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Sustaining insect biodiversity in agricultural systems to ensure future food security

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An additional threat to sustainable food production, besides climate change, is declining biodiversity, especially in insects. To mitigate this threat, we need to determine the drivers of biodiversity decline. Insect biodiversity decline can be mainly attributed to the intensification of agriculture with the main drivers being habitat loss and use of agro-chemicals. We must view changes to more sustainable practices in agricultural management critically to determine whether these changes will sustain insect biodiversity. The first consideration for farmers is to make a profit and the priority in choosing a certain farming practice will be based on agronomic and economic gains. Damage to crops by insects, pathogens and weeds has always been a major limitation to crop yield and the management of pests, pathogens and weeds is therefore an important consideration. To reach the goal of sustaining biodiversity farmers will have to find a tradeoff between economic gain and protecting biodiversity. They will have to decide how much land they can spare for natural areas and still make a profit. Farmers will also need incentives to consider this. We will have to concentrate more on the restoration of habitats in agricultural lands and find interventions to limit the expansion of land use for agricultural development. This will enable us to reach the goal of the half-earth theory,proposed by Prof E.O. Wilson, where half of the land is conserved to safeguard biodiversity,

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1 Introduction

We are currently faced with not only a challenge in our environment because of climate change, but also an accelerated loss of biodiversity. Humans and our domestic animals, that we raise for food, make up 96% of mammalian mass (domestic animals, mainly cows, pigs and sheep make up 60%) and only 4% of the mass of all mammals on earth is made up of wild mammals (Attenborough, 2022). Wild populations have been declining rapidly as agriculture expanded and intensified. According to the WWF's Living Planet Report 2022 wildlife populations have declined by an average of 69% in the past 50 years (WWF, 2022). Agriculture today covers around 5 billion hectares (Ritchie and Roser, 2019) with around

11% of the Earth's land area devoted to crops, while about 30% is used for grazing (Raven and Wagner, 2021). This means that almost half of all the habitable land on Earth is used to produce food for human consumption. According to the Global Footprint Network (2022) our biggest ecological footprint in 2020, making up 30% of the total, was through the production of food. This agricultural expansion is causing a pronounced change in natural ecosystems. Our attempts to feed the growing human population have left very little space for other species sharing the planet with us and these species cannot survive in the changing environment leading to biodiversity loss.

Insects are vital in agriculture through the ecosystem functions such as pollination, pest control and recycling of nutrients in agricultural soil. Unfortunately, agricultural expansion and intensification has also impacted insect biodiversity severely. Sánchez-Bayo and Wyckhuys (2019) estimated that a third of all insect species are threatened with extinction and Outhwaite et al. (2022) found that the combined effects of climate warming and intensive agricultural land use is responsible for the reductions of almost 50% in the abundance and 27% in the number of species within insect assemblages. Dainese et al. (2019) believe that ecosystem function sustained by insect biodiversity is essential to sustain agriculture and production of food and future food security. The loss of insect biodiversity will therefore have economic and social consequences, and lasting effects on agricultural productivity, impacting future food security. To ensure future food security we will need fundamental changes in our production and consumption of food. To sustain biodiversity in agriculture we will have to first determine and address the drivers of biodiversity loss and set determined goals in conservation and restoration. For sustainable production of food, agricultural systems will have to be managed with biodiversity and diverse ecosystem functions as priorities. In this review the causes of insect biodiversity decline are investigated. The different agricultural production practices are discussed and compared to determine the best practice to mitigate further decline in insect biodiversity (Figure 1).

