A review of the interactions between biodiversity, agriculture, climate change and international trade: Research and policy priorities.

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Summary

Striving to feed a population set to reach almost 10 billion people by 2050 in a sustainable way is high on the research and policy agendas. Further intensification and expansion of agricultural lands would be of major concern for the environment and biodiversity. There is, therefore, a need to understand better the impacts on biodiversity from the global food system. Since biodiversity underpins functions and services that are essential to agriculture, greater consideration of the role of biodiversity in the food system is needed. Here, we have generated a conceptual framework, separating the environment-agriculture-trade system into its key components, revealing complex interactions and highlighting the role of biodiversity. This process identified components that are well-studied, and gaps preventing a better understanding of the interactions, trade-offs and synergies between biodiversity, agriculture, climate change and international trade. We highlight eight priorities that will promote a greater understanding of the complexities of the environment-agriculture-trade system.

1. Introduction

Many of the Sustainable Development Goals (SDGs) - including zero hunger, clean water, maintaining life on land and in water, and climate action - are influenced by the global food production system and the maintenance of biodiversity within and around agricultural land. Maintaining biodiversity whilst also supporting food security is therefore key to meeting these goals. However, biodiversity is under threat: vertebrate populations are estimated to have declined in abundance by 68% since 1970[1], extinction rates are estimated to be 100 to 1000 times greater than background levels[2,3], and over one million species are at risk of extinction in the coming decades unless action is taken[4,5]. Additionally, none of the 20 Aichi global targets to stop biodiversity loss have been achieved by the 2020 target date[6]. Increased human activity is often the root of negative impacts on biodiversity: the major direct drivers of change are currently land-use change, overexploitation of species, invasive species, and pollution, with human-induced climate change predicted to be a major driver of biodiversity loss in the near future[4,7,8].

These direct drivers are in turn driven by an increasing human population and changing consumption patterns linked to increasing affluence, often resulting in greater demand for resource-intensive products[9], which will likely lead to an increase in negative biodiversity impacts. Agricultural land-use change is the greatest current threat to biodiversity, and the probable need for future agricultural expansion means that this land-use change will remain a major threat to biodiversity for the foreseeable future[10–12]. Whilst modern agriculture has been successful in increasing food production (and consequently, food security), it has also caused extensive environmental damage. Agricultural practices have direct impacts on biodiversity via land-use change, habitat degradation, and pollution. Indeed, species richness in cropland sites is estimated to be 40% lower on average than in primary vegetation[12]. Add to these impacts the on-going effects of climate change, via increasing temperatures, increased variability in precipitation, and increasing frequency of extreme weather events, and we see additional impacts on biodiversity. Although impacts on biodiversity can be both positive and negative[13,14], negative impacts, such as those resulting from an inability to track suitable climate or from phenological mismatches, are likely to dominate in the future[15]. Climate change also interacts with land use, altering how species respond to land use change[16,17] which adds to the complexity of the system. The consideration of climate change impacts on agriculture is also important, since change in the frequency of extreme weather events, including droughts, can lead to production losses[18]. Climate change is clearly a key driver of change in both biodiversity and agricultural contexts with the ability to cause both direct and indirect responses through broad-scale interactions.

Alongside increases in agriculture and the threat of climate change, the increasing ease of the international trade of agricultural products is also a major contributor to biodiversity impacts resulting from food production. The globalisation of food production has led to a spatial decoupling of production and consumption, where subsistence needs that used to be met by local resources are now being supplied by other regions via increased trade flows[4,19,20]. This has made it easier for biodiversity losses to be outsourced outside of where consumers can readily perceive these impacts. As a result, developed regions often import from developing, typically highly biodiverse, regions[21]. This international trade can contribute to increased pressure on habitats with a high potential for land conversion, such as tropical forests, which has major consequences for biodiversity[22]. For example, between 2000 and 2011, the production of beef, soybeans, palm oil and wood products in seven countries (Argentina, Bolivia, Brazil, Paraguay, Indonesia, Malaysia, and Papua New Guinea) was responsible for 40% of total tropical deforestation and resulting carbon losses[23]. It has been estimated that approximately 20% of the total global cropland area was used for growing crops for export in 2008, and that between 1969 and 2009 land for export production grew rapidly (by about 100 Mha), while land supplying crops for direct domestic use remained virtually unchanged[24]. Whilst the international trade of crops grown in developing countries has an important role in facilitating agricultural expansion that leads to biodiversity loss, production and export from industrialised countries can also have significant impacts. For example, 50% of the world trade of wheat is between the EU and the US[25], the US exports millions of tonnes of maize, soy, wheat, beef, chicken and pork[26], and trade liberalisation has enabled the large-scale exchange of dairy between the EU, US, and Oceania[27]. Thus, regional agreements and policies, which have tripled in number since 2000[28], are instrumental in changes in the nature of food production and consumption.

Although many current international trade patterns lead to negative impacts on biodiversity, by facilitating the connections to meet growing global food demand through the expansion of agricultural land area in highly-biodiverse regions as well as the displacement of local biodiversity including by invasive species[29,30], international trade could also be used to alleviate biodiversity loss. For example, the UN Conference on Trade and Development has established the BioTrade Initiative: an instrument to enable countries to harmonise economic development with conservation of biodiversity through the trade of biodiversity-based goods and services, including extracts from plants, ornamental flora and fauna, and food products[31]. Additionally, public-private partnerships work toward zero-deforestation commitments, such as the Tropical Forest Alliance 2020, which aims to align climate, forest, and development goals in the soy, cattle, palm oil, and wood pulp sectors in Colombia[32]. Further understanding of the interactions between international trade, production and biodiversity will enable the design of evidence-based policies and programmes that can help to minimise trade-driven impacts.

Recent studies have begun to address the large-scale environmental implications of food production and international trade, both in the present context and under future scenarios (e.g.[33–36]). There is growing evidence that the external and internal dynamics of our global food system are compromising its resilience in providing food, fibre and fuel in a sustainable way[28,37]. However, the impacts on, or interactions with, biodiversity are not often considered with sufficient depth in these quantitative and resilience-based approaches. Therefore, to inform efforts to meet biodiversity targets and the SDGs that biodiversity supports, there needs to be a continued and strengthened focus on the inclusion of biodiversity within large-scale studies of agriculture and international trade impacts on the environment, as well as a consideration of the interactions and feedbacks within the environment-agriculture-trade system.

