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Agroecological strategies to safeguard insect pollinators in biodiversity hotspots: Chile as a case study

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Abstract

Industrial agriculture (IA) is the predominant model of food production since the Green Revolution in the 1950s. IA has been recognized among the main drivers of biodiversity loss, climate change and native pollinator decline. This is controversial, given that native agricultural pollinators are an important resource biota already contributing to crop yield, especially in areas defined as "world biodiversity hotspots" (WBH). These areas often overlap with agricultural zones hosting a significant proportion of cultivated land, mainly through intensive agricultural practices. Pollinator biodiversity and pollination services in these places are currently under threat due to the negative consequences of IA. The dual role of insects as key players allowing the maintenance of the natural ecosystem, as well as main crop pollinators, is particularly exacerbated and urgently requires conservation actions in WBH and food-producing zones. Here we summarize the known negative effects of IA on pollinator biodiversity and illustrate these problems by considering the case of Chile. Food exports represent a considerable part of the economy in this OECD "developing country" in the "Global South", and a large part of its surface has been highlighted as a unique WBH. This area is currently being replaced by IA businesses at a fast pace, threatening local biodiversity. We present agroecological strategies for sustainable food production and pollinator conservation in food-producing WBHs like Chile. These alternatives recognize native pollinators as internal inputs that cannot be replaced by IA technological packages or external inputs and support the development of agroecological and biodiversity restoration practices to protect their existing biodiversity. We suggest a starting point strategy for food production change that integrates four fundamental pillars for producing food in a sustainable way, recognizing biodiversity and local cultural heritage: 1) Share the land, restore and protect; 2) Ecological intensification; 3) Localized knowledge, research and technological development; and 4) Territorial planning and implementation of socio-agroecological policies. We suggest that this approach does not need greater modification of native pollination services that sustain the world with food and basic subsistence goods, but a paradigm change where the interdependency of nature and human wellbeing are recognized for ensuring the present and future of the world's food security and sovereignty as well as considering the reduction of consumerism and food waste.

Key words: Agroecology, sacrifice zones, Apoidea, water deficit, pesticides.

Introduction

Industrial agriculture (hereafter "IA") promoted by the Green Revolution has arguably brought about significant increases in food production globally over the past 70 years[1]. These models involve the use of a «technical package» with strong dependency on fossil fuels, which includes: large-scale monocrop landscapes of improved/selected seeds, increased mechanization and the incorporation of "external inputs" to enhance plant growth and yield such as the introduction of managed pollinators, synthetic fertilizers and pesticides[2]. Yet these welcomed apparent enhancements in production are also partly responsible for the ongoing massive release of greenhouse gases, the unsustainable use of water and land resources[3] and the contamination of soil as well as both surface and underground water reservoirs by fertilizers and pesticides. Under the current market model this intensive agriculture production is widely requested by "countries with higher developmental level"[4], driving unprecedented amounts of food waste[5]. IA functions at the expense of ever-increasing socio-ecological crises, and has been recognized among the main drivers of irreparable biodiversity losses, especially in areas chiefly focused on producing and exporting food crops (*i.e.* "developing countries")[6–9]. Biodiversity decline has been associated with the above-mentioned negative externalities of IA such as habitat loss and fragmentation, pollution and climate change, among others[10–15]. This reduction in biological diversity is currently jeopardizing ecosystem functions and associated processes (including pollination, water and nutrient cycling) and putting human wellbeing at risk[10,16–19]. Considering these problems derived from IA and its associated market model, several authors have stressed the need for a paradigm shift in agriculture if we are to meet future food demands while preserving the ecosystems that sustain this food production[20–22].

Agroecology (hereafter "AE") is considered today as the most relevant alternative to IA by a wide range of actors involved in food production, such as stakeholders, farmers, scientists, NGOs and policymakers[23–25]. AE is a scientific discipline as well as a practice that involves the development of diversified farming systems and short supply chains, the promotion of low external input schemes and conservation and regenerative agriculture[2,23,26–30]. As a political movement, AE promotes food security and sovereignty (see Appendix 1) as an essential human dimension of agricultural transitions in the world's political agenda[28]. Agroecology goals include the application of ecologically-based knowledge to agriculture, with the aim of a sustainable food production while at the same time reducing the environmental impact by spending less energy and resources in the process[31,32], for example by lessening agriculture dependency on the application of external inputs (such as exotic managed pollinators, pesticides and fertilizers) to maintain food production[23]. AE is considered as the scientific rediscovery of some of the ancient agricultural practices developed and preserved by peasant and native cultures as alternatives to IA around the world[33–35]. AE takes advantage of local biotic components and abiotic conditions found in the agricultural landscape, seeking to match crops with local abiotic conditions and promote beneficial associated organisms[36]; highlighting the value of local knowledge and biodiversity that benefits agricultural production[37]. For instance, AE considers available organisms that improve crop productivity such as pollination, biological control and decomposition as "resource biota"[38,39]. Through this lens, local diversity is regarded as a natural "internal input" (II), as opposed to "external inputs" required for IA production, enhancing sustainable food production in agroecologically-managed fields. II provides different ecosystem services and ecological interactions[30,40]. This latter include pollinators, predators, parasites and herbivores as well as non-crop vegetation, soil invertebrates and microorganisms, among other components of local biodiversity helping crop yield[41].

