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THEMATIC STUDY

CONTRIBUTIONS OF BIODIVERSITY TO THE SUSTAINABLE INTENSIFICATION OF FOOD PRODUCTION

Thematic Study for *The State of the World's Biodiversity for Food and Agriculture*

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Executive summary

Biodiversity supports sustainable food production, although recognition of its roles has been relatively neglected in the sustainable intensification literature. In the current study, the roles of biodiversity in sustainable food production are considered, assessing how these roles can be measured, the current state of knowledge and opportunities for intervention. The trajectory of global food production, and the challenges and opportunities this presents for the roles of biodiversity in production, are also considered, as well as how biodiversity-based interventions fit within wider considerations for sustainable food systems.

The positive interactions between a diverse array of organisms, including annual crops, animal pollinators, trees, micro-organisms, livestock and aquatic animals, support food production globally. To support these interactions, a range of interventions related to access to materials and practices are required. For annual crops, major interventions include breeding crops for more positive crop–crop interactions, and the integration of a wider range of crops into production systems. For animal pollinators, major interventions include the introduction of pollinator populations into production landscapes and the protection and improvement of pollinator habitat. For trees, a major required intervention is the greater integration of perennial legumes into farmland. For micro-organisms, the implementation of agronomic practices that support beneficial crop-microbe interactions is crucial. For livestock production, breed and crop feedstock diversification are essential, and the implementation of improved methods for manure incorporation into cropland. Finally, in the case of aquatic production, it is essential to support the wider adoption of multi-trophic production systems and to diversify crop- and animal-based feed resources. These and other interventions, and the research needs around them, are discussed.

Looking to the future, understanding the drivers behind trends in food systems is essential for determining the options for biodiversity in supporting sustainable food production. The increased dominance of a narrow selection of foods globally indicates that efforts to more sustainably produce these foods are crucial. From a biodiversity perspective, this means placing a strong emphasis on breeding for resource use efficiency and adaptation to climate change. It also means challenging the dominance of these foods through focusing on productivity improvements for other crop, livestock and aquaculture species, so that they can compete successfully and find space within production systems.

New biodiversity-based models that support food production need not only to be productive but to be profitable. Thus, as well as describing appropriate production system management practices that enhance production and support the environment, the labour, knowledge, time required to operationalize, and other costs of new production approaches, must be considered and minimized.

To support the future roles of biodiversity in sustainable food production, we recommend that particular attention be given to the longitudinal analysis of food sectors to determine how the diversity of foods consumed from these sectors has changed over time. Analysis is already available for crops, but related research is needed for livestock and aquaculture sectors. This analysis will then support more optimal cross-sectoral interactions, in terms of the contributions each sector provides to supplying the different components of human diets.

Additional meta-analyses and synthetic reviews of case studies are required as an evidence base for biodiversity-based food production system interventions, but future studies should pay more attention to articulating the potential biases in case study compilation (the problem of ‘cherry picking’ positive examples) and the measures that have been taken to minimize such effects.

I. Introduction

Policy-makers, scientists and observers in wider society agree that food production must be carried out more sustainably. This is in order to address the current dietary needs of existing human populations (Foley *et al*., 2011), as well as the human population growth that is expected in future decades (United Nations, 2015), in the context of a global food production system that already dominates much of the planet's terrestrial surface, and has major negative impacts on the Earth's ecosystems. Environmental costs include land degradation, salinization, pollution and freshwater depletion, and these costs exceed planetary boundaries related to sustainable food production (Rockström *et al.*, 2009; Steffen *et al.*, 2015). The world is becoming less biodiverse and there is good evidence that biodiversity losses at genetic, species and ecosystem levels reduce ecosystem functions that directly or indirectly affect food production, through effects such as the lower cycling of biologically-essential resources, reductions in compensatory dynamics and lower niche occupation (Hersch-Green, Turley and Johnson, 2011; Cardinale *et al.*, 2012). The detrimental effects of losses in genetic diversity can sometimes be of the same magnitude as losses in species diversity (Reusch *et al.*, 2005; Crutsinger *et al.*, 2006; Crutsinger, Souza and Sanders, 2008).

The situation has grown worse in recent decades with greater demand for animal products (FAO, 2009a) that are not produced as efficiently in terms of human calories realized for each unit of energy or land area and other resources (e.g. water) invested in production, when compared to the direct human consumption of plant foods. It is estimated, for example, that currently more than 30 percent of the calories produced by the world's crops are being used for animal feed, but that only 12 percent of those feed calories ultimately contribute to the human diet as meat and other animal products (Cassidy *et al.*, 2013). Moreover, the greenhouse gas emissions of animals, coupled with the emissions from the enormous use of fossil fuels in crop production, in industry and in domestic energy provision, are expected to cause major production shocks in the global food system (Global Food Security, 2015; Ray *et al.*, 2015), exacerbating current deficiencies in resilience.

In support of the objective of sustainability and in parallel with the publication of *The State of the World's Biodiversity for Food and Agriculture* (SoW-BFA) report (FAO, 2019), the current study explores the roles of biodiversity in the sustainable intensification of food production. The term 'sustainable intensification' is concerned with the processes in the development of more efficient food production systems that come from better exploiting synergies in production, minimizing trade-offs and properly accounting for otherwise often hidden environmental costs (FAO, 2014). Godfray (2015) described sustainable intensification as "a process designed to achieve higher agricultural [food] yields whilst simultaneously reducing the negative impact of farming [food production] on the environment", and we use this definition, which is clearly linked to the concept of resource use efficiency, as the starting point for the current study.

The roles of biodiversity are relatively neglected in the sustainable intensification literature, as evinced by a recent survey of Attwood *et al.* (2016) that showed a focus on individual 'major' crop yield improvements in plant breeding initiatives, and emphasis on measures such as water management and residue integration, for enhancing crop production. While such efforts are clearly essential for realizing sustainability, they neglect a much wider range of measures based on the biological diversity of production systems that can support food supply (Bioversity International, 2017). Here, we help to correct current neglect by considering the roles of biological diversity at genetic, species and ecosystem levels in supporting food production, taking a global view but paying particular attention to production systems in low- and middle-income tropical and subtropical nations. Deficits in both food calories and key nutrients are often high in such countries and interventions here are therefore particularly important (Foley*et al.*, 2011), while these locations are often very rich in both wild and agricultural biodiversity (e.g. Jamnadass *et al*., 2011; Attwood *et al*., 2017a), so biodiversity-based solutions to food production may be of particular relevance.

In the following sections of this study we explore the roles of biodiversity in sustainable food production. In section 2, we consider how these roles can be measured, the current state of knowledge and opportunities for intervention to support these roles. In section 3, we look to the future by considering the trajectory of food production and the challenges and opportunities this trajectory presents for the roles that biodiversity will be able to play in supporting future production. We conclude in section 4 by presenting wider considerations for sustainable food systems and discussing the means for implementation of biodiversity-based food production options, with recommendations for future action.

II. The roles of biodiversity in sustainable food production

2.1 Methods for measuring the roles of biodiversity in sustainable food production

There are many ways by which the productivity, resilience and costs of different food production systems can be quantified, and which can in principle be employed to explore the effects of biodiversity on production. These methods are based on measuring the various inputs and outputs into systems, using calculations such as gross food calorie or protein output per unit production input of energy/fertilizer/water/labour/land, etc., the economic profitability of production per unit of area planted/pollutants emitted etc. and formal life cycle analyses that take account of all aspects of production and use (Elliot *et al.*, 2013; Notarnicola *et al.*, 2017; Smith *et al.*, 2017). These metrics can be compared against what is considered theoretically attainable in production systems and can be measured over multiple cycles of production to explore aspects of resilience as well as overall production. These measures can be modified so that not only the quantity and calorific values of produced foods are considered, but their nutritional benefits in supplying vitamins and minerals, etc. are taken into account too (Bioversity International, 2017). Measuring the effects of biodiversity in systems can thus consider the efficiency, quantity, quality and stability of food production. Once a direct link has been established with production, the presence of biodiversity is often inferred to have beneficial effects without necessarily directly measuring impacts (i.e. the use of indirect measures to extrapolate from known direct effects).

One of the most common measures that has been applied to explore the role of biodiversity in crop production systems is known as the 'land equivalent ratio' (LER) (Mead and Willey, 1980). This is calculated as the sum of the relative crop yields (or total biomass, etc.) of the different 'biological' components (crop species or varieties or genotypes) in a production system where they are grown together as intercrops, compared to the respective elements when they are grown separately. A value above 1 therefore indicates that having the biodiversity present in the system provides productivity benefits, while a value of less than 1 indicates dis-benefits. Because the LER measure is widely used, it allows comparisons to be made across different crop and production system case studies. The compilation of LER results can therefore support meta-analyses and synthetic reviews that place cropping system examples into a globally relevant interpretation framework. We further explore the use of LER in measuring the roles of biological diversity in crop production in section 2.2.

The LER measure is, however, a purely agronomic indicator and it does not, therefore, consider the economic and social aspects of production. These must also be taken into account in determining the overall value of practices, especially any increases in labour costs or in the knowledge required to implement intercropping. These costs may be high in some cases (Lithourgidis *et al.*, 2011). A discussion of these aspects, which are primary causes for the absence of adoption of agronomically more sustainable biodiversity-based practices, is continued later in this study.

2.2 The known roles of biodiversity in food production

Apart from the obvious role of plant and animal biodiversity in providing a variety of different foods that are consumed by humans, the positive interactions between a diverse array of organisms, including annual crops, animal pollinators, trees (in farmland and associated habitat), micro-organisms, livestock and aquatic animals, are required or at least provide important support to the production of many foods globally, in terms of enhancing and stabilizing production (Altieri *et al*., 2015, Bioversity International, 2017). We discuss these interactions below.

Annual crops

The importance of positive interactions between annual crops for food production are best exemplified by a consideration of LER values for intercrop systems. In a recent meta-analysis of LER values by Yu *et al*. (2015), which was primarily concerned with cereal–legume intercrops globally, an average LER of 1.22 was found. Their analysis indicated that the majority of intercrop systems gave higher land-use efficiency than sole crops and demonstrated the magnitude of the positive effect on production that can be gained from deploying crop diversity. At the same time, however, Yu *et al*.'s assessment indicated that positive effects were not always realized in intercropping as, in a minority, but nevertheless still significant number of cases, LER values were less than 1 in the assessed systems. Realizing benefits is therefore context-specific.

The analysis of Yu *et al*. (2015) also found an overall negative effect of nitrogen fertilization on LER when cereals and legumes were intercropped, which is consistent with theory on the relative strength of beneficial and competitive interactions in systems depending on the level of optimality of growth conditions (beneficial interactions are expected to become less important and competitive interactions more important as growth conditions improve). Data therefore indicated that intercrop production is likely to be more advantageous for smallholder farmers in low- and middle-income nations where access to inputs such as mineral fertilizer is limited.

Yu *et al.*'s review of 2015 also indicated that temporal niche differentiation (i.e. a move in the direction of relay intercropping) contributed substantially to high LER in some systems. By exploiting the relationship between crops' relative sowing times, as well as levels of fertilisation applied and sowing densities in intercrop performance, farmers can enhance crop complementarity, productivity and profit (Yu *et al.*, 2016). A move towards temporal differentiation of crops culminates eventually in the crop rotation systems that are traditional practised widely in agriculture globally and that can carry significant productivity and stability advantages (Gaudin *et al*., 2015).

