropping systems, non-crop plantings and management of non-crop land, including natural and semi-natural habitats, which enhance species richness at larger scales (Kremen and Miles, 2012). These measures directly and indirectly enhance crop productivity and yield stability, thus contributing to food security.

6.1. *Diversified crop production and landscapes*

There is surprisingly little information synthesized on long-term effects of different types of agricultural diversification on crop yield and the biotic processes that support or reduce primary production, but there are promising examples and a growing interest among agricultural researchers and practitioners. We know that monocultures or short rotations with few crop species reduce yield in the short term and can negatively affect soil fertility, and pest and weed control long-term (Bennett et al., 2012). The loss of plant species over time diminishes returns from fertilization (Isbell et al., 2011).

How we diversify can have profound effects on yields and the generation of biotic processes supporting production. For instance, at the field scale, nitrogen uptake increases and losses decreases in mixed species plantings (intercropping) compared with monocultures (Niklaus et al., 2006; Li et al., 2007; Mueller et al., 2013; Cong et al., 2015). This, exemplifies how diversification can improve nitrogen use efficiency and decrease environmental impact. Furthermore, intercropping generally reduced yield variability, thus stabilizing food availability (Raseduzzaman and Jensen, 2017). Diversification in time, with more crop species in the rotation, was shown to increase soil microbial biomass as well as the soil carbon and nitrogen pools (McDaniel et al., 2014), potentially promoting ES delivered by below-ground biota. Further, incorporation of perennial crops in crop rotations can enhance the provision of a wide range of ES, not only supporting beneficial organisms, but also enhancing water- and nutrient-uptake efficiency (Tilman and Wedin, 1991), reducing soil erosion and nutrient loss, and improving soil structure (Culman et al., 2013). Cropping systems with perennial crops typically also emit less nitrous oxide (Gelfand et al., 2016; Thompson et al., 2016). There are indications that perennial crops stabilize yields in the face of fluctuating growing conditions (Vico and Brunsell, 2018), although the productivity of currently available perennial grain crops is still lower than that of their annual counterparts (Vico et al., 2016). Importantly, diversification of crops creates a portfolio effect and reduces risk to the farmer (Di Falco, 2012a, 2012b).

Diversified crop rotations and habitat diversification in the agricultural landscape also affect the delivery and stability of ES. For example, both crop pollinators and natural enemies to pests are severely suppressed and deliver less services by high-input agriculture in landscapes devoid of natural habitats (Chaplin-Kramer et al., 2011; Kennedy et al., 2013). The inclusion of mass-flowering crops, such as oilseed rape, clover or perennial grass for biomass production can offer resources to beneficial insects that enhance pollination and insect pest control in the landscape (Rundlöf et al., 2014; Rusch et al., 2013). Whether type of landscape-level diversification has a measurable impact on other beneficial organisms and the ES they provide above and below ground in a field has not been investigated to any extent.

6.2. Targeted diversification

The general results on overall effects of diversification show promise, and this suggests that targeted diversification approaches could be key to enhance ES and food security based on available means that are economically evaluated and viable to the farmer. Regarding beneficial organisms, acquiring ecological information on which forces (e.g. resource, or mortality factors) limit their population growth can help us devise targeted interventions that relax such pressures, which can be applied into cropping systems to bolster service-providing species. One such approach is to introduce food resources, as already adopted for pollination and pest control services (Schellhorn et al., 2015). Incorporating perennial vegetation, and even small, strategically placed areas can suffice to support functional biodiversity at the landscape scale (Asbjornsen et al., 2013). The key here is the ecological know-how on what action that is strategic in relation to the ES in need of promotion. An exceptional example of targeted ecological intensification based on beneficial organisms is the "push-pull" technique that draws from the ecology of host-plant interactions to reduce insect pest attacks in maize (Cook et al., 2007). It has been adopted by over 130 000 small holder farmers in east Africa, increasing their maize yields from 1 to 3.5 t/ha (www.push-pull.net). Maize is being intercropped with a non-crop plant (e.g. the legume *Desmodium*) that repels the stemboring lepidopteran pest. This is the "push", which is then complemented with the planting of a trap plant (e.g. Napier grass, *Pennisetum purpureum*) along the field borders that attracts the pest out from the field, which would be the "pull" in this example (Cook et al., 2007). Added value is gained from the *Desmodium*, as it inhibits weed growth and enhances soil fertility through nitrogen fixation. Since the *Desmodium* is not harvested, it also adds to the build-up of soil organic matter.

Soil biodiversity and beneficial plant-microbe interactions are receiving increasing attention as a means to improve crop production. In particular, plant-microbe interactions can not only promote plant health and nutrient acquisition, but also minimize negative environmental impact (Chaparro et al., 2012; Philippot and Hallin, 2011; Philippot et al., 2013; Bender et al., 2016). Experiments have shown that increased biodiversity of plant symbionts can support crop production (Wagg et al., 2011). For example, an increase in the species diversity of mycorrhizal fungi resulted in more than 50% increase in above-ground biomass (van der Heijden et al., 1998). But to transfer this to practical management is not trivial, considering the overwhelming diversity of soil biota (Thompson et al., 2017) and that the soil itself has the largest influence on the composition of the root-associated microbial communities (Berg and Smalla, 2009; Bulgarelli et al., 2012; Graf et al., 2016). The trend has therefore been to focus on innovative plant breeding and genetically modified plants and in this way affect the soil biota and the ES they deliver (e.g. Subbarao et al., 2009; Sun et al., 2015). How these measures affect the soil community and the ES they contribute, as well as other ES, in addition to the dependency of external inputs and resilience in the system, is not yet known.