2 The biodiversity crisis and consequences for food production

Biodiversity is complex and includes genes, organisms, species, and the interactions that keep an ecosystem functional (National Academies of Sciences, Engineering, and Medicine, 2022). Throughout the planet's history species not able to adapt to the constantly changing environment became extinct, new species evolved and populations fluctuated over time, but currently humans are driving a massive loss of biodiversity with around 1 million species under threat, with additional declines in genetic diversity, habitats, and ecosystems (Ceballos et al., 2020). We are either directly or indirectly dependent on plants for our food. In turn plants are dependent on soil-dwelling organisms for nutrient recycling and decomposition services to ensure the fertility that sustains them in agricultural landscapes. There is also a whole host of organisms that manage insect pests and diseases on agricultural crops, and many food crops depend on organisms, mainly insects, to pollinate them. These are the ecosystem services provided by a diversity of organisms interacting and sustaining ecosystems. Insect biodiversity is therefore essential for the proper functioning of all ecosystems and the current loss of this biodiversity will impact these ecosystem services, provided by insects (Aizen et al., 2009). Declining populations will not be able to provide these services effectively and local population declines can cause drastic ecosystem impacts even if the species overall does not go extinct (National Academies of Sciences, Engineering, and Medicine, 2022). If biodiversity loss continues at this rate agricultural systems will be impacted severely leading to food insecurity. Cock et al. (2012) believe that invertebrate species are predominant in the foodwebs and have a major influence on agricultural productivity and consequently food security. According to Samways et al. (2020) when agro-ecological diversity is near-natural, essential ecosystem processes, such as pollination, decomposition, and biological control will be sustained. These processes will sustain agricultural food production and contribute to food security.

Apart from the important role that insects play in agricultural ecosystems they can also contribute to food security as an alternative source of protein. The advantages of using insects as alternative source of protein are their efficiency of feed conversion, nutritional value, easy production, and low content of water use (Grasso and Bordiga, 2023). This will allow the production of protein with less pressure on natural ecosystems. Naseem et al. (2021) believe the production of insect products to be a viable, sustainable, cheaper, and highly nutritive solution to alleviate the burden of crops, improve human health and diet and ensure future food security. Although new processing techniques, product availability and attractive marketing strategies have increased per capita consumption (Naseem et al., 2021), basic methods for production, storage, marketing, processing, distribution, and legislation are still needed before insect use and commercialization as food can become a reality (Grasso and Bordiga, 2023). Insects may also contribute to food security indirectly through an alternative food source in aquaculture. According to Hameed et al. (2022), using insects as a replacement for fishmeal in aquaculture is an eco-friendly approach since insects can potentially recover nutrients from waste aquaculture products, and insects are a natural food source to many fish species.

3 Causes of biodiversity decline

"The conversion of wild habitat to farmland as humankind expanded its territory throughout the Holocene has been the single greatest direct cause of biodiversity loss during our time on Earth" (Attenborough, 2022). It is generally agreed that the decline in insect biodiversity is a result of intensification of agricultural systems (Newbold et al., 2015; Habel et al., 2019; Seibold et al., 2019; Wepprich et al., 2019; Wagner, 2020). Agricultural ecosystems function in completely different ways to natural habitats. Natural habitats are self-sustainable, and communities are self-sufficient and become more complex in structure and more biodiverse with passing time (Figure 2). Industrial agricultural systems are sustained by humans using fertilisers,

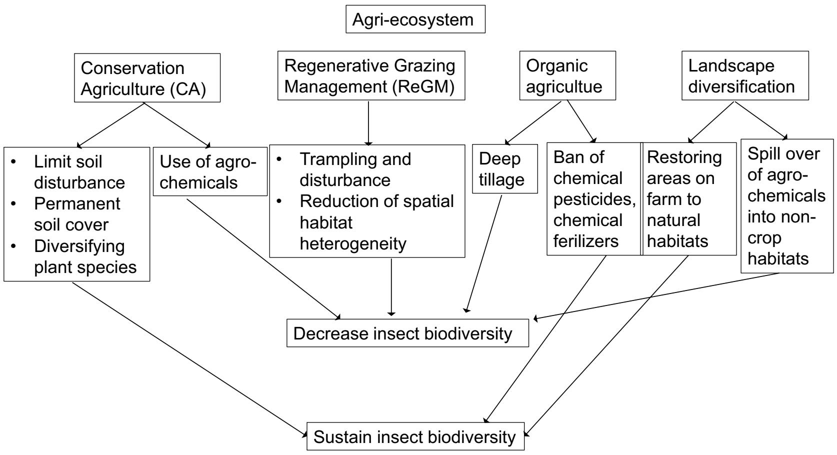

FIGURE 1
Agricultural production practices decreasing or sustaining insect biodiversity.

irrigation, herbicides, and pesticides (Figure 2). These systems are simplified by excluding communities and consequently decreasing biodiversity. The initiation of biodiversity loss is caused by changing the landscape to monocultures, reducing the refuges available for insects, herbaceous plants, vertebrate insectivores and other organisms. Biodiversity loss is then increased by increasing inputs of agro-chemicals (Raven and Wagner, 2021). The main drivers of biodiversity loss in insects are therefore habitat loss and fragmentation, expansion of monocultures and use of agro-chemicals.