Insects provide several ecosystem services to food production, and are considered irreplaceable resource biota under an AE approach[42–44]. For example, it has been established worldwide that native bee species can improve yield and production quality[22,45–49]. Insect pollinators can contribute to food production even in cases where crops are capable of autonomous self-reproduction[50]; as selfing can have detrimental effects on yield and quality due to inbreeding[51,52]. Regarding the economic relevance of insect pollination, it has been found that the productivity of five of the seven main crops of USA is limited by unavailability of pollinators. The USA annual production value of native pollinator services to these crops has been estimated to be over $1.5 billion[53,54]. In the case of pollinator species not visiting crops but associated with farmland hedgerow flora and/or wild plant patches, this additional diversity has also been found to contribute to agroecosystem functioning, thus the preservation of these native species must also be considered[54,55]. Pollinating insects are currently contributing to world food production, even though intensive IA practices are paying them back with detrimental effects on their health and survival (Figure 1A; Appendix 2)[44,56–58]. All this is currently negatively impacting food security[59,60], especially when managed pollinators may not be the solution to present wild pollination losses[61,62].

AE, by contrast, acknowledges the contribution of native pollinators and highlights them as priceless players for a lasting food production strategy[63]. Using the AE framework, this study proposes an agroecological strategy (AES) to face the current decline of native pollinators due to IA applying four fundamental AES pillars (Figure 1B). AES can be put in practice in order to counteract known biodiversity threats produced by IA and overcome these negative impacts. AES aims to enhance crop production while maintaining healthy ecosystems and native pollinator diversity[64]. To support AES, we emphasize the relevance and urgency of AE research, practices and policy-making, especially for areas of the planet currently considered reservoirs of pollinator diversity[65] such as WBHs[66]. The reason for this emphasis is the fact that WBHs often overlap with prime agriculture zones[67].

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Therefore the continuity of food supply may be at stake, considering that biodiversity is a key contributing factor to world agricultural production[4]. Ironically, WBHs' unique assembly of species and ecosystem services are being jeopardized by IA practices and its associated globalized market schemes[6,68,69]. As irreplaceable resource biota, native pollinator biodiversity could contribute to a sustainable long-term food production model[39,70–73], therefore it merits a place in the design of a modern food production system. In this study we briefly outline the main effects of IA on native pollinators and its implication on insect decline. We use Chile as a case study, a fruit-exporting OCDE developing country with considerable endemism that hosts an unprotected biodiversity hotspot[66,74,75]. IA practices in Chile are one of the main causes of environmental and social problems[76,77]. This pattern can also be found in other countries around the world hosting WBHs, where raw material export-oriented economies have been often maintained with disregard for social unrest and damage to the environment produced[78–80]. We discuss to what extent a change in food production procedures which includes AE pillars may contribute to ameliorate native pollinator biodiversity decline in WBHs, and highlight the relevance to consider this not as local issues concerning agriculture-oriented economies but as a key matter for world environmental health and food security.

Effects of IA on pollinators

In the last five decades there has been a significant global increase in land use changes for agricultural production purposes[81,82]. As a consequence, landscapes on Earth have been simplified and homogenized[83–86]. This is concerning as both human-managed and natural ecosystems rely on their biodiversity for the provision of diverse services that allow their functioning[87–89]. Industrialized agriculture manages agroecosystems through the constant application of external inputs with the goal to maximize the production of commodities based on a small variety of crop species, mostly to supply to international food market demands[6,90]. As was previously mentioned, this highly industrialized agribusiness is conducted largely in underdeveloped areas of the planet at the expense of reducing biodiversity, soil and water sources quality as well as the wellbeing of workers and local communities[91–98]. For instance, pesticides and fertilizers are among several indispensable external inputs needed for the maintenance of IA goals. These are often applied in massive amounts to fields in order to attain high productivity[13,39], with disregard for the negative effects on biotic and abiotic components of these managed habitats[99,100], including the resources needed by different insect species to complete their life cycle (*e.g.* nesting materials, resting refuge, egg laying and suitable larval development microhabitats)[101]. Industrialized agriculture has been recognized among the main threats to insect pollinators[58,102,103]. Great reductions in pollinator populations reported have been attributed to the IA practices for food production[9,44,104–108], causing a general decline in native pollinator richness and visitation rates not only in surrounding patches of native vegetation but also in croplands[109,110]. In this section we summarize how landscape changes as well as the incorporation of external inputs by IA affect native insect pollinators, including native bees, drivers that act together and additively under an intensive agricultural scheme (Figure 1A)[111].

