PAB Pesquisa Agropecuária Brasileira 60 years

COP30
Ecology/ Review

jornada pelo CLIMA #TemQueTerCiência

ISSN 1678-3921

Journal homepage: www.embrapa.br/pab

For manuscript submission and journal contents, access: www.scielo.br/pab

Pollination as an ecosystem service in soybean production for climate change mitigation

Abstract – The objective of this review was to present the benefits of *Apis mellifera* pollination on soybean yield, emphasizing the reduction of greenhouse gas emissions. Several authors have shown that soybean yield is increased by pollination, explaining why supplementary pollination has been adopted by those interested in the integration of soybean and bees. Ecosystem services, biocapacity, and ecological footprints were the concepts used to establish the interrelationships between this integration and crop yield increment using supplementary pollination, highlighting that this technology does not modify the production system. Such analysis supports the logic to calculate the reduction of greenhouse gas emissions per megagram of soybean harvested, aiming to mitigate climate change. The Google Scholar database was used to select the scientific papers used for this review. Results indicate that, to obtain the same soybean production, the required area would be reduced in the same proportion of yield increment, with an additional emission reduction of 0.047 Mg CO_2 equivalent per megagram of harvested soybean. Actions and policies to maximize the adoption of supplementary pollination are proposed, aiming to mitigate climate change, improving the natural ecosystem service of pollination, while incrementing the net income of growers and the production by beekeepers.

Index terms: *Apis mellifera*, *Glycine max*, biocapacity, ecological footprint, food security, GHG emissions.

Polinização como serviço ecossistêmico na produção de soja para a mitigação de mudanças climáticas

Resumo – O objetivo desta revisão foi apresentar os benefícios da polinização por *Apis mellifera* na produtividade da soja, enfatizando a redução da emissão de gases de efeito estufa. Vários autores mostraram que a produtividade da soja é aumentada pela polinização, o que explica porque a polinização suplementar tem sido adotada pelos interessados na integração entre soja e abelhas. Os conceitos de serviços ecossistêmicos, biocapacidade e pegada ecológica foram utilizados para estabelecer as inter-relações entre essa interação e o incremento da produtividade da cultura por meio da polinização suplementar, a qual não o sistema de produção. Esta análise sustenta a lógica para o cálculo da redução das emissões de gases de efeito estufa por megagrama de grãos de soja colhida, a fim de mitigar a mudança climática. A base de dados do Google Academics foi utilizada para selecionar os artigos científicos relevantes para esta revisão. Os resultados indicam que, para obter a mesma produção de grãos, a área necessária é reduzida na mesma proporção do incremento de

Décio Luiz Gazzoni (✉)
Embrapa Soja, Londrina, PR, Brazil.
E-mail: decio.gazzoni@embrapa.br

Clara Beatriz Hoffmann-Campo
Embrapa Soja, Londrina, PR, Brazil.
E-mail: clarabeatriz.campo@embrapa.br

Guilherme Julião Zocolo
Embrapa Soja, Londrina, PR, Brazil.
E-mail: guilherme.zocolo@embrapa.br

Mauricio do Carmo Fernandes
BASF S.A., São Paulo, SP, Brazil.
E-mail: mauricio.fernandes@basf.com

✉ Corresponding author

Received
April 28, 2025

Accepted
July 17, 2025

How to cite
GAZZONI, D.L.; HOFFMANN-CAMPO, C.B.; ZOCOLO, G.J.; FERNANDES, M. do C. Pollination as an ecosystem service in soybean production for climate change mitigation. **Pesquisa Agropecuária Brasileira**, v.60, e04108, 2025. DOI: https://doi.org/10.1590/S1678-3921.pab2025.v60.04108.

produtividade, com uma redução adicional de emissões de 0,047 Mg de CO_2 equivalente por megagarama de soja colhida. Ações e políticas para maximizar a adoção da polinização suplementar são propostas para mitigar as mudanças climáticas e incrementar o serviço ecossistêmico de polinização, aumentando a renda líquida de produtores e a produção de apicultores.

Termos de indexação: *Apis mellifera*, *Glycine max*, biocapacidade, pegada ecológica, segurança alimentar, emissões de GEE.

Introduction

The leading factor of climate change is the greenhouse gases (GHG) emissions (Filonchyk et al., 2024). These emissions affect almost all economic and social aspects of human life on our planet (Carleton & Hsiang, 2016).

Climate change is rising at an accelerating pace and, therefore, it represents a serious threat to food security and the achievement of the Sustainable Development Goal number 2 (Zero Hunger) (Mugambiwa & Tirivangasi, 2017; United Nations, 2025) because of the increasingly frequent and extreme weather events (Saleem et al., 2024). The impact can be direct, like excess or lack of water supply, higher temperatures, typhoons, and similar events (IPCC, 2023).

Agriculture depends on ecosystem services, which are also negatively affected by adverse climate conditions, as mentioned by Locatelli (2016) and Maia et al. (2018). Kumar et al. (2022) discussed the intricate link between biodiversity, ecosystem services, and biocapacity affected by climate change and threatened by our ecological footprint, while Settele et al. (2016) stated that climate change will pose diverse challenges for pollination, exacerbating other threatening factors. Otieno et al. (2022) mentioned that the registered increasing greenhouse gas emissions (GHG) is linked to the disruption of ecosystem services, though the ozone and carbon dioxide impacts on pollination services are not well understood. However, Farré-Armengol (2016) found that high ozone concentrations in the atmosphere caused fast degradation of *Brassica nigra* floral scent, with increasing distance from the scent source, reducing the range over which flowers can be identified by pollinators.

About 87% of the world's wild flowering plants are pollinated by insects and other animals (Basu & Cetzal-Ix, 2018; Zattara & Aizen, 2021); more than three quarters of the leading types of global food crops at least partially benefit from biotic pollination; and estimated one-third of global food supply is directly benefitted from biotic pollination (Potts et al., 2017). These last authors provided a comprehensive review, reporting the increment of crop yield and quality directly promoted by pollination.

Despite the importance of pollination to the world's crop production, no study could be found investigating the reduction of GHG emissions due to pollination, according to the Google Scholar database. The present review aimed to fulfill that lacuna, and its rationale is presented (Figure 1). Four major anchors were selected (food security, soybeans, climate change, and supplementary pollination) because of their central importance to establish the intricate relationships with other factors.

Food security means that all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their food preferences and dietary needs for an active and healthy life. Over the coming decades, a changing climate, growing global population, volatile food prices, and environmental stressors will put significant pressure on food security (IFPRI, 2025). According to Ranganathan et al. (2018), feeding 10 billion people sustainably by 2050, as compared to 2010, requires: a) 56% more food production; b) incorporation of additional 593 million hectares; c) reduction of 11-gigatonnes of GHG emissions for preventing the worst climate impacts on food production. According to the data compiled by Potts et al. (2017), both natural and supplementary pollination can strongly help to reach those requirements, though reducing the area required for food production due to its production-enhancing effects.

Soybean is part of the world food security, with an estimated harvest of 421 million tonnes (Mt) in 2025 (United States, 2025b), with projections of about 770 Mt for 2050 (Gazzoni & Dall'Agnol, 2018). Soybean is an important source for feed and food, and a major source of edible vegetable oil and protein, playing an important role in maintaining balanced dietary nutrients for human health, as stated by Guo et al. (2022). Soybean yield can be sustainably increased up to 20% through supplementary pollination by bees (Gazzoni & Barateiro, 2023), but both soybean cultivation (Zhu et al., 2024) and bees (Zapata-Hernández et al., 2024; DeGrande-Hoffman et al., 2025) can be adversely affected by climate change, resulting in a declining pollinator population (Vasiliev & Greenwood, 2021).

The biotic pollination is one of the ecosystem services (Porto et al., 2020) provided by pollinators belonging to the biodiversity, which is an essential component of the biocapacity that, in turn, has to absorb the ecological footprint (Lazarus et al., 2015). This is the nexus (Figure 1) connecting the need to produce more food (food security), while reducing the ecological footprint by using sustainable technologies like pollination (one of the ecosystem services), and reducing the emissions of greenhouse gases responsible for the climatic change, thus avoiding adverse impacts on the biocapacitiy, biodiversity, ecosystem services, and food production. To achieve these benefits, good agricultural practices should be adopted by growers, incentivized by public policies, resulting in benefits to the growers, consumers, and to the environment.

The objective of this review was to present the effects of *Apis mellifera* pollination on soybean yield and its benefits for growers, beekeepers, and the environment, emphasizing the reduction of emissions of greenhouse gases.

Materials and Methods

This review was performed using the database of Google Scholar (GS) (2025). Initially, the database was used for studies relating natural or supplementary pollination with of greenhouse gas emissions, either on soybean or other crops. The search was unsuccessful, and no study was retrieved.

To estimate the amount of GHG reduction of emissions, due to the use of a combination of natural and supplementary pollination on soybean, the interrelationships involving pollination and associated parameters were firstly established by linking the concept of ecosystem services to food security, highlighting important searching keywords like "supplementary pollination", "climate change" and "soybeans". Other important parameters selected were "biodiversity", "biocapacity", "ecological footprint", "declining pollinator population", and "good practices", together with "GHG emissions", "GHG sequestration", "public sector", and "private sector". Several references showed overlapping between the keywords and were retrieved more than once.

The rationale of the review was the assessment of the concepts of each parameter considered, for a

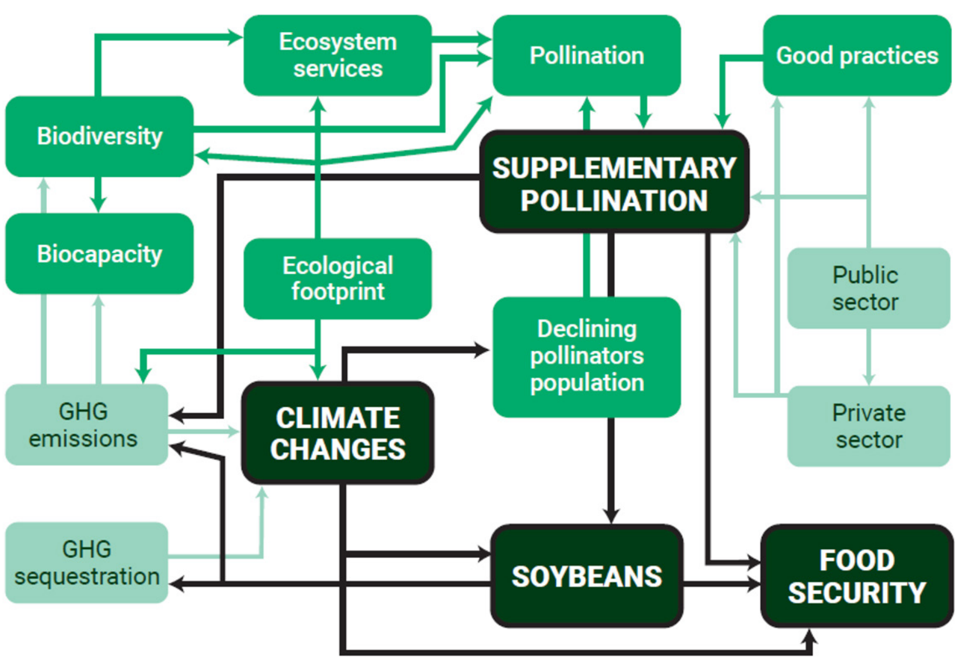

Figure 1. Interrelationships of factors affecting the link between climate change and food security.

DOI: 10.1590/S1678-3921.pab2025.v60.04108

concise explanation about each one of them, to clearly disclose the network of linkage among them. The relation between GHG emissions and climate change was reviewed, and the search on the GS retrieved 2,530,000 results, 33 of which were selected, and 14 were used for reviewing. Following, search was carried out for ecosystem services, classification, and main conceptual terms, including biodiversity − responsible for the majority of the services −, biocapacity, and ecological footprint. The database search retrieved 393,000 results, out of which 63 were considered the most relevant ones, and 42 articles were reviewed.