In another recent meta-analysis of intercrop systems, which also primarily considered cereal-legume intercrops, Raseduzzaman and Jensen (2017) found that intercrops stabilised yields compared with sole crop production.

An example of a mixed crop production system is banana farming in Central and East Africa (see van Asten *et al*., 2011; Mulumba *et al*., 2012; Staver *et al*., 2015 for detailed information). Here, diverse banana varieties are grown by smallholders in several intercrop systems that provide a range of foods that support diverse diets and that minimize banana pest and disease risks that include black leaf streak, fusarium and bacterial wilt, and banana bunchy top virus. Manure from zero-grazed goats also helps support banana yields.

Animal pollinators

The importance of animal (mostly insect) pollinators for crop production globally was explored in a review by Klein *et al*. (2007), who determined that the production of dozens of major and lesser-used crops is supported significantly by animal pollination. Crops analysed where animal pollination was deemed essential to production included, at least for most varieties, atemoya, Brazil nut, cantaloupe, cocoa, kiwi fruit, macadamia nut, passion fruit, papaya, rowanberry, sapodilla, squashes/pumpkins, vanilla and watermelon (see Klein *et al*. [2007] for further information on these crops). The authors identified that many of the crops that were highly dependent or relied entirely on animal pollinators for production were those providing key micronutrients in human diets, with therefore an important link to nutrition.

Based on an unlikely but illustrative scenario of complete pollinator disappearance globally, Gallai *et al*. (2009) estimated the total economic value of insect pollination to agricultural output for crops consumed directly by humans as EUR 153 billion (about USD 185 billion) annually, with values particularly high for vegetables, fruits, edible oil crops and stimulants. On a country basis, Lautenbach *et al*. (2012) indicated that China was the most important beneficiary economically of crop pollination services, followed by India and then the United States of America. In terms of the role of animal pollination of crops in supporting healthy human diets, Smith *et al*. (2015) modelled the effects of complete pollinator loss for the production of nutritious crops at least partially dependent on animal pollination (supplementing any deficit in calories with less nutritious staple foods). The results suggested that globally 1.4 million people more would die annually from non-communicable and malnutrition-related diseases, with many more people also suffering worse health.

Trees in farmland and forests

The importance of trees in farmland and in neighbouring wild habitats such as forests for ecosystem service provision to support agricultural food production was reviewed by Reed *et al*. (2017). Among the studies they included in their compilation of the available literature, half reported a net positive effect from tree presence on food yields or food yield proxies, although a number of studies each indicated neutral, mixed or negative effects. Positive effects of woody nitrogen-fixing legumes in nutrient cycling and soil fertility improvement in African agriculture were explored in a meta-analysis by Sileshi *et al*. (2008), who found significant positive effects on maize production for tree–crop intercrops and planted tree fallows (where crops and trees were planted in rotation). The effects of woody legumes extended to the stabilization of crop production (Sileshi, Debusho and Akinnifesi, 2012). Similar effects on crop production were observed when trees were allowed to naturally regenerate in agroforestry systems (Binam *et al*., 2015).

A meta-analysis conducted by Ricketts *et al*. (2008) explored the role of forests and other natural or semi-natural habitats in the animal pollination of crops. The authors found that pollinator richness and native pollinator visitation rates in agricultural land declined exponentially with distance from natural and semi-natural vegetation that can host pollinators, with corresponding drops in crops' fruit and seed set observed in several individual case studies. Tropical crops pollinated primarily by social bees and dependant on only one or a few pollinator taxa appeared to be the most susceptible to the loss of pollinator habitat including trees and forests. Crops pollinated by non-bee insects appeared less reliant on remnant natural or semi-natural vegetation (Rader *et al*., 2016).

An example of mixed tree-crop production is dudukuhan farming in West Java, Indonesia (see Manurung *et al*., 2008; Roshetko *et al*., 2012; Narendra *et al*., 2013 for detailed information). Here, smallholders use a range of dudukuhan systems, from a timber production system (of lowest biodiversity), through a mixed fruit-timber-banana-annual crop production system (where trees provide shade for understory annual crops), to a mixed fruit-timber system (of highest biodiversity). Transition between these systems is effected by tree enrichment planting, the selective retention of natural tree regenerants and by varying timber harvesting intensity, among other measures. Dudukuhan farming reduces the vulnerability of producers to market vagaries and climatic uncertainties, and produces a wider range of foods and other products for home use.

Micro-organisms

The importance of below-ground micro-organisms in supporting terrestrial ecosystem functions was reviewed by Bardgett and van der Putten (2014) and Vandenkoornhuyse *et al*. (2015). Key roles identified in agricultural production included support for nutrient retention and nutrient cycling, as illustrated by Wagg *et al*. (2014) through manipulations of model microcosms simulating European grassland communities, where losses of soil fungal and bacterial diversity impaired these among other functions. As illustrated by the analyses of Yu *et al.* (2015), Sileshi *et al.* (2008) and Sileshi, Debusho and Akinnifesi (2012) already mentioned above, nitrogen-fixing legume-rhizobia nodular symbioses that benefit the production of legumes and associated non-legume crops play a crucial role in agriculture (Gruber and Galloway, 2008). The conversion of insoluble phosphates by below-ground plant growth-promoting bacteria to a form that is accessible to plants is also important in increasing crop yields (Hayat *et al*., 2010). Foliar micro-organisms too have a direct effect on the production of crops through their impacts on disease susceptibility (Ritpitakphong *et al*., 2016), growth and general stress tolerance.

Livestock production

Mixed crop–livestock production systems account for around 60 percent of all animal production globally, with animal manure supporting crop production, draught animal power providing for the tilling of fields and crop residues being an important source of animal feed (Herrero *et al*., 2013). Based on an assessment of global nitrogen flows in cropland, for example, Liu *et al*. (2010) indicated that around 13 percent of gross nitrogen fertilizer input is provided by livestock manure, with the contribution much higher in some regions. The integration of livestock with crop production can support adaptation to, and the mitigation of, climate change, in ways that crops or livestock alone are unable to do (Thornton and Herrero, 2015). The use of plant forages including trees such as leucaena and calliandra mitigates some of the climate impacts of livestock production (Thornton and Herrero, 2010), and minimizes competition for grains that are also important human foods (Cassidy *et al*., 2013; Rudel *et al*., 2015). Pastures used for livestock production enhance crop pollination when they provide habitat for insect pollinators (Morandin *et al*., 2007). Symbiotic associations between ruminant animals and their gut microbiota are essential in food digestion and the synthesis of important nutrients (Hanning and Diaz-Sanchez, 2015).

Aquatic production

Aquatic agricultural systems (AAS) that are often ecotones of terrestrial and aquatic resources in spatially and seasonally complex shifting mosaics of land and water use contain important interactions that support coastal and inland capture fisheries, aquaculture, crop farming and livestock grazing, and that strengthen environmental resilience (Castine *et al*., 2013; Attwood *et al*., 2017b). In a meta-analysis of fish and rice co-culture in paddy fields, for example, Ren *et al*. (2014) found positive effects on rice yields and lower usage of pesticides when fish were present compared to rice monocultures, with organic nitrogen from fish providing a renewable source of fertilizer to promote rice growth and fish controlling rice pests. The rates of organic matter accumulation and methane emissions in such systems have been reported to be relatively high and low, respectively, when compared to conventional rice production, supporting production and mitigating climate change (Berg, Berg and Nguyen, 2012). In China, silkworms are fed on leaves of the mulberry tree grown around fish ponds and fish are fed on the mulberry and silkworms. An integrated system is created by fish waste fertilizing mulberry production (Lee, 2004).

In aquaculture, polycultures have achieved production synergies, such as in oyster farms that include seaweed and fish species, where the water filtering properties of oysters improve the environment for algae and fish production (FAO, 2016). Intensive aquaculture industries that generate nutrient-rich wastewater streams that can cause eutrophication use algae to remove excess dissolved nutrients (Lawton *et al*., 2013). The use of ‘cleaner fish’ such as wrasse, which remove dead skin and ectoparasites from other fish, is a popular option in salmon farming for controlling sea lice, as an alternative to other non-biological treatments (Skiftesvik *et al*., 2014).

An example of a complex AAS is sorjan production in southern Bangladesh (see Haq *et al*., 2012; Attwood *et al*., 2013 for detailed information). Here, in a variety of sorjan system types, smallholders produce vegetables, fruits, other crops and timber trees on and around elevated earth bunds that border shallow water canals that contain fish, as well as rice and ducks. High levels of structural and compositional diversity allow ecological processes such as episodic flooding to be harnessed, providing valuable opportunities to intensify production across seasons and in different niches, and supporting local, context-specific adaptation to anthropogenic climate change. The range of crops and animals produced supports year-round food availability, the organic nitrogen released from fish and ducks supports crop growth, alternate ridges and canals improve crop drainage, and fish and ducks help control crop insect pests.

2.3 Interventions to support the roles of biodiversity in food production

It is evident from section 2.2 that to better use biodiversity to support the sustainable intensification of food supply, measures to improve positive interactions among the different biological components that constitute food production systems are crucial. Required interventions for the interactions explored in the previous section are indicated in Table 1, and examples are mentioned below. It is clear that to practically exploit positive interactions requires combinations of different interventions that include farmers' access to crop varieties, animal breeds and other genetic materials, as well as changes in management practices in farming systems and of associated landscapes.

In the case of annual crops, required interventions include breeding and selecting crops for more positive crop–crop and within-crop genotype–genotype interactions, and the integration of a wider range of crops, including new and 'orphan' crops, to support diversification in production systems, both spatially and temporally.

In the case of animal pollinators, required interventions include the introduction (or reintroduction) of pollinator populations into production landscapes, the protection, improvement and expansion of pollinator habitat, joint management plans for wild and introduced pollinators, and the reduction of farmland insecticide use.

In the case of trees in farmland and forests, required measures include the greater integration of perennial legumes into farmland, greater attention to the domestication of new tree crops to support agricultural diversification, and the adoption of more effective delivery systems for tree planting materials so that smallholder farmers can establish their desired diversity of tree species.

For micro-organisms, required interventions include the implementation of agronomic practices that support beneficial crop-microbe interactions, direct inoculation with microbes where necessary, and breeding crops for more productive interactions with micro-organisms.

For livestock production, important interventions include the restoration of degraded pastures, breed and crop feedstock diversification, and the implementation of improved methods for manure incorporation into cropland.

Finally, in the case of aquatic production, important interventions include the introduction of a greater range of flooding-tolerant crops into AAS, the wider adoption of multi-trophic production systems, and the diversification of fish and other aquatic organisms raised along with their crop- and animal-based feed resources.

To explore the efficacy of these interventions, appropriate metrics need to be employed, with direct and indirect approaches to do so given in Table 1 (see also section 2.1). These interventions also need to be supported by research to address particular knowledge gaps, with key areas for work also indicated in the table.