These are examples of how in-depth ecological knowledge can help us develop cheap and locally available techniques for productive and resource-use efficient cropping systems with minimal negative environmental impact. Many more such techniques would need to be developed.

7. Consequences for public goods

In the process of increasing local production in areas yield gaps are large, it is important to safeguard the environment and public goods (Zhang et al., 2016). Economic growth of a society has historically been seen to bring an initial phase of environmental degradation through pollution, followed by a phase of improvement and adoption of more environmentally friendly production (Grossman and Krueger, 1995). This historical pattern - an environmental Kuznets curve (Fig. 1) - has been demonstrated also for nitrogen use efficiency in agriculture (Zhang et al., 2015), for which enhanced efficiency increases productivity and decreases environmental degradation (Cassman et al., 2003). To avoid pressure on the environment and public goods in regions with low *per capita* income in need of, or undergoing, economic development, there is the option to develop a locally-tailored ecological enhancement approaches, thus tunnelling through the inefficiency-bump, as described by Zhang et al. (2015). In other words, when increasing production, mistakes historically or currently being made in high-producing regions should be avoided. We need make efforts to shorten the inefficiency phase to reach resource efficient and high yielding production systems (Fig. 1). Instead, there is the opportunity to achieve increased efficiency of inputs such as mineral nutrients, energy and pesticides, by managing for bolstered ES in low-input (but not necessarily no-input) cropping. We expect this approach to be effective also from livelihood, food security and self-sufficiency perspectives in regions where latent resource limitations give at hand that yield increases need to be based on the efficient use of locally available resources and accessible technology (Godfray et al., 2010; Zhang et al., 2016).

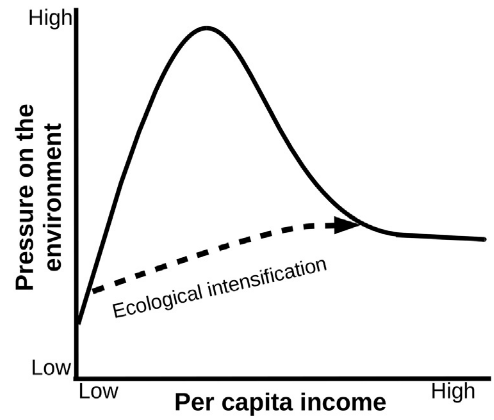

Fig. 1. Ecological intensification with increased reliance on ES gives opportunity to bypass (dotted arrow) the production inefficiency bump (solid line). Environmental degradation is often observed when *per capita* income increases in an economy, due to pollution from an initially inefficient production (see Zhang et al., 2015). Bypassing the bump avoids wasteful and leaky use of external inputs such as mineral nutrients and pesticides that put pressure on the environment and public goods.

8. Knowledge needed

Agriculture based on ES is knowledge intensive. In terms of natural science, it requires fundamental insights into the ecology of the organisms delivering the ES and the underlying mechanisms resulting in said ES. In particular, we need to better understand how species richness, community composition and interactions among community members determine the flow and stability of ES and ultimately the resource capture by the crop. Explorations in highly controlled experiments have shown that increased plant diversity does indeed enhance biomass production (Duffy et al., 2017). This research needs to be extended to include communities and functions at other trophic levels (Gagic et al., 2015) and transferred to agricultural settings (Bender et al., 2016). Systematic syntheses of experimental work, particularly long-term experiments, as well as new experimental trials will be needed.

Further, we need to better understand how land use and other environmental factors affect the distribution, abundance, and community composition of organisms that contribute to crop production. This is critical to avoid cropping practices that are detrimental to service-providers, and to develop targeted measures that effectively bolster beneficial organisms. A measure aimed at enhancing one ES might affect the delivery of other ES – both positively and negatively. Nevertheless, ES are generally studied in isolation, even though we know that organisms interact. In agroecosystems, the interactions are particularly relevant at the interface between below and above ground (van Der Putten et al., 2001; de Vries et al., 2013), but it is poorly explored how they together subsidize or counteract primary production and influence processes at the ecosystem level. Experimental evidence suggests that below-ground organisms can affect above-ground plant-insect interactions with benefits for the plant (Orrell and Bennett, 2013). Even just at the field scale, this includes increased attraction of herbivore enemies, decreased herbivore fitness, more visits by pollinator and protection against pathogens. With an improved understanding of these multi-trophic interactions, we could potentially manage soil microbial communities to improve crop production. Finally, at the landscape scale, little is understood about how biodiversity and community composition determine multi-functionality in agroecosystems (Wagg et al., 2014). Recently, habitat diversity at the landscape level was shown to directly support both biodiversity and ecosystem multi-functionality in marine sediments (Alsterberg et al., 2017), but whether this can be transferred to agriculture is still to be determined. More importantly, focusing on habitats instead of species diversity could be a framework for scaling up biodiversity-ecosystem functioning relationships, which would be more tractable from a management perspective.

From a more practical agricultural perspective, and for ES to truly become an integral part of farming, agricultural researchers and practitioners should gather around four interlinked targets that emerge as beacons for agricultural innovation:

i. minimal environmental impact,
ii. increased resource use efficiency,
iii. flexibility and capacity to buffer extreme events (resilience) from climate change or pest outbreaks, and
iv. adaptation to local conditions.