To facilitate the consideration of interactions, trade-offs and synergies between the environment, agriculture, climate change and international trade, and to highlight the important role of biodiversity within this system, we review recent literature and use a systems approach to present a conceptual framework outlining the complex and interacting suite of variables that combine to drive biodiversity impacts (Figure 1). Systems thinking is useful for disentangling complex systems, often highlighting that causes and effects are less straightforward than suggested by studying just parts of the system[38]. As a result, systems thinking is viewed as fundamental to understanding and addressing complex environmental problems such as climate change[39]. Practical approaches for modelling these problems include system dynamics tools and causal loop diagrams, which can assist decision-makers in understanding the dynamic behaviour of complex systems[40]. A review of recently published studies identified major components of the system, their impacts, and remaining research gaps. We then constructed a causal loop diagram to represent the feedbacks between important variables in the environment-agriculture-trade system. Starting with the main elements of agriculture, biodiversity, trade and climate change, we identified influences on these main nodes as described in the scientific literature. For example, land use, agricultural expansion and intensification are known to negatively influence biodiversity[11,41], and are increasingly influenced by the growing global demand for food due to increasing affluence[9]. These elements were discussed among all the authors, and relevant connections and symbols were added. We use the term “environment-agriculture-trade system” for brevity but consider biodiversity and climate change as key elements within this system.

In the causal loop diagrams (Figures 1-4), arrows represent a connection between variables, with a correlation, or feedback, represented by a plus or minus sign at the arrowhead. This represents the expected numerical relationship between the variables at the global scale, where increases in one variable leads to either an increase (+) or decrease (-) in the other. For example, increasing fertiliser use generally leads to higher yields, whilst greater carbon sequestration reduces atmospheric carbon (See Supplemental Note 1 for more information). Although not an exhaustive review, we have endeavoured to compile key references that highlight the current understanding in the field. In reality, the interactions between biodiversity, agriculture, climate change and international trade may be more ambiguous or complicated than the simple positive or negative effects we have identified, and our causal loop diagrams will no doubt be unable to represent the complete system with all of its complexity and subtleties. However, this representation allows a visual mapping of some of the major connections within the system to achieve our goals of highlighting the importance of biodiversity.

The generation of this framework reveals the complexity of the system with gaps in knowledge becoming more pronounced as a wider network of interactions is considered. The framework highlights the important role of biodiversity and, alongside an assessment of recent literature, reveals major gaps and uncertainties that prevent the better integration of biodiversity into the environment-agriculture-trade system and associated research. Using systems thinking to generate the framework also reveals the importance of considering the interactions and feedbacks between elements within analyses. By considering this framework alongside recent literature, we determine eight key priorities for future research and policy. We hope this will encourage the multidisciplinary approach that will be required to understand more fully the environment-agriculture-trade system and the consequences for biodiversity.

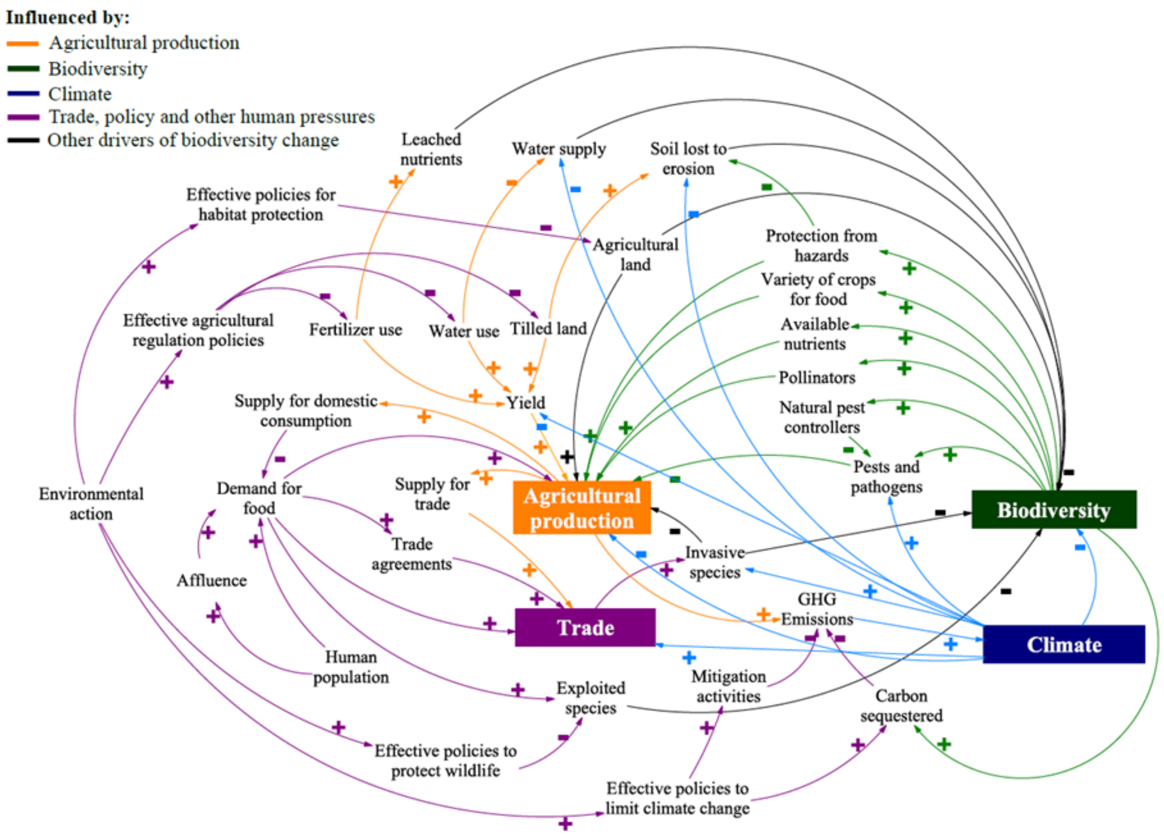

Figure 1: The Environment-Agriculture-Trade Framework: *To understand this system, interactions within the framework must be considered. However, the more interactions that are included, the more complicated the picture becomes. Biodiversity has important effects on factors within this system, driving interactions as well as being impacted by them. The challenge is to incorporate insights from across research sectors (including ecology, climate science, economics) to gain a better understanding of the role of biodiversity in this complex system. Arrows indicate a connection between variables, with a (+) signifying a generally positive effect and (-) a generally negative effect. Colours signify variables that are influenced by biodiversity (green), agricultural production (orange), climate change (blue), by trade, policy and other human pressures (purple), plus drivers of biodiversity change (black).*

2. The Environment-Agriculture-Trade Framework

The environment-agriculture-trade system is complex and consists of many variables, interactions and trade-offs (Figure 1). Using the systems approach described, alongside a review of the recent literature, it becomes clear which of these interactions, or subsets of the system, are well-studied and those that are not.