Landscape

Landscape changes due to intensive agriculture may negatively impact pollinators[9,108,112], by changing their composition (percentage of natural/semi-natural habitats in the landscape) and/or configuration (*i.e.* patch density and interpatch connectivity)[113]. The effects on native pollinators will also depend on species-specific traits of these insects and the landscape context[114–122]. For example, nesting resource availability seems to explain 61% of the variation found in different nesting guilds such as ground nesters, pre-existing cavity nesters, carpenters, hollow stem nesters and cleptoparasite bee species[123]. Thus, the effects of IA may cause both overall decline and community structure alternations.

IA farms are characterized by large-scale crops isolated from natural and/or semi-natural habitats, lacking enough floral and nesting resources as well as decreasing production and survival of insect pollinator offspring[124]. These industrialized croplands typically harbor low insect pollinator richness and abundance[125], reducing pollination services and functional diversity[115]. Vulnerable species have been found to be the most affected under these circumstances[126], losing millions of years of plant-pollinator evolution in the process[127]. Landscape homogenization (hereafter "LH"; Appendix 1; Figure 1), appears to be an important driver of IA effects on biodiversity[83]. This might be linked to agroecosystems' reduction of natural habitat patches and/or natural habitat elements[115], decrease of available resources needed for the different components of biodiversity[128] and the loss in connectivity of farmland to natural remnant patches[120,129]. LH also affects mutually beneficial interactions between flowering plants and insect pollinator communities[130]. Pollinator diversity in agricultural habitats under LH might end up being replaced by the few species able to survive these depauperated conditions, leading to further biotic homogenization[131]. This is represented in Figure 1A by native bee specimens pictured in grayscales. The reduced surviving pollinators that remain may not guarantee the delivery of sufficient pollination services, both for human-managed and natural ecosystems[132]. For instance, coevolved associations between native insect pollinators and functionally specialized plants may become at risk of pollen limitation due to LH[133]. This evidence suggests that not only native pollinators currently visiting crop plants must be the focus of concern due to current agricultural practices, but also the whole wild bee guild that may also contribute to the maintenance of local plant diversity near agricultural landscapes[134].

External inputs

Because IA simplifies landscapes and their biological diversity, hampering their contribution to agricultural production[13,135], it needs to incorporate "external inputs" ("EI" in Figure 1A and B) to replace the lost regulatory and supporting ecological services in modified landscapes otherwise provided by internal inputs (II)[39]. External inputs include abiotic and biotic factors. For example, chemical formulations such as fertilizers and pesticides are often used along with modified seeds (*e.g.* herbicide-tolerant crops) capable of enduring these applications while most local biodiversity cannot[100]. IA also introduces exotic managed organisms to provide pollination and biological control. Both pesticides and the use of managed pollinators have been regarded as main external inputs responsible for the decline in native pollinators [136]. Below we detail this evidence.

Pesticides: Pollinators under IA food production plans are exposed to multiple pesticides[137], which have demonstrated deleterious effects in their nervous system, behavior and cognition as well as their development, reproduction and overall survival[138–147] (Appendix 2). It has also been suggested that sublethal exposure to pesticides may produce immune suppression in pollinators[148], increasing their susceptibility to pathogens. Recent evidence regarding epigenetic inheritance has demonstrated that pesticides drive pathological alterations in insect pollinators[149], while in target organisms it has been reported the development of IA promotes epigenetic transgenerational resistance against pesticides[150]. Thus while pesticide detrimental impact may last several generations on non-target organisms, their efficacy on pest species may be reduced as they became immune to their effects[151].