For the pollination ecosystem service, the search identified 145,000 references, and 74 were considered relevant, from which 43 were selected to be included in the review. Then, the soybean development and reproduction, including visitation of bees to flowers and pollination, were reviewed, and the search on GS identified 713,000 references, from which 82 were selected, and 57 were used for reviewing the subject.

For supplementary pollination and reduction of GHG emissions, mainly on soybean, 18,900 articles were retrieved, from which only five were selected for the review. The estimation of saved GHG emissions by using supplementary pollination was calculated using data on soybean production and yield (Conab, 2025), GHG emissions attributed to soybean cultivation (Balanço…, 2022), emissions attributed to land-use change (LUC) (Garofalo et al., 2022; Embrapa Meio Ambiente, 2025), and soybean yield increase due to supplementary pollination (Garibaldi et al., 2021).

Analysis of the intervenient factors

Greenhouse gas emissions and climate change

In 2018, the Special Report on Global Warming of 1.5ºC (SR15) was published by the Intergovernmental Panel on Climate Change (IPCC, 2018). The report, prepared by 91 authors from 40 countries, includes over 6,000 scientific references. It was delivered at the United Nations' 48th session of the IPCC, to convey an authoritative, scientific guide for governments to cope with climate change. Its key finding is that to meet the target of 1.5ºC increase above pre-industrial levels, it undoubtedly requires deep emission reductions and rapid, far-reaching, and unprecedented changes in all aspects of society.

The Paris Agreement of the United Nation Framework Convention for Climate Change (UNFCCC, 2025) is a mandatory international treaty, established by world leaders, aiming to reduce GHG emissions and adaptation to climate change. Adopted in 2015, during the COP 21, and entered into force in 2016 (UNFCCC, 2016), the treaty established the target limit for temperature increase at 1.5°C above pre-industrial levels. The following editions of the Conference of the Parties (UNFCCC, from COP 22 to COP 29, reinforced and deepened the statements of the Paris Agreement.

The IPCC report and further discussions at the different COP editions alerted that limiting global warming to a 1.5°C increase, in comparison with 2°C increase, would reduce challenging impacts on ecosystems, human health, and well-being. Conclusions were that 2°C temperature increase would exacerbate extreme weather, rising sea levels, diminishing Arctic sea ice, coral bleaching, and loss of ecosystems, among other impacts. It also mentioned a negative effect on food security, since the rise of the frequency and intensity of extreme events, would reduce yields in almost all producing countries, thus affecting the food supply and increasing the price of food.

Less than five years after the IPCC report presentation, in February 2024, the 1.5°C global warming threshold was breached for a full 12 months for the first time, according to the EU's Copernicus Climate Change Service (Copernicus, 2025a). Likewise, the World Meteorological Organization reported that 2023 was the warmest year on record, reaching the global average near-surface temperature established at 1.45°C (with a margin of uncertainty of ± 0.12°C) above the pre-industrial baseline (WMO, 2024; NOAA, 2025).

In 2024, the record of average annual temperature was broken again (NOAA, 2025), with the Earth's average temperature being 1.29°C higher than the 20th-century average, and the global temperature exceeded by 1.46ºC the pre-industrial (1850–1900) average (WMO, 2024; NOAA, 2025). January 2025 was 1.75 ºC above the pre-industrial levels and was the 18th month, in the last nineteen months, for which the global average surface air temperature was more than 1.5ºC beyond the pre-industrial levels (Copernicus, 2025b). February 2025 was the third warmest February globally (Copernicus, 2025c). Above all, since 1850, the 10 warmest years on the planet have all occurred in the last 10 years, starting in 2015 (NOAA, 2025). To limit the progression of climate change, emissions of greenhouse gases (GHG) must be reduced. One of the tools that can help assure food security with a lesser amount of GHG emissions is the use of ecosystem services, as supplementary pollination, for food or fiber crops, reducing the area required for production, or avoiding the deforestation of new areas.

Ecosystem services, classification, and main conceptual terms

Ecosystem services are the benefits to citizens and the whole society obtained from the natural ecosystems (Hernández-Blanco et al., 2022). Humanity has benefited from them for millennia. However, only after the approval of The United Nations Convention on Biological Diversity (CBD), on June 5, 1992, during the Earth Summit in Rio de Janeiro, RJ, Brazil (Convention…, 1992) this concept was embedded in international agreements and national public policies, so the global society became progressively aware of its importance for life on the planet (Griggs et al., 2013).

On this ground, individual countries or regional blocs proposed and implemented several actions to preserve or halt the degradation of ecosystem services (Maes et al., 2016). At the international level, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) was established to strengthen the science-policy interface for biodiversity and ecosystem services, for the conservation and sustainable use of biodiversity, long-term human well-being, and sustainable development (IPBES, 2025).

Several countries are assessing the economic value of ecosystem services, and incorporating these values into accounting and reporting systems, as well as evaluating how they are impacted by climate change (Scheiter, 2019). Balvanera et al. (2017) considered that this approach can be efficacious for making decisions on using and managing planetary resources, especially when trade-offs and synergies need consideration. As pointed out by Egoh et al. (2012), the availability of information, datasets, and assessments to measure the advances toward goals for ecosystem services is paramount to support effective decision-making for the sustainable use of natural resources.

Among ecosystem services, regulating services — such as climate regulation (Cohn, 2017), pest control (Dainese et al., 2017; Deutsch et al., 2018; Perennes et al., 2023), water purification (La Notte & Dalmazzone, 2018; Wall et al., 2018), and particularly pollination (Garibaldi et al., 2016; Hipólito et al., 2018; Porto et al., 2020) — are critical to agriculture (Breeze et al., 2016). Pollination is essential as it directly influences crop productivity (Tamburini et al., 2019; Bishop & Nakagawa, 2020), stability (Bishop et al., 2022), and quality (Fijen et al., 2018). The sustainability of agriculture can be improved by integrating the management of ecosystem services, such as insect pollination, into farming practices. Bees and other pollinators significantly enhance agricultural yields (Garibaldi et al., 2017), which shows the importance of sustainable agricultural practices, aiming to maintain and protect these ecosystem services to ensure global food security (Rehman et al., 2022) and economic well-being (Hausmann et al., 2016).

Ecosystem services are categorized into four main types (Hasan et al., 2020), as follows:

a. **Provisioning**: Tangible products obtained from ecosystems, such as food, fresh water, timber, fiber, wood, bioactive molecules, and genes. Examples of food are cultivated or noncultivated plants, fodder, and animal species that provide meat, milk, and eggs. Other products are fisheries and other aquatic organisms, biofuels, and hydropower generation.

b. **Regulating**: Includes climate regulation, pest control, water purification, and pollination. This category also encompasses the carbon stored over the long term in vegetation and carbon taken from the atmosphere via photosynthesis. Marine and freshwater quality regulation, soil erosion, soil fertility regulation, flood regulation and coastal protection, and biological nitrogen fixation are other regulating services. One of the most important regulating services is pollination, whose agents are bees, bats, birds, and other animals that pollinate cultivated species or natural vegetation, contributing to increased yield, quality, and stability of food supply.

c. **Cultural**: Nonmaterial benefits conquered by people through recreation, cognitive development, spiritual enrichment, reflection, and aesthetic experiences. There are boundaries between these services of social and economic aspects, like a landscape with aesthetic characteristics appreciated by the people. Nature-based tourism and open-field recreation (hiking, angling, cycling, birding, swimming, diving, etc.) are also included in this category.

d. **Supporting**: Services necessary for supporting other ecosystem services, like nutrient cycling, soil formation, and primary production. Soil formation and nutrient cycling are essential for primary production and for providing wildlife habitats. This category also includes fruit and seed dispersal − an important topic for genetic and biological diversity.

Ecosystem services are frequently associated with one or more living agents. Mace et al. (2012) remark that biodiversity is related to ecosystem services through many mechanisms operating at different spatial frameworks. Cardinale et al. (2012) add that biodiversity regulates the state, the rates, and the stability of ecosystem processes. According to Hristov et al. (2020), the pollination service is strongly associated with biotic agents, especially bee species, as referred to in the review performed by Khalifa et al. (2021).

Biocapacity is conceptualized as the amount of renewable resources made available by the biosphere's regenerative capacity in a given time frame, usually one year (Świąder et al., 2020). It represents the biosphere's regenerative capacity, an aggregate of the production of various ecosystems in a given area, mainly arable land, pasture, forest, productive sea, and rivers. The biocapacity of the Earth increases with a higher biomass productivity per unit of area (Sarkodie, 2021; Wackernagel et al., 2005). It is expressed in global hectares (gha) per person, which is a standardized unit that represents the average global productivity (agriculture, pastures, cultivated forests, fisheries, etc.) and the absorptive capacity for waste, for instance, the greenhouse gases (GHG). The present estimate of the average planetary biocapacity is 1.6 gha/person (GFN, 2025b).

Biocapacity and ecological footprint calculator tools were developed by the Global Footprint Network (GFN) and used worldwide in sustainability studies (GFN, 2025c). Biocapacity, used together with a corresponding ecological footprint, is a measuring method for the human impact on the environment, depending on natural conditions and prevailing land use, farming, and husbandry technologies. Agricultural production can generate different forms of pressure on biodiversity, ecosystems and their services, chiefly changes in land use, water depletion and pollution, loss of biodiversity, and greenhouse gas emissions, as deeply analyzed by Brunetti et al. (2019).

Biocapacity can be improved by incrementing the yield of its components, as conceptualized by Guo et al. (2017), and pollination is one of the factors that improve crop yield (Woodcock et al., 2019), consequently expanding the biocapacity (Bilal & Ali, 2025), while reducing the ecological footprint.

Conceptually, ecological footprint (EF) is closely associated with ecosystem services and biocapacity, meaning how much of the biosphere's regenerative capacity is occupied by human activities (Schaeffer et al., 2006). Thus, similarly to biocapacity, the EF expresses the consumption of renewable resources (crops, animal products, timber, fish, etc.), the result of the consumption of energy, and the use of built-up areas in standardized units of biologically productive areas (gha/person).

EF is the total area required to produce food and fiber for the consumption of a given population (community, municipality, country, world), the resources to absorb its waste, and the space for its infrastructure. As people consume resources and ecological services from different parts of the world, their footprint is the sum of these areas, wherever the location is (Wackernagel et al., 2005).

In 2024, the calculated global EF was 2.74 gha/person. Every year, the GFN announces the Earth Overshooting Day (EOD) to represent the day of the year on which biocapacity was exceeded (GFN, 2025a). The first calculation occurred in 1972, and the EOD fell on December 30, meaning the global society only operated on the negative side for two days. However, in 2024, the date was August 1, so the Earth exceeded its biocapacity and overdrew for 152 days. Thus, over the last 52 years, global society has been inexorably crossing, earlier and earlier, the dangerous limits of the capacity to regenerate natural resources. To illustrate this fact, in 2024, the use of natural resources was equivalent to 1.74 planets, 74% above the renewal capacity of Earth.

The pollination ecosystem service

A flowering plant can be highly, partially, or not dependent on pollination, while some partially or not dependent ones can benefit from supplementary pollination. According to the IPBES report (Ferrier et al., 2016), pollinator-dependent crops contribute about one-third of global crop production. The IPBES estimated that 75% of the globally most consumed food crops rely to some extent on animal pollination. Moreover, 87 out of the 115 main crops grown worldwide depend, to some degree, on biotic pollination to produce fruits, grains, and seeds, according to Klein et al. (2007). Indeed, nearly 90% of wild flowering plant species partially depend on biotic-mediated pollination (Ollerton et al., 2011).

Gallai & Vaissière (2009) provided guidelines for the monetary evaluation of pollination services. Porto et al. (2020) examined 100 articles published in scientific journals with that approach and summarized the annual economic value of pollination services for some crops globally. Furthermore, these authors identified the most relevant studies on a global scale, and, after updating them for inflation up to 2020 values, for the following reports: a) US$206 billion, Costanza et al. (1997); b) US$324 billion, Pimentel et al. (1997); c) US$210 billion, Gallai et al. (2009); d) US$387 billion, Lautenbach et al. (2012); and e) US$195 billion, Bauer & Wing (2016). In their conclusion, Porto et al. (2020) considered that most of the estimates represent only a fraction of the actual global food production attributed to animal pollination and can, therefore, be considered as an assessment of the gross overall monetary value of animal pollination services.