For food security purposes, the focus should be on the development and adoption of ecological enhancement in regions with currently large yield gaps. Technological developments such as innovative machinery, tailored breeding and biotechnology will serve food security effectively only if contrived in support of, and from the very start intended to be integrated with, regionally tuned low-input cropping systems that exploit ES.

In addition to the research needs in the natural sciences, social and economic aspects have to be considered for a wide adoption of ecological intensification to enhance food security. Social and economic aspects coupled with the development of ecological intensification have to be developed and monitored in parallel with technically innovative agriculture (Garibaldi et al., 2017). Importantly, both practitioners and scientists can contribute knowledge, new ideas and the capacity to validate and disseminate technology linked to sustainable crop production and a multi-actor effort will be needed for effective innovation and wide uptake. Research has demonstrated that farming systems need to be anchored in supportive institutions, otherwise short-term investments will miss opportunities to realise ecological benefits in the medium and long terms (Bacon et al., 2012). Thus, the understanding about ecological intensification among many concerned actors, such as land managers, authorities and scientists needs to be considered as they affect sustainable agricultural practices (Noe et al., 2015).

9. Conclusions

The improved use of ES delivered by biodiversity shows promise to enhance food security by increasing food availability and crop yield stability. This is especially the case for regions with currently large yield gaps, poverty and poor food security. Diversification of crop production systems appears as a promising general way to enhance ES, resource use efficiency and yields. Applications of ecological intensification is knowledge intensive and requires fundamental understanding of the ecology and socio-economy of ES. New knowledge and technologies will increase food security effectively only if contrived in support of regionally adapted cropping systems that exploit ES. Beacons for researcher and practitioners in co-developing ecologically intensified farming systems should be: increased resource use efficiency, minimal environmental impact, capacity to buffer extreme events, and adaptation to local climatic, edaphic, biotic and socio-economic conditions.

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Declaration of conflicts of interest

Our submitted manuscript *"Exploiting ecosystem services in agriculture for increased food security"* has not been published previously in any form, it is not under consideration for publication elsewhere, and its publication is approved by all authors. If accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyright-holder.

References

Aizen, M.A., Harder, L.D., 2009. The global stock of domesticated honey bees is growing slower than agricultural demand for pollination. Curr. Biol. 19, 915–918 DOI: 0.1016/j.cub.2009.03.071.
Alsterberg, C., Roger, F., Sundbäck, K., Juhanson, J., Hulth, S., Hallin, S., Gamfeldt, L., 2017. Habitat diversity and ecosystem multifunctionality - the importance of direct and indirect effects. Science Advances 3, e1601475. http://dx.doi.org/10.1126/sciadv.1601475.
Altieri, M.A., Nicholls, C.I., 2017. The adaptation and mitigation potential of traditional agriculture in a changing climate. Climatic change 140, 33–45. http://dx.doi.org/10.1007/s10584-013-0909-y.
Asbjornsen, H., Hernandez-Santana, V., Liebman, M.Z., Bayala, J., Chen, J., Helmers, M., Ong, C.K., Schulte, L., 2013. Targeting perennial vegetation in agricultural landscapes for enhancing ecosystem services. Renewable Agriculture and Food Systems 29, 101–125. http://dx.doi.org/10.1017/S1742170512000385.
Bacon, C.M., Getz, C., Kraus, S., Montenegro, M., Holland, K., 2012. The social dimensions of sustainability and change in diversified farming systems. Ecol. Soc. 17, 41. http://dx.doi.org/10.5751/ES-05226-170441.
Barbosa, P., 1998. Conservation Biological control. Elsevier ISBN: 978-0-12-078147-8.
Bender, S.F., Wagg, C., van der Heijden, M.G., 2016. An underground revolution: biodiversity and soil ecological engineering for agricultural sustainability. Trends Ecol. Evol. 31 (6), 440–452. http://dx.doi.org/10.1016/j.tree.2016.02.016.
Bennett, A.J., Bending, G.D., Chandler, D., Hilton, S., Mills, P., 2012. Meeting the demand for crop production: the challenge of yield decline in crops grown in short rotations. Biol. Rev. 87, 52–71. http://dx.doi.org/10.1111/j.1469-185X.2011.00184.x.
Berg, G., Smalla, K., 2009. Plant species and soil type cooperatively shape the structure and function of microbial communities in the rhizosphere. FEMS Microbiol Ecol 68 (1), 1–13. http://dx.doi.org/10.1111/j.1574-6941.2009.00654.x.
Bommarco, R., Kleijn, D., Potts, S.G., 2013. Ecological intensification: harnessing ecosystem services for food security. Trends in Ecology and Evolution 28 (4), 230–238. http://dx.doi.org/10.1016/j.tree.2012.10.012.
Bouwman, L., Goldewijk, K.K., Van Der Hoek, K.W., Beusen, A.H.W., Van Vuuren, D.P., Willems, J., Rufino, M.C., Stehfest, E., 2013. Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period. Proc. Natl Acad. Sci. USA 110, 20882–20887. http://dx.doi.org/10.1073/pnas.1012878108.
Bulgarelli, D., Rott, M., Schlaeppi, K., Ver Loren van Themaat, E., Ahmadinejad, N., Assenza, F., Rauf, P., Huettel, B., Reinhardt, R., Schmelzer, E., Peplies, J., Gloeckner, F.O., Amann, R., Eickhorst, T., Schulze-Lefert, P., 2012. Revealing structure and assembly cues for Arabidopsis root-inhabiting bacterial microbiota. Nature 488, 91–95. http://dx.doi.org/10.1038/nature11336.
Busby, P.E., Soman, C., Wagner, M.R., Friesen, M.L., Kremer, J., Bennett, A., Morsy, M., Eisen, J.A., Leach, J.E., Dangl, J.L., 2017. Research priorities for harnessing plant

microbiomes in sustainable agriculture. PLOS Biology 15 (3), e2001793.