3.1 Habitat loss and fragmentation

To provide food for a growing human population agriculture had to be intensified and expanded. The change of land-use to accommodate agriculture causes destruction and fragmentation of natural habitat and is the biggest current threat to natural ecosystems and species (National Academies of Sciences, Engineering, and Medicine, 2022; WWF, 2022). Currently 50% of all habitable land on earth is cleared for agricultural crops and feeding domesticated livestock. When natural habitats are changed to agricultural lands, complex ecosystems with a high diversity of plants are changed to simplified ecosystems with limited plant diversity, which in turn impacts insect biodiversity. Different insect taxa are affected differently with some experiencing elevated rates of loss, while others are not severely affected, and a few are benefitted. Sánchez-Bayo and Wyckhuys (2019) found that in Coleoptera, Lepidoptera and Hymenoptera, land-use change, and landscape fragmentation is the main reason for a decrease in biodiversity. Because of the widespread transformation to agricultural croplands grassland habitats globally has become the most threatened ecosystems exposing the insect taxa of these grasslands to high rates of loss (Raven and Wagner, 2021).

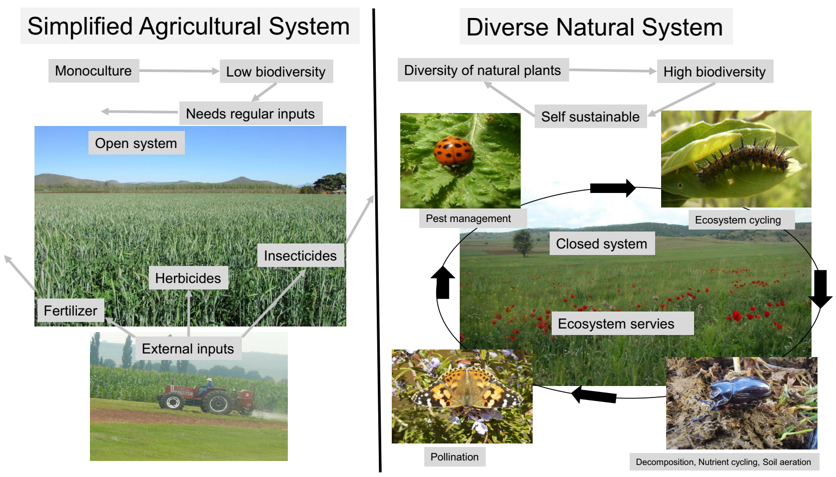

FIGURE 2
Comparison of a simplified agricultural system and a diverse natural system.

3.2 Monocultures

Monoculture is the cultivation of a single variety of a single species, often genetically similar, on a large scale in a specific area. Many insects will be excluded from this system because they are unable to survive in this simplified system, while one or two species will thrive in simplified systems, becoming pests and causing extensive damage to this crop. With the absence of competition and predation in a habitat with an endless supply of suitable food and shelter these insects become dominant leading to a decrease in insect biodiversity in this system. Aizen et al. (2019) believe that dependence on crop monocultures will impact the future food security of the specific country, because of this decrease in biodiversity in a monoculture system.

3.3 Agro-chemicals

Sánchez-Bayo and Wyckhuys (2019) believe that the second major driver of insect declines, after habitat destruction, is the use of agro-chemicals in agriculture. The most important nutrient for plant growth is nitrogen and this is heavily applied in agricultural crops through fertilizers. There is, however, a loss of up to 50% of nitrogen availability for plants in agricultural crops because of nitrification (Beeckman et al., 2018). Water-soluble nitrate is flushed out of agricultural soils in runoff and pollutes the environment. Nitrification from agriculture has been identified as an important driver of insect declines (Wagner, 2020; Wagner et al., 2021).

A large percentage of yield in agricultural crops is lost to damage by pest insects and therefore considerable effort is put into the control of these insects. In most cases chemical insecticides are used, often preventatively, spraying large areas indiscriminately. Chemical insecticides are not target specific and these insecticides will kill all insects in the area. Insecticides are most toxic to all insects and other arthropods, and it is therefore no surprise that insecticides will have a significant and lasting effect on insect biodiversity. Milman (2022) found that the impact of insecticides is severe on insect biodiversity and can also spill over from target areas into natural ecosystems. Ramzan et al. (2021) concluded that management techniques, primarily chemical, in agricultural systems, affected some insect orders adversely that resulted in lower diversity and abundance in these insect orders. Majeed et al. (2022) observed an uneven pest-to-predator ratio and believe that this was a result of heavy pesticide usage.