A key factor in intervention is determining its appropriate spatial scale, and this varies depending on the interaction in question. Crop-microbial interactions, for example, occur at a very fine scale, while crop-animal pollinator interactions may operate over much larger distances (Ricketts *et al*., 2008). Again, in livestock production, considering scale at the across-field level within the same farm is important, for the transfer of crop residues, the production of other feedstuffs and manuring. Even in relatively simple production systems, it is therefore important to consider the multiple scales of operation of interactions (Mitchell, Bennett and Gonzalez, 2014). In complex systems, such as the farms typical of tropical smallholders, such consideration is doubly necessary (Tscharntke *et al*., 2012).

Considering the scale of operation of interactions can for example inform where maintaining forest and woodland cover that provides important animal pollinator habitat to support crop production is most necessary, and where cutting of woody vegetation will have less of an impact on production (Ricketts and Lonsdorf, 2013). The appropriate spatial planning of interventions is supported by the recent development of a wide range of medium- to high-resolution global and regional geospatial reference data sets covering production system configurations, farm sizes, natural vegetation patterns, environmental variables and other features that impact on intervention options and can be used to predict and plan for the effects of climate change and design 'climate smart' approaches (e.g. Herrero *et al*., 2013; Fritz *et al*., 2015; Samberg *et al*., 2016; WorldClim, 2016; FAO, 2017; ISRIC, 2017; vegetationmap4africa, 2017).

Table 1. Interventions to support positive interactions in food production systems, with approaches to measure possible positive impacts and knowledge gaps/research needs for the further optimization of systems

Interactions	**Interventions to support food production**	**Approaches to measure the impacts of interventions**	**Knowledge gaps/research needs**
Annual crops	Breed and select crops for more positive crop-crop interactions in production systems, exploiting wild and landrace gene pools; as well as crop-crop combinations, exploit within-crop genotype-genotype mixtures to support disease resistance and climatic resilience; explore the integration of a wider range of crops, including new and orphan crops that may be able to interact positively with other components, into cropping systems, over spatial (intercrop) and temporal (rotation) scales (Finckh *et al*., 2000; Döring *et al*., 2015; Litrico and Violle, 2015; AOCC, 2017; Dawson *et al*., 2018)	Land equivalent ratio (LER), stability and quality of production (direct measures); rate of artificial fertiliser application, soil fertility, crop species diversity in intercrops and rotations (indirect measures)	Interactions among annual crops are some of the best-researched in food production systems. Developing breeding methods that effectively account for these interactions requires a paradigm shift from current breeding methods, however, and this is still in its infancy (Litrico and Violle, 2015). A better understanding of genetic variation in important interaction traits in the crop gene pools available for breeding is required, exploring landraces and wild germplasm where variation in important traits may be more evident than in advanced crop cultivars grown in high input monocultures (Palmgren *et al*., 2015). For integrating new and orphan crops into production systems, more research is required to determine effective cropping options in combination with major crops, using cropping system modelling frameworks and beginning with knowledge on existing production systems (Reckling *et al*., 2016a)
Animal pollinators	Introduce (or reintroduce) a range of pollinators into agricultural landscapes; protect remaining natural habitat/mosaics and further improve and expand animal-pollinator habitat in farmland with agroforestry, border planting and fallow practices, etc.; implement joint management plans for wild and introduced pollinators in landscapes; reduce insecticide use in farmland; adopt integrated, pollinator-friendly 'environmental certification' approaches for animal-pollinated crops (Klein *et al*., 2007; FAO, 2008; Garibaldi *et al.,* 2013; IPBES, 2016; Kovacs-Hostyanszki *et al.,* 2017)	Yield, stability and quality of animal-pollinated crops (direct measures); number, range and stability of pollinators/ pollinator populations in agricultural landscapes, especially over the crop flowering period (indirect measures). Many animal-pollinated crops are of particular nutritional significance, so increases in crop production may be modelled as human nutritional benefits	There are gaps in understanding in levels of pollinator dependency of different crops. More realistic estimates of pollinator dependency in different production contexts are required, especially for: important staples (e.g. soybean) where the range of quoted effects is large; new and orphan crops; and low- and middle-income country production contexts (Klein *et al*., 2007; Melathopoulos, Cutler and Tyedmers, 2015; Teichroew *et al*., 2017). Climate change impacts on pollinator-crop mutualisms, caused, e.g. by the introduction of life cycle asynchronies, are often unknown and require elucidation, especially for major animal-pollinated crops (Gilman *et al*., 2011; Kerr *et al.,* 2015)

Table 1 *Cont'd*

Interactions	Interventions to support food production	Approaches to measure the impacts of interventions	Knowledge gaps/research needs
Trees in farmland and forests	Protect remaining forest/farm landscape mosaics; further integrate trees, including leguminous species, into farms, with a focus on soil rehabilitation and improvement; domesticate a wider range of tree species to increase productivity, to successfully compete with annual crops and thereby support agricultural diversification; develop new markets for more tree products and 'shade-produced' commodities; adopt more effective delivery systems for tree planting materials to reach smallholder growers (Leakey, 2010; Lillesø *et al*., 2011, 2018)	LER, production resilience, life cycle analysis (direct measures); soil fertility, soil retention, niche occupation, species and market diversity (indirect measures). Many trees provide important habitat for animal pollinators, so distance-related effects on agricultural production from tree habitat can be measured (pollinator effects measured as above, previous row)	Limited longer-term and larger-scale research has been undertaken to understand forest- and tree-based ecosystem services and associated impacts on food production. Further research over longer time periods and over a wider range of scales is required (Reed *et al*., 2017). Positive spillovers from farms to forests are generally not well understood; further research is needed to describe them (e.g. farm habitat pollination services for forest food production; Blitzer *et al*., 2012). Agroforestry impacts on land use changes and food security are only partially understood and require further establishment (van Noordwijk *et al*., 2014). The best approaches to bring trees into cultivation, to support agricultural diversification, are often unknown and further research is especially required on participatory tree domestication, considering the particular needs of women and men, and with particular emphasis on farm niche (Mulyoutami *et al*., 2015)
Micro-organisms	Implement soil/farm management practices that enhance beneficial microbe populations and support nutrient cycling and soil fertility, such as the greater use of intercrops, rotations and appropriate tillage methods, and more incorporation of crop residues; directly inoculate with microbial populations; breed crops for more effective beneficial interactions with micro-organisms by exploiting wild and landrace crop gene pools (Kapulnik and Kushnir, 1991; FAO, 2003; Mutch and Young, 2004; Brooker *et al*., 2015)	Crop yield and stability (direct measures); rate of artificial fertiliser application, soil fertility, soil texture, soil biome quantity and composition, water run-off quality (indirect measures)	The role of below-ground biodiversity in nutrient cycling is often poorly characterised; more research is required on the mechanisms involved in shaping complex soil communities and their functions (Bardgett and van der Putten, 2014). Inoculation methods are often not very effective; research is needed to address colonisation problems (Compant, Clément and Sessitsch, 2010). There is only limited knowledge of how to create more effective crop-microbe interactions at the genotype-to-genotype level; research is required on a range of genotype combinations (Tikhonovich and Provorov, 2011). Limited understanding of how domestication and selective breeding has affected the ability of crops to establish beneficial interactions with rhizosphere microbes means research is required on this topic (Pérez-Jaramillo, Mendes and Raaijmakers, 2016)

Table 1 *Cont'd*

Interactions	Interventions to support food production	Approaches to measure the impacts of interventions	Knowledge gaps/research needs
Livestock production	Restore degraded pastures to support overall production and increase resilience; adjust and diversify: the breeds raised, the plant feeds grown and the composition of ruminal gut fauna, to enhance productivity/synergies and minimise environmental costs; implement improved methods of manuring (Dijkstra, Oenema and Bannink, 2011; Hayes, Lewin and Goddard, 2013; Dawson *et al*., 2014)	Animal weight changes and milk yields; crop yield and stability from manuring; life cycle analysis (all direct measures); soil fertility; animal health; animal gut microfauna composition; fodder diversity (all indirect measures)	There is currently only limited detailed understanding of the interactions between animals and other components in production systems, including under climate change; further research on animal-crop(-tree) interactions is required (Thornton and Herrero, 2015). Methods for the analysis of greenhouse gas balances, to determine appropriate mitigation interventions in the context of other production components, are available, but need to be refined (de Boer *et al*., 2011)
Aquatic production	Promote a wider range of production systems involving algae, cleaner fish, etc.; promote a greater range of crops capable of tolerating flooding and salinity in aquatic agricultural systems (AAS), and that have increased complementarity in broader floodplain management; domesticate and breed a range of fish to increase the productivity, and support the diversification and resilience, of aquaculture, and to increase the nutritional diversity of production; diversify animal- and plant-based fish feed resources (Hall *et al*., 2011; Wijkström, 2012; Olesen *et al*., 2015; FAO, 2016; Thilsted *et al*., 2016)	Fish catch, catch stability and fish growth rate; crop yield and stability (all direct measures); fish diversity; fish feed diversity and conversion efficiency; fish and crop pest prevalence (all indirect measures). Many fish are important for nutritionally-balanced diets, so increases in production can be modelled as human nutritional benefits	There is frequently little information on the interactions in and with AAS and aquaculture, including between terrestrial and aquatic elements, and between aquaculture and fisheries; further research is required to allow the development of more effective integrated production strategies (Soto *et al*., 2012; Attwood *et al*., 2017b). The development of multi-trophic aquaculture systems where appropriate species from different trophic levels are grown in combination (including fish, bivalves, algae, etc.) has received only limited attention; further research is required to create more synergistic relationships in resource use and recycling (Barrington, Chopin and Robinson, 2009). Addressing the negative on- and off-site environmental impacts of aquaculture has received only limited attention and further research is needed

III. Looking to the future: the trajectory of food production and the roles of biodiversity in supporting future production

Looking to the medium- to long-term future, understanding the drivers behind trends in global, regional and national food systems over time is essential for determining the options for biodiversity in supporting sustainable food production. Such an understanding will indicate developing opportunities and opposing constraints for production interventions, and will provide a dose of realism in what future interventions are likely to be successful.

Over the last decades, human consumption of plant foods globally has relied increasingly on a narrow range of calorie-rich but nutritionally limited crops. Khoury *et al*. (2014) illustrated this through an analysis of crop plant food supply balance sheets, which are a proxy for human food consumption, based on an assessment of 152 nations' data over the 1961 to 2009 period. The authors suggested that global homogenization in crop plant consumption could be due to a range of factors, including greater international trade in crops, the increased reach of multi-national food companies, the wider adoption of more western diets, government subsidy patterns that relatively support major crop breeding, production and consumption over other crops, the consolidation of plant breeding companies, a focus on a narrow range of crop options when educating farmers, and the effects of farm mechanization. Of the crops that relatively speaking have significantly increased in importance over the last 50 years based on Khoury *et al*.'s analysis, several of these (such as oil palm, sunflower, soybean, rice and wheat) are produced in low diversity farm environments, showing increasing threats to agrobiodiversity and the potentially greater dangers of individual crop failure for global food supply resilience (Clay, 2004). Expanding oil palm and soybean production have also had particularly negative impacts on natural biodiversity because of directly- or indirectly-associated clearance of highly biodiverse tropical and sub-tropical forests (Donald, 2004).