A number of recent studies have assessed the broad environmental impacts of global food production (e.g.[33–35]). However, these studies have neglected to include biodiversity either as being impacted by food production or as benefitting agriculture. For example, Poore & Nemecek (2018) combine studies that estimate the impacts of various major foods (from production to retail) on greenhouse gas (GHG) emissions, land use, acidification, eutrophication and water scarcity[33]. One of the largest meta-analyses of life cycle studies to date, this study incorporates 40 products that constitute around 90% of global protein and calorie consumption. However, this study does not consider how the production process might impact biodiversity, or how the environmental indicators monitored (GHG emissions, land-use change, acidification, eutrophication, water scarcity), via their impacts on biodiversity, might affect production. Similarly, Springmann *et al* (2018) compare current and potential future impacts of food production, showing that the overall environmental impact of the global food system (based on percentage of present (2010) impact), including from GHG emissions, cropland use, irrigation, nitrogen application and phosphorus application, could increase by 50-90% by 2050[34]. Again, the direct impacts on biodiversity were not considered. Finally, another angle that has been explored is the food-trade-water nexus: Pastor *et al* (2019) find that a 100Mha increase in land use and a near tripling of international trade will be required to double food production by 2050[35]. The authors evaluate how changes in the distribution of croplands could contribute to more sustainable water use[35], yet do not consider the effects on biodiversity. Our framework presents key variables and feedbacks that are found within the environment-agriculture-trade system, highlighting the major role of, and interactions with, biodiversity. Overall, although previous studies show the broad range of impacts of the environment-agriculture-trade system (e.g. on land use, water use and GHG emissions), they fail to recognise the important interconnections and interactions with biodiversity and its role in food production at the global scale (however, see Research Priority 1 for a discussion of two recent approaches).

Considerable research has been undertaken to explore the impacts of agricultural production on biodiversity (e.g.[42,43]) and, more recently, the impacts that biodiversity can have on food production, via the provision of services such as pollination and pest control[44], or through improved system resilience[45,46]. However, there is a tendency for research to focus on a single direction of impact (e.g. land-use change -> biodiversity, or agriculture -> land-use change -> biodiversity) or a subset of interactions (e.g. the interactions between land-use and climate change, and the subsequent impacts on biodiversity). As more variables, such as climate change and international trade or additional interactions, are considered alongside these more well-studied elements, the more complicated the picture becomes. In the following sections, we present some of the research to date that has started to explore the environment-agriculture-trade system, starting from the simpler interactions and building in complexity. We then highlight key research gaps that need to be addressed to gain a better understanding of the understudied connections in the global food system, presenting eight research and policy priorities that would focus future research on these gaps. It must be made clear that although we focused our review on terrestrial studies associated with food production, aquatic biodiversity also plays a vital role in addressing global food security[47].

2.1. Bilateral agriculture-biodiversity interactions

The impact of agricultural production on biodiversity has been intensively studied; from the local-scale impacts of intensification strategies such as fertiliser use[48,49], pesticide application[50,51], tillage[52,53] or alternative farming methods[54–56], to large-scale analyses of the effects of land conversion or intensification on biodiversity[11,12,57–59]. With the development of post-2020 biodiversity targets and the SDGs being high on the research and policy agendas, there is a requirement that the growing demand for food be met with as little negative impact on biodiversity and the environment as possible. Therefore, options to achieve more sustainable agriculture have been explored, including organic farming[54], sustainable intensification approaches[60] and the implementation and testing of agri-environment schemes[61]. However, there is little research on the large-scale responses of biodiversity to agricultural inputs or alternative farming approaches. This is primarily due to the lack of fine-scale and large-extent data on the use of agricultural inputs. Relatively fine-scale (10 by 10km resolution) data are available for fertiliser use[62,63], and recently for pesticides[64] globally, but these data are downscaled from regional or national estimates and so may be imprecise.

More recently, research has examined the agriculture–biodiversity relationship from the other direction: the impacts of biodiversity on agriculture. These studies have shown the benefits of services supplied by biodiversity to agricultural production, such as pollination and pest control, which can improve both yield[44,65,66] and system resilience[45]. However, these studies tend to be limited to groups of organisms that are more easily monitored such as bees and beetles. Despite the recognised ecosystem services supplied by biodiversity to agriculture, the feedback loop of agricultural production impacts on biodiversity and then biodiversity's impact on agricultural production is not often considered (Figure 2). This feedback is important since it will determine the ability of biodiversity to provide services to agriculture whilst adjusting to the impact of agricultural processes. If biodiversity is negatively impacted by some aspect of agriculture, for example pesticide use, this could feed back to negatively impact agriculture, such as through a decrease in biodiversity-driven pest control. This feedback loop is further complicated by the fact that patches of natural habitat may act as a source of biodiversity, maintaining local biodiversity in nearby croplands and thus providing ecosystem services[67–71]. Understanding the importance of biodiversity for agriculture is key to understanding the relative benefits and risks of land-sparing versus land-sharing approaches to land management[72]. Although there has been much study of agricultural impacts on biodiversity, and vice versa, a greater understanding of the biodiversity-agriculture feedback loop is required, both locally, and at large scales.

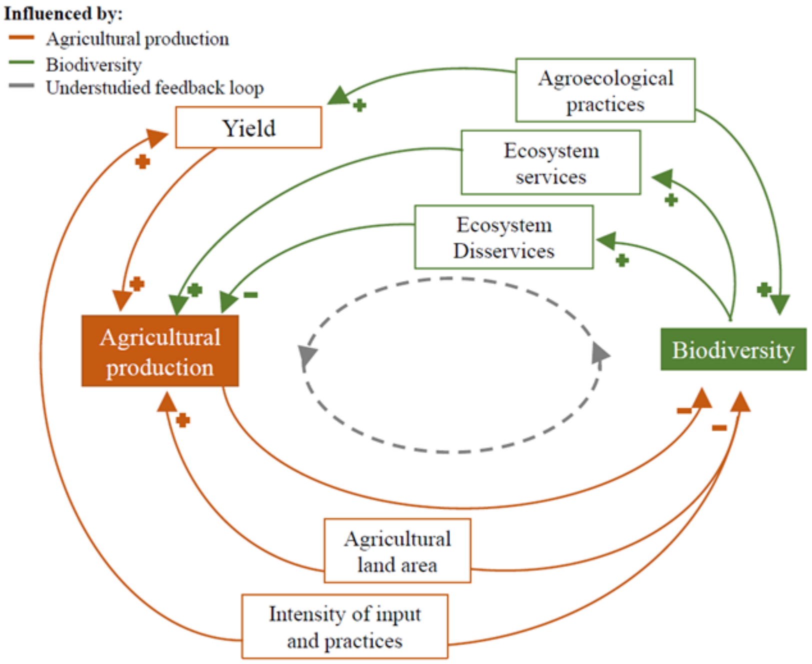

Figure 2: The feedback loop between biodiversity and agriculture. *The negative impacts on biodiversity from activities linked to food production such as tillage, and the use of inputs e.g. fertilisers and pesticides are well studied. The services (and disservices) of biodiversity and their role in agricultural systems are also increasingly understood. However, the feedback loop between agricultural production and biodiversity (represented by the grey dashed lines) is not often considered, especially at large scales. The inter-relationships are additionally complicated by landscape-level context (e.g. through the availability of source habitat). A better understanding of the feedback loop between food production and biodiversity will be essential for meeting two major SDGs (2 and 15). Arrows indicate a connection between variables, with a (+) signifying a generally positive effect and (-) a generally negative effect. Colours signify variables that are influenced by biodiversity (green), and agricultural production (orange).*