Pesticides reduce the richness and abundance of pollinators and other beneficial native insects[152–154], resulting in mid- and long-term declines and higher extinction rates, whether they forage in treated crops or not (Figure 1A)[25,155,156]. Pesticide exposure routes are correlated with the different

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materials these insects need to complete their life cycles (*e.g.* nesting and food resources)[157–159]. Pesticide residues have been found in food items and substrates used by target and non-target insects[160–165]. This impairs the delivery of pollination services, reducing pollen collection efficiency and affecting crop yield[166–168]. It has also been demonstrated that native pollinators respond differently to pesticide exposure compared to managed pollinators such as honeybees[169], and in some cases they are more susceptible to their toxic effects[170,171]. Pollinator species may have different responses to pesticides (Appendix 2), making it difficult to predict the adverse consequences of these chemicals on pollination services[172,173]. The availability of this kind of data for every species seems unfeasible in the short-term, and thus species-specific traits (such as nesting behavior and sociality type) could be used as proxies to predict pesticide response[116,158,174]. While there is a sustained use of large amounts of pesticides in IA schemes[67], claims of a reduction of their environmental damage have been questioned by researchers. For example, recent reports considering the toxic effects of several pesticides for eight non-target species groups revealed a noticeable increase in the toxicity of applied insecticide over the last 25 years for both aquatic invertebrates and pollinators[100]. This was mainly attributed to the contributions of pyrethroids and neonicotinoids, respectively. The increase of pesticide toxicity included studies in GM corn crops (towards aquatic invertebrates and pollinators) as well as in GM herbicide-tolerant soybeans, where coexisting plant species were also heavily affected[100]. These updated findings stress the urgency to change how food is being produced, leaving current dependency on these external inputs for the sake of the survival of pollinating insects and human health.

Managed pollinators: Regarding this external input largely use in IA schemes to secure crop pollination, most studies have reported negative effects on native pollinators due to the introduction/spread of exotic competing managed bee species (*e.g. Apis mellifera*, *Bombus* *terrestris*) in agroecosystems[9175–177]. Managed bees affect the development and reproduction of native bee species that are close to their colonies[178]. For instance, sometimes managed bees mate with local species, resulting in inviable hybrids[179,180]. EI pollinators introduced under IA management might also compromise food and nesting resources available to other native insect pollinators through competition[181]. When managed bees become naturalized outside of their native range they can adapt easily to varied nesting substrates, potentially being less susceptible to nesting site shortages[182], and overcoming this shortage by usurping closely related species' nests[183]. In the presence of greater floral abundance, the number of managed bees visiting floral species is higher than those of pollinators[184], potentially outcompeting them[185]. They are also able to amass a great amount of provisions rapidly [186], possibly depleting resources for other native insects[187].

Pathogen spillover might also be of concern in this context; managed bees are usually social insects and given their behavior could be more likely to host and spread pathogens[188]. These exotic pollinators are able to transport and spread pathogens to flower species while visiting [189]. These then are transmitted to other wild flower visitors, including native pollinators[190]. Although pathogens have been indicated as one of the drivers of lower pollinator abundance[191], their impact on native and introduced bee species seems to be so widely distributed that is difficult to pinpoint the direction of these spillovers[192]. Nonetheless, this is a recognized source of deterioration of native pollinator wellbeing.

IA and AE in biodiversity hotspots: Chile, a case study

Biodiversity hotspots are highly endemic biogeographic regions threatened by human activity[66]. The Neotropical region includes several of these areas, hosting an outstanding diversity and richness of native pollinators[9]. This area of the planet produces a considerable portion of food crops by IA and it has been regarded as the zone has suffered one of the greatest declines in biodiversity and ecosystem services[4,80]. Chile includes in its territory almost an entire hotspot, named the "Chilean Winter rainfall-Valdivian Forests". This consists of several biomes hosted within the Chilean Matorral and the Valdivian temperate rainforest[66,193]. The former could be considered a WBH and largely overlaps with IA food production areas[194,195]. Unfortunately, only 1.8% of Matorral land is under the Chilean national protection program[196]. The Chilean Matorral is also a region that hosts an important bee species diversity with elevated endemism[65,197].

Chile has subscribed to environmental treaties to know, conserve and restore its biodiversity as well as reforest endangered areas[198–201], but so far there are no territorial management plans that aim to make agricultural production compatible with biodiversity conservation (appendix 2). This has resulted in a significant loss of natural habitats in a few decades[202,203]. National records report that approximately 70% (12,900,682 ha) of the land used for agriculture, livestock and plantation forestry is within the "Chilean Winter rainfall-Valdivian Forests" hotspot[204]. This hotspot holds an area of 30,000,000 ha, which means that nearly 43% of it has already been replaced by these production schemes[193]. Even more concerning is that habitat loss rate in this hotspot keeps growing[205].