Over the same time period as the above trend for plant-based foods, there has been a massive expansion in food consumption from the livestock and aquaculture sectors, especially in Asia (FAO, 2009a, 2009b). Between 1961 and 2010, for example, global meat production was estimated to quadruple, resulting in increased competition for land for raising crops either for animal feedstuffs or for human consumption (HLPE, 2016). Over the same period, the diversity of animal breeds at risk of extinction increased (FAO, 2015). In the case of aquaculture, the "blue revolution" saw an annual growth rate in production between 1970 and 2006 of around 7 percent (FAO, 2009b), placing increased pressure on water, energy and feed resources. A trend to intensive mono-specific aquaculture systems has threatened the species diversity that has traditionally sustained the sector (Bostock *et al*., 2010).

An examination of productivity trends may help to shed light on why particular foods have become more or less important in the global food system in recent decades. Accordingly, for the purpose of the current study we undertook an analysis of production data for a subset of crop foods that had been assessed by Khoury *et al*. (2014). Our analysis, presented in Box 1 and illustrated in Figure 1, indicated that 'winner' crops in the global food system have sustained larger yield increases than 'loser' crops, and this may be an important factor that has allowed them to compete effectively with other crops in production systems.

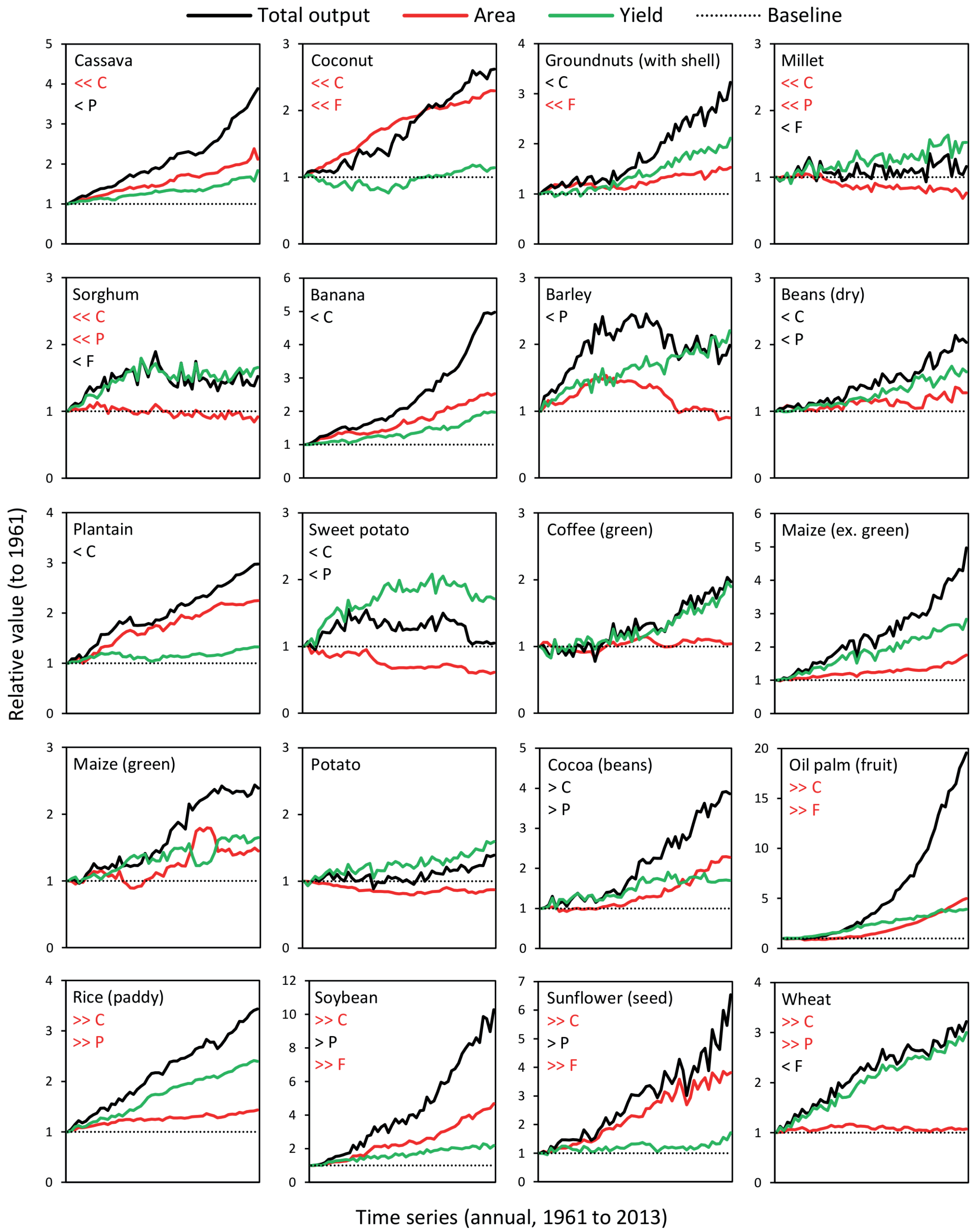

Figure 1. Production trend data for 20 food crops over the 53-year time period 1961 to 2013

Annual global data for total production quantity, area harvested and yield were extracted from FAOSTAT (2016). Figures are expressed as the proportion of the year 1961 (baseline). Large increases or decreases in relative food importance ('>>' and '<<', respectively) for three food components (C = calories, P = protein, F = fat) are shown in red. Crops with '>>' or '<<' for one or more of these three food components are classified as 'winners' and 'losers' in the global food system, respectively. Crops with '>' and '<' indicate 'moderate winners' and 'moderate losers', respectively, while 'little change' crops have no trend indications provided. Note changes in scale on the y axis. See Box 1 for further information.

BOX 1. Productivity trends of 'winner' and loser' crops in global food systems

Khoury *et al.*'s (2014) analysis of crop plant food supply balance sheets indicated crops that had become more or less important in the global food system over the 1961 to 2009 period for different food components. To understand the productivity trends for crops that had become more or less important as global foods, we chose a subset of 20 of the food crops they had analysed that showed different responses over the assessed time period, from large increases in relative importance (we term these 'winner' crops) to large decreases ('loser' crops) for the provision of calories, proteins and/or fat. (Crops at intermediate positions between these extremes were defined as 'moderate winners', 'little change' or 'moderate losers'.)

For these 20 crops, annual global crop production data for total production, area planted and yield were extracted from FAOSTAT (2016) for the time period 1961 to 2013, which equates roughly to the period of Khoury *et al.*'s (2014) assessment, but includes a few extra years' data. The FAOSTAT datasets are a useful source of information on crop production, consumption and trade, although their use is also subject to certain caveats, which in the context of our current analysis are indicated in Annex.

Profiles of production shown in Figure 1 indicated that for five winner crops (oil palm, sunflower, soybean, rice and wheat) mean total global production increased by a factor of 7.8 globally over the assessed time period, while for five loser crops (cassava, coconut, groundnut, millet and sorghum) there was only a mean increase of 2.3-fold (mean 2009 to 2013 values compared to 1961). For winner crops, the mean global yield increase was by a factor of 2.5 (equating roughly to a 1.5 percent year-on-year increase), while for loser crops it was 1.6.

An equivalent analysis to that of Khoury *et al*. (2014), which was on crop plants, has not yet been undertaken for the livestock and aquaculture sectors, but some general conclusions may be drawn. First, the dominance of current major crop, livestock and animal species in food production is likely to be reinforced in future decades. This means that efforts to more sustainably produce these species are crucial. From a biodiversity-utilization perspective, this means placing a strong emphasis on breeding these species to produce food from them more sustainably, focusing on issues such as resource use efficiency and adaptation to climate change. New breeding methods to overcome bottlenecks in conventional breeding will be required, exploiting extensive and genetically-diverse gene pools that, at least for major crops, are maintained in genebank collections worldwide, and which could be sources of the required allelic forms of the key genes involved in the relevant biological pathways (McCouch *et al*., 2013).

Second, if the increasingly dominant position of a few foods globally is to be effectively challenged, the productivity of other crop, livestock and aquaculture species will need to be substantially raised, by breeding and other methods. Only then will it be possible for these other foods to compete successfully with, and find space within, production systems. Many currently underutilized 'orphan' crops and wild plants potentially suitable for *de novo* domestication have very large extant gene pools from which major genetic gains can be realized through selection. As with major crops, these gene pools can be exploited through new genomic breeding methods (Dawson *et al*., 2018). Many orphan crops have superior nutritional profiles to staple crops, so they can have a particular role in addressing 'hidden hunger' associated with dietary nutritional deficiencies (AOCC, 2017). Similarly, much genetic variation in production traits in undomesticated or only incipiently domesticated fish species is observed that can be exploited through new genomic approaches, to increase feed

BOX 2. Assessing the stability of production of crops and the opportunities for compensatory combinations

Some authors have expressed concerns that many new and orphan crops, including fruit trees, may have unstable production characteristics because of the high degree of dependence of production on animal pollinators, which could lead to large year-on-year variations in yields because of vagaries in pollinator activity based on habitat, climate and weather (Garibaldi *et al.,* 2011). To explore this issue, we extracted country-level yearly yield data for ten countries (Australia, Brazil, Ecuador, India, Mexico, Peru, South Africa, Syrian Arab Republic, Turkey and the United States of America) from FAOSTAT (2016) for three 'control' annual cereals (maize, rice and wheat; the yields of none of which are influenced by animal pollination) and a range of 19 perennial fruit crops (almond, apple, apricot, avocado, blueberry, cashew apple, cherry, chestnut, cocoa, coconut, coffee, cranberry, grape, oil palm, olive, orange, papaya, pear and raspberry; these can be considered as proxies for perennial new and orphan crops or are orphan crops themselves) with varying levels of animal pollinator dependency (from none to essential, according to Klein *et al.,* 2007). On average, each country had data for 12.6 crops. Data were extracted for the years 1961 to 2013. Annex provides further information on the data extraction method.

Consecutive year-on-year differences in yield as a fraction of the yield in the earlier year were then calculated and a log10 transformation of values used as an estimator of yield instability across seasons. The crops with the single largest deviations in year-on-year yield over the time period were then determined. Analysis revealed that the yield instability of perennial fruits and annual crops was country specific. One of the perennial fruits, olive, showed very high instability across a number of countries (it was the most unstable crop for four nations), but interestingly olive has no dependence on animal pollinators for production, illustrating the role of other biotic and abiotic variables in determining the yields of perennials. For four countries, wheat was one of the top three most unstable species, and in one case maize was, indicating that although perennial fruits can show unstable yields, so can annual staples.

Further analysis of two chosen nations (Australia and Peru) revealed that the directions of year-on-year changes in yield can be statistically significantly negatively correlated between particular pairs of crops (Figure 2).

use efficiency and productivity, and to support the diversification of aquaculture systems that currently rely on only one or a few fish species (Benzie *et al*., 2012; Olesen *et al*., 2015).

An argument against the use of some new and orphan crops is that they may not have as stable production characteristics as other crops. Our assessment of the evidence for this indicated that this may be the case, but that the concern may also be overplayed (Box 2). In addition, our analysis indicated particular opportunities that may exist for compensatory production through employing specific crop combinations at a country level, where the different components respond differently to that season's environment. These combinations may have a stabilizing effect on overall food production.