2.2. Interactions with Climate Change

The relationships between biodiversity and agriculture are further complicated when we consider the role of climate change (including warming temperatures, changes in precipitation, and increasing frequency of extreme weather events). Climate change has both positive and negative influences on biodiversity[13,14]. Although it is not currently the greatest threat to biodiversity, it will likely surpass the impacts of land-use change in the future[8,15], and can cause additional impacts through interactions with land-use change[73]. Climate change has been observed to cause shifts in species‘ ranges towards higher latitudes or elevations[74] or alter seasonal timings[75–77]. These observed shifts in range include climate-driven, pole-ward shifts in crop pests and pathogens[78], as well as in pollinators like bumblebees[79]; these shifts in both service providers and pests represent significant threats to food security. Climate change also impacts agricultural production through changes in the frequency and severity of droughts, floods and heat waves, plus potential consequences for future food security as a result of shifts in agricultural suitability and changes in productivity[18,80,81]. Most of this previous research has focused on the effects of climate change either on agriculture or on biodiversity.

There has also been a growing interest in the influence of biodiversity on climate change. It is well known that deforestation leads to an increase in atmospheric carbon dioxide which can contribute to climate change[82], and regeneration of natural forests has been suggested as a way to reduce future global temperature increases[83]. Biodiversity is also considered as a natural way to protect against the effects of climate change through the implementation of ecosystem-based approaches to adaptation[84]. These include practical approaches to reduce exposure or sensitivity to flooding, erosion, coastal hazards, and extreme heat through mangroves, protection of wetlands and forests, or adding green spaces[85,86], all of which fall under the broad concept of nature-based solutions[87]. A number of approaches within the agricultural sector have been investigated to improve system resilience under climate change: landscape mosaics, diversification, restoration and agroforestry are a few examples[45]. Policy-based instruments for climate change adaptation or mitigation that can regulate agricultural activities, including forestry (e.g. through protected areas, payment for ecosystem services, or community management, including REDD+ (Reducing Emissions from Deforestation and forest Degradation in developing countries)) are also based on conserving biodiversity and ecosystem services[88]. There are still, however, critical gaps in our understanding of the full suite of interactions and feedbacks between climate change, biodiversity and agricultural change (Figure 3).

Crop- and region-specific studies have started to look at the broader implications of climate change effects on agriculture via resulting changes in biodiversity. For example, climate change is expected to lead to a spatial decoupling between areas suitable for crops and for their respective pollinators, such as for coffee in Latin America[89], and for orchards in Britain[90]. At the global scale, climate change will reduce the yield of the three staple grains; rice, maize and wheat (although this effect varies among crops and locations[91]), with reductions potentially exacerbated by changes in pest insect population growth and their increased metabolic rates that are results of future warming[92]. These studies show the consequences of the two-step process of climate change impacting biodiversity, and the subsequent effects of biodiversity change on agriculture. These studies highlight that the global food system cannot be treated in isolation, and that climate change is an on-going process that has the potential to dramatically alter food systems both now and in the future. These and similar interactions between climate change and both agriculture and biodiversity (Figure 3) must be considered and are currently understudied, both in terms of taxonomic and geographic coverage.

Another important feedback loop concerns the future impact of increases in GHG emissions from agricultural processes. Currently, emissions from food production (including pre- and post-production activities) make up between 21 and 37% of total anthropogenic GHG emissions[93,94]. As food production increases into the future, and diets shift to be more meat intensive, so too will the GHG emissions produced as a result. These emissions will contribute towards global climate change, exacerbating the already apparent effects of climate on both biodiversity and agriculture. While agriculture has become more carbon efficient via the net effect of increased yields[95], this efficiency does not necessarily lead to decreases in resource use[96]. It needs to be understood how this efficiency could mitigate increases in emissions due to increased demand and changing consumption patterns. Climate change will play an increasingly important role in the future of food production, so understanding the feedbacks and interactions of current and future impacts of climate on both biodiversity and agriculture will be essential.

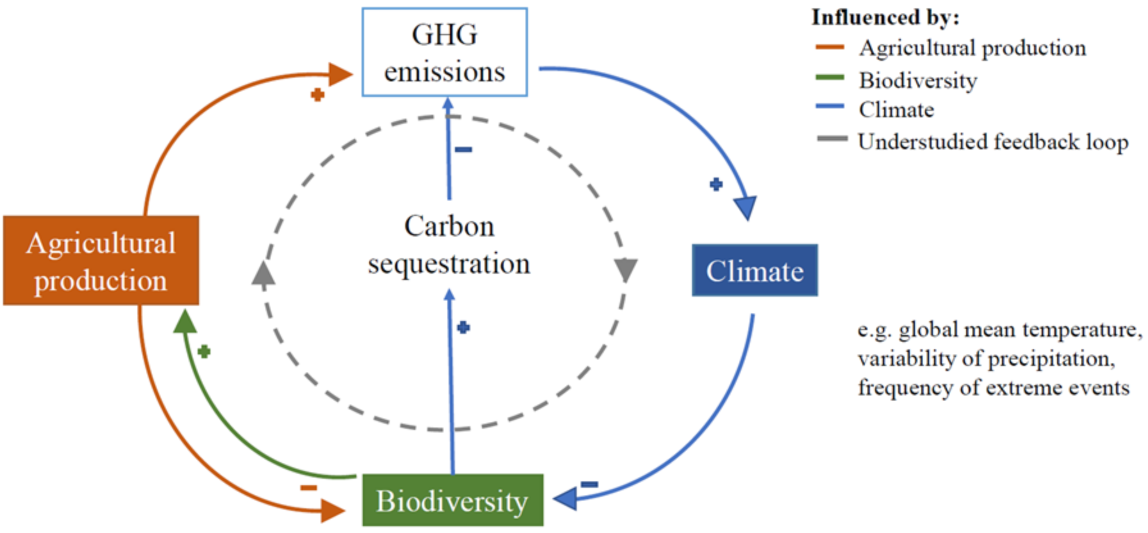

Figure 3: Interactions with climate change. *Climate change can influence agriculture directly, through changes in the abiotic factors suitable for growing crops or through changes in frequency and severity of extreme weather events. However, climate change can also impact agriculture indirectly via the associated impacts on biodiversity. Therefore, understanding the feedback loop between climate change, agriculture and biodiversity (represented by the grey dashed lines) will be key for meeting*

future food security and biodiversity targets. Although changes to climate may bring some positive impacts to agriculture, this is generally thought of to be only in the short-term and most impacts are negative. Arrows indicate a connection between variables, with a (+) signifying a generally positive effect and (-) a general negative effect. Colours signify variables that are influenced by biodiversity (green), agricultural production (orange) and climate (blue).