Cameron, K.C., Di, H.J., Moir, J.L., 2013. Nitrogen losses from the soil/plant system: a review. Ann Appl Biol. 162, 145–173. http://dx.doi.org/10.1111/aab.12014.

Cassman, K.G., 1999. Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture. Proc. Natl. Acad. Sci. USA. 96 (11), 5952–5959.

Cassman, K.G., Dobermann, A., Walters, D.T., Yang, H., 2003. Meeting cereal demand while protecting natural resources and improving environmental quality. Annu. Rev. Environ. Resour. 28, 315–358. http://dx.doi.org/10.1146/annurev.energy.28.040202.122858.

Challinor, A.J., Watson, J., Lobell, D.B., Howden, S.M., Smith, D.R., Chhetri, N., 2014. A meta-analysis of crop yield under climate change and adaptation. Nature Climate Change 4, 287. http://dx.doi.org/10.1038/nclimate2153.

Chaplin-Kramer, R., O'Rourke, M.E., Blitzer, E.J., Kremen, C., 2011. A meta-analysis of crop pest and natural enemy response to landscape complexity 14 (9), 922–932. http://dx.doi.org/10.1111/j.1461-0248.2011.01642.x.

Chaparro, J.M., Shelifin, A.M., Manter, D.K., Vivanco, J.M., 2012. Manipulating the soil microbiome to increase soil health and plant fertility. Biol. Fert. Soils. 5, 489–499. http://dx.doi.org/10.1007/s00374-012-0691-4.

Chirwa, E., Dorward, A., 2013. Agricultural Input Subsidies: The Recent Malawi Experience. Oxford University Press.

Cong, W.-F., Hoffland, E., Li, L., Six, J., Sun, J.-H., Bao, X.-G., Zhang, F.-S., Van Der Werf, W., 2015. Intercropping enhances soil carbon and nitrogen. Glob. Change Biol. 21, 1715–1726. http://dx.doi.org/10.1111/gcb.12738.

Cook, S.M., Khan, Z.R., Pickett, J.A., 2007. The use of push-pull strategies in integrated pest management. Annu Rev Entomol. 2007 (52), 375–400. http://dx.doi.org/10.1146/annurev.ento.52.110405.091407.

Culman, S.W., Snapp, S.S., Ollenburger, M., Basso, B., DeHaan, L.R., 2013. Soil and water quality rapidly responds to the perennial grain kernza wheatgrass. Agronomy J. 105, 735–744. http://dx.doi.org/10.2134/agronj2012.0273.

Denning, G., Kabambe, P., Sanchez, P., Malik, A., Flor, R., Harawa, R., et al., 2009. Input subsidies to improve smallholder maize productivity in Malawi: toward an African green revolution. PLoS Biol. 7 (1), e1000023. http://dx.doi.org/10.1371/journal.pbio.1000023.

Di Falco, S., 2012a. On the value of agricultural biodiversity. Annu. Rev. Resour. Econ. 4, 207–223. http://dx.doi.org/10.1146/annurev-resource-110811-114543.

Di Falco, S., 2012b. On the value of agricultural biodiversity. Annu. Rev. Resour. Econ. 4, 207–223. http://dx.doi.org/10.1146/annurev-resource-110811-114543.

Duffy, J.E., Godwin, C.M., Cardinale, B.J., 2017. Biodiversity effects in the wild are common and as strong as key drivers of productivity. Nature 549, 261. http://dx.doi.org/10.1038/nature23886.

Eilers, E.J., Kremen, C., Greenleaf, S.S., Garber, A.K., Klein, A.-M., 2011. Contribution of pollinator-mediated crops to nutrients in the human food supply. PLOS One 6, e2136. http://dx.doi.org/10.1371/journal.pone.0021363.

FAO, 2011. Save and Grow: A Policymaker's Guide to the Sustainable Intensification of Smallholder Crop Production. FAO, Rome.

FAO, 2014. The State of Food Insecurity in the World 2014. Food and Agriculture Organization, Rome.

Foley, J.A., Defries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global consequences of land use. Science. 309 (5734), 570–574. http://dx.doi.org/10.1126/science.1111772.

Gagic, V., Bartomeus, I., Jonsson, T., Taylor, A., Winqvist, C., Fischer, Ch, Slade, E.M., Steffan-Dewenter, I., Emmerson, M., Potts, S.G., Tscharntke, T., Weisser, W., Bommarco, R., 2015. Functional identity and diversity of animals predict ecosystem functioning better than species-based indices. 8p. Proc. R. Soc. B 282 (1801). http://dx.doi.org/10.1098/rspb.2014.2620.

Gallai, N., Salles, J.-M., Settele, J., Vaissièr, B.E., 2009. Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. Ecol. Econ. 68, 810–821. http://dx.doi.org/10.1016/j.ecolecon.2008.06.014.

Galloway, J.N., Townsend, A.R., Erisman, J.W., Bekunda, M., Cai, Z., Freney, J.R., Martinelli, L.A., Seitzinger, S.P., Sutton, M.A., 2008. Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. Science. 320 (5878), 889–892. http://dx.doi.org/10.1126/science.1136674.