Potts et al. (2010) alerted about the global pollinator decline, consequently reducing the ecosystem service of pollination, with serious consequences for agricultural production and food supply, along with environmental negative impacts. Dicks et al. (2021) warned that food security is closely linked to pollinators, as an estimated 75% of the food crops depend on biotic pollination, especially for fruit production (Singh & Adhikary, 2021).

Although it is highly benefited from the adequate offer of pollination services, agriculture is considered one of the main factors responsible for pollinator decline because of the expansion of crop cultivation and husbandry, and consequent deforestation, besides the use of non-selective pesticides (Dicks et al., 2016). A further important factor is the reduction or fragmentation of habitat, due to other economic activities like industry, infrastructure, and the expansion of urbanized boundaries.

The proportion of pollinator-dependent crops grown globally is continuously increasing, as reported by Aizen et al. (2009). Thus, if potential yield ceilings are not approachable due to a deficit of pollination, then additional area will be required, as well as more seeds, pesticides, fertilizers, energy, and irrigation, to adequately supply the food demand, meaning higher GHG emissions, turning the climate emergency even more severe.

Pollination deficit occurs when inadequate pollen transference limits the sexual plant reproduction (Smith et al., 2022). High pollinator demand and low pollinator availability mean a crucial pollination constraint, reducing the yield of pollinator-dependent crops (Webber et al., 2020). This constraint raises concerns regarding potential risks to global food security and economic development, where, to a high proportion, the economy depends on agriculture (Kluser & Peduzzi, 2007).

A supplemental pollination, provided by managed bees, might overcome an estimated global yield limitation of 34% because modern agriculture is becoming increasingly pollinator-dependent, according to Sáez et al. (2022). However, the global population of domesticated honeybees is growing more slowly than the demand for supplementary pollination (Mashilingi, 2022), concomitantly with the worldwide decline of wild bees.

There is no doubt that urgent actions are required to reverse the present pollinator decline trend. Nevertheless, in the meantime, the global society should focus on technologies and attitudes to mitigate the adverse impact of the pollination deficit. In this sense, managed honeybees represent the most economically important pollinator for a wide variety of crops (Calderone, 2012; Aslan et al., 2016; Hung et al., 2018, 2019; Hristov et al., 2020).

Apis mellifera is the most abundant crop pollinator on a global scale (Garibaldi et al., 2012; Hung et al., 2018). Other species of managed bees, predominantly stingless bees (Chévez et al., 2023), are also becoming important in overcoming pollination deficit or providing pollination in special conditions (Dicks et al., 2021), like closed environment agriculture, as mentioned by Dorin et al. (2018) and Zhang et al. (2022a). Nevertheless, honeybees have been always recognized as the most important pollinators for their highly developed social behavior, generalist diet, and

DOI: 10.1590/S1678-3921.pab2025.v60.04108

large populations (Free, 1993; Partap, 2011), being widely used for supplementary pollination (Morse & Calderon, 2000; Allsopp et al., 2008; Zhang et al., 2022b).

Moreover, managed bees are good indicators of environmental health (Mair et al., 2023), and all the practices to preserve them will benefit feral bees which, in turn, will also help reverse the pollinator decline, as proposed by Hall & Steiner (2019) and Zabala (2019). Then, it is obvious the importance of spreading the use of managed bees to surpass the limitation on the availability of the ecosystem service of pollination, which presently constrains agricultural yields as determined by Turo et al. (2024).

Soybean development and reproduction

Soybean − *Glycine max* (L.) Merrill – a species that presents countless and varied uses − is the fourth most important crop at the global level. Soybean grains contain about 20% oil and over 35% protein, which characterizes it as a highly valuable oil and protein-producing crop worldwide, according to Qin et al. (2022) and Martignone et al. (2024). In 2025, estimates of world soybean production reached 420 million tons, produced on about 150 million hectares (United States, 2025a). Brazil (40%), USA (28%), Argentina (12%), and China (5%) are the top soybean producers, comprising 85% of the total production. Other countries with significant soybean production are India, Paraguay, Canada, Russia, Ukraine, and Bolivia. The expectation is that the demand for soybean will continue to grow in the forthcoming decades, highlighting the importance of increasing its sustainable yield, to avoid undesirable area expansion (Gazzoni & Dall'Agnol, 2018).

Soybean cultivars can either hold a determinate or an indeterminate growth habit. Determinate cultivars stop their vegetative growth at the beginning of the reproductive phase, while indeterminate ones continue to grow during part of this phase. The blooming period of soybean responds to several genetic, physiological, management, and environmental factors. The determinate cultivars usually flower for 15 days, and indeterminate ones bloom for up to 30 days, overlapping with pod set and pod filling stages (Gazzoni, 2016). A longer blooming period (indeterminate cultivars) furnishes more resources to bees visiting soybean flowers.

Information in the scientific literature states that soybean is a naturally cleistogamic, self-pollinating plant (Gazzoni, 2016). Therefore, when the flower opens, the pollination cycle has been completed (Ellatar et al., 2021). Though several authors mentioned self-pollination, the occurrence of cross-pollination was also recorded. The pioneer studies indicated cross-pollination rates on soybean to be from 0.04% to 3.62% (Woodhouse & Taylor, 1913; Woodworth, 1922; Cutler, 1934; Riede, 1935). However, at the same time, beekeepers often reported that honeybees produce significant amounts of soybean honey (Hambleton, 1936; Milum, 1940; Johnson, 1944; Pellett, 1947, 1976; Davis, 1952; Jaycox, 1970), indicating active foraging for nectar and pollen collection on soybean flowers. Additionally, van der Linden (1981) reported that 97% of honey samples analyzed in Iowa contained soybean pollen, indicating that bees were largely foraging on soybean.

With the alarming evidence of the decline of pollinators, the interest in maintaining bees and the necessity for improved yield and agricultural sustainability has increased. Many authors reported increases of soybean yield from 8% to 35% by the action of pollinators (Chiari et al., 2005, 2013; Milfont et al., 2013; Santos et al., 2013; Blettler et al., 2018; Santone et al., 2022; Gazzoni & Barateiro, 2023). Additionally, a meta-analysis carried out by Garibaldi et al. (2021) pooled together data from 23 contrasts (open field, enclosures with and without bee hives, etc.), obtained in five soybean-growing countries (Argentina, Brazil, Cameron, Uruguay, and the United States), indicating that soybean yield improvement reached 21% average, surpassing genetic and other management strategies employed in Brazil, Argentina, and the USA to get higher yields.

Some authors reported that the low number of pods, associated with the previous number of flowers, might be attributed to a pollination deficit, thus reducing soybean yield (Free, 1993; Delaplane & Mayer, 2000). In a controlled environment, only 33% of the soybean flowers were pollinated up to 3.5 hours after the onset of the light photophase, contrasting with 58% at 6.5 hours after the artificial dawn (Robacker et al., 1983). Forrester et al. (2024) found large populations of bees in soybean fields, verifying that temperature had no significant effect on bee activity, but bee activity differed significantly between soybean varieties,

DOI: 10.1590/S1678-3921.pab2025.v60.04108

suggesting that soybean attractiveness to honeybees might be dependent on varietal characteristics. These results are a sound indication that pollination continues after the anthesis of the flower, a cue for the success of supplementary pollination.

In conclusion, studies showed that even though soybean can be considered a self-pollinated crop, it is not entirely cleistogamic, and the stigma of the soybean flower remains receptive for a time lapse of several hours after the flower anthesis, allowing for a successful biotic pollination, notably by bees. Accordingly, many authors classified soybean as a crop partially dependent on pollinators, implying that an improvement of the crop yield can be achieved by entomophilic pollination (Klein et al., 2007; Gallai et al., 2009; Giannini et al., 2015, 2020; Bergamo et al., 2021). Soybean cultivars that were cropped according to the best location for their maturity group seemed to elicit the most intense bee/flower interactions, which can be associated with volatile emissions to guide the pollinators, according to Erickson (1984). These results suggest that soybean flowers actively attract honeybees for pollination, and that cross-pollination is likely to occur before flowers are self-pollinated later in the day (Erickson, 1984).

Honey bee waggle dances recorded during soybean bloom showed that honey bees preferred soybean fields for foraging over other habitat types (Lin et al., 2022). In Brazil, Chiari et al. (2005) found higher soybean yields in a comparison between caged plots without honey bees to one with a beehive inside (51%–57%) and to uncaged plots (48%); they repeated the study (Chiari et al., 2013), and the increases of yield were 38% (caged plot with beehive/without beehive) and 41% (open plot/caged plot without beehive). Milfont et al. (2013) obtained increases of up to 18% of soybean yield, comparing different strategies for favoring soybean pollination by bees. Based on a three-year study, Gazzoni & Barateiro (2023) found soybean yield increases ranging from 8% to 18%, with 13% overall average.

In Argentina, Blettler et al. (2018) observed 18% yield increase due to bee pollination of soybean flowers. Garibaldi et al. (2021) performed a meta-analysis of 16 papers retrieved from the literature using the keywords "soybean" and "pollinator". These authors observed 21% average yield increase. Such a figure surpasses genetic and other management strategies to obtain increased soybean yield in Brazil, Argentina, and in the USA. In their results, these authors pointed to a large distribution of rates of yield increases, reaching up to 57.7%, showing the availability of solid scientific data to support the close association between soybean yield and bee pollination.

In the long run, the collection of soybean nectar by honeybee populations will result in a sound payback for soybean growers by considerably increasing soybean yield. Overall, it is essential to remember that the biocapacity of the Earth increases with a higher productivity per unit of area (Wackernagel et al., 2005), which is a comprehensive example of the importance of the soybean yield increases by supplemental pollination to expand the biocapacity and reduce the ecological footprint, while helping to assure the food security and mitigate the climate change.

Public and private institutions in Brazil are encouraging soybean producers to continuously improve technologies and develop even more sustainable production systems. In this context, the harmonious integration of wild or managed bees with soybean farms is paramount because soybean production is getting constantly closer to native bee repositories or managed apiaries (Gazzoni, 2016). In addition, beekeepers place their beehives close to farms, allowing honeybees to forage on soybeans (Gazzoni, 2016) to obtain higher honey production.

Soybean cropping closer to natural habitats shows higher yields (Kremen et al., 2002; Morandin & Winston, 2006); and, according to Klein et al. (2007), this is one of the main attributes attracting diverse pollinators in higher abundance. However, a set of good practices needs to be implemented, before harmoniously integrating soybean cultivation with feral or managed bees.

Among the several good practices, the most important ones are linked to pest control, as chemical pesticide usage may directly affect bees visiting soybean flowers, or nesting/foraging on neighboring sites (Walker & Wu, 2017). This way, adherence to the recommendations of the Integrated Pest Management (IPM) practices and the strict observance of the technologies for pesticide application are considered utmost for the harmonious integration of bees and soybean cultivation. In parallel, soybean stinkbug-tolerant cultivars were developed (Block platform) (Embrapa, 2025), reducing the use of pesticides, facilitating the integrated pest management, and increasing the harmony and coexistence with bees. Cultivars with this technology show improved yield and good quality seed, alongside less foliar retention and green stems, in comparison with the standard for yield and development cycle, when growing in the same environmental conditions and subjected to a similar stinkbug population (Arias et al., 2022). Moreover, in the areas with Block technology, the insecticide application can be delayed or even not used, considering the high-tolerance of plants to stinkbug damage, thus reducing possible adverse impacts of pesticides on bees visiting soybean flowers or nesting/foraging in the vicinity.

In Brazil, the government of Paraná state, Brazil, was the first one to officially adopt a protocol of good practices, to allow of bees and agriculture integration, to guide extension, technical assistance, and phytosanitary regulation agency activities (IDR-Paraná, 2024). The protocol was also adopted by private and third-sector institutions as a directive for their technical assistance.