2.3. Interactions with International Trade

The system becomes more complex again when we consider that trade across various distances is a key feature of the global food system. Nearly one billion people consume internationally traded products to cover their daily nutrition[97]. This spatial decoupling of the location of consumption and production adds another layer of complexity to the environment-agriculture-trade system. Trade occurs across a wide range of spatial scales, with international, regional, and domestic exchange of goods all potentially leading to impacts on biodiversity. In the case of international trade, demand for products from outside a country's borders contributes substantially to local environmental impacts in the products' country of origin[21,98]. Much of the international trade-related pressure on biodiversity occurs in developing countries, which have high agricultural land-use potential and typically high biodiversity[21,99]. This pressure is often a result of demand from developed countries for imported products such as bananas, beef, cane sugar, chocolate, coconut, coffee, palm oil, soybeans, and tea, to name a few, which are all produced in previously forested areas[100–103]. Nevertheless, regional trade and domestic production also use substantial areas of land and thus have the potential for large biodiversity impacts (e.g.[9,101,104]). Consumption of internationally traded goods drives 25% of bird species losses[21], while 83% of total terrestrial species loss is due to domestic agricultural land use[104]. Similarly, while international demand drives more than half of the biodiversity impacts due to loss of suitable habitat from soybean production in the Brazilian Cerrado, the domestic market is responsible for the greatest share of impacts of any country[98]. While it is not trade itself that is driving these changes, the changes in demand and the resulting dislocation of production and consumption can lead to greater biodiversity impacts. It is unlikely that more localised food systems will be advantageous for biodiversity, since certain products are suited to production in certain locations, thereby reducing the need for additional inputs. However, the implications of the interconnected food system need to be considered to better understand synergies and trade-offs.

Studies have attempted to determine the impacts of internationally traded food using indirect approaches, such as life cycle assessment (LCA) (See [105] for a generalised modelling framework for assessing biodiversity impacts in LCA) or assessment of IUCN threat records, to link species threats to traded products[101]. LCA is emerging as an important methodology for evaluating the end-to-end environmental impacts of products, and it can be used to link a final commodity with its associated biodiversity loss[106]. Current LCA approaches focus mainly on land use impacts, and have sought to improve the representation of biodiversity impacts at different life cycle stages by utilising ecological modelling approaches such as species-area relationships and species distribution models as well as meta-analysis[105,107,108]. Two recent studies have utilised the countryside species-area relationship to estimate species extinctions resulting from the habitat loss caused by the consumption and production of internationally traded products[21,109]. However, in LCA it can be challenging to measure and aggregate impacts occurring across a product's life cycle, on a global scale, using a single metric (e.g. potentially disappearing fraction of species)[110]. Similarly, IUCN threat categories are assessments of threats across a species entire range and as a result are not spatially explicit. Although biodiversity loss due to the land-use change associated with internationally traded products is an important avenue of research, other drivers related to food production and consumption, such as agricultural intensification, also need to be taken into account[102,111] since these impacts will likely have additional detrimental effects.

While studies have focused on the effects of internationally traded food products on biodiversity through land-use changes, effects mediated via climate change have not been considered. Regions that may benefit from a future local climate more suitable for agriculture could take on new trade roles, thus reshaping the distribution of agricultural commodities globally. Furthermore, changes in demand due to productivity shocks during climate change-induced extreme events, such as floods or droughts, will also likely alter agricultural distribution. Although not an easy task, countries could design trade policies that consider climate change and biodiversity in order to avoid the worst climate and biodiversity related damages at least cost, to maximise benefits from agriculture, and to make the international trade network more distributed and resilient[112,113]. This could be accomplished through policy-led requirements for agricultural land distribution (i.e. away from highly biodiverse areas), could incentivise biodiversity-friendly practices, or discourage production of high-impact products. Research is needed to characterise how international trade can be used to mitigate the negative impacts or take advantage of the benefits of climate change, and how these changes will in turn affect biodiversity, food security, international trade, and sustainable development.

International trade itself contributes to climate change via the GHG emissions associated with traded commodities and their transport. Although GHG emissions from food transport make up a small proportion (~6%) of the total GHG emissions from food production[33], there is considerable variation across products. It has been estimated that the transport of raw crops increases emissions by 359 g of

CO_2 per dollar of trade on average; this estimate does not include the carbon-intensive transport of processed agriculture via air cargo[114,115]. However, reducing trade is not necessarily the best approach to reduce emissions associated with production, since distance travelled may not be the most significant factor to consider in a product's sustainability[116]. International trade can allow for a more efficient global food system where products for export may be produced in a less carbon-intensive manner than if they were produced locally. For example, shifts from imported to domestic livestock products can reduce GHG emissions associated with international trade and transport, but only when implemented in regions with relatively low emissions intensities[117]. However, there is still work to be done in connecting these trade-offs to biodiversity impacts. While other work has analysed scenarios of increased trade liberalisation on agricultural sector emissions, prices and cropland expansion[118], biodiversity impacts were not considered. Understanding these feedbacks and the various contributing elements, are essential for a more complete picture of impacts on biodiversity (Figure 4).

Finally, trade also impacts biodiversity through the introduction of invasive species. Merchandise imports have been shown to be the most important explanatory variable when investigating differences in invasive alien species presence[30]. The increase in global transport networks and the increasing demand for externally sourced products has contributed to the increased risk of biological invasions[119]. Trade as a route of species introductions has relevance to local agriculture if those introduced species are crop pests or diseases, or if they contribute to agriculture in a beneficial way. The implications of these introductions (actual or potential) on local biodiversity and agricultural systems, and how these might change with future food demand and climate change, still need to be explored.