Garbach, K., Milder, J.C., DeClerck, F.A.J., Montenegro de Wit, M., Driscoll, L., Gemmill-Herren, B., 2017. Examining multi-functionality for crop yield and ecosystem services in five systems of agroecological intensification. Int. J. Agric. Sust. 15 (1), 11–28. http://dx.doi.org/10.1080/14735903.2016.1174810.

Garibaldi, L.A., Steffan-Dewenter, I., Winfree, R., Aizen, M.A., Bommarco, R., Cunningham, S.A., Kremen, C., Carvalheiro, L.G., Harder, L.D., Afik, O., Bartomeus, I., Benjamin, F., Boreux, V., Cariveau, D., Chacoff, N.P., Dudenhöffer, J.H., Freitas, B.M., Ghazoul, J., Greenleaf, S., Hipólito, J., Holzschuh, A., Howlett, B., Isaacs, R., Javorek, S.K., Kennedy, C.M., Krewenka, K., Krishnan, S., Mandelik, Y., Mayfield, M.M., Motzke, I., Munyuli, T., Nault, B.A., Otieno, M., Petersen, J., Pisanty, G., Potts, S.G., Rader, R., Ricketts, T.H., Rundlöf, M., Seymour, C.L., Schüepp, C., Szentgyörgyi, H., Taki, H., Tscharntke, T., Vergara, C.H., Viana, B.F., Wanger, T.C., Westphal, C., Williams, N., Klein, A.M., 2013. Wild pollinators enhance fruit set of crops regardless of honey-bee abundance. Science 339 (6127), 1608–1611. http://dx.doi.org/10.1126/science.1230200.

Garibaldi, L.A., Gemmill-Herren, B., D'Annolfo, R., Cunningham, S.A., Breeze, T.D., 2017. Farming approaches for greater biodiversity, livelihoods, and food security farming approaches for greater biodiversity, livelihoods, and food security. TREE 32 (1), 68–80. http://dx.doi.org/10.1016/j.tree.2016.10.001.

Gelfand, I., Shcherbak, I., Millar, N., Kravchenko, A.N., Robertson, G.P., 2016. Long-term nitrous oxide fluxes in annual and perennial agricultural and unmanaged ecosystems in the upper Midwest USA. Global Change Biol. 22, 3594–3607. http://dx.doi.org/10.1111/gcb.13426.

Gil, J.D.B., Cohn, A.S., Duncan, J., Newton, P., Vermeulen, S., 2017. The resilience of integrated agricultural systems to climate change. WIREs Clim Change 8. http://dx.doi.org/10.1002/wcc.461.

Glotter, M., Elliot, J., 2016. Simulating US agriculture in a modern dust bowl drought. Nature Plants. 12 (3), 16193. http://dx.doi.org/10.1038/nplants.2016.193.

Godfray, H.C., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. Science 327 (5967), 812–818. http://dx.doi.org/10.1126/science.1185383.

Gordon, L.J., Peterson, G.D., Bennett, E.M., 2008. Agricultural modifications of hydrological flows create ecological surprises. Trends Ecol. Evol. 23, 211–219. http://dx.doi.org/10.1016/j.tree.2007.11.011.

Graf, D.R.H., Zhao, M., Jones, C.M., Hallin, S., 2016. Soil type overrides plant effect on genetic and enzymatic N_2O production potential in arable soils. Soil Biol. Biochem. 100, 125–128. http://dx.doi.org/10.1016/j.soilbio.2016.06.006.

Grossman, G.M., Krueger, A.B., 1995. Economic growth and the environment. Q. J. Econ. 110, 353–377. http://dx.doi.org/10.3386/w4634.

Hartman, K., van der Heijden, M.G.A., Wittwer, R.A., Banerjee, S., Walser, J.-C., Schlaeppi, K., 2018. Cropping practices manipulate abundance patterns of root and soil microbiome members paving the way to smart farming. Microbiome 6 (1), 14.

Hertela, T.W., Burke, M.B., Lobell, D.B., 2010. The poverty implications of climate-induced crop yield changes by 2030. Glob. Environ. Change. 20 (4), 577–585. http://dx.doi.org/10.1016/j.gloenvcha.2010.07.001.

Hobbs, P.R., Sayre, K., Gupta, R., 2008. The role of conservation agriculture in sustainable agriculture. Philos. Trans. R. Soc. Lond. Ser. B, Biol. Sci. 363 (1491), 543–555. http://dx.doi.org/10.1098/rstb.2007.2169.

Hooper, D.U., Adair, E.C., Cardinale, B.J., Byrnes, J.E.K., Hungate, B.A., Matulich, K.L., Gonzalez, A., Duffy, J.E., Gamfeldt, L., O'Connor, M.I., 2012. A global synthesis reveals biodiversity loss as a major driver of ecosystem change. Nature 486, 105–108. http://dx.doi.org/10.1038/nature11118.

IPBES, 2016. Summary for Policymakers of the Assessment Report of the Intergovernmental Science-policy Platform on Biodiversity and Ecosystem Services on Pollinators, Pollination, and Food Production. Secretariat of IPBES, Bonn, Germany.

Isaacs, R., Williams, N., Ellis, J., Pitts-Singer, T.L., Bommarco, R., Vaughan, M., 2017. Integrated Crop Pollination: combining strategies to ensure stable and sustainable yields of pollination-dependent crops. Basic appl. ecol. 22, 44–60. http://dx.doi.org/10.1016/j.baae.2017.07.003.