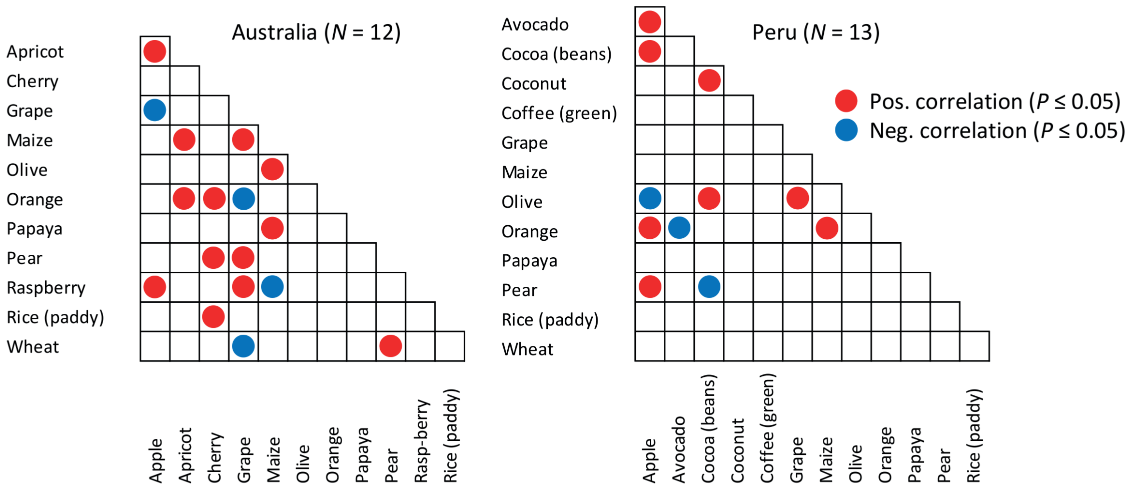

Figure 2. Pairwise comparisons of yield changes for a selection of crops in Australia and Peru over 52 year-on-year intervals, 1962/1961 to 2013/2012

For Australia and Peru, representing a high-income and middle-income nation, respectively, data on consecutive year-on-year yield differences for each crop were regressed against all other crops over the time series. Coloured circles in the matrix indicate statistically significant (P ≤ 0.05) positive (red circles, yields for a pair of crops increase or decrease in the same direction over yearly intervals) or negative (blue circles, yield for one member of a pair of crops increases and yield for the other decreases over yearly intervals) correlations. A preponderance of significant positive values indicates that many crops respond similarly to seasonal conditions. However, some crops have opposite responses, indicating the possibilities for deliberately planning compensatory crop combinations, which vary by country. See Box 2 for further information.

IV. Final considerations and recommendations

Sustainable food systems are about much more than sustainable food production. Governance, ethics, human rights, market mechanisms, the equitability of the distribution of benefits by gender, wealth, age and location, the nutritional quality of foods, and food processors' and consumers' behavioural patterns, are all important factors that have to be considered and addressed (Pretty *et al*., 2010; Foran *et al*., 2014; Dawson *et al*., 2018). Taken along with the complexity and particular contexts of production systems that have been described in this paper, this means that inter-disciplinary collaborative research is required to gain a proper understanding of food systems and sectoral and cross-sectoral interactions, carefully considering the many synergies and trade-offs at different scales, including time scales.

A crucial factor is not only whether new biodiversity-based models that support food production are productive, but whether they are profitable. Thus, as well as describing appropriate production system management practices that enhance production and support the environment, the labour, knowledge, time required to operationalize, and other costs of new production approaches, must be considered in comparison with current practices, justified and where possible minimized through simplification (Lithourgidis *et al*., 2011). Models have been developed to assess the synergies and trade-offs between the environmental, social and economic impacts of (potential) new more biodiverse production systems, and these require further development and adoption to design and support the introduction of more appropriate farming practices in relevant locations (Reckling *et al*., 2016a, b). A major difficulty in implementing change with farmers and local communities, however, is that new biodiversity-based approaches to support food production are often relatively knowledge-intensive (Jackson *et al*., 2012). Close collaboration between farmers, local communities and public and private extension services is therefore required in the building of capacity to educate producers and bring about positive change (Gabriel *et al*., 2009; FAO, 2011; IPES-Food, 2015).

Determining how and when particular (potential) practices will be adopted requires a better insight into the different perceptions women and men farmers have of the roles of biodiversity in supporting food availability, and the different options they have for bringing about change (Cole *et al*., 2014). Farmers, especially male farmers, may see the primary role of production diversification as increasing incomes that can be used to purchase foods or for other purposes, rather than diversification supporting direct household provisioning. This influences farmers' attitudes to further diversification (Thorlakson and Neufeldt, 2012).

The steps to be taken to bring new food products to market to support the diversification of production and consumption options are not trivial. New private–public partnerships in market development are required, more efficient eco-certification approaches that favour biodiverse production systems are needed, the culture of (new) food use needs to be addressed, innovative incorporation of new ingredients into existing processed foods is important, and investments in infrastructure and information systems are essential (Jamnadass *et al.,* 2014). Work in these areas may ultimately be more important for driving adoption than the more efficient production of a new food (Dawson *et al.*, 2018).

To support the future role of biodiversity in sustainable food production we recommend that particular attention be given to the longitudinal analysis of livestock and aquaculture sectors to determine how – and explore why – the diversity of foods consumed from these sectors has changed over time. This could refer to the analysis already available for crops (Khoury *et al*., 2014) and would help inform specific opportunities for intervention to support diversification of the sectors. The analysis of livestock and crop sectors could then, coupled with the work already done on crops, be used to explore in more detail the positive and negative interactions in crop–livestock–aquaculture production. This would help optimize the contributions each sector provides to supplying different components of human diets, and would guide the relative levels of investment that should be targeted to the sectors.

In addition, although meta-analyses and synthetic reviews provide a crucial evidence base for biodiversity-based food production system interventions, ‘cherry-picking’ of the case studies considered in these syntheses to support particular positions is not uncommon. We recommend therefore that future syntheses should pay more attention to articulating potential biases, the measures taken to minimize them and the remaining uncertainties (Seufert and Ramankutty, 2017). This is a complex issue to address in practice, especially addressing unconscious biases, but can be supported by multi-institutional teams that bring different perspectives to the concepts and measurement of sustainability.

Finally, many of the authors of the current study are part of the CGIAR research centre network. With its ‘boundary work’ on natural resource management systems, the CGIAR is in theory ideally placed to construct and manage the interfaces among the various stakeholders needed to research and adopt biodiversity-based sustainable food production practices (Clark *et al*., 2016). To begin to play a pivotal role, however, the CGIAR with its partners needs to engage in more innovative integrated research on production and extension models that integrate crop and animal production, and more widely communicate the findings of such research.

References

Altieri, M.A., Nicholls, C.I., Henao, A. & Lana, M.A. 2015. Agroecology and the design of climate change-resilient farming systems. *Agronomy for Sustainable Development*, 35: 869–890.

AOCC. 2017. *The African Orphan Crops Consortium*. www.africanorphancrops.org/ [Accessed 21 April 2017.]

Attwood, S.J., Park, S.E., Marshall, P., Fanshawe, J.H. & Gaisberger, H. 2017a. An argument for integrating wild and agricultural biodiversity conservation. *In* D. Hunter, L. Guarino, C. Spillane & P.C. McKeown, eds. *Routledge handbook of agricultural biodiversity*, pp. 326–342. London, UK, Routledge.

Attwood, S.J., Park, S.E., Loos, J., Phillips, M., Mills, D. & McDougall, C. 2017b. Does sustainable intensification offer a pathway to improved food security for aquatic agricultural system-dependent communities? *In* I. Oborn, B. Vanlauwe, M. Phillips, R. Thomas, W. Brooijmans & K. Atta-Krah, eds. *Sustainable intensification in smallholder agriculture: an integrated systems research approac*h, pp. 71–87. Abingdon, UK, Earthscan from Routledge.

Attwood, S.J., Ranieri, J., Park, S.E., Kennedy, G. & Smith, P. 2016. *The rise of sustainable intensification, limitations of its focus, and the need for evidence*. Paper presented at the EcoSummit Conference, Montpellier, France, 28 August to 1 September, 2016.

Attwood, S.J., van Asseldonk, I., Hossain, M.E., Golam, F., Kamp, K.T. & Braun, M. 2013. *Sorjan farming systems in south-western Bangladesh: an exploration of the dynamics of the system, its productivity and profitability*. Penang, Malaysia, WorldFish.

Bardgett, R.D. & van der Putten, W.H. 2014. Belowground biodiversity and ecosystem functioning. *Nature*, 515: 505–511.

Barrington, K., Chopin, T. & Robinson, S. 2009. Integrated multi-trophic aquaculture (IMTA) in marine temperate waters. *In* D. Soto, ed. *Integrated mariculture: a global review*, pp. 7–46. FAO Fisheries and Aquaculture Technical Paper No. 529. Rome, FAO.

Benzie, J.A.H., Nguyen, T.T.T., Hulata, G., Bartley, D.M., Brummett, R., Davy, B., Halwart, M., Na-Nakorn, U. & Pullin, R. 2012. Promoting responsible use and conservation of aquatic biodiversity for sustainable aquaculture development. *In* R.P. Subasinghe, J.R. Arthur, D.M. Bartley, S.S. De Silva, M. Halwart, N. Hishamunda, C.V. Mohan & P. Sorgeloos, eds., *Farming the waters for people and food*, pp. 337–383. Proceedings of the global conference on aquaculture 2010, Phuket, Thailand, 22–25 September 2010. Rome, FAO, and Bangkok, Network of Aquaculture Centres in Asia-Pacific.

B**erg, H., Berg, C. & Nguyen, T.T.** 2012. Integrated rice-fish farming: safeguarding biodiversity and ecosystem services for sustainable food production in the Mekong Delta. *Journal of Sustainable Agriculture*, 36: 859–872.

Binam, J.N., Place, F., Kalinganire, A., Hamade, S., Boureima, M., Tougiani, A., Dakouo, J., Mounkoro, B., Diaminatou, S., Badji, M. *et al.* 2015. Effects of farmer managed natural regeneration on livelihoods in semi-arid West Africa. E*nvironmental Economics and Policy Studies*, 17: 543–575.

Bioversity International. 2017. *Mainstreaming agrobiodiversity in sustainable food systems: scientific foundations for an agrobiodiversity index*. Rome.

Blitzer, E.J., Dormann, C.F., Holzschuh, A., Klein, A-M., Rand, T.A. & Tscharntke, T. 2012. Spillover of functionally important organisms between managed and natural habitats. *Agriculture, Ecosystems and Environment*, 146: 34–43.

Bostock, J., McAndrew, B., Richards, R., Jauncey, K., Telfer, T., Lorenzen, K., Little, D., Ross, L., Handisyde, N., Gatward, I. & Corner, R. 2010. Aquaculture: global status and trends. *Philosophical Transactions of the Royal Society B*, 365: 2897–2912.

Brooker, R.W., Bennett, A.E., Cong, W-F., Daniell, T.J., George, T.S., Hallett, P.D., Hawes, C., Iannetta, P.P.M., Jones, H.G., Karley, A.J. *et al.* 2015. Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. *New Phytologist*, 206: 107–117.

Cardinale, B.J., Duffy, J.E., Gonzalez, A., Hooper, D.U., Perrings, C., Venail, P., Narwani, A., Mace, G.M., Tilman, D., Wardle, D.A. *et al.* 2012. Biodiversity loss and its impact on humanity. *Nature*, 486: 59–67.