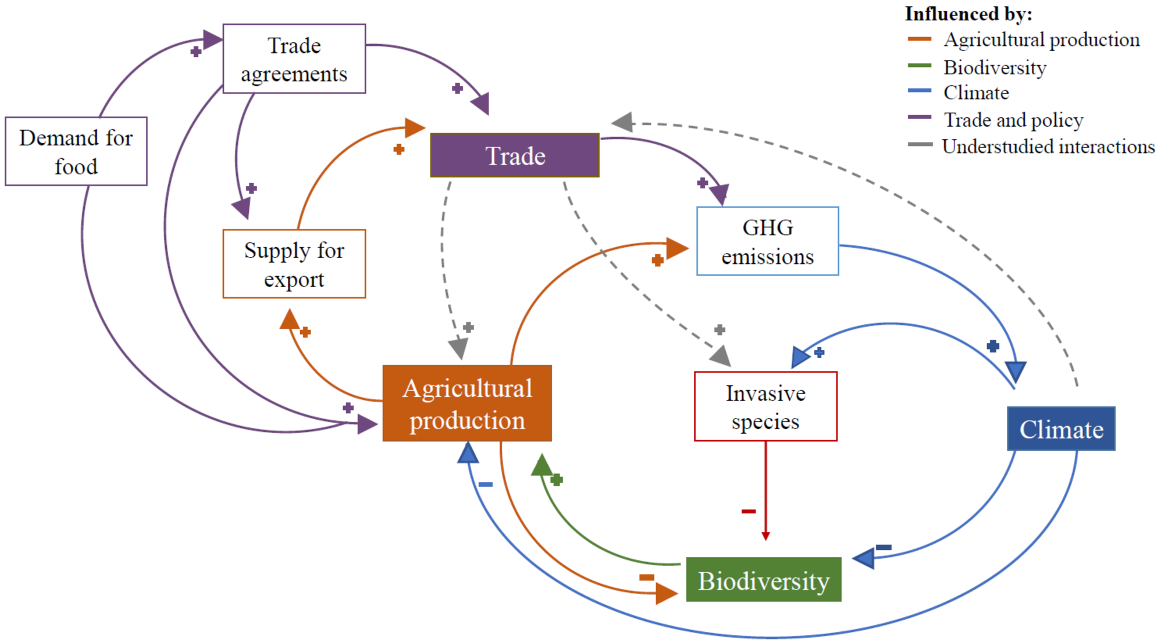

Figure 4: Interactions with international trade. *Apart from the direct influence of spatially decoupled demand and supply connected by trade on land use, trade in food products can indirectly impact biodiversity through various routes, including change in agricultural production, changes in associated emissions, and the spread of invasive species. It is therefore a key element of the environment-agriculture-trade system and so should be considered where possible, along with its interactions and feedbacks, in studies on the impacts of food production. Whilst climate change may have some positive impacts on food production and biodiversity, on average the effect is expected to be negative, particularly over long timescales. Dashed grey lines represent less well-studied interactions. Arrows indicate a connection between variables, with a (+) signifying a generally positive effect and (-) a general negative effect. Colours signify variables that are influenced by biodiversity (green), agricultural production (orange), climate (blue), and human activities including trade and policy (purple), plus drivers of biodiversity change (black).*

3. Research and Policy Priorities

It will likely be impossible to understand the complexity of the global food system and its interactions in their entirety. However, the creation of the conceptual environment-agriculture-trade framework using a systems approach has enabled the identification of key elements of the system, highlighting the important role of biodiversity and those areas which have so far been well-studied. Importantly, by using this framework alongside recent literature we can highlight some critical research and policy gaps. In this section, we present 6 research and 2 policy-focussed priorities for future action.

Research Priority 1: Better inclusion of biodiversity in large-scale studies

One key omission highlighted by the framework is that biodiversity is often absent from recent, global-scale studies of the impact of food production on the environment (e.g.[33–35]). These studies have pulled together vast amounts of data to determine the wide-ranging impacts of the global food system on the environment, yet biodiversity is not considered. By not considering biodiversity, key trade-offs between environmental outcomes of agricultural production and international trade will be missed. Similarly, the positive impacts that biodiversity can have on the system, which could contribute to system resilience, are also being missed. Some studies have begun to address this gap, for example, a study by Bal *et al* assesses biodiversity risk resulting from population growth, consumption and international trade using an integrated ecological-economic analysis[120]. This approach combines economic, biodiversity and land-use modelling to gain a better understanding of the complex environment-agriculture-trade system. Additionally, the recent EAT-Lancet report uses a global food systems model[34] to project biodiversity losses based on different scenarios of production and food waste combined with diets ranging in sustainable practices (i.e. more or less meat or dairy consumption). Biodiversity change from food production is estimated as the number of extinctions per million species per year, and the report finds potential reductions of biodiversity loss with sustainable dietary changes and improved production practices[37]. This report marks major progress in understanding the impacts of alternative diets on biodiversity and the wider environment, and acts as an example of how to incorporate biodiversity into large scale analyses of present and future impacts. However, the assessment of biodiversity was limited to endemic species only and was not able to consider the direct impacts of farm inputs (e.g. pesticides and fertiliser) nor habitat fragmentation on potential species loss[34]. We recommend similar incorporations of biodiversity into future large-scale studies so that the true impact of agriculture on the environment can be assessed and the consequences considered. These approaches and their future development will require collaboration across disciplines to take advantage of the various datasets, methods and approaches required (see Research Priority 6).

Research Priority 2: Improving data availability, access and coverage

Limited availability and access to high-quality data with a large geospatial coverage is a major barrier to understanding better the environment-agriculture-trade system and its interactions. Studies addressing this system are challenged with data that can be limited in a number of ways, such as taxonomic coverage for biodiversity data, spatial coverage or resolution for driver data, or, for footprint and trade data, difficulties in determining spatially-explicit footprints and how these relate to distant food demand. These limitations have meant that certain elements and links of the system are understudied.

While studies have begun to investigate the role of biodiversity in the provision of pollination and pest control services and how changes in these services impact yield (e.g. [44,65,66]), there is a need to go beyond these taxa to consider other groups of organisms, such as those that have a role in decomposition and nutrient cycling. Recent studies have highlighted the importance of soil diversity (including microorganisms and invertebrates) in providing ecosystem services including biological control of soil-borne pests and diseases, restoration/remediation of degraded soils and agroecosystems, and mitigation and adaptation to climate change[121–124]. It is challenging, however, to explore less well-studied taxa unless the data are available. Although global databases of biodiversity exist (e.g. GBIF (www.gbif.org), PREDICTS[125], BioTime[126]), understudied groups are not so well represented, with datasets often dominated by vertebrates and the presence of geographical biases in data coverage.

Similarly, a lack of data has limited the spatial domain that studies of the environment-agriculture-trade system can cover. Many studies on the effects of local and landscape characteristics on cropland biodiversity, such as the effect of nearby natural habitat, crop diversity or field size, are undertaken at relatively small scales (e.g. [69,127,128]). To make management recommendations that are broadly applicable, there is a need to determine the large-scale impacts of these factors, to understand how biodiversity is impacted and/or supported in agricultural systems globally and to determine whether these relationships are consistent across regions and scales. Small-scale studies have, for example, shown the importance of nearby natural habitat for cropland biodiversity, but consistencies across biomes and across scales are less well-explored (although see [129]). This becomes challenging when the data required are not available. A drive toward the generation and aggregation of large-scale datasets on drivers of change in a central database to facilitate large-scale analyses would greatly benefit research of the environment-agriculture-trade system.

This need for large-scale datasets is particularly relevant to the study of the impacts of agricultural intensification. To date, estimates of the impacts of large-scale change in agriculture on biodiversity have typically been based on change in the area harvested (e.g. [22,130]). Much less is known about the large-scale impacts of intensification within agricultural land uses, for example through the addition of fertilisers, pesticides or other practises (although see [11,99,131]). This gap is largely due to a lack of fine-grained data on agricultural inputs and practises across large areas. Therefore, there should be a focus on bringing together available information on intensification to generate the required datasets, including data from remote sensing and earth observations. This work has the potential to highlight biodiversity thresholds above which the effective provision of benefits to large-scale agricultural processes could be at risk.