Isbell, F., Calcagno, V., Hector, A., Connolly, J., Harpole, W.S., Reich, P.B., Scherer-Lorenzen, M., Schmid, B., Tilman, D., van Ruijven, J., Weigelt, A., Wilsey, B.J., Zavaleta, E.S., Loreau, M., 2011. High plant diversity is needed to maintain ecosystem services. Nature 477, 199–202. http://dx.doi.org/10.1038/nature1028Nature. 477:199.

Jones, C.M., Spor, A., Brennan, F.P., Breuil, M.-C., Bru, D., Lemanceau, P., Griffiths, B., Hallin, S., Philippot, L., 2014. Recently identified microbial guild mediates soil N_2O sink capacity. Nature Climate Change 4, 801–805.

Kehoe, L., Romero-Muñoz, A., Polaina, E., Estes, L., Kreft, H., Kuemmerle, T., 2017. Biodiversity at risk under future cropland expansion and intensification. Nature Ecol. Evol. 1, 1129–1135. http://dx.doi.org/10.1038/s41559-017-0234-3.

Kennedy, C.M., Lonsdorf, E., Neel, M.C., Williams, N.M., Ricketts, T.H., Winfree, R., Bommarco, R., Brittain, C., Burley, A.L., Cariveau, D., Carvalheiro, L.G., Chacoff, N.P., Cunningham, S.A., Danforth, B.N., Dudenhöffer, J.-H., Elle, E., Gaines, H.R., Gratton, C., Garibaldi, L.A., Holzschuh, A., Isaacs, R., Javorek, S.K., Jha, S., Klein, A.M., Krewenka, K., Mandelik, Y., Mayfield, M.M., Morandin, L., Neame, L.A., Otieno, M., Park, M., Potts, S.G., Rundlöf, M., Saez, A., Steffan-Dewenter, I., Taki, H., Felipe Viana, B., Veldtman, R., Westphal, C., Wilson, J.K., Greenleaf, S.S., Kremen, C., 2013. A global quantitative synthesis of local and landscape effects on native bee pollinators in agroecosystems. Ecol. lett. 16 (5), 584–599. http://dx.doi.org/10.1111/ele.12082.

Klein, A.-M., Vaissière, B.E., Cane, J.H., Steffan-Dewenter, I., Cunningham, S.A., Kremen, C., Tscharntke, T., 2007. Importance of pollinators in changing landscapes for world crops. Proc. R. Soc. Lond. B Biol. Sci. 274, 303–313. http://dx.doi.org/10.1098/rspb.2006.3721.

Kremen, C., Miles, A., 2012. Ecosystem services in biologically diversified versus conventional farming systems: benefits, externalities, and trade-offs. Ecol. Soc. 17 (4), 40. http://dx.doi.org/10.5751/ES-05035-170440.

Li, L., Li, S.-M., Sun, J.-H., Zhou, L.-L., Bao, X.-G., Zhang, H.-G., Zhang, F.-S., 2007. Diversity enhances agricultural productivity via rhizosphere phosphorus facilitation on phosphorus-deficient soils. Proc. Nat. Acad. Sci. 104 (27), 11192–11196. http://dx.doi.org/10.1073/pnas.0704591104.

Liang, J., Crowther, T.W., Picard, N., et al., 2016. Positive biodiversity-productivity relationship predominant in global forests. Science 354 (6309). http://dx.doi.org/10.1126/science.aaf8957.

Lobell, D.B., Tebaldi, C., 2014. Getting caught with our plants down: the risks of a global crop yield slowdown from climate trends in the next two decades. Environmental Research Lett. 9, 074003. http://dx.doi.org/10.1088/1748-9326/9/7/074003.

Lobell, D.B., Cassman, K.G., Field, C.B., 2009. Crop yield gaps: their importance, magnitudes, and causes. Annu. Rev. Environ. Resour. 34, 1–26. http://dx.doi.org/10.1146/annurev.environ.041008.093740.

Losey, J.E., Vaughan, M., 2006. The economic value of ecological services provided by insects. BioScience 56 (4), 311–323. http://dx.doi.org/10.1641/0006-3568(2006)56[311:TEVOES]2.0.CO;2.

Maxwell, S.L., Fuller, R.A., Brooks, T.M., Watson, J.E., 2016. The ravages of guns, nets and bulldozers. Nature 536 (7615), 143–145. http://dx.doi.org/10.1038/536143a.

McDaniel, M.D., Tiemann, L.K., Grandy, A.S., 2014. Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. Ecol. Appl. 24, 560–570. http://dx.doi.org/10.1890/13-0616.1.

Mueller, K.E., Hobbie, S.E., Tilman, D., Reich, P.B., 2013. Effects of plant diversity, N fertilization, and elevated carbon dioxide on grassland soil N cycling in a long-term experiment. Glob. Change Biol. 19, 1249. http://dx.doi.org/10.1111/gcb.12096.

Mueller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N., Foley, J.A., 2012. Closing yield gaps through nutrient and water management. Nature 490, 254. http://dx.doi.org/10.1038/nature11420.

Niklaus, P.A., Wardle, D.A., Tate, K.R., 2006. Effects of plant species diversity and composition on nitrogen cycling and the trace gas balance of soils. Plant Soil 282, 83–98. http://dx.doi.org/10.1007/s11104-005-5230-8.