4 Change in production practices in agriculture to mitigate biodiversity loss

During recent years there has been considerable efforts in agriculture to change production practices to more sustainable practices. Because of the vital role of insects in ecosystems to ensure future food security protecting declining insect biodiversity will be a key priority when considering these changes.

4.1 Conservation agriculture

Conservation agriculture (CA) is characterized by minimum tillage and soil disturbance, permanent soil cover with crop residues and live mulches, intercropping and diversifying plant species (Baker et al., 2006). Practices that are related to conservation agriculture are permaculture, agroecology, holistic management, restoration ecology, Keyline design and agroforestry (Stanojevic, 2021). It is claimed that CA practices result in increased diversity because of groundcover and mulch (Jaipal et al., 2002). The diversification of plants through added cover crops in CA is not necessarily natural occurring plants in the environment and will therefore not necessarily support local insect biodiversity. In CA there is also no restriction on the use of agro-chemicals and does allow farmers to apply synthetic chemical fertilizers, fungicides, pesticides, and herbicides. Many farmers rely on using these to control weed and pest problems. Despite the benefits of groundcover and mulch, since agro-chemicals have a significant impact on insect biodiversity, it is doubtful that this production practice will contribute to sustaining insect biodiversity. The full benefits of CA also take time and this influence farmers to adopt other practices that result in more immediate economic gain (Hobbs, 2007).

4.2 Regenerative grazing management

Regenerative Grazing Management (ReGM) is often combined with CA and is characterized by managing large herds of domesticated livestock on fields for short periods followed by long periods of rest, in an attempt to mimic the migration of natural herds of wild megaherbivores being chased by predators across the African landscape (Savory and Butterfield, 2016). ReGM includes biodiversity as an important indicator of the success of this management practice (Savory Institute, 2019). It must, however, be noted that in ReGM large herds of only domesticated animals with limited genetic diversity are present in the landscape. With these large herds there will also be considerable trampling and disturbance impacting different life cycles of insects in the area. Continuous and uniform disturbance by intense grazing and trampling across the landscape may negatively affect certain communities. This will result in a reduction of the spatial habitat heterogeneity that is necessary to sustain biodiversity (Benton et al., 2003). Raven and Wagner (2021) believe that lightly grazed pasturelands can be rich in successional plant and insect biodiversity. Morris (2021) argues that because of the variable responses within and between taxa the claim of ReGM to increase biodiversity cannot be supported.

4.3 Organic agriculture

Organic agriculture is characterized by a ban of chemical pesticides, chemical fertilizers, growth hormones, antibiotics, and genetically modified organisms (GMOs). It is claimed that organic farming maintains a higher diversity of natural enemies than conventional systems by using practices that are more favorable to natural enemies such as organic fertilization (Garratt et al., 2011) or absence of pesticide use (Theiling and Croft, 1988). Organic farmers, however, rely on alternative strategies to compensate for the absence of chemical pesticides and fertilizers to control weeds, diseases, and pests and to maintain soil fertility. These include more frequent tillage, longer rotations, and sowing of more crop varieties together on the same field at higher densities than conventional farmers (Puech et al., 2014). Organic farmers may frequent and deep tillage, which are allowed by the specifications but are potentially lethal for arthropods. Because of the disturbance to the soil and the effect on ground-dwelling arthropods the claims that organic agriculture contributes to sustaining insect biodiversity cannot be supported. Puech et al. (2014) found that individual farming practices can promote the populations of natural enemies irrespective of whether the practice is conventional or organic and there is not necessarily higher diversity in organic systems.

4.4 Landscape diversification

This is an approach to land management that is characterized by not using all areas on a farm for agriculture and consciously restoring these areas to natural habitats. Non-crop habitats in agricultural landscapes close to crops may benefit natural enemies of crop pests by providing shelter and alternative resources and this may enhance biological control in crop systems (Griffiths et al., 2008; Alignier et al., 2014; Blaauw and Isaacs, 2015; Heimoana et al., 2017). Once established these areas in agricultural landscapes have the potential of supporting biodiversity (Kemmerling et al., 2022). Rare local plants and the associating organisms can be protected by establishment of naturally regenerated margins free from agro-chemicals and competition from crop species (Boatman, 1998). These conserved areas, that are uncropped and unsprayed, present a sustainable habitat for a variety of insects (Chiverton & Sotherton, 1991; Moreby & Southway, 1999). If agro-chemicals are used indiscriminately, however, these chemicals can also spill over into the non-crop habitats and influence the diversity of invertebrates in these areas.