Supplementary pollination and reduction of GHG emissions

Due to the severe impact of climate change on food production (Leal Filho et al., 2022), it is no surprise that the FAO Food Price Index (FFPI) averaged 127.1 points, in March 2025 (FAO, 2025), which is up 2.0 points (1.6 percent) from the January level, and 27.1 points over the baseline (2014 - 2016 = 100). The surge in the FAO index indicates the urgent need for prompt actions from governments and the whole society, to guarantee food security for all in the coming years and decades.

To overcome the food price rise, one of the possible solutions is to increment the ecosystem service of pollination and implement supplementary pollination on dependent and benefitted crops, aiming to increase crop yields without any additional land area, and using the same amount of inputs (seeds, fertilizers, pesticides, energy, etc.) that would be used without the application of this technology.

The required good practices, especially integrated pest management (IPM) and all its tactics (biocontrol, insect-pest-tolerant genotypes, no spraying insecticides during blooming period), higher use of bioinputs, and correct pesticide application technology will safeguard the feral pollinators, especially bees, providing a further increase of the pollination service. Carnevalli et al. (2024) published the implementation of the IPM technology results in Paraná state, Brazil, from 2014 to 2024. The results indicated a reduction of 53% of insecticide application for pest control (1.7 applications for IPM adopters versus 3.6 for nonadopters), with an equivalent (53%) reduction of application costs, with growers harvesting equivalent soybean yields in both situations. Additionally, the authors observed a delay of 26 days for the first insecticide application (47 versus 73 days), which is essential to avoid insecticide application during soybean blooming, escaping from adverse effects upon bees visiting soybean flowers.

The nongovernmental organization Solidaridad calculated the GHG emissions of 50 soybean farms located in the region called MATOPIBA in Brazil (Balanço…, 2022). According to its base scenery, the estimated total emissions were 0.97 t CO_2-equivalent ha^{-1} per year, not considering land use change (LUC). The average soybean yield for the monitored farms was 3,480 kg ha^{-1}, with estimated emissions of 0.28 Mg CO_2-equivalent Mg^{-1} of soybean produced.

The emission rate associated with LUC for soybean, using the BR-LUC approach (Embrapa Meio Ambiente, 2025), was calculated to be 2.3 Mg CO_2 ha^{-1} per year, as an average for Brazilian conditions (Garofalo et al., 2022).

On meta-analysis of supplementary pollination studies with *A. mellifera* in soybean farms, Garibaldi et al. (2021) found a range of yield increases from 6.4% to 57.7%. Several other authors found results showing soybean yield gains about 15% to 25% (Monasterolo et al., 2015; Blettler et al., 2018). Studies conducted at Embrapa Soja (Chiari et al., 2005; Gazzoni & Barateiro, 2023) resulted in yields from 8% to 57.74% higher than those in the absence of honeybee pollination. This way, 20% soybean yield increase may be considered a fair estimation, quite close to the 21% average reported by Garibaldi et al. (2021). Hence, 20% soybean yield increase will be applied in the following exercise to estimate the reductions of GHG emissions using the supplementary pollination technology.

If an increase of 20% of the soybean yield is achieved, then 20% less area is necessary to obtain the same production. In other words, a 20% higher soybean production from the same land area is possible. In both cases, there is no need to incorporate additional areas, meaning there is no impact of land change use. Just for theoretical considerations, expanding this rationale to the whole Brazilian soybean area of 47,450,000 ha cultivated in the 2024/2025 season (Conab, 2025), about 9.5 Mha could have been saved, if supplementary pollination would have been used in the whole Brazilian soybean area, avoiding emissions of 21.8 Mt of CO_2-equivalent, according to the study of Garofalo et al. (2022).

More GHG emissions can be avoided by using the supplementary pollination on soybean. The data for the following calculation, come from the monitoring by Solidaridad (Balanço…, 2022), which found emissions of 0.28 Mg CO_2-equivalent Mg^{-1} of soybean produced.

On the 2024/2025 soybean season, the Brazilian soybean yield average was 3,527 kg ha^{1} (Conab, 2025), resulting in 0.987 Mg CO_2-equivalent ha^{-1} emissions. Considering the yield increase of 20%, the soybean productivity would be 4,232 kg ha^{-1}. However, no changes in the production system are needed for this improved yield, meaning that the same amount of inputs and the same practices would be used, consequently resulting in the same GHG emissions. Yet, the proportional emissions would be reduced to 0.233 Mg CO_2-equivalent Mg^{-1} of soybean. That is a conservative approach because, if it is considered that, for integrating bees into soybean production, the grower should fully adopt the IPM recommendations, then 53% reduction of insecticide application will occur (Carnevalli et al., 2024), reducing the GHG emissions associated to the insecticide production and transportation, and also to its application in the field.

From the economic, social, and environmental standpoints, other positive externalities are associated with this technology usage. As the increase in the yield does not imply changing the production system, the production cost is the same, even with a higher yield, so the net income for growers would improve. In addition, by observing the good practices recommended for the harmonic integration of managed bees and agriculture, the feral pollinators and the general biodiversity will also benefit and improve the availability of ecosystem services.

Concluding Remarks

Based on the above review and the demonstration of a real opportunity to reduce GHG emissions, thus mitigating climate change, some active actions should be directed at target stakeholders. In the private sector, an intense communication campaign focused on growers should be conducted regarding the awareness of the economic, social, and environmental benefits of the ecosystem service of pollination. At the same time, growers and beekeepers should receive training on the established good practices to integrate their activities harmoniously.

The implementation of public policies is the responsibility of the government. First, technology generation to amplify the soybean case to an expanded crop area should be supported, followed by an intense campaign of communication and technology transfer. Besides, governments should encourage growers and beekeepers to integrate their activities, using tools like credit lines or certifications like a “bee-friendly crop”, to adequately communicate crop management good practices to the market and the consumers / civil society.

References

AIZEN, M.A.; GARIBALDI, L.A.; CUNNINGHAM, S.A.; KLEIN, A.M. How much does agriculture depend on pollinators? Lessons from long-term trends in crop production. **Annals of Botany**, v.103, p.1579-1588, 2009. DOI: https://doi.org/10.1093/aob/mcp076.

ALLSOPP, M.H.; DE LANGE, W.J.; VELDTMAN, R. Valuing insect pollination services with cost of replacement. **PLoS ONE**, v.3, e3128, 2008. DOI: https://doi.org/10.1371/journal.pone.0003128.

ARIAS, C.A.A.; HOFFMANN-CAMPO, C.B.; SOARES, R.M.; MEYER, M.C. Contribuição do melhoramento genético da soja para o manejo de doenças e pragas. In: MEYER, M.C.; BUENO, A. de F.; MAZARO, S.M.; SILVA, J.C. da (Ed.). **Bioinsumos na cultura da soja**. Brasília: Embrapa, 2022. p.53-72. Available at: <https://www.alice.cnptia.embrapa.br/alice/bitstream/doc/1147038/1/cap-3-Bioinsumos-na-cultura-da-soja.pdf>. Acessed on: Mar. 15 2025.

ASLAN, C.E.; LIANG, C.T.; GALINDO, B.; KIMBERLY, H.; TOPETE, W. The role of honey bees as pollinators in natural areas. **Natural Areas Journal**, v.36, p.478-488, 2016. DOI: https://doi.org/10.3375/043.036.0413.

BALANÇO de carbono na produção de soja do MATOPIBA. São Paulo: Fundação Solidaridad, 2022. Available at: <https://solidaridadlatam.org/wp-content/uploads/2022/10/balanco_de_carbono_na_producao_de_soja_no_matopiba.pdf>. Accessed on: Mar. 15 2025.

BALVANERA, P.; QUIJAS, S.; KARP, D.S.; ASH, N.; BENNETT, E.M.; BOUMANS, R.; BROWN, C.; CHAN, K.M.A.; CHAPLIN-KRAMER, R.; HALPERN, B.S.; HONEY-ROSÉS, J.; KIM, C.-K.; CRAMER, W.; MARTÍNEZ-HARMS, M.J.; MOONEY, H.; MWAMPAMBA, T.; NEL, J.; POLASKY,

S.; REYERS, B.; ROMAN, J.; TURNER, W.; SCHOLES, R.J.; TALLIS, H.; THONICKE, K.; VILLA, F.; WALPOLE, M.; WALZ, A. Ecosystem Services. In: WALTERS, M.; SCHOLES, R.J. (Ed.). **The GEO Handbook on Biodiversity Observation Networks**. Cham: Springer, 2017. p.39-78. Available at: <https://link.springer.com/chapter/10.1007/978-3-319-27288-7_3>. Accessed on: Mar. 15 2025.

BASU, S.K.; CETZAL-IX, W. Call of the wild: conservation of natural insect pollinators should be a priority. **Biodiversity**, v.19, p.240-243, 2018. DOI: https://doi.org/10.1080/14888386.2018.1523747.

BAUER, D.M.; WING, I.S. The macroeconomic cost of catastrophic pollinator declines. **Ecological Economics**, v.126, p.1-13, 2016. DOI: https://doi.org/10.1016/j.ecolecon.2016.01.011.

BERGAMO, P.J.; WOLOWSKI, M.; TAMBOSI, L.R.; GARCIA, E.; AGOSTINI, K.; GARIBALDI, L.A.; KNIGHT, T.M.; LUGHADHA, E.N.; OLIVEIRA, P.E.A.M.; MARQUES, M.C.M.; MARUYAMA, P.K.; MAUÉS, M.M.; OPPATA, A.K.; RECH, A.R.; SARAIVA, A.M.; SILVA, F.D.S.; SOUSA, G.; TSUKAHARA, R.Y.; VARASSIN, I.G.; VIANA, B.F.; FREITAS, L. Areas requiring restoration efforts are a complementary opportunity to support the demand for pollination services in Brazil. **Environmental Science & Technology**, v.55, p.12043-12053, 2021. DOI: https://doi.org/10.1021/acs.est.1c02546.

BILAL, M.; ALI, A. Projecting ecological footprint and biocapacity: insights into sustainable agriculture and development. In: RANI, S.; DUTTA, S.; ROCHA, A.; CENGIZ, K. (Ed.). **AI and Data Analytics in Precision Agriculture for Sustainable Development**. Cham: Springer, 2025. (Studies in Computational Intelligence, v.1215). DOI: https://doi.org/10.1007/978-3-031-93087-4_13.

BISHOP, J.; GARRATT, M.P.D.; NAKAGAWA, S. Animal pollination increases stability of crop yield across spatial scales. **Ecology Letters**, v.25, p.2034-2047, 2022. DOI: https://doi.org/10.1111/ele.14069.

BISHOP, J.; NAKAGAWA, S. Quantifying pollinator dependence and its heterogeneity using multi levels meta-analysis. **Journal of Applied Ecology**, v.58, p.1030-1042, 2020. DOI: https://doi.org/10.1111/1365-2664.13830.

BLETTLER, D.C.; FAGÚNDEZ, G.A.; CAVIGLIA, O.P. Contribution of honeybees to soybean yield. **Apidologie**, v.49, p.101-111, 2018. DOI: https://doi.org/10.1007/s13592-017-0532-4.

BREEZE, T.D.; GALLAI, N.; GARIBALDI, L.A.; LI, X.S. Economic measures of pollination services: shortcomings and future directions. **Trends in Ecology & Evolution**, v.31, p.927-939, 2016. DOI: https://doi.org/10.1016/j.tree.2016.09.002.

BRUNETTI, I.; TRIDBALL, M.; COUVET, D. Relationship between biodiversity and agricultural production. **Natural Resource Modeling**, v.32, e12204, 2019. DOI: https://doi.org/10.1111/nrm.12204.

CALDERONE, N.W. Insect pollinated crops, insect pollinators and US agriculture: trend analysis of aggregate data for the period 1992–2009. **PLoS ONE, v.**7, e37235, 2012. DOI: https://doi.org/10.1371/journal.pone.0037235.