Noe, E., Alrøe, H.F., Thorsøe, M.H., Olesen, J.E., Sørensen, P., Melander, B., Fog, E., 2015. Knowledge asymmetries between research and practice: a social systems approach to implementation barriers in organic arable farming. Sociologia Ruralis. 55 (4), 1467–9523. http://dx.doi.org/10.1111/soru.12078.

Orrell, P., Bennett, A.E., 2013. How can we exploit above-belowground interactions to assist in addressing the challenges of food security? Frontiers in Plant Science 4, 432.

Philippot, L., Hallin, S., 2011. Towards food, feed and energy crops mitigating climate change. Trends in Plant Science 16, 476–480. http://dx.doi.org/10.1016/j.tplants.2011.05.007.

Philippot, L., Raaijmakers, J.M., Lwemanceau, P., van der Putten, W.H., 2013. Going back to the roots: the microbial ecology of the rhizosphere. Nature Reviews Microbiology 11, 789–799. http://dx.doi.org/10.1038/nrmicro3109.

Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, et al., 1995. Environmental and economic costs of soil erosion and conservation benefits. Science 267, 1117–1123. http://dx.doi.org/10.1126/science.267.5201.1117.

Pywell, R.F., Heard, M.S., Woodcock, B.A., Hinsley, S., Ridding, L., Nowakowski, M., Bullock, J.M., 2015. Wildlife-friendly farming increases crop yield: evidence for ecological intensification. Proc. R. Soc. B 282, 1816. http://dx.doi.org/10.1098/rspb.2015.1740.

Raseduzzaman, Md, Jensen, E.S., 2017. Does intercropping enhance yield stability in arable crop production? A meta-analysis. European Journal of Agronomy 91, 25–33. http://dx.doi.org/10.1016/j.eja.2017.09.009.

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

Rundlöf, M., Persson, A.S., Smith, H.G., Bommarco, R., 2014. Late-season mass-flowering red clover increases bumble bee queen and male densities. Biol. cons. 172, 138–145. http://dx.doi.org/10.1016/j.biocon.2014.02.027.

Rusch, A., Bommarco, R., Jonsson, M., Smith, H.G., Ekbom, B., 2013. Flow and stability of natural pest control services depend on complexity and crop rotation at the landscape scale. J. appl. ecol. 50, 345–354. http://dx.doi.org/10.1111/1365-2664.12055.

Rütting, T., Boeckx, P., Müller, C., Klemedtsson, L., 2011. Assessment of the importance of dissimilatory nitrate reduction to ammonium for the terrestrial nitrogen cycle. Biogeosciences 8, 1779–1791. http://dx.doi.org/10.5194/bg-8-1779-2011. 2011.

Schellhorn, N.A., Gagic, V., Bommarco, R., 2015. Time will tell: resource continuity bolsters ecosystem services. Trends Ecol. Evol. 30, 524–530. http://dx.doi.org/10.1016/j.tree.2015.06.007.

Settle, W.H., Hartjahyo, A., Endah Tri, A., Widyastama, C., Arief Lukman, H., Dadan, H., Alifah Sri, L., 1996. Managing tropical rice pests through conservation of generalist natural enemies and alternative prey. Ecology 77 (7), 1975–1988. http://dx.doi.org/10.2307/2265694.

Simons, N.K., Weisser, W.W., 2017. Agricultural intensification without biodiversity loss is possible in grassland landscapes. Nature Ecol. Evol. 1, 1136–1145. http://dx.doi.org/10.1038/s41559-017-0227-2.

Smith, P., House, J.I., Bustamante, M., Sobocká, J., Harper, R., Pan, G., West, P.C., Clark, J.M., Adhya, T., Rumpel, C., Paustian, K., Kuikman, P., Cotrufo, M.F., Elliott, J.A., McDowell, R., Griffiths, R.I., Asakawa, S., Bondeau, A., Jain, A.K., Meersmans, J., Pugh, T.A.M., 2016. Global change pressures on soils from land use and management. Glob. Change Biol. 22, 1008–1028. http://dx.doi.org/10.1111/gcb.13068.

Snapp, S.S., Blackie, M.J., Gilbert, R.A., Bezner-Kerr, R., Kanyama-Phiri, G.Y., 2010. Biodiversity can support a greener revolution in Africa. Proc. Natl. Acad. Sci. 107 (48), 20840–20845 10.1073/pnas.1007199107.

Stern, V.M., Smith, R.F., van der Bosch, R., Hagen, K.S., 1959. The integrated control concept. Hilgardia 29, 81–101.

Subbarao, G.V., Kishii, M., Nakahara, K., Ishikawa, T., Ban, T., Tsujimoto, H., George, T.S., Berry, W.L., Hash, C.T., Ito, O., 2009. Biological nitrification inhibition (BNI)-isthere potential for genetic interventions in the *Triticeae*? Breed. Sci. 59, 529–545. http://dx.doi.org/10.1270/jsbbs.59.529.

Sun, J., et al., 2015. Expression of barley SUSIBA2 transcription factor yields high-starch low-methane rice. Nature 523, 602–606. http://dx.doi.org/10.1038/nature14673.

Thompson, K.A., Bent, E., Abalos, D., Wagner-Riddle, C., Dunfield, K.E., 2016. Soil microbial communities as potential regulators of in situ N_2O fluxes in annual and perennial cropping systems. Soil Biol. Biochem. 103, 262–273. http://dx.doi.org/10.1016/j.soilbio.2016.08.030.