We recommend a drive toward the generation and aggregation of datasets in a central database to facilitate large-scale analyses. Large biodiversity databases such as PREDICTS[125,132] and BioTime[126] are already publicly available and are useful for addressing such broad-scale questions, but the updating of these databases with new data to increase both taxonomic and geographical coverage and the creation of further such initiatives is needed. Importantly, long-term and sustainable funding and resources are needed to support conservation science and ecological research to provide institutions and people with the capability for data collection, species and habitat monitoring, and dissemination of research findings.

Research Priority 3: Interactions with climate change and resulting feedbacks

The impacts of climate change on agriculture and on biodiversity are relatively well studied separately. However, further research is required on the resulting feedbacks of these effects. For example, the feedback of climate-induced biodiversity change on agriculture urgently needs to be understood. Some research has been conducted on potential spatial mismatches between crops and their pollinators, or on potential changes in pest distributions. However, this research needs to be expanded to a broader set of taxa and across larger spatial scales. Another feedback to consider is how agriculture affects the climate (as a source and sink of GHG emissions), and consequently contributes to biodiversity changes (with potential feedbacks on agriculture). Research needs to move from considering unidirectional, bilateral relationships to considering full feedback loops. Using a systems approach, as shown here, can be useful in identifying the key steps involved and so the feedbacks that need to be considered. For example, an important area of research that should be considered is how shifts in pests and pathogens due to climate change will affect biodiversity and agriculture. Most current approaches for analysing future crop productivity lack tools for analysing pests and pathogens[133], and rarely consider biodiversity more generally. Since the consequences of interactions will be greater in the future as the threat to biodiversity from climate change increases, understanding the role of these feedbacks will be essential for understanding risks to future food security.

Research Priority 4: Trade as a facilitator of biodiversity and climate change impacts

Global and regional trade are important routes through which society obtains and distributes food. However, trade and its liberalisation facilitate impacts on biodiversity across large geographical distances due to the spatial decoupling of food production from consumption. It should be a priority to understand better future scenarios of food security that consider higher or lower levels of international and/or regional trade, for example due to potential shifts in diet. A global shift towards healthier and more nutritious diets could lead to a win-win scenario for public and planetary health[134], but how this will affect biodiversity, food production and international trade needs to be investigated more fully. Since climate change will alter the productivity of agricultural systems, including what can be grown where, this will also feedback impacts on production and international trade. Increasing the spatial resolution as well as coverage of trade-based studies will also be required to understand the impacts associated with local food consumption, given that growing international trade carries agri-food commodities across the globe. Understanding how these concurrent complex shifts in international trade, climate change, agriculture and biodiversity is essential for developing scenarios of future food security.

Research Priority 5: Additional measures of biodiversity in impact analyses

A growing body of research is focused on quantifying the large-scale impact of agriculture and international trade on biodiversity using methods ranging from life cycle assessment, footprint approaches, economic modelling and input-output analyses. Most studies use change in species richness[105], often estimated as a result of change in land area via the species-area relationship, to assess biodiversity change. However, species richness change is just one representation of the complexity of global biodiversity change[135]. As a result, this metric does not provide information on other facets of biodiversity that we may be interested in, for example, species traits to assess ecosystem functioning, species abundance for conservation management, or genetic diversity for resilience. Additionally, species richness can be a poor indicator of biodiversity change if the presence of non-native species is not accounted for, i.e. species richness may appear to be increasing but is in fact being driven by the introduction on non-native species. The limitations of using species richness as a sole biodiversity metric should be considered, and additional metrics investigated where possible.

It has been argued that the increasing diversity and availability of other indicators of biodiversity means that data availability should no longer be a valid argument for using only species richness[105]. Similarly, studies often assume a linear relationship between the amount of land used and the effect on biodiversity, but biodiversity responses can be non-linear and scale-dependent[136,137]. Testing alternative metrics of biodiversity change, such as changes in abundance or functional diversity to measure the impacts of international trade and agricultural production should be a research priority, as well as the development of methods that determine the direct causal relationship between estimated ecological footprints, or related indicators, and impacts on biodiversity[137,138]. Recent work on projecting biodiversity intactness (mean species abundance) under different socio-economic scenarios and climate marks important progress in assessing impacts on biodiversity via the use of a terrestrial biodiversity model (GLOBIO4)[139,140].

Research Priority 6: Encourage and enable multidisciplinary approaches

Various tools and methods have been used to address questions relating to subsets of the environment-agriculture-trade framework. This research has taken place in several broad fields, including ecology, climate science, trade and production flow analysis, and hydrology. To understand better the full complexity of the system, a collaborative, cross-disciplinary approach is essential. This is because there is currently no single approach that can consolidate the methods of each primary research area, so a major challenge will be determining the most appropriate methods that can be combined, while understanding their assumptions and limitations[141]. For example, the availability of biodiversity and ecosystem service data, and the ability to include them within large-scale studies of agriculture and international trade impacts, is an ongoing issue which has been discussed in the ecological footprint literature[105,137,142]. Therefore, sharing data and methods is key to developing these interdisciplinary collaborations. To address biodiversity loss, we encourage thinking outside of disciplinary silos, and to forge research partnerships between health, life, natural and social sciences.

Policy Priority 1: Increased recognition of international trade in biodiversity targets, goals and policy

Our approach highlights the interconnections between biodiversity, agriculture and international trade and provides evidence of a need to advocate for better accounting of system interactions within existing frameworks and policies. Effectively implemented policy plays a major role in regulating harmful agricultural practices, minimising and preventing the threats to wildlife and habitats, and mitigating greenhouse gas emissions. However, policy in the form of trade agreements is also a key driver of biodiversity impacts. For example, soybean trade between China, Brazil and the United States was influenced by changes in tariffs on imported soybeans, market liberalisation, and structural reforms in South America. This system has had significant consequences for the environment, both where land is cleared for cropland, and also for importers who then shift to different crops[19,143–148]. International trade agreements, such as EU-Mercosur, have also had tremendous positive impacts on communities and their livelihoods, and there is an urgent call to transform trade agreements into robust mechanisms that strive for sustainable resource use, and protect the rights of Indigenous peoples, local communities, and the environment[149]. It should therefore be a priority that the role and importance of international trade is well-articulated in major biodiversity and climate change policies, and trade routes that could be beneficial for biodiversity, climate change and communities are explored. This is not always the case, for example, current international, legal and political frameworks related to biodiversity, climate change, and land use, including the United Nations Convention on Biological Diversity (CBD) and the United Nations Framework Convention on Climate Change, do not make the link between deforestation and commodity production and consumption (i.e. trade)[150]. Currently the CBD does not have measures that are directly related to international trade[151], and the Zero Draft of the post-2020 Global Biodiversity Framework that will define biodiversity targets until 2050 only deals with trade in terms of direct exchange of wildlife and their products[152], and not the impacts of the ongoing large-scale trade of commodities. This failure of major policies to recognise the role of both trade and consumers severely hinders efforts to safeguard tropical forests and other ecosystems for biodiversity conservation and climate change mitigation. Policy recognition of the complex role of international trade in food systems is needed to prevent further impacts in countries with high biodiversity where impacts are outsourced due to consumer demand in developed countries, whilst maintaining the benefits that international trade facilitates, including access to food and lower carbon production of certain products than could be achieved elsewhere.