CARDINALE, B.J.; DUFFY, J.E.; GONZALEZ, A.; HOOPER, D.U.; PERRINGS, C.; VENAIL, P.; NARWANI, A.; MACE, G.M.; TILMAN, D.; WARDLE, D.A.; KINZIG, A.P.; DAILY, G.C.; LOREAU, M.; GRACE, J.B.; LARIGAUDERIE, A.; SRIVASTAVA, D.S.; NAEEM, S. Biodiversity loss and its impact on humanity. **Nature**, v.486, p.59-67, 2012. DOI: https://doi.org/10.1038/nature11148.

CARLETON, T.A.; HSIANG, S.M. Social and economic impacts of climate. **Science**, v.353, n.6304, p.9837-1-aad9837-15, 2016. DOI: https://doi.org/10.1126/science.aad9837.

CARNEVALLI, R.A.; PRANDO, A.M.; LIMA, D. de; BORGES, R. de S.; POSSAMAI, E.J.; REIS, E.A.; GOMES, E.C.; ROGGIA, S. **Resultados do manejo integrado de pragas da soja na safra 2023/2024 no Paraná**. Londrina: Embrapa Soja, 2024. 51p. (Embrapa Soja. Documentos, 467).

CHÉVEZ, E.; PORTER-BOLLAND, L.; GARCÍA-FRAPOLLI, E.; LANDGRAVE, R.; REVOLLO-FERNÁNDEZ, D. Bee landscape relations in changing contexts, implications for stingless bee management. **Regional Environmental Change**, v.23, art.106, 2023. DOI: https://doi.org/10.1007/s10113-023-02093-4.

CHIARI, W.C.; HOFFMANN-CAMPO, C.B.; ARIAS, C.A.; LOPES, T. da S.; TOLEDO, T.C.S. de O.A. de; CHAMBÓ, E.D.; RUVOLO-TAKASUSUKI, M.C.; TOLEDO, V. de A.A. de. Floral biology and africanized honey bee behaviour in transgenic (Roundup Ready var. BR-245 RR) and conventional (var. BRS-133) soybean (*Glycine max* L. Merrill) flowers. In: PRICE, A.; KELTON, J. (Ed.). **Herbicides**: advances in research. London: IntechOpen, 2013. chap.14, p.277-298. E-Book. DOI: https://doi.org/10.5772/55847.

CHIARI, W.C.; TOLEDO, V. de A.A. de; RUVOLO-TAKASUSUKI, M.C.C.; OLIVEIRA, A.J.B. de; SAKAGUTI, E.S.; ATTENCIA, V.M.; COSTA, F.M.; MITSUI, M.H. Pollination of soybean (*Glycine max* L. Merrill) by honeybees (*Apis mellifera* L.). **Brazilian Archives of Biology and Technology**, v.48, p.31-36, 2005. DOI: https://doi.org/10.1590/S1516-89132005000100005.

COHN, A. Leveraging climate regulation by ecosystems for agriculture to promote ecosystem stewardship. **Tropical Conservation Science**, v.10, p.1-7, 2017. DOI: https://doi.org/10.1177/1940082917720672.

CONAB. Companhia Nacional de Abastecimento. **Boletim da safra de grãos**. 2025. Available at: <https://www.conab.gov.br/component/k2/item/download/57188_05e9073e9c260b51fe301c47da0130ce>. Accessed on: Mar. 15 2025.

CONVENTION ON BIOLOGICAL DIVERSITY. **Biodiversity convention**. 1992. Available at: <https://www.cbd.int/>. Access on: Mar. 25 2025.

COPERNICUS. **ERA5 hourly data on single levels from 1940 to present**. 2025a. Available at: <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview>. Accessed on: Mar. 15 2025.

COPERNICUS. **January 2025 – Surface air temperature and sea surface temperature highlights**. 2025b. Available at: <https://climate.copernicus.eu/copernicus-january-2025-was-warmest-record-globally-despite-emerging-la-nina#:~:text=Global%20

Temperatures&text=January%202025%20was%201.75%C2%B0-,above%20the%20pre%2Dindustrial%20level>. Accessed on: Apr. 20 2025.

COPERNICUS. **Surface air temperature for February 2025**. 2025c. Available at: <https://climate.copernicus.eu/surface-air-temperature-february-2025#:~:text=February%202025%20was%20the%20third,the%20fourth%20warmest%20of%202020>. Accessed on: Apr. 30 2025.

COSTANZA, R.; ARGE, R. d'; de GROOT, R.; FARBER, S.; GRASSO, M.; HANNON, B.; LIMBURG, K.; NAEEM, S.; O'NEILL, R.V.; PARUELO, J.; RASKIN, R.G.; SUTTON, P.; VAN DEN BELT, M. The value of the world's ecosystem services and natural capital. **Nature**, v.387, p.253-260, 1997. DOI: https://doi.org/10.1038/387253a0.

CUTLER, G.H. A simple method for making soybean hybrids. **Agronomy Journal**, v.26, p.252-254, 1934. DOI: https://doi.org/10.2134/AGRONJ1934.00021962002600030016X.

DAINESE, M.; SCHNEIDER, G.; KRAUS, J.; STEFFAN-DEWENTER, I. Complementarity among natural enemies enhances pest suppression. **Scientific Reports**, v.7, art.8172, 2017. DOI: https://doi.org/10.1038/s41598-017-08316-z.

DAVIS, J.H. Soybeans for honey production. **American Bee Journal**, v.92, p.18-19, 1952.

DEGRANDE-HOFFMAN, G.; GRAHAM, H.; CORBY-HARRIS, V.; CHAMBERS, M.; WATKINS-DEJONG, E.; IHLE, K.; BILODEAU, L. Adapting overwintering honey bee (*Apis mellifera* L.) colony management in response to warmer fall temperatures associated with climate change. **Insects**, v.16, art.266, 2025. DOI: https://doi.org/10.3390/insects16030266.

DELAPLANE, K.S.; MAYER, D.F. **Crop pollination by bees**. Wallingford: CABI Publishing, 2000. 301p.

DEUTSCH, C.A.; TEWKSBURY, J.J.; TIGCHELAAR, M.; BATTISTI, D.S.; MERRILL, S.C.; HUEY, R.B.; NAYLOR, R.L. Increase in crop losses to insect pests in a warming climate. **Science**, v.361, p.916-919, 2018. DOI: https://doi.org/10.1126/science.aat3466.

DICKS, L.V.; BREEZE, T.D.; NGO, H.T.; SENAPATHI, D.; AN, J.; AIZEN, M.A.; BASU, P.; BUCHORI, D.; GALETTO, L.; GARIBALDI, L.A.; GEMMILL-HERREN, B.; HOWLETT, B.G.; IMPERATRIZ-FONSECA, V.L.; JOHNSON, S.D.; KOVÁCS-HOSTYÁNSZKI, A.; KWON, Y.J.; LATTORFF, H.M.G.; LUNGHARWO, T.; SEYMOUR, C.L.; VANBERGEN, A.J.; POTTS, S.G. A global-scale expert assessment of drivers and risks associated with pollinator decline. **Natural Ecology & Evolution**, v.5, p.1453-1461, 2021. DOI: https://doi.org/10.1038/s41559-021-01534-9.

DICKS, L.V.; VIANA, B.; BOMMARCO, R.; BROSI, B.; ARIZMENDI, M. del C.; CUNNINGHAM, S.A.; GALETTO, L.; HILL, R.; LOPES, A.V.; PIRES, C.; TAKI, H.; POTTS, S.G. Ten policies for pollinators. What governments can do to safeguard pollination services. **Science**, v.354, p.975-976, 2016. DOI: https://doi.org/10.1126/science.aai9226.

DORIN, A.; DYER, A.; TAYLOR, T.; BUKOVAC, Z. Simulation-governed design and tuning of greenhouses for successful pollination. In: CONFERENCE ON ARTIFICIAL LIFE, 2018, Tokyo. **Proceedings**. Tokyo: [s.n.], 2018. p.171-178. ALIFE 2018. Available at: <https://direct.mit.edu/isal/proceedings/alife2018/30/171/99618>. Accessed on: July 18 2025.

EGOH, B.; DRAKOU, E.G.; DUNBAR, M.B.; MAES, J.; WILLEMEN, L. **Indicators for mapping ecosystem services**: a review. Luxembourg: European Union, 2012. Available at: <https://publications.jrc.ec.europa.eu/repository/handle/111111111/26749>. Accessed on: Mar. 15 2025.

ELLATAR, M.A.; KARIKARI, B.; LI, S.; SONG, S.; CAO, Y.; ASLAM, M.; HINA, A.; ABOU-ELWAFA, S.F.; ZHAO, T. Identification and validation of major QTLs, epistatic interactions and candidate genes for soybean seed shape and weight using two related RIL populations. **Frontiers in Genetics**, v.12, art.666440, 2021. DOI: https://doi.org/10.3389/fgene.2021.666440.

EMBRAPA MEIO AMBIENTE. **BRLUC – Brazilian Land Use Change**. 2025. Available at <https://brluc.cnpma.embrapa.br/>. Accessed on: March 20 2025.

EMBRAPA. **Tecnologia Block**. 2025. Available at: <https://www.infoteca.cnptia.embrapa.br/infoteca/bitstream/doc/1110408/1/folderblock.pdf>. Accessed on: July 18 2025.

ERICKSON, E.H. Soybean floral ecology and insect pollination. **Soybean Genetics Newsletter**, v.11, p.152-162, 1984.

FAO. Food and Agriculture Organization of the United Nations. **The FAO Food Price Index rose in February 2025**. 07 mar. 2025. Available at: <https://www.fao.org/worldfoodsituation/foodpricesindex/en/>. Accessed on: Mar. 15 2025.

FARRÉ-ARMENGOL, G.; PEÑUELAS, J.; LI, T.; YLI-PIRILÄ, P.; FILELLA, I.; LLUSIA, J.; BLANDE, J.D. Ozone degrades floral scent and reduces pollinator attractin to flowers. **New Phytologist**, v.209, p.152-160, 2016. DOI: https://doi.org/10.1111/nph.13620.

FERRIER, S.; NINAN, K.N.; LEADLEY, P.; ALKEMADE, R.; ACOSTA, L.A.; AKÇAKAYA, H.R.; BROTONS, L. ; CHEUNG, W. ; CHRISTENSEN, V.; HARHASH, K. A.; KABUBO-MARIARA, J.; LUNDQUIST, C.; OBERSTEINER, M.; PEREIRA, H.; PETERSON, G.; PICHS-MADRUGA, R.; RAVINDRANATH, N. H.; RONDININI, C.; WINTLE, B. (Ed.). **The methodological assessment report on scenarios and models of biodiversity and ecosystem services**: summary for policymakers. Bonn: IPBES, 2016. 32p. Available at: <https://www.ipbes.net/>. Accessed on: Mar. 12 2025.

FIJEN, T.P.M.; SCHEPER, J.A.; BOOM, T.M.; JANSSEN, N.; RAEMAKERS, I.; KLEIJN, D. Insect pollination is at least as important for marketable crop yield as plant quality in a seed crop. **Ecology Letters**, v.21, p.1704-1713, 2018. DOI: https://doi.org/10.1111/ele.13150.

FILONCHYK, M.; PETRSON, M.P.; ZHANG, L.; HURYNOVICH, V.; HE, Y. Greenhouse gases emissions and global climate change: examining the influence of CO_2, CH_4 and N_2O. **Science of the Total Environment**, v.935, art.173359, 2024. DOI: https://doi.org/10.1016/j.scitotenv.2024.173359.

FORRESTER, K.C.; LIN, C.-H.; JOHNSON, R.M. Measuring factors affecting honey bee attraction to soybeans using bioacoustics monitoring. **Journal of Insect Science**, v.24, p.1-9, 2024. DOI: https://doi.org/10.1093/jisesa/ieae036.

FREE, J.B. **Insect pollination of crops**. 2nd ed. Cardiff: University Press, 1993.