5 Discussion

Instead of proposing new directions in conservation, conservation debate should be concentrated on what is working or not and why (Godet and Devictor, 2018). Farmers choose and follow specific production practices for economic and agronomic gains (Reganold et al., 2011). Damage to crops by insects, pathogens and weeds has always been a major limitation to crop yield and in agriculture the management of pests, pathogens and weeds is an important consideration since this will have a direct impact on yield and subsequent economic gain. Before adapting to individual practices, the whole farming system will have to be considered (Figure 3). Drivers of biodiversity loss must be addressed, natural habitats need to be protected, habitats in agricultural lands and field margins need to be conserved and the use of agro-chemicals will have to be limited (Figure 3). This will result in increased insect biodiversity (Figure 3). By linking agricultural systems with natural systems agricultural landscapes will be improved leading to further conservation of biodiversity, resulting in sustainable and resilient natural systems protecting biodiversity and ecosystem services (Figure 3). This will ultimately result in lower dependence on external inputs, reduced environmental pollution and increased water use efficiency and soil fertility, ensuring our survival under conditions of economic and environmental uncertainty (Figure 3).

Natural fluctuations in populations of different guilds and taxa occur within and between fields. Holland et al. (2008) argues that this can be compensated for by encouraging a diverse range of natural enemies through habitat management and reaching a more effective biocontrol system. Of all the land management practices in agriculture landscape diversification has the greatest potential of

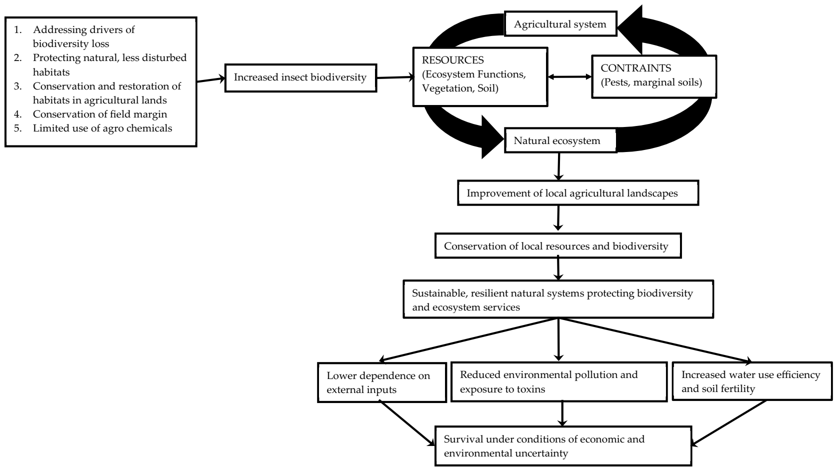

FIGURE 3
Holistic approach to changing of agricultural systems to ensure sustainable systems.

protecting insect biodiversity. The biodiversity in an agricultural landscape will be determined by the structural heterogeneity (Schmidt et al., 2004; Tscharntke et al., 2005), presence of specific taxa in the area, and factors such as landscape context (Fahrig et al., 2011). Abiotic factors may have a major effect on insect diversity and distribution and Majeed et al. (2022) believe that environmental changes and the impact on pest species need to be considered to ensure sustainable agricultural management. Semi-natural habitats in agricultural landscapes will increase the biological control of insect pests because of the presence of local beneficial insects, by providing them with alternative prey and hosts, resources, and refuges for overwintering. Many insect predators do not complete their life cycles in the agricultural fields where their prey occur, but their larvae often feed on a completely different food sources and therefore rely on semi-natural ecosystems to complete their life cycles and survive to adult (Hani and Boller, 1998). Because semi-natural habitats enhance population increase, protecting these habitats in an agricultural landscape will be an effective strategy to increase natural enemies of crop pests (Alignier et al., 2014). When chemicals are used in crop fields it can spill over to the semi-natural ecosystems. Pandey et al. (2022) found that intense insecticide uses in crop fields negated the benefits of adjacent natural vegetation and benefits provided by adjacent vegetation were evident only under conditions of low pesticide use. For this practice to be successful chemical application in the crop fields will therefore have to be limited to only when it is necessary to protect yield. This can be achieved by regular monitoring and only using chemicals when a potential threat is noticed and limiting the application to the specific area affected.