Cassidy, E.S., West, P.C., Gerber, J.S. & Foley, J.A. 2013. Redefining agricultural yields: from tonnes to people nourished per hectare. *Environmental Research Letters*, 8: 034015 (available at http://iopscience.iop.org/article/10.1088/1748-9326/8/3/034015/pdf).

Castine, S.A., Sellamuttu, S.S., Cohen, P., Chandrabalan, D. & Phillips, M. 2013. *Increasing productivity and improving livelihoods in aquatic agricultural systems: a review of interventions*. Working Paper AAS-2013-30. Penang, Malaysia, CGIAR Research Program on Aquatic Agricultural Systems.

Clark, W.C., Tomich, T.P., van Noordwijk, M., Guston, D., Catacutan, D., Dickson, N.M. & McNie, E. 2016. Boundary work for sustainable development: natural resource management at the Consultative Group on International Agricultural Research (CGIAR). *Proceedings of the National Academy of Sciences USA*, 113: 4615–4622.

Clay, J.W. 2004. *World agriculture and the environment: a commodity-by-commodity guide to impacts and practices*. Washington, DC, Island Press.

Cole, S.M., Kantor, P., Sarapura, S. & Rajaratnam, S. 2014. *Gender-transformative approaches to address inequalities in food, nutrition and economic outcomes in aquatic agricultural systems.* Working Paper AAS-2014-42. Penang, Malaysia, CGIAR Research Program on Aquatic Agricultural Systems.

Compant, S., Clément, C. & Sessitsch, A. 2010. Plant growth-promoting bacteria in the rhizo- and endosphere of plants: their role, colonization, mechanisms involved and prospects for utilization. *Soil Biology & Biochemistry*, 42: 669–678.

Crutsinger, G.M., Collins, M.D., Fordyce, J.A., Gompert, Z., Nice, C.C. & Sanders, N.J. 2006. Plant genotypic diversity predicts community structure and governs an ecosystem process. *Science*, 313: 966–968.

Crutsinger, G.M., Souza, L.. & Sanders, N.J. 2008. Intraspecific diversity and dominant genotypes resist plant invasions. *Ecology Letters*, 11: 16–23.

Dawson, I.K., Carsan, S., Franzel, S., Kindt, R., van Breugel, P., Graudal, L., Lillesø, J-P.B., Orwa, C. & Jamnadass, R. 2014. Agroforestry, livestock, fodder production and climate change adaptation and mitigation in East Africa: issues and options. ICRAF Working Paper No. 178. Nairobi, World Agroforestry Centre.

Dawson, I.K., Hendre, P., Powell, W., Sila, D., McMullin, S., Simons, T., Revoredo-Giha, C., Odeny, D.A., Barnes, A.P., Graudal, L. *et al.* 2018. *Supporting human nutrition in Africa through the integration of new and orphan crops into food systems: placing the work of the African Orphan Crops Consortium in context*. ICRAF Working Paper No. 276. Nairobi, World Agroforestry Centre.

de Boer, I.J.M., Cederberg, C., Eady, S., Gollnow, S., Kristensen, T., Macleod, M., Meul, M., Nemecek, T., Phong, L.T., Thoma, G. *et al.* 2011. Greenhouse gas mitigation in animal production: towards an integrated life cycle sustainability assessment. *Current Opinion in Environmental Sustainability*, 3: 423–431.

Dijkstra, J., Oenema, O. & Bannink, A. 2011. Dietary strategies to reducing N excretion from cattle: implications for methane emissions. *Current Opinion in Environmental Sustainability*, 3: 414–422.

Donald, P.F. 2004. Biodiversity impacts of some agricultural commodity production systems. *Conservation Biology*, 18: 17-37.

Döring, T.F., Annicchiarico, P., Clarke, S., Haigh, Z., Jones, H.E., Pearce, H., Snape, J., Zhan, J. & Wolfe, M.S. 2015. Comparative analysis of performance and stability among composite cross populations, variety mixtures and pure lines of winter wheat inorganic and conventional cropping systems. *Field Crop Research*, 183: 235–245.

FAO. 2003. *Biological management of soil ecosystems for sustainable agriculture*. Report of the international technical workshop organized by EMBRAPA and FAO, Londrina, Brazil, 24–27 June 2002. World Soil Resources Reports 101. Rome.

FAO. 2008. *Rapid assessment of pollinators' status: a contribution to the International Initiative for the Conservation and Sustainable Use of Pollinators*. Global Action on Pollination Services for Sustainable Agriculture. Rome.

FAO. 2009a. *The State of Food and Agriculture: livestock in the balance.* Rome.

FAO. 2009b. The State of world Fisheries and Aquaculture 2008. Rome.

FAO. 2011. *Save and grow. A policymaker's guide to the sustainable intensification of smallholder crop production*. Rome.

FAO. 2014. B*uilding a common vision for sustainable food and agriculture. Principles and approaches*. Rome.

FAO. 2015. *The State of the World's Animal Genetic Resources for Food and Agriculture. 2nd report*. Rome. (available at http://www.fao.org/3/CA3129EN/CA3129EN.pdf).

FAO. 2016. *Sustainable intensification of aquaculture in the Asia-Pacific region. Documentation of successful practices*. Bangkok, Regional Office for Asia and the Pacific.

FAO. 2017. *GeoNetwork: the portal to spatial data and information*. www.fao.org/geonetwork/ [Accessed 19 February 2017.]

FAO. 2019. *The State of the World's Biodiversity for Food and Agriculture.* Rome.

FAOSTAT. 2016. *Statistics Division portal*. http://faostat3.fao.org/ [Accessed 09 February 2016.]

Finckh, M.R., Gacek, E.S., Goyeau, H., Lannou, C., Merz, U., Mundt, C.C., Munk, L., Nadziak, J., Newton, A.C., de Vallavieille-Pope, C. *et al.* 2000. Cereal variety and species mixtures in practice, with emphasis on disease resistance. *Agronomie*, 20: 813–837.

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C. *et al.* 2011. Solutions for a cultivated planet. *Nature*, 478: 337–342.

Foran, T., Butler, J.R.A., Williams, L.J., Wanjura, W.J., Hall, A., Carter, L. & Carberry, P.S. 2014. Taking complexity in food systems seriously: an interdisciplinary analysis. *World Development*, 61: 85–101.

Fritz, S., See, L., McCallum, I., You, I., Bun, A., Moltchanova, E., Duerauer, M., Albrecht, F., Schill, C., Perger, C. *et al.* 2015. Mapping global cropland and field size. *Global Change Biology*, 21: 1980–1992.

Gabriel, D., Carver, S.J., Durham, H., Kunin, W.E., Palmer, R.C., Sait, S.M., Stagl, S. & Benton, T.G. 2009. The spatial aggregation of organic farming in England and its underlying environmental correlates. *Journal of Applied Ecology,* 46: 323–333.

Gallai, N., Salles, J-M., Settelem, J. & Vaissière, B.E. 2009. Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. *Ecological Economics,* 68: 810–821.

Garibaldi, L.A., Aizen, M.A,, Klein, A.M., Cunningham, S.A. & Harder, L.D. 2011. Global growth and stability of agricultural yield decrease with pollinator dependence. *Proceedings of the National Academy of Sciences USA*, 108: 5909–5914.

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. *et al.* 2013. Wild pollinators enhance fruit set of crops regardless of honeybee abundance. *Science*, 339: 1608–11.

Gaudin, A.C.M., Tolhurst, T.N., Ker, A.P., Janovicek, K., Tortora, C., Martin, R.C. & Deen, W. 2015. Increasing crop diversity mitigates weather variations and improves yield stability. *PLoS One*, 10: e0113261 (available at http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0113261).

Gilman, R.T., Fabina, N.S., Abbott, K.C. & Rafferty, N.E. 2011. Evolution of plant–pollinator mutualisms in response to climate change. *Evolutionary Applications*, 5: 2–16.

Global Food Security. 2015. *Extreme weather and resilience of the global food system.* Final project report from the UK-US Taskforce on Extreme Weather and Global Food System Resilience. Swindon, UK, The Global Food Security Programme.

Godfray, H.C.J. 2015. The debate over sustainable intensification. *Food Security*, 7: 199–208.

Gruber, N. & Galloway, J.N. 2008. An Earth-system perspective of the global nitrogen cycle. *Nature*, 451: 293–296.

Hall, S.J., Delaporte, A., Phillips, M.J., Beveridge, M. & O'Keefe, M. 2011. *Blue frontiers: managing the environmental costs of aquaculture*. Penang, Malaysia, WorldFish Center.

Hanning, I. & Diaz-Sanchez, S. 2015. The functionality of the gastrointestinal microbiome in non-human animals. *Microbiome*, 3: 51 (available at https://microbiomejournal.biomedcentral.com/articles/10.1186/s40168-015-0113-6).

Haq, M.Z., Robbani, M., Ali, M., Hasan, M.M., Hasan, M.M., Uddin, M.J., Begum, M., Teixeira da Silva, J.A., Pan. X-Y. & Karim, M.R. 2012. Damage and management of cyclone Sidr-affected homestead tree plantations: a case study from Patuakhali, Bangladesh. *Natural Hazards*, 64: 1305–1322.

Hayat, R., Ali, S., Amara, U., Khalid, R. & Ahmed, I. 2010. Soil beneficial bacteria and their role in plant growth promotion: a review. *Annals of Microbiology*, 60: 579–598.

Hayes, B.J., Lewin, H.A. & Goddard, M.E. 2013. The future of livestock breeding: genomic selection for efficiency, reduced emissions intensity, and adaptation. *Trends in Genetics*, 29: 206–214.

Herrero, M., Havlík, P., Valin, H., Notenbaert, A., Rufino, M.C., Thornton, P.K., Blümmel, M., Weiss, F., Grace, D. & Obersteiner, M. 2013. Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. *Proceedings of the National Academy of Sciences USA*, 110: 20888–20893.

Hersch-Green, E.I., Turley, N.E. & Johnson, M.T.J. 2011. Community genetics: what have we accomplished and where should we be going? *Philosophical Transactions of the Royal Society B*, 366: 1453–1460.

HLPE. 2016. *Sustainable agricultural development for food security and nutrition: what roles for livestock?* A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome.

IPBES. 2016. *The assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on pollinators, pollination and food production*. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany.

IPES-Food. 2015. *The new science of sustainable food systems: overcoming barriers to food systems reform*. Report 01. International Panel of Experts on Food Systems, Université Catholique de Louvain, Louvain-la-Neuve, Belgium.

ISRIC. 2017. *ISRIC – World Soil Information*. http://www.isric.org/ [Accessed 11 February 2017.]

Jackson, L.E., Pulleman, M.M., Brussaard, L., Bawa, K.S., Brown, G.G., Cardoso, I.M., de Ruiter, P.C., Garcia-Barrios, L., Hollander, A.D., Lavelle, P. *et al.* 2012. Social-ecological and regional adaptation of agrobiodiversity management across a global set of research regions. *Global Environmental Change*, 22: 623–639.

Jamnadass, R., Langford, K., Anjarwalla, P. & Mithöfer, D. 2014. Public-private partnerships in agroforestry. *In* N.K. Van Alfen, ed. *Encyclopedia of agriculture and food systems*. Volume 4, pp. 544–564. San Diego, USA, Elsevier.