GALLAI, N.; SALLES, J.M.; SETTELE, J.; VAISSIERE, B.E. Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. **Ecological Economics**, v.68, p.810-821, 2009. DOI: https://doi.org/10.1016/j.ecolecon.2008.06.014.

GALLAI, N.; VAISSIÈRE, B.E. **Guidelines for the economic valuation of pollination services at national scale**. Roma: FAO, 2009. Available at: <http://www.fao.org/3/a-at523e.pdf>. Accessed on: Mar. 25 2025.

GARIBALDI, L.A.; CARVALHEIRO, L.G.; VAISSIERE, B.E.; GEMMILL-HERREN, B.; HIPOLITO, J.; FREITAS, B.M.; NGO, H.T.; AZZU, N.; SÁEZ, A.; ASTRÖM, J.; AN, J.; BLOCHTEIN, B.; BUCHORI, D.; GARCÍA, F.J.C.; SILVA, F.O. da; DEVKOTA, K.; RIBEIRO, M. de F.; FREITAS, L.; GAGLIANONE, M.C.; GOSS, M.; IRSHAD, M.; KASINA, M.; PACHECO FILHO, A.J.S.; KIILL, L.H.P.; KWAPONG, P.; PARRA, G.N.; PIRES, C.; PIRES, V.; RAWAL; R.S.; RIZALI, A.; SARAIVA, A.M.; VELDTMAN, R.; VIANA, B.F.; WITTER, S.; ZHANG, H. Mutually beneficial pollinator diversity and crop yield outcomes in small and large farms. **Science**, v.351, p.388-391, 2016. DOI: https://doi.org/10.1126/science.aac7287.

GARIBALDI, L.A.; REQUIER, F.; ROLLIN O.; ANDERSSON, G.K.S. Towards integrated species and habitat management of crop pollination. **Current Opinion in Insect Science**, v.21, p.105-114, 2017. DOI: https://doi.org/10.1016/j.cois.2017.05.016.

GARIBALDI, L.A.; SCHULTE, L.A.; JODAR, D.N.N.; CARELLA, D.S.G.; KREMEN, C. Time to integrate pollinator science into soybean production. **Trends in Ecology & Evolution**, v.36, p.573-575, 2021. DOI: https://doi.org/10.1016/j.tree.2021.03.013.

GARIBALDI, L.A.; STEFFAN-DEWENTER, I.; WINFREE, R.; AIZEN, M.A.; BOMMARCO, R.; CUNNINGHAM, S.A.; KREMEN, C.; CARVALHEIRO, L.G.; HARDER, L.D.; AFIK, O.; BARTOMEUS, I.; BENJAMIN, F.; BOREUX, V.; CARIVEAU, D.; CHACOFF, N.P.; DUDENHÖFFER, J.H.; FREITAS, B.M.; GHAZOUL, J.; GREENLEAF, S.; HIPÓLITO, J.; HOLZSCHUH, A.; HOWLETT, B.; ISAACS, R.; JAVOREK, S.K.; KENNEDY, C.M.; KREWENKA, K.M.; KRISHNAN, S.; MANDELIK, Y.; MAYFIELD, M.M.; MOTZKE, I.; MUNYULI, T.; NAULT, B. A.; OTIENO, M.; PETERSEN, J.; PISANTY, G.; POTTS, S.G.; RADER, R.; RICKETTS, T.H.; RUNDLÖF, M.; SEYMOUR, C.L.; SCHÜEPP, C.; SZENTGYÖRGYI, H.; TAKI, H.; TSCHARNTKE, T.; VERGARA, C.H.; VIANA, B.F.; WANGER, T.C.; WESTPHAL, C.; WILLIAMS, N.; KLEIN, A.M. Wild pollinators enhance fruit set of crops regardless of honeybee abundance. **Science, v.**339, p.1608-1611, 2012. DOI: https://doi.org/10.1126/science.1230200.

GAROFALO, D.F.T.; NOVAES, R.M.L.; PAZIANOTTO, R.A.A.; MACIEL, V.G.; BRANDÃO, M.; SHIMBO, J.Z.; FOLEGATTI-MATSUURA, M.I.S. Land-use change CO_2 emissions associated with agricultural products at municipal level in Brazil. **Journal of Cleaner Production**, v.364, art.132549, 2022. DOI: https://doi.org/10.1016/j.jclepro.2022.132549.

GAZZONI, D.L. **Soybean and bees**. Brasília: Embrapa, 2016. Available at: <https://core.ac.uk/download/pdf/78557951.pdf>. Accessed on: July 4 2025.

GAZZONI, D.L.; BARATEIRO, J.V.G.R.P. Soybean yield is increased through complementary pollination by honey bees. **Journal of Apicultural Research**, v.63, p.801-812, 2023. DOI: https://doi.org/10.1080/00218839.2022.2161219.

GAZZONI, D.L.; DALL'AGNOL, A. **A saga da soja**: de 1050 a.C. A 2050 d.C. Brasília: Embrapa, 2018. Available at: <https://www.alice.cnptia.embrapa.br/alice/bitstream/doc/1093166/1/ID-38839-Livro-Saga-da-Soja-versao-web.pdf>. Accessed on June 28 2025.

GFN. Global Footprint Network. **Earth overshoot day**. 2025a. Available at: <https://overshoot.footprintnetwork.org/>. Accessed on: Mar. 15 2025.

GFN. Global Footprint Network. **Footprint Network**. 2025b. Available at: <data.footprintnetwork.org>. Accessed on: Mar. 17 2025.

GFN. Global Footprint Network. **What is your ecological footprint?** 2025c. Available at: <https://www.footprintcalculator.org/. Accessed on: Mar. 15 2025.

GIANNINI, T.C.; ALVES, D.A.; ALVES, R.; CORDEIRO, G.D.; CAMPBELL, A.J.; AWADE, M.; BENTO, J.M.S.; SARAIVA, A.M.; IMPERATRIZ-FONSECA, V.L. Unveiling the contribution of bee pollinators to Brazilian crops with implications for bee management. **Apidologie**, v.51, p.406-421, 2020. DOI: https://doi.org/10.1007/s13592-019-00727-3.

GIANNINI, T.C.; CORDEIRO, G.D.; FREITAS, B.M.; SARAIVA, A.M.; IMPERATRIZ-FONSECA, V.L. The dependence of crops for pollinators and the economic value of pollination in Brazil. **Journal of Economic Entomology**, v.108, p.849-857, 2015. DOI: https://doi.org/10.1093/jee/tov093.

GOOGLE SCHOLAR. Available at: <https://scholar.google.com.br/>. Accessed on: July 2 2025.

GRIGGS, D.; STAFFORD-SMITH, M.; GAFFNEY, O.; ROCKSTROM, J.; OHMAN, M.C.; SHYAMSUNDAR, P.; STEFFEN, W.; GLASER, G.; KANIE, N.; NOBLE, I. Sustainable development goals for people and planet. **Nature**, v.495, p.305-307, 2013. DOI: https://doi.org/10.1038/495305a.

GUO, B.; SUN, L.; JIANG, S.; REN, H.; SUN, R.; WEI, Z.; HONG, H.; LUAN, X.; WANG, J.; WANG, X.; XU, D.; LI, W.; GUO, C.; QIU, L.J. Soybean genetic resources contributing to sustainable protein production. **Theoretical and Applied Genetics**, v.135, p.4095-4121, 2022. DOI: https://doi.org/10.1007/s00122-022-04222-9.

GUO, J.; YUE, D.; LI, K.; HUI, C. Biocapacity optimization in regional planning. **Scientific Reports**, v.7, art.41150, 2017. DOI: https://doi.org/10.1038/srep41150.

HALL, D.M.; STEINER, R. Insect pollinator conservation policy innovations at subnational levels: lessons for lawmakers. **Environmental Science & Policy**, v.93, p.118-128, 2019. DOI: https://doi.org/10.1016/j.envsci.2018.12.026.

HAMBLETON, J.I. Soybean for pollen and nectar. **Bee Culture**, v.64, p.431, 1936.

HASAN, S.S.; ZHEN, L.; MIAH, G.; AHAMED, T.; SAMIE, A. Impact of land use change on ecosystem services: A review. **Environmental Development**, v.34, art.100527, 2020. DOI: https://doi.org/10.1016/j.envdev.2020.100527.

HAUSMANN, A.; SLOTOW, R.; BURNS, J.K.; MININ, E. The ecosystem service of sense of place: benefits for human well-being and biodiversity conservation. **Environmental Conservation**, v.43, p.117-137, 2016. DOI: https://doi.org/10.1017/S0376892915000314.

HERNÁNDEZ-BLANCO, M.; CONSTANZA, R.; CHEN, H.; DEGROOT, D.; JARVIS, D.; KUBISZEWSKI, I.; MONTOYA, J.; SANGHA, K.; STOECKL, N.; TURNER, K.; HOFF, V.V. Ecosystem health, ecosystem services, and the well-being of humans and the rest of nature. **Global Change Biology**, v.28, p.5027-5040, 2022. DOI: https://doi.org/10.1111/gcb.16281.

HIPÓLITO, J.; BOSCOLO, D.; VIANA, B.F. Landscape and crop management strategies to conserve pollination services and increase yields in tropical coffee farms. **Agriculture, Ecosystems and Environment**, v.256, p.218-225, 2018. DOI: https://doi.org/10.1016/j.agee.2017.09.038.

HRISTOV, P.; NEOV, B.; SHUMKOVA, R.; PALOVA, N. Significance of Apoidea as main pollinators. Ecological and economic impact and implications for human nutrition. **Diversity**, v.12, art.280, 2020. DOI: https://doi.org/10.3390/d12070280.

HUNG, K.J.; KINGSTON, J.M.; LEE, A.; HOLWAY, D.A.; KOHN, J.R. Non-native honey bees disproportionately dominate the most abundant floral resources in a biodiversity hotspot. **Proceedings of the Royal Society B - Biological Sciences**, v.286, art.20182901, 2019. DOI: https://doi.org/10.1098/rspb.2018.2901.

HUNG, K.-L.J.; KINGSTON, J.M.; ALBRECHT, M.; HOLWAY, D.A.; KOHN, J.R. The worldwide importance of honey bees as pollinators in natural habitats. **Proceedings of the Royal Society B - Biological Sciences**, v.285, art.20172140, 2018. DOI: https://doi.org/10.1098/rspb.2017.2140.

IDR-PARANÁ. Instituto de Desenvolvimento Rural do Paraná. **Boas práticas para integração entre agricultura e abelhas**. 2024. Available at: <https://www.idrparana.pr.gov.br/system/files/publico/Diversos/2024/BoasPraticasIntegracaoAgriculturaApicultura29abril24.pdf>. Accessed on: Mar. 15 2025.

IFPRI. International Food Policy Research Institute. **Food security**. 2025. Available at: <https://www.ifpri.org/topic/food-security/#:~:text=TOPIC-,Food%20Security,an%20active%20and%20healthy%20life>. Accessed on: Jun. 20 2025.

IPBES. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. **History of the establishment of IPBES**. 2025. Available at: <https://www.ipbes.net/history-establishment>. Accessed on: July 5 2025.

IPCC. Intergovernmental Panel on Climate Change. **AR6 Synthesis Report**: chapter 11: Weather and climate extreme events in a changing climate. 2023. Available at: <https://www.ipcc.ch/report/ar6/wg1/chapter/chapter-11/>. Accessed on: June 25 2025.

IPCC: SR15 summary for policymakers. In: IPCC. Intergovernmental Panel on Climate Change. **Global Warming of 1.5°C an IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty**. Cambridge: Cambridge University Press, 2018. p.3-24. Editors: V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield. DOI: https://doi.org/10.1017/9781009157940.001.

JAYCOX, E.R. Ecological relationships between honeybees and soybeans. I. Introduction. **American Bee Journal**, v.110, p.306-307, 1970.

JOHNSON, A.P. Honey from soybeans. **American Bee Journal**, v.84, p.306, 1944.