Thompson, L.R., et al., 2017. A communal catalogue reveals Earth's multiscale microbial diversity. Nature 551, 457–463. http://dx.doi.org/10.1038/nature24621.

Tilman, D., Wedin, D., 1991. Plant traits and resource reduction for 5 grasses growing on nitrogen gradient. Ecology 72, 685–700.

Tilman, D., Fargione, J., Wolff, B., D'Antonio, C., Dobson, A., Howarth, R., Schindler, D., Schlesinger, W.H., Simberloff, D., Swackhamer, D., 2001. Forecasting agriculturally driven global environmental change. Science 292 (5515), 281–284. http://dx.doi.org/10.1126/science.1057544.

Tittonell, P., Griffin, K.E., 2013. When yield gaps are poverty traps: the paradigm of ecological intensification in African smallholder agriculture. Field Crops Res. 143, 76–90. http://dx.doi.org/10.1016/j.fcr.2012.10.007.

Tylianakis, J.M., Romo, C.M., 2010. Natural enemy diversity and biological control: making sense of the context-dependency. Basic Appl. Ecol. 11, 657–668. http://dx.doi.org/10.1016/j.baae.2010.08.005.

van der Heijden, M.G.A., Klironomos, J.N., Ursic, M., Moutoglis, P., Streitwolf-Engel, R., Boller, T., Wiemken, A., Sanders, I.R., 1998. Mycorrhizal fungal diversity determines plant biodiversity, ecosystem variability and productivity. Nature 396, 69–72. http://dx.doi.org/10.1038/23932.

van Der Putten, W.H., Vet, L.E.M., Harvey, J.A., Wackers, F.L., 2001. Linking above- and belowground multitrophic interactions of plants, herbivores, pathogens, and their antagonists. Trends Ecol Evol 16, 547. http://dx.doi.org/10.1016/S0169-5347(01)02265-0.

van Ittersum, M.K., Rabbinge, R., 1997. Concepts in production ecology for analysis and quantification of agricultural input-output combinations. Field Crop Res. 52, 197–208. http://dx.doi.org/10.1016/S0378-4290(97)00037-3.

van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z., 2013. Yield gap analysis with local to global relevance - a review. Field Crops Res. 143 (1), 4–17. http://dx.doi.org/10.1016/j.fcr.2012.09.009.

van Noordwijk, M., Brussaard, L., 2014. Minimizing the ecological footprint of food: closing yield and efficiency gaps simultaneously? Current Opinion Env. Sust. 8, 62 DOI: 70.10.1016/j.cosust.2014.08.008.

Vico, G., Brunsell, N.A., 2018. Tradeoffs between water requirements and yield stability in annual vs. perennial crops. Advances in Water Resources 112, 189–202. http://dx.doi.org/10.1016/j.advwatres.2017.12.014.

Vico, G., Manzoni, S., Nkurunziza, L., Murphy, K., Weih, M., 2016. Trade-offs between seed output and life span – a quantitative comparison of traits between annual and perennial congeneric species. New Phytol. 209, 104–114. http://dx.doi.org/10.1111/nph.13574.

de Vries, F.T., Thébault, E., Liiri, M., Birkhofer, K., Tsiafouli, M.A., Bjørnlund, L., Bracht Jørgensen, H., Brady, M.V., Christensen, S., de Ruiter, P.C., d'Hertefeldt, T., Frouz, J., Hedlund, K., Hemerik, L., Hol, W.H., Hotes, S., Mortimer, S.R., Setälä, H., Sgardelis, S.P., Uteseny, K., van der Putten, W.H., Wolters, V., Bardgett, R.D., 2013. Soil food web properties explain ecosystem services across European land use systems. Proc Natl Acad Sci U S A 110 (35), 14296–14301. http://dx.doi.org/10.1073/pnas.1305198110.

Wagg, C., Jansa, J., Schmid, B., van der Heijden, M.G., 2011. Belowground biodiversity effects of plant symbionts support aboveground productivity. Ecol.Lett. 14 (10), 1001–1009. http://dx.doi.org/10.1111/j.1461-0248.2011.01666.x.

Wagg, C., Bender, S.F., Widmer, F., van der Heijden, M.G.A., 2014. Soil biodiversity and soil community composition determine ecosystem multifunctionality. Proc. Natl. Am. Sci U.S.A 111 (149), 5266–5270. http://dx.doi.org/10.1073/pnas.1320054111.

Zhang, W., Cao, G., Li, X., Zhang, H., Wang, C., Liu, Q., Chen, X., Cui, Z., Shen, J., Jiang, R., Mi, G., Miao, Y., Zhang., F., Dou, Z., 2016. Closing yield gaps in China by empowering smallholder farmers. Nature 537, 671–674. http://dx.doi.org/10.1038/nature19368.

Zhang, W.F., Dou, Z.X., He, P., Ju, X.T., Powlson, D., Chadwick, D., Norse, D., Lu, Y.L., Zhang, Y., Wu, L., Chen, X.P., Cassman, K.G., Zhang, F.S., 2013. New technologies reduce greenhouse gas emissions from nitrogenous fertilizer in China. Proc. Natl. Am. Sci U.S.A 110 (21), 8375–8380. http://dx.doi.org/10.1073/pnas.1210447110.

Zhang, X., Davidson, E.A., Mauzerall, D.L., Searchinger, T.D., Dumas, P., Shen, Y., 2015. Managing nitrogen for sustainable development. Nature 528 (7580), 51–59. http://dx.doi.org/10.1038/nature15743.