Jamnadass, R.H., Dawson, I.K., Franzel, S., Leakey, R.R.B., Mithöfer, D., Akinnifesi, F.K. & Tchoundjeu, Z. 2011. Improving livelihoods and nutrition in sub-Saharan Africa through the promotion of indigenous and exotic fruit production in smallholders' agroforestry systems: a review. *International Forest Review*, 13: 338–354.

Kapulnik, Y. & Kushnir, U. 1991. Growth dependency of wild, primitive and modern cultivated wheat lines on vesicular-arbuscular mycorrhiza fungi. *Euphytica*, 56: 27–36.

Kerr, J.T., Pindar, A., Galpern, P., Packer, L., Potts, S.G., Roberts, S.M., Rasmont, P., Schweiger, O,, Colla, S.R., Richardson, L.L. *et al.* 2015. Climate change impacts on bumblebees converge across continents. *Science*, 349: 177–180.
Khoury, C.K., Bjorkman, A.D., Dempewolf, H., Ramirez-Villegas, J., Guarino, L., Jarvis, A., Rieseburg, L.H. & Struik, P.C. 2014. Increasing homogeneity in global food supplies and the implications for food security. *Proceedings of the National Academy of Sciences USA,* 111: 4001–4006.
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. *Proceedings of the Royal Society B,* 274: 303–313.
Kovacs-Hostyanszki, A., Espındola, A., Vanbergen, A.J., Settele, J., Kremen, C. & Dicks, L.V. 2017. Ecological intensification to mitigate impacts of conventional intensive land use on pollinators and pollination. *Ecology Letters*, 20: 673–689.
Lautenbach, S., Seppelt, R., Liebscher, J. & Dormann, C.F. 2012. Spatial and temporal trends of global pollination benefit. *PLoS One*, 7: e35954 (available at http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0035954).
Lawton, R.J., Mata, L., de Nys, R. & Paul, N.A. 2013. Algal bioremediation of waste waters from land-based aquaculture using Ulva: selecting target species and strains. *PLoS One*, 8: e77344 (available at http://journals.plos.org/plosone/article/related?id=10.1371/journal.pone.0077344).
Leakey, R.R.B. 2010. Agroforestry: a delivery mechanism for multi-functional agriculture. *In* L.R. Kellimore, ed. *Handbook on agroforestry: management practices and environmental impact,* pp. 461–471. Environmental Science, Engineering and Technology Series. Hauppauge, USA, Nova Science Publishers.
Lee, Y. 2004. *Mulberry dyke fish pond model, China: a sustainable traditional method of land-water ecosystem*. Asia-Pacific Environmental Innovation Strategies (APEIS), Research on Innovative and Strategic Policy Options (RISPO), Good Practices Inventory. University of Hong Kong, Hong Kong, China.
Lillesø, J-P.B., Harwood, C., Derero, A., Graudal, L., Roshetko, J.M., Kindt, R., Moestrup, S., Omondi, W.O., Holtne, N., Mbora, A. *et al.* 2018. Why institutional environments for agroforestry seed systems matters. *Development Policy Review*, 36: O89–O112.
Lillesø, J-P.B., Graudal, L., Moestrup, S., Kjær, E.D., Kindt, R., Mbora, A., Dawson, I., Muriuki, J., Ræbild, A. & Jamnadass, R. 2011. Innovation in input supply systems in smallholder agroforestry: seed sources, supply chains and support systems. *Agroforestry Systems*, 83: 347–359.
Lithourgidis, A.S., Dordas, C.A,, Damalas, C.A.. & Vlachostergios, D.N. 2011. Annual intercrops: an alternative pathway for sustainable agriculture. *Australian Journal of Crop Science*, 5: 396–410.
Litrico, I. & Violle, C. 2015. Diversity in plant breeding: a new conceptual framework. *Trends in Plant Science*, 20: 604–613.
Liu, J., You, L., Amini, M., Obersteiner, M., Herrero, M., Zehnder, A.J.B. & Yang, H. 2010. A high-resolution assessment on global nitrogen flows in cropland. *Proceedings of the National Academy of Sciences USA,* 107: 8035–8040.
Manurung, G.E., Roshetko, J.M., Budidarsono, S. & Kurniawan, I. 2008. Dudukuhan tree farming systems in West Java: how to mobilize self-strengthening of community-based forest management? *In* D.J. Snelder & R. Lasco, eds. *Smallholder tree growing for rural development and environmental services. Lessons from Asia*. Advances in Agroforestry. Volume 5, pp. 99–116. New York, USA, Springer Sciences + Business Media.
McCouch, S., Baute, G.J., Bradeen, J., Bramel, P., Bretting, P.K., Buckler, E., Burke, J.M., Charest, D., Cloutier, S., Cole, G. *et al.* 2013. Agriculture: feeding the future. *Nature*, 499: 23–24.

Mead, R. & Willey, R.W. 1980. The concept of a 'land equivalent ratio' and advantages in yields from intercropping. *Experimental Agriculture*, 16: 217–228.

Melathopoulos, A.P., Cutler, G.C. & Tyedmers, P. 2015 Where is the value in valuing pollination ecosystem services to agriculture? *Ecological Economics*, 109: 59–70.

Mitchell, M.G.E., Bennett, E.M. & Gonzalez, A. 2014. Forest fragments modulate the provision of multiple ecosystem services. *Journal of Applied Ecology*, 51: 909–918.

Morandin, L.A., Winston, M.L,, Abbottm V.A. & Franklin, M.T. 2007. Can pastureland increase wild bee abundance in agriculturally intense areas? *Basic and Applied Ecology*, 8: 117–124.

Mulumba, J.W., Nankya, R., Adokorach, J., Kiwuka, C., Fadda, C., De Santis, P. & Jarvis, D.I. 2012. A risk-minimizing argument for traditional crop varietal diversity use to reduce pest and disease damage in agricultural ecosystems of Uganda. *Agriculture, Ecosystems & Environment*, 157: 70–86.

Mulyoutami, E., Roshetko, J.M., Martini, E., Awalina, D. & Janudianto. 2015. Gender roles and knowledge in plant species selection and domestication: a case study in South and Southeast Sulawesi. *International Forestry Review*, 17(S4): 99–111.

Mutch, L.A. & Young, J.P.W. 2004. Diversity and specificity of *Rhizobium leguminosarum* biovar *viciae* on wild and cultivated legumes. *Molecular Ecology*, 13: 2435–2444.

Narendra, B.H., Roshetko, J.M., Tata, H.L. & Mulyoutami, E. 2013. Prioritizing underutilized tree species for domestication in smallholder systems of West Java. *Small-scale Forestry*, 12: 519–538.

Notarnicola, B., Sala, S., Anton, A., McLaren, S.J., Saouter, E. & Sonesson, U. 2017. The role of life cycle assessment in supporting sustainable agri-food systems: a review of the challenges. *Journal of Cleaner Production*, 140: 399–409.

Olesen, I., Bentsen, H.B., Phillips, M. & Ponzoni, R.W. 2015. Can the global adoption of genetically improved farmed fish increase beyond 10%, and how? *Journal of Marine Science and Engineering*, 3: 240–266.

Palmgren, M.G., Edenbrandt, A.K., Vedel, S.E., Andersen, M.M., Landes, X., Østerberg, J.T., Falhof, J., Olsen, L.I., Christensen, S.B., Sandøe, P. *et al.* 2015. Are we ready for back-to-nature crop breeding? *Trends in Plant Science*, 20: 155–164.

Pérez-Jaramillo, J.E., Mendes, R. & Raaijmakers, J.M. 2016. Impact of plant domestication on rhizosphere microbiome assembly and functions. *Plant Molecular Biology*, 90: 635–644.

Pretty, J., Sutherland, W.J., Ashby, J., Auburn, J., Baulcombe, D., Bell, M., Bentley, J., Bickersteth, S., Brown, K., Burke, J. *et al.* 2010. The top 100 questions of importance to the future of global agriculture. International *Journal of Agricultural Sustainability*, 8: 219–236.

Rader, R., Bartomeus, I., Garibaldi, L.A., Garratt, M.P.D., Howlett, B.G., Winfree, R., Cunningham, S.A., Mayfield, M.M., Arthur, A.D., Andersson, G.K.S. *et al.* 2016. Non-bee insects are important contributors to global crop pollination. *Proceedings of the National Academy of Sciences USA*, 113: 146–151.

Raseduzzaman, M. & Jensen, E.S. 2017. Does intercropping enhance yield stability in arable crop production? A meta-analysis. *European Journal of Agronomy*, 91: 25-33.

Ray, D.K., Gerber, J.S,, MacDonald, G.K. & West, P.C. 2015. Climate variation explains a third of global crop yield variability. *Nature Communications*, 6: 5989 (available at http://www.nature.com/ncomms/2015/150122/ncomms6989/full/ncomms6989.html).

Reckling, M., Hecker, J-M., Bergkvist, G., Watson, C.A., Zander, P., Schläfke, N., Stoddard, F.L., Eory, V., Topp, C.F.E., Maire, J. *et al.* 2016a. A cropping system assessment framework – evaluating effects of introducing legumes into crop rotations. *European Journal of Agronomy*, 76: 186–197.

Reckling, M., Bergkvist, G., Watson, C.A., Stoddard, F.L., Zander, P.M., Walker, R.L., Pristeri, A., Toncea, I. & Bachinger, J. 2016b. Trade-offs between economic and environmental impacts of introducing legumes into cropping systems. *Frontiers in Plant Science*, 7: 669 (available at http://journal.frontiersin.org/article/10.3389/fpls.2016.00669/full).

Reed, J., van Vianen, J., Foli, S., Clendenning, J., Yang, K., MacDonald, M., Petrokofsky, G., Padoch, C. & Sunderland, T. 2017. Trees for life: the ecosystem service contribution of trees to food production and livelihoods in the tropics. *Forest Policy and Economics*, 84: 62–71.

Ren, W., Hu, L., Zhang, J., Sun, C., Tang, J., Yuan, Y. & Chen, X. 2014. Can positive interactions between cultivated species help to sustain modern agriculture? *Frontiers in Ecology and the Environment,* 12: 507–514.

Reusch, T.B.H., Ehlers, A., Hämmerli, A. & Worm, B. 2005. Ecosystem recovery after climatic extremes enhanced by genotypic diversity. *Proceedings of the National Academy of Sciences USA*, 102: 2826–2831.

Ricketts, T.H. & Lonsdorf, E. 2013. Mapping the margin: comparing marginal values of tropical forest remnants for pollination services. *Ecological Applications*, 23: 1113–1123.

Ricketts, T.H., Regetz, J., Steffan-Dewenter, I., Cunningham, S.A., Kremen, C., Bogdanski, A., Gemmill-Herren, B., Greenleaf, S.S., Klein, A.M., Mayfield, M.M. *et al.* 2008. Landscape effects on crop pollination services: are there general patterns? *Ecology Letters*, 11: 499–515.

Ritpitakphong, U., Falquet, L., Vimoltust, A., Berger, A., Métraux, J.P. & L'Haridon, F. 2016. The microbiome of the leaf surface of Arabidopsis protects against a fungal pathogen. *New Phytologist,* 210: 1033–1043.

Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, III. F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J. *et al.* 2009. A safe operating space for humanity. *Nature*, 461: 472–475.