KHALIFA, S.A.M.; ELSHAFIEY, E.H.; SHETAIA, A.A.; ABD EL-WAHED, A.A.; ALGETHAMI, A.F.; MUSHARRAF, S.G.; ALAJMI, M.F.; ZHAO, C.; MASRY, S.H.D.; ABDEL-DAIM, M.M.; HALABI, M.F.; KAI, G.; AL NAGGAR, Y.; BISHR, M.; DIAB, M.A.M.; EL-SEEDI, H.R. Overview of bee pollination and its economic value for crop production. **Insects**, v.12, art.688, 2021. DOI: https://doi.org/10.3390/insects12080688.

KLEIN, A.M.; VAISSIÈRE, B.E.; CANE, J.H.; STEFFAN-DEWENTER, I.; CUNNINGHAM, S.A.; KREMEN, C.; TSCHARNTKE, T. Importance of pollinators in changing landscapes for world crops. **Proceedings of the Royal Society B - Biological Sciences**, v.274, p.303-313, 2007. DOI: https://doi.org/10.1098/rspb.2006.3721.

KLUSER, S.; PEDUZZI, P. **Global pollinator decline**: a literature review. Geneva: UNEP/GRID-Europe, 2007. Available at: <https://unepgrid.ch/storage/app/media/legacy/37/Global_pollinator_decline_literature_review_2007.pdf>. Accessed on: Mar. 15 2025.

KREMEN, C.; WILLIAMS, N.M.; THORP, R.W. Crop pollination from native bees at risk from agricultural intensification. **PNAS**, v.99, p.16812-16816, 2002. DOI: https://doi.org/10.1073/pnas.262413599.

KUMAR, S.; CHATTERJEEE, U.; RAJ, A.D. Ecological footprints in changing climate: an overview. In: CHATTERJEE, U.; AKANWA, A.O.; KUMAR, S.; SINGH, S.K.; DUTTA ROY, A. (Ed.). **Ecological Footprints of Climate Change**: adaptative approaches and sustainability. Springer Climate. Cham: Springer, 2022. p.3-30. DOI: https://doi.org/10.1007/978-3-031-15501-7_1.

LA NOTTE, A.; DALMAZZONE, S. Sustainability assessment and causality nexus through ecosystem service accounting: the case of water purification in Europe. **Journal of Environmental Management**, v.223, p.964-974, 2018. DOI: https://doi.org/10.1016/j.jenvman.2018.06.072.

LAUTENBACH, S.; SEPPELT, R.; LIEBSCHER, J.; DORMANN, C.F. Spatial and temporal trends of global pollination benefit. **PLoS One**, v.7, e35954, 2012. DOI: https://doi.org/10.1371/journal.pone.0035954.

LAZARUS, E.; LIN, D.; MARTINDILL, J.; HARDIMAN, J.; PITNEY, L.; GALLI, A. Biodiversity loss and the ecological footprint of trade. **Diversity**, v.7, p.170-191, 2015. DOI: https://doi.org/0.3390/d7020170.

LEAL FILHO, W.; SETTI, A.F.F.; AZEITEIRO, U.M.; LOKUPITIYA, E.; DONKOR, F.K.; ETIM, N.N.; MATANDIROTYA, N.; OLOOTO, F.M.; SHARIFI, A.; NAGY, G.J.; DJEKIC, I. An overview of the interactions between food production and climate change. **Science of the Total Environment**, v.838, art.156438, 2022. DOI: https://doi.org/10.1016/j.scitotenv.2022.156438.

LIN, C.-H.; SURESH, S.; MATCHAM, E.; MONAGAN, P.; CURTIS, H.; RICHARDSON, R.T.; JOHNSON, R.M. Soybean is a common nectar source for honey bees (Hymenoptera: Apidae) in a Midwestern agricultural landscape. **Journal of Economic Entomology**, v.115, p.1846-1851, 2022. DOI: https://doi.org/10.1093/jee/toac140.

LOCATELLI, B. Ecosystem services and climate change. In: POTSCHIN, M.; HAINES-YOUNG, R.; FISH, R; TURNER, R.K. (Ed.). **Routledge Handbook of Ecosystem Services**. London: Taylor & Francis Group, 2016. chapter 38.

MACE, G.M.; NORRIS, K.; FITTER, A.H. Biodiversity and ecosystem services: a multilayered relationship. **Trends in Ecology & Evolution**, v.27, p.19-26, 2012. DOI: https://doi.org/10.1016/j.tree.2011.08.006.

MAES, J.; LIQUETE, C.; TELLER, A.; ERHARD, M.; PARACCHINI, M.L.; BARREDO, J. I.; GRIZZETTI, B.; CARDOSO, A.; SOMMA, F.; PETERSEN, J.-E.; MEINER, A.; GELABERT, E.R.; ZAL, N.; KRISTENSEN, P.; BASTRUP-BIRK, A.; BIALA, K.; PIRODDI, C.; EGOH, B.; DEGEORGES, P.; FIORINA, C.; LAVALLE, C. An indicator framework for assessing ecosystem services in support of the EU Biodiversity Strategy to 2020. **Ecosystem Services**, v.17, p.14-23, 2016. DOI: https://doi.org/10.1016/j.ecoser.2015.10.023.

MAIA, A.G.; MIYAMOTO, B.C.B.; GARCIA, J.R. Climate change and agriculture: do environmental preservation and ecosystem services matter? **Ecological Economics**, v.152, p.27-39, 2018. DOI: https://doi.org/10.1016/j.ecolecon.2018.05.013.

MAIR, K.S.; IRRGHER, J.; HALUZA, D. Elucidating the role of honey bees as biomonitors in environmental health research. **Insects**, v.14, art.874, 2023. DOI: https://doi.org/10.3390/insects14110874.

MARTIGNONE, G.M.B.; GHOSH, B.; PAPADAS, D; BEHRENDT, K. The rise of soybean in international commodity markets: a quantile investigation. **Heliyon**, v.10, e34669, 2024. DOI: https://doi.org/10.1016/j.heliyon.2024.e34669.

MASHILINGI, S.K.; SHANG, H.; GARIBALDI, L.A.; AN, J. Honeybees are far too insufficient to supply optimum pollination services in agricultural systems worldwide. **Agriculture, Ecosystems & Environment**, v.335, art.108003, 2022. DOI: https://doi.org/10.1016/j.agee.2022.108003.

MILFONT, M. de O.; ROCHA, E.E.M.; LIMA, A.O.N.; FREITAS, B.M. Higher soybean production using honeybee and wild pollinators, a sustainable alternative to pesticides and autopollination. **Environmental Chemistry Letters**, v.11, p.335-341, 2013. DOI: https://doi.org/10.1007/s10311-013-0412-8.

MILUM, V.G. Bees and soybeans. **American Bee Journal**, v.80, p.22, 1940.

MONASTEROLO, M.; MUSICANTE, M.L.; VALLADARES, G.R.; SALVO, A. Soybean crops may benefit from forest pollinators. **Agriculture, Ecosystems & Environment**, v.202, p.217-222, 2015. DOI: https://doi.org/10.1016/j.agee.2015.01.012.

MORANDIN, L.A.; WINSTON, M.L. Pollinators provide economic incentive to preserve natural land in agroecosystems. **Agriculture, Ecosystems & Environment**, v.116, p.289-292, 2006. DOI: https://doi.org/10.1016/j.agee.2006.02.012.

MORSE, R.A.; CALDERON, N.W. The value of honeybees as pollinators of US crops in 2000. **Bee Culture, v.**128, p.1-15, 2000.

MUGAMBIWA, S.S.; TIRIVANGASI, H.M. Climate change: a threat towards achieving "Sustainable Development Goal number two" (end hunger, achieve food security and improved nutrition and promote sustainable agriculture) in South Africa. **JÀMBÁ: Journal of Disaster Risk Studies**, v.9, a350, 2017. DOI: https://doi.org/10.4102/jamba.v9i1.350.

NOAA. National Oceanic and Atmospheric Administration. **2024 was the world´s warmest year on record**. 2025. Available at: <https://www.noaa.gov/news/2024-was-worlds-warmest-year-on-record>. Accessed on: July 3 2025.

OLLERTON, J.; WINFREE, R.; TARRANT, S. How many flowering plants are pollinated by animals? **Oikos**, v.120, p.321-326, 2011. DOI: https://doi.org/10.1111/j.1600-0706.2010.18644.x.

OTIENO, M.; PETERS, M.K.; DUQUE, L.; STEFFAN-DEWENTER, I. Interactive effects of ozone and carbon dioxide on plant-pollinator interactions and yields in a legume crop. **Environmental Advances**, v.9, art.100285, 2022. DOI: https://doi.org/10.1016/j.envadv.2022.100285.

PARTAP, U. The pollination role of honeybees. In: HEPBURN, H.R.; RADLOFF, S.E. (Ed.). **Honeybees of Asia**. Berlin: Springer, 2011. p.227-255. DOI:

PELLETT, F.C. **American honey plants**. 4th ed. New York: Orange Judd Publ. Co, 1947. 321p.

PELLETT, F.C. **American honey plants**. 5st ed. Hamilton: Dadant and Sons, 1976. 467p.

PERENNES, M.; DIEKÖTTER, T.; HOFFMANN, H.; MARTIN, E.A.; SCHRÖDER, B.; BURKHARD, B. Modelling potential natural pest control ecosystem services provided by arthropods in agricultural landscapes. **Agriculture, Ecosystems & Environment**, v.342, art.108250, 2023. DOI: https://doi.org/10.1016/j.agee.2022.108250.

PIMENTEL, D.; WILSON, C.; MCCULLUM, C.; HUANG, R.; DWEN, P.; FLACK, J.; TRAN, Q.; SALTMAN, T.; CLIFF, B. Economic and environmental benefits of biodiversity. **BioScience**, v.47, p.747-757, 1997. DOI: https://doi.org/10.2307/1313097.

PORTO, R.G.; ALMEIDA, R.F. de; CRUZ-NETO, O.; TABARELLI, M.; VIANA, B.F.; PERES, C.A.; LOPES, A.V. Pollination ecosystem services: a comprehensive review of economic values, research funding and policy actions. **Food Security**, v.12, p.1425-1442, 2020. DOI: https://doi.org/10.1007/s12571-020-01043-w.

POTTS, S.G.; BIESMEIJER, J.C.; KREMEN, C.; NEUMANN, P.; SCHWEIGER, O.; KUNIN, W.E. Global pollinator declines: trends, impacts and drivers. **Trends in Ecology & Evolution**, v.25, p.345-353, 2010. DOI: https://doi.org/10.1016/j.tree.2010.01.007.

POTTS, S.G.; IMPERATRIZ-FONSECA, V.; NGO, H.T. (Ed.). **The assessment report on pollinators, pollination and food production of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services**. 2017. Available at: <https://files.ipbes.net/ipbes-web-prod-public-files/downloads/pdf/individual_chapters_pollination_20170305.pdf>. Accessed on: June 4 2025.

QIN, P.; WANG, T.; LUO, Y. A review on plant-based proteins from soybean: health benefits and soy product development. **Journal of Agriculture and Food Research**, v.7, art.100265, 2022. DOI: https://doi.org/10.1016/j.jafr.2021.100265.

RANGANATHAN, J.; WAITE, R.; SEARCHINGER, T.; HANSON, C. **How to sustainably feed 10 billion people by 2050, in 21 charts**. 2018. Available at: <https://www.wri.org/insights/how-sustainably-feed-10-billion-people-2050-21-charts>. Accessed on: June 26 2025.

REHMAN, A.; FAROOQ, J.; LEE, D.-J.; SIDDIQUE, K.H.M. Sustainable agricultural practices for food security and ecosystem services. **Environmental Science and Pollution Research**, v.29, p.84076-84095, 2022. DOI: https://doi.org/10.1007/s11356-022-23635-z.

RIEDE, W. Soybean breeding in Germany. **Mitteilungen für die Landwirtschaft**, v.50, p.804-805, 1935.

ROBACKER, D.C.; FLOTTUM, P.K.; SAMMATARO, D.; ERICKSON JUNIOR, E.H. Effects of climatic and edaphic factors on soybean flowers and on the subsequent attractiveness of the plants to honeybees. **Field Crops Research**, v.6, p.267-278, 1983. DOI: https://doi.org/10.1016/0378-4290(83)90067-9.