Although semi-natural habitats will protect some taxa this will not be effective to protect all taxa and the complex interactions that occur in undisturbed natural ecosystems. There is a need for more general conservation of arthropods in agricultural landscapes and not only consider some taxa that is of apparent and immediate advantage in agriculture. We will have to consider key ecological traits relating to dispersal capacity and life history of all taxa. Natural communities are formed by consumptive and non-consumptive ecological interactions, but these interaction networks are being changed or eliminated by global warming or biodiversity loss (Wyckhuys et al., 2022). Mountain ecosystems provide answers to how population adaptation to thermal floors shapes the distribution of species globally and show species and context-dependent shifts with altitude. This can shed light on thermal niche space of individual natural enemy taxa overall thermal resilience of biological control (Wyckhuys et al., 2022). Raven and Wagner (2021) believe that the more natural habitats that we can preserve now, the more options we will have in future. To slow biodiversity loss we will have to protect areas where there is no or minimal agricultural disturbance. Our current global system of protected areas, however, has been unable to slow biodiversity loss (Maxwell et al., 2020). Wilson (2016) proposed that the only solution to the accelerated rate of biodiversity loss would be to increase the area of natural land to half the surface of the Earth (Half-Earth). The only way that we can reach this goal is to convert existing cropland to natural areas and link these areas on farms to protected undisturbed areas. Kemmerling et al. (2022) found that converting just 5% of cropland to natural habitat is an effective strategy for conserving biodiversity and can in some cases be implemented without impacting crop yield. The mitigation of reductions in insect abundance and richness resulting from agricultural land use will depend not only on a high availability of nearby natural habitat, but also changing agricultural systems to low-intensity systems. Outhwaite et al. (2022) showed that preserving natural habitat within landscapes and reducing the intensity of agriculture will increase and sustain insect biodiversity. Practicing agriculture in a way to sustain natural areas within or next to agricultural fields will preserve the existing insect biodiversity (Raven and Wagner, 2021). To reach the goal to sustain biodiversity farmers will have to find a tradeoff between economic gain and protecting biodiversity. They will have to decide how much land they can spare for natural areas and still make a profit. Farmers will also need incentives to consider this. South Africa's biodiversity stewardship model, which grants landowners formal recognition of protection of their land while retaining ownership, may provide a long-term solution to sustain local biodiversity. The protected areas of their land will sustain biodiversity and subsequently will provide necessary ecosystem services to the rest of the farmed area (Coetzee, 2023). Agro-ecology in rural areas and greenspace development in cities will also be necessary to improve the fragmentation of landscapes and create functional connectivity and habitats that will sustain insect biodiversity (Samways et al., 2020). Samways et al. (2020) propose the use of tools of insect conservation psychology, which includes education and citizen science to address the lack of sufficient collective political will and concerted effort to mitigate insect biodiversity decline.

6 Conclusion

Insect biodiversity is vital in agriculture and important to ensure future food security. Global insect biodiversity is, however under severe threat and has become a matter of urgent concern. Slowing accelerated biodiversity loss will need determined goals and we will have to identify the main drivers of biodiversity loss to begin addressing this problem. The main drivers of biodiversity loss are habitat fragmentation, monoculturing and the use of agro-chemicals that stem from agricultural intensification to produce enough food for a growing human population. To mitigate the pressure of agriculture on insect biodiversity we need to concentrate on which of the existing practices contribute and identify those that do not instead of proposing new directions. We need to concentrate more on restoration of natural habitats in agricultural lands and less on alternative production practices. Restoration and conservation of natural habitats can in part be achieved by strict human population control, more sustainable consumption, and production practices such as sustainable increases in yield, reduction of waste, and the adoption of a higher percentage of plant-based products in our diets. We then need to prioritize the restoration of land to natural habitats within agricultural landscapes. These interventions will limit the expansion of land use for agricultural development and will leave more land for nature, to reach the goal of the half-earth theory proposed by Prof E.O. Wilson.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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