Roshetko, J.M., Manurung, G., Susila, A., Anggakusuma, D. & Rahmanulloh, A. 2012. Understory vegetable production in smallholder agroforestry systems of West Java – a viable option? *In* A.D. Susila, B.S. Purwoko, J.M. Roshetko, M.C. Palada, J.G. Kartika, L. Dahlia, K. Wijaya, A. Rahmanulloh, M. Raimadoya, T. Koesoemaningtyas *et al.* eds. *Vegetable-agroforestry systems in Indonesia*, pp. 19–47. Special Publication 6c. Beijing, World Association of Soil and Water Conservation, and Nairobi, World Agroforestry Centre.

Rudel, T.K., Paul, B., White, D., Rao, I.M., Van Der Hoek, R., Castro, A., Boval, M., Lerner, A., Schneider, L. & Peters, M. 2015. LivestockPlus: forages, sustainable intensification, and food security in the tropics. *Ambio*, 44: 685–693.

Samberg, L.H., Gerber, J.S., Ramankutty, N., Herrero, M. & West, P.C. 2016. Subnational distribution of average farm size and smallholder contributions to global food production. *Environmental Research Letters*, 11: 124010 (available at http://iopscience.iop.org/article/10.1088/1748-9326/11/12/124010/meta).

Seufert, V. & Ramankutty, N. 2017. Many shades of gray—the context-dependent performance of organic agriculture. *Science Advances*, 3: e1602638 (available at http://advances.sciencemag.org/content/3/3/e1602638).

Sileshi, G., Akinnifesi, F.K., Ajayi, O.C.& Place, F. 2008. Meta-analysis of maize yield response to planted fallow and green manure legumes in sub-Saharan Africa. *Plant and Soil*, 307: 1–19.

Sileshi, G.W., Debusho, L.K. & Akinnifesi, F.K. 2012. Can integration of legume trees increase yield stability in rainfed maize cropping systems in Southern Africa? *Agronomy Journal*, 104: 1392–1398.

Skiftesvik, A.B., Blom, G., Agnalt, A.L., Durif, C.M.F., Browman, H.I., Bjelland, R.M., Harkestad, L.S., Farestveit, E., Paulsen, O.I., Fauske, M. *et al.* 2014. Wrasse (Labridae) as cleaner fish in salmonid aquaculture – The Hardangerfjord as a case study. *Marine Biology Research*, 10: 289–300.

Smith, M.R., Singh, G.M., Mozaffarian, D. & Myers, S.S. 2015. Effects of decreases of animal pollinators on human nutrition and global health: a modelling analysis. *The Lancet*, 386: 1964–1972.

Smith, A., Snapp, S., Chikowo, R., Thorne, P., Bekunda, M. & Glover, J. 2017. Measuring sustainable intensification in smallholder agroecosystems: a review. *Global Food Security*, 12: 127–138.

Soto, D., White, P., Dempster, T., De Silva, S., Flores, A., Karakassis, Y., Knapp, G., Martinez, J., Miao, W., Sadovy, Y. *et al.* 2012. Addressing aquaculture-fisheries interactions through the implementation of the ecosystem approach to aquaculture (EAA). *In* R.P. Subasinghe, J.R. Arthur, D.M. Bartley, S.S. De Silva, M. Halwart, N. Hishamunda, C.V. Mohan & P. Sorgeloos, eds. *Farming the waters for people and food*, pp. 385–436. Proceedings of the global conference on aquaculture 2010, Phuket, Thailand, 22–25 September 2010. Rome, FAO, and Bangkok, Network of Aquaculture Centres in Asia-Pacific.

Staver, C., Siles, P., Bustamante, O., Castellon, N. & Mpiira, S. 2015. *Improving banana agroecosystem productivity – lessons for integrated systems intensification*. International conference on integrated systems research for sustainable intensification in smallholder agriculture, 3–6 March 2015. Ibadan, Nigeria, International Institute of Tropical Agriculture.

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A. *et al.* 2015. Planetary boundaries: guiding human development on a changing planet. *Science*, 347 (available at www.sciencemag.org/content/347/6223/1259855).

Teichroew, J.L., Xu, J., Ahrends, A., Huang, Z.Y., Tan, K. & Xie, Z. 2017. Is China's unparalleled and understudied bee diversity at risk? *Biological Conservation*, 210, Part B: 19–28.

Thilsted, S.H., Thorne-Lyman, A., Webb, P., Bogard, J.R., Subasinghe, R., Phillips, M.J. & Allison, E.H. 2016. Sustaining healthy diets: the role of capture fisheries and aquaculture for improving nutrition in the post-2015 era. *Food Policy*, 61: 126–131.

Thorlakson, T. & Neufeldt, H. 2012. Reducing subsistence farmers' vulnerability to climate change: evaluating the potential contributions of agroforestry in western Kenya. *Agriculture & Food Security*, 1: 15 (available at www.agricultureandfoodsecurity.com/content/1/1/15).

Thornton, P.K. & Herrero, M. 2010. Potential for reduced methane and carbon dioxide emissions from livestock and pasture management in the tropics. *Proceedings of the National Academy of Sciences of the USA,* 46: 19667–19672.

Thornton, P.K. & Herrero, M. 2015. Adapting to climate change in the mixed crop and livestock farming systems in sub-Saharan Africa. *Nature Climate Change*, 5: 830–836.

Tikhonovich, I.A. & Provorov, N.A. 2011. Microbiology is the basis of sustainable agriculture: an opinion. *Annals of Applied Biology*, 159: 155–168.

Tscharntke, T., Clough, Y., Wanger, T.C., Jackson, L., Motzke, I., Perfecto, I., Vandermeer, J. & Whitbread, A. 2012. Global food security, biodiversity conservation and the future of agricultural intensification. *Biological Conservation*, 151: 53–59.

United Nations. 2015. *World population prospects: the 2015 revision. Key findings and advance tables.* Working Paper No. ESA/P/WP.241. Department of Economic and Social Affairs, Population Division, New York, USA.

van Asten, P.J.A., Wairegi, L.W.I., Mukasa, D. & Uringi, N.O. 2011. Agronomic and economic benefits of coffee-banana intercropping in Uganda's smallholder farming systems. *Agricultural Systems,* 104: 326–334.

van Noordwijk, M., Bizard, V., Wangpakapattanawong, P., Tata, H.L., Villamor, C.B. & Leimona, B. 2014.Tree cover transitions and food security in Southeast Asia. *Global Food Security*, 3: 200–208.

Vandenkoornhuyse, P., Quaiser, A., Duhamel, M., Le Van, A. & Dufresne, A. 2015. The importance of the microbiome of the plant holobiont. *New Phytologist,* 206: 1196–1206.

vegetationmap4africa. 2017. *Potential natural vegetation of eastern Africa.* www.vegetationmap4africa.org/ [Accessed 18 September 2016.]

Wagg, C., Bender, S.F., Widmer, F. & van der Heijden, M.G.A. 2014. Soil biodiversity and soil community composition determine ecosystem multifunctionality. *Proceedings of the National Academy of Sciences USA,* 111: 5266–5270.

Wijkström, U.N. 2012. Is feeding fish with fish a viable practice? *In* R.P. Subasinghe, J.R. Arthur, D.M. Bartley, S.S. De Silva, M. Halwart, N. Hishamunda, C.V. Mohan & P. Sorgeloos, eds.

Farming the waters for people and food, pp. 33–55. Proceedings of the global conference on aquaculture 2010, Phuket, Thailand, 22–25 September 2010. Rome, FAO, and Bangkok, Network of Aquaculture Centres in Asia-Pacific.

WorldClim. 2016. *WorldClim – global climate data.* http://www.worldclim.org/ [Accessed 18 September 2015.]

Yu, Y., Stomph, T-J., Makowski, D., Zhang, L. & van der Werf, W. 2016. A meta-analysis of relative crop yields in cereal/legume mixtures suggests options for management. *Field Crops Research*, 198: 269–279.

Yu, Y., Stomph, T-J., Makowski, D. & van der Werf, W. 2015. Temporal niche differentiation increases the land equivalent ratio of annual intercrops: a meta-analysis. *Field Crops Research*, 184: 133–144.

Annex

Caveats and qualifications in the analysis of FAOSTAT production data

The open-access online databases of the FAO Statistics Division (FAOSTAT, 2016) provide useful data on crop production, but there are important caveats in their use and interpretation. Here, we list important qualifications relevant to our own analyses that are given in Box 1 and Box 2 and Figure 1 and Figure 2 of the current study.

Reporting of fractional 'area harvested' values

An important concern for the current study is accurate assignment of land area for crop production. Specific information is not available, but it appears likely that individual countries deal with the assignment of fractional land areas in intercropped lands in different ways when collecting production data and reporting it to FAO. As a result, comparisons in yield and area harvested across countries are susceptible to error. Errors may also occur when over time there is a change in the production approach for a crop within a country, for example, when there is a move from production in intercrops to monoculture (e.g. a switch from shade to full sun cocoa or coffee production). An artificial inflation in monoculture yields could be the result, if fractional areas were not properly accounted for earlier in the intercropped system.

We were not able to address this concern in our current compilation of production data.

Changing political boundaries

Political developments alter the geographic boundaries of nations, changing the production areas reported and confounding across-time comparisons.

To counter this in our analyses, the yield data we used to assess crop production stability (Box 2) were only from nations with unchanged boundaries and that had complete data sets over the time series.

Across-crop differences in reporting accuracy

Countries may report production data more accurately for staple crops because these are more important in overall calorific and/or economic terms and are therefore likely to be more closely monitored. While the use of more approximate yield values for non-staple crops is not normally a major concern for studying overall yield trends, it is important when using FAOSTAT data to make year-on-year yield stability comparisons. The use of rough estimations only could, for example, artificially reduce observations of yield instability.

To help counter this in our analyses, the perennial crop yield data used in Box 2 and Figure 2 were first screened to see when year-on-year yield values were identical in the time series. A high proportion of equal year-on-year values would suggest that entries are approximations, so if this was observed on six or more occasions for a country-crop combination, then that combination was excluded from our compilation. For a small number of country-crop combinations, data were also excluded if any yield figures appeared very highly atypical of the general trend (e.g. if the difference between consecutive years was of an order of magnitude in otherwise stable yield series). Such differences may indicate transcription errors in data entry.

Opacity of yield data

A proper interpretation of FAOSTAT yield data requires a deep understanding of the various factors that could support trends and stability. As an illustration, yield trends do not necessarily indicate 'absolute' productivity changes (measured at the same location under the same conditions), since, for example, crops may over time be shifted to more fertile or marginal lands within nations, depending on the wider context of production (relative economic values, government policies, etc.). Reported data for annual crops is more likely to be affected in this regard, since perennial crops once established produce from the same locations for at least a few years. This might tend to increase yield instability data for annual crops, although in theory it could also reduce instability if an element of climate forecasting were involved (i.e. if planting took account of predicted weather conditions for the season ahead).

For perennial crops in particular, seasonal changes in quoted yields may also reflect harvesting intensity, which may be reduced if the value of the crop that season is lower in local or global markets (i.e. yield data may not represent actual 'biological' production – a greater or lesser proportion of the crop may have been left on the plant).

We did not attempt to account for these factors in our analyses.

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