There is still scope for addressing biodiversity as a cross-cutting issue within international trade and climate policies[153]. To address this, the conceptual framework presented here can be used to identify key interactions across biodiversity, agriculture, trade and climate change to inform unifying policies with the SDGs in the forefront. This is particularly relevant since SDG 17 (‘Partnerships for the goals’) is focussed on strengthening the global partnerships that are needed to implement change towards sustainable development. Beyond increasing the number of policies or the addition of relevant text, however, action must be taken to ensure the proper implementation and monitoring of progress toward shared goals.

Policy Priority 2: Increased communication of the impacts of food on biodiversity

Lastly, there is a need to communicate the impacts of food on biodiversity in a meaningful way in order to raise awareness and inform environmental action for both producers and consumers. Communicating the biodiversity impacts of food can be established through the determination and dissemination of information on the specific biodiversity impacts of products[154]; however given the multi-faceted nature of biodiversity, this is no simple task. The research outcomes from Priority 5 (Additional measures of biodiversity in impact analyses) should be used to inform consumers of the 'outsourced' or 'embodied' biodiversity impacts inherent in commodities and that are amplified through international trade and destructive production practises. Research is needed to determine what and how this is communicated, as consumers may not be aware of the full extent of the impact of production. This will require collaboration alongside behavioural economics and psychology to learn more about how information on biodiversity impacts can affect consumer choices, and how consumer perception and culture can also affect what information should be shared. However, this is also a broader policy issue since regulatory measures for food producers, who are being induced to harm local biodiversity within the complex dynamics of world trade, policies, tariffs and economics, will be required. There should be a drive for policy to implement these reporting strategies and support the required research to ensure consumers are provided with the information needed to make informed choices. Therefore, there is a need for partnerships in research and policy to investigate how harmful food production is to biodiversity, and how policy can effectively aid in the fight against biodiversity loss from food production and consumption.

4. Concluding remarks

Biodiversity is a key element of the environment-agriculture-trade system that is not always considered in studies assessing the impact of food production on the environment. Biodiversity is required for effective food production through the provision of essential ecosystem services, the removal of which could have large negative consequences for food production. Certain forms of agricultural and land-use management can promote biodiversity conservation in some situations. More thoughtful consideration of multiple elements within the system and their interactions will enable a bigger picture view of the negative impacts on biodiversity, but also on the benefits that biodiversity can provide to the environment-agriculture-trade system.

The interactions between biodiversity, agricultural production, climate change and international trade have not been completely unstudied. There has been significant progress in connecting biodiversity impacts to trade and agriculture using a variety of tools and methods from multiple disciplines and more studies are starting to look at the climate change impacts on biodiversity, agriculture and their interactions. However, previous studies have tended to treat interactions in isolation, and there is an urgent need for a more comprehensive, integrated approach to estimate the global impacts of food production on the environment. The generation of the environment-agriculture-trade conceptual framework has allowed the identification of some key research gaps around the role that biodiversity plays within the system which needs further consideration in future research.

To address the research priorities established here, further collaborative and interdisciplinary work between researchers will be necessary. Whilst developing a comprehensive approach that can inform both consumers and producers of the impact of agriculture on biodiversity may be challenging, urgent work is needed to stop irreversible biodiversity loss and avert its detrimental effects on food security and sustainable development. Having a better understanding of the interactions within the environment-agriculture-trade system will be essential to meet the SDGs and develop a future food production system that is able to support the demand of a growing human population and to conserve biodiversity.

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Author contributions

Conceptualisation, all authors; Methodology, AMDO.; Writing – Original Draft, AMDO. and CLO.; Writing – Review & Editing, all authors.

Declaration of interests

The authors declare no competing interests.

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Figure titles and legends:

Figure 1: The Environment-Agriculture-Trade Framework: *To understand this system, interactions within the framework must be considered. However, the more interactions that are included, the more complicated the picture becomes. Biodiversity has important effects on factors within this system, driving interactions as well as being impacted by them. The challenge is to incorporate insights from across research sectors (including ecology, climate science, economics) to gain a better understanding of the role of biodiversity in this complex system. Arrows indicate a connection between variables, with a (+) signifying a generally positive effect and (-) a generally negative effect. Colours signify variables that are influenced by biodiversity (green), agricultural production (orange), climate change (blue), by trade, policy and other human pressures (purple), plus drivers of biodiversity change (black).*

Figure 2: The feedback loop between biodiversity and agriculture. *The negative impacts on biodiversity from activities linked to food production such as tillage, and the use of inputs e.g. fertilisers and pesticides are well studied. The services (and disservices) of biodiversity and their role in agricultural systems are also increasingly understood. However, the feedback loop between agricultural production and biodiversity (represented by the grey dashed lines) is not often considered, especially at large scales. The inter-relationships are additionally complicated by landscape-level context (e.g. through the availability of source habitat). A better understanding of the feedback loop between food production and biodiversity will be essential for meeting two major SDGs (2 and 15). Arrows indicate a connection between variables, with a (+) signifying a generally positive effect and (-) a generally negative effect. Colours signify variables that are influenced by biodiversity (green), and agricultural production (orange).*

Figure 3: Interactions with climate change. *Climate change can influence agriculture directly, through changes in the abiotic factors suitable for growing crops or through changes in frequency and severity of extreme weather events. However, climate change can also impact agriculture indirectly via the associated impacts on biodiversity. Therefore, understanding the feedback loop between climate change, agriculture and biodiversity (represented by the grey dashed lines) will be key for meeting future food security and biodiversity targets. Although changes to climate may bring some positive impacts to agriculture, this is generally thought of to be only in the short-term and most impacts are negative. Arrows indicate a connection between variables, with a (+) signifying a generally positive effect and (-) a general negative effect. Colours signify variables that are influenced by biodiversity (green), agricultural production (orange) and climate (blue).*

Figure 4: Interactions with international trade. *Apart from the direct influence of spatially decoupled demand and supply connected by trade on land use, trade in food products can indirectly impact biodiversity through various routes, including change in agricultural production, changes in associated emissions, and the spread of invasive species. It is therefore a key element of the environment-agriculture-trade system and so should be considered where possible, along with its interactions and feedbacks, in studies on the impacts of food production. Whilst climate change may have some positive impacts on food production and biodiversity, on average the effect is expected to be negative, particularly over long timescales. Dashed grey lines represent less well-studied interactions. Arrows indicate a connection between variables, with a (+) signifying a generally positive effect and (-) a general negative effect. Colours signify variables that are influenced by biodiversity (green), agricultural production (orange), climate (blue), and human activities including trade and policy (purple), plus drivers of biodiversity change (black).*