SÁEZ, A.; AGUILAR, R.; ASHWORTH, L.; GLEISER, G.; MORALES, C.L.; TRAVESET, A.; AIZEN, M.A. Managed honeybees decrease pollination limitation in self-compatible but not in self-incompatible crops. **Proceedings of the Royal Society B - Biological Sciences**, v.289, art.20220086, 2022. DOI: https://doi.org/10.1098/rspb.2022.0086.

SALEEM, A.; ANWAR, S.; NAWAZ, T.; FAHAD, S.; SAUD, S.; RAHMAN, T.U.; KHAN, M.N.R.; NAWAZ, T. Securing a sustainable future: the climate change threat to agriculture, food security, and sustainable development goals. **Journal of Umm Al-Qura University for Applied Sciences**, 2024. DOI: https://doi.org/10.1007/s43994-024-00177-3.

SANTONE, A.; MAZZEI, M.P.; VESPRINI, J.; TORRES, C.; AMARILLA, L.D.; GALETTO, L. Pollination service and soybean yields. **Acta Oecologica**, v.116, art.103846, 2022. DOI: https://doi.org/10.1016/j.actao.2022.103846.

SANTOS, E.; MENDOZA, Y.; VERA, M.; CARRASCO-LETELIER, L.; DÍAZ, S.; INVERNIZZI, C. Aumento en la producción de semillas de soja (*Glycine max*) empleando abejas melíferas (*Apis mellifera*). **Agrociencia**, v.17, p.81-90, 2013. DOI: https://doi.org/10.31285/AGRO.17.518.

SARKODIE, S.A. Environmental performance, biocapacity, carbon & ecological footprint of nations: drivers, trends and mitigation options. **Science of the Total Environment**, v.751, art.141912, 2021. DOI: https://doi.org/10.1016/j.scitotenv.2020.141912.

SCHAEFER, F.; LUKSCH, U.; STEINBACH, N.; CABEÇA, J.; HANAUER, J. **Ecological Footprint and Biocapacity**: the world's ability to regenerate resources and absorb waste in a limited time period. Luxembourg: Office for Official Publications of the European Communities, 2006. 11p. (European Commission working papers and studies). Available at: <https://ec.europa.eu/eurostat/documents/3888793/5835641/KS-AU-06-001-EN.PDF>. Accessed on: Mar. 15 2025.

SCHEITER, S.; SCHULTE, J.; PFEIFFER, M.; MARTENS, C.; ERASMUS, B.F.N.; TWINE, W.C. How does climate change influence the economic value of ecosystem services in savanna rangelands? **Ecological Economics**, v.157, p.342-356, 2019. DOI: https://doi.org/10.1016/j.ecolecon.2018.11.015.

SETTELE, J.; BISHOP, J.; POTTS, S.G. Climate change impacts on pollination. **Nature Plants**, v.2, art.16092, 2016. DOI: https://doi.org/10.1038/nplants.2016.92.

SMITH, M.R.; MUELLER, N.D.; SPRINGMANN, M.; SULSER, T.B.; GARIBALDI, L.A.; GERBER, J.; WIEBE, K.; MYERS, S.S. Pollinator deficits, food consumption, and consequences for human health: a modeling study. **Environmental Health Perspectives**, v.130, p.127003-1-127003-12, 2022. DOI: https://doi.org/10.1289/EHP10947.

ŚWIĄDER, M.; LIN, D.; SZEWRAŃSKI, S.; KAZAK, J.K.; IHA, K.; HOOF, J.V.; BELČÁKOVÁ, I.; ALTIOK, S. The application of ecological footprint and biocapacity for environmental carrying capacity assessment: a new approach for European cities. **Environmental Science and Policy**, v.105, p.56-74, 2020. DOI: https://doi.org/10.1016/j.envsci.2019.12.010.

TAMBURINI, G.; BOMMARCO, R.; KLEIJN, D.; VAN DER PUTTEN, W.H.; MARINI, L. Pollination contribution to crop yield is often context-dependent: a review of experimental evidence. **Agriculture, Ecosystems & Environment**, v.280, p.16-23, 2019. DOI: https://doi.org/10.1016/j.agee.2019.04.022.

TURO, K.J.; TEILLY, J.R.; FIJEN, T.P.M.; MAGRACH, A.; WINFREE, R. Insufficient pollinator visitation often limits yield in crop systems worldwide. **Nature Ecology & Evolution**, v.8, p.1612-1622, 2024. DOI: https://doi.org/10.1038/s41559-024-02460-2.

UNFCCC. United Nations Framework Convention on Climate Change. **Key aspects of the Paris Agreement**. 2025. Available at: <https://unfccc.int/most-requested/key-aspects-of-the-paris-agreement>. Accessed on: July 8 2025.

UNFCCC. United Nations Framework Convention on Climate Change. **The Paris Agreement**. 2016. Available at: <https://unfccc.int/process-and-meetings/the-paris-agreement>. Accessed on: Mar. 15 2025.

UNITED NATIONS. Sustainable Development.**Goal 2**: Zero Hunger. 2025. Available at: <https://www.un.org/sustainabledevelopment/hunger/>. Accessed on: July 20 2025.

UNITED STATES. Department of Agriculture. Foreign Agricultural Service. **Production – Soybeans**. 2025a.

Available at: <https://www.fas.usda.gov/data/production/commodity/2222000>. Accessed on: Mar. 15 2025.

UNITED STATES. Department of Agriculture. **World Agricultural Supply and Demand Estimates**. 2025b. Available at: <https://www.usda.gov/oce/commodity/wasde/wasde0525v2.pdf>. Accessed on: June 30 2025.

VAN DER LINDEN, J.O. Soybean *Glycine max* honey production in Iowa USA. **American Bee Journal**, v.121, p.723-725, 1981.

VASILIEV, D.; GREENWOOD, S. The role of climate change in pollinator decline across the Northern Hemisphere is underestimated. **Science of the Total Environment**, v.775, art.145788, 2021. DOI: https://doi.org/10.1016/j.scitotenv.2021.145788

WACKERNAGEL, M.; MORAN, D.; GOLDFINGER, S.; MONFREDA, C.; WELCH, A.; MURRAY, M.; BURNS, S.; KÖNIGEL, C.; PECK, J.; KING, P.; BALLESTEROS, M. **Europe 2005 - The Ecological Footprint**. Brussels: WWF, 2005. Available at: <https://wwfeu.awsassets.panda.org/downloads/europe2005ecologicalfootprint.pdf>. Accessed on: Mar. 15 2025.

WALKER, L.; WU, S. Pollinators and pesticides. In: STEIER, G.; PATEL, K.K. (Ed.). **International Farm Animal, Wildlife and Food Safety Law**. Cham: Springer, 2017. p.495-513. DOI: https://doi.org/10.1007/978-3-319-18002-1_17.

WALL, D.; O'SULLIVAN, L.; DEBELJAK, M.; TRAJANOV, A.; SCHRODER, J.; HENRIKSEN, C.B.; CREAMER, R.E.; CACOVEAN, H.; DELGADO, A. **Key indicators and management strategies for water purification and regulation**. 2018. Available at: <https://www.researchgate.net/profile/Aneta-Ivanovska/publication/329238003_Key_indicators_and_management_strategies_for_water_purification_and_regulation/links/5bfe46f1a6fdcc35428cc158/Key-indicators-and-management-strategies-for-water-purification-and-regulation.pdf. Accessed on: July 5 2025.

WEBBER, S.M.; GARRATT, M.P.D.; LUKAC, M.; BAILEY, A.P.; HUXLEY, T.; POTTS, S.G. Quantifying crop pollinator-dependence and pollination deficits: the effects of experimental scale on yield and quality assessment. **Agriculture, Ecosystems & Environment**, v.304, e107106, 2020. DOI: https://doi.org/10.1016/j.agee.2020.107106.

WMO. World Meteorological Organization. **State of the global climate 2023**. Geneva, 2024. Available at: <https://wmo.int/publication-series/state-of-global-climate-2023>. Accessed on: Mar. 15 2025.

WOODCOCK, B.A.; GARRATT, M.P.D.; POWNEY, G.D.; SHAW, R.F.; OSBORNE, J.L.; SOROKA, J.; LINDSTRÖM, S.A.M.; STANLEY, D.; OUVRARD, P.; EDWARDS, M.E.; JAUKER, F.; MCCRACKEN, M.E.; ZOU, Y.; POTTS, S.G.; RUNDLÖF, M.; NORIEGA, J.A.; GREENOP, A.; SMITH, H.G.; BOMMARCO, R.; VAN DER WERF, W.; STOUT, J.C.; STEFFAN-DEWENTER, I.; MORANDIN, L.; BULLOCK, J.M.; PYWELL, R.F. Meta-analysis reveals that pollinator functional diversity and abundance enhance crop pollination and yield. **Nature Communications**, v.10, art.1481, 2019. DOI: https://doi.org/10.1038/s41467-019-09393-6.

WOODHOUSE, E.J.; TAYLOR, C.S. The varieties of soybeans found in Bengol, Bikar, and Orissa and their commercial possibilities. **India Department of Agriculture Memories of Botanical Series**, v.5, p.103-175, 1913.

WOODWORTH, C.M. The extent of natural cross-pollination in soybeans. **Agronomy Journal**, v.14, p.278-283, 1922. DOI: https://doi.org/10.2134/agronj1922.00021962001400070004x.

ZABALA, A. Pollinator policies. **Nature Sustainability**, v.2, art.86, 2019. DOI: https://doi.org/10.1038/s41893-019-0238-x.

ZAPATA-HERNÁNDEZ, G.; GAJARDOJJ-ROJAS, M.; CALDERÓN-SEGUEL, M.; MUÑOZ, A.A.; YÁÑEZ, K.P.; REQUIER, F.; FONTÚRBEL, E.; ORMEÑO-ARRIAGADA, P.I.; ARRIETA, H. Advances and knowledge gaps on climate change impacts on honey bees and beekeeping: a systematic review. **Global Change Biology**, v.30, e17219, 2024. DOI: https://doi.org/10.1111/gcb.17219.

ZATTARA, E.E.; AIZEN, M.A. Worldwide occurrence records suggest a global decline in bee species richness. **One Earth**, v.4, p.114-123, 2021. DOI: https://doi.org/10.1016/j.oneear.2020.12.005.

ZHANG, H.; HAN, C.; BREEZE, T.D.; LI, M.; MASHILINGI, S.K.; HUA, J.; ZHANG, W.; ZHANG, X.; ZHANG, S.; AN, J. Bumblebee pollination enhances yield and flavor of tomato in Gobi desert greenhouses. **Agriculture,** v.12, art.795, 2022a. DOI: https://doi.org/10.3390/agriculture12060795.

ZHANG, K.; LI, Y.; SUN, K.; BAO, J.; HE, C.; HOU, X. Supplementary honey bee (*Apis mellifera* L.) pollination enhances fruit growth rate and fruit yield in *Paeonia ostii* (family: Paeoniaceae). **PLoS ONE**, v.17, e0272921, 2022b. DOI: https://doi.org/10.1371/journal.pone.0272921.

ZHU, W.; LI, J.; XIE, T. Impact of climate change on soybean production: research progress and response strategies. **Advances in Resources Research**, v.4, p.474-496, 2024. DOI: https://doi.org/10.50908/arr.4.3_474.

Author contributions

Décio Luiz Gazzoni: conceptualization, data curation, literature search, original draft & final writing; **Clara Beatriz Hoffmann-Campo**: literature search, writing, review; **Guilherme Julião Zocolo**: writing, review; **Mauricio do Carmo**: writing, review.

Chief editor: Edemar Corazza
Edited by: Mírian Baptista

Data availability statement

Data in article: research data are available in the published article.

Declaration of use of AI technologies

No generative artificial intelligence (AI) was used in this study.

Conflict of interest statement

The authors declare no conflicts of interest.