Agricultural practices in Chile are deeply rooted in export-oriented IA models[67,206], directly attributed to the economic liberalization policies mandated by the military dictatorship after 1973[207]. Measures established by force during this period included the privatization of the public sector, resulting in the concentration of agricultural land in the hands of a few and a significant exploitation of natural resources to supply international markets[208], creating a globalized and capitalized commercial IA scheme at the expense of neglecting and marginalizing small farmers and indigenous people[209,210].

The rediscovery of AE alternatives in Chile began as a reaction towards the economic crisis that unfolded immediately after the application of Milton Friedman's neoliberal policies in the early

1980s, due to an exponential increase in rural poverty and abandonment of the urban and rural working classes[69,211]. Chilean AE advances were made by a small number of NGOs, small farmers and academics[35]. Although some of these developments were recognized by the Food and Agriculture Organization of the United Nations[212], only in rare cases have AE practices been adopted by corporations and promoted by policy makers, and at present these practices are not used on a productive scale in Chile[69,213].

Pesticides

Around 9.6% of the pesticides approved by the Chilean government[214] have been already banned by the European Union (Appendix 2), one of the main consumers of Chile's fruit exports[67]. Most of these pesticides are highly toxic, with demonstrated negative effects on bees at sublethal doses (Appendix 2). For example, while neonicotinoids (*e.g.* clothianidin, imidacloprid, thiamethoxam) are being questioned by experts around the world and have restricted use in Europe due to harmful effects on native and managed bees[98,156,215–218], they are widely used in Chile due to an alleged "absence of proof in the country of their negative effects"[219,220]. This is concerning given the chemical behavior of these pesticides, as these widely-used formulations are adsorbed by mineral clays and organic matter that form agricultural volcanic ash-derived soils[221], damaging biodiversity as a consequence[222], and most likely affecting native bee species directly, as nearly 70% of Chile's wild Apoidea nest in soil substrates[233]. Despite the aforementioned issues, current regulatory protocols for the approval of new formulations and maintenance of pesticide use in Chile have not been updated based on current scientific acknowledge and do not require the development of local science-based risk-assessments over biodiversity for their approval for IA use[224].

Managed Pollinators

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External biotic inputs in Chile are already impacting the environment; the main exotic bumblebee species commercially used for providing pollination services, the buff-tailed bumblebee *Bombus terrestris* Linnaeus, 1758 and *B. ruderatus* Fabricius, 1775 have rapidly replaced the Patagonian giant "moscardón" bumblebee *Bombus dahlbomii* Guérin-Méneville, 1835[228,229] (Figure 2). *B. dahlbomii* was a source of medicinal honey and considered a sacred being by Mapuche, one of the First Nations people of Chile[230]. Scientists have demonstrated that Introduced bumblebee species are displacing native *B. dahlbomii* in Chile and Argentina, colonizing natural areas in most of the southern cone of South America, and have urged authorities to ban the imports of these IA-managed pollinators[231,232]. Even though this is a concerning situation, government policy still allows the importation of buff-tailed bumblebees for IA crop pollination in Chile[231].

In the Mediterranean region of central Chile, a bee biodiversity hotspot[65], avocado orchards have been recorded to be profusely visited by managed *A. mellifera,* while five native bees species have also been reported visiting this crop[233]. Although this finding was proposed as a demonstration of the compatibility of IA avocado production with native bee biodiversity, these observations were conducted through one-season focal observations and with no additional collection methods or control of native vegetation or wild bee abundance comparisons. Scarce and often preliminary local research in combination with fast-paced habitat loss in Chile paints a concerning picture for pollinators and their ecosystem services in the agricultural production canvas. Chile probably hosts around 800 bee species, with more than 450 species described and 70% endemicity[197]. Very little research has been published in regard to native insect performance as pollinators for native and crop plant species. For example, in the case of the endangered *B. dahlbomii*[234], this native Apidae has been described as a possible pollinator of greenhouse tomatoes[235], and has been seen visiting blueberry and avocado orchards[233]. Considering this evidence and the research from neighboring countries[246–248], it seems likely that most native insect pollinators may already be pollinating crops of economic importance. The knowledge of wild bee species association with native plants is largely incomplete[197,239]. Chile may hold an irreplaceable pollinator workforce in its native bee pollinators, contributing both to crop yield and the preservation of unique biomes, nonetheless they are threatened by intensive IA production and neglected by government policy makers. This highlights the unsuitability of Chile's current agricultural production and market and jeopardizes the mid- and long-term contribution of this country to the production of fruit commodities and also to its own resilience against future environmental and food crises. In the following section we develop our proposal to face these issues and be able to protect pollinators in agriculturally-oriented WBHs like Chile.

Protecting pollination: strategies for the future

Human practices, including agriculture, need to return within the limits that keep our planet habitable[89,240], for the sake of our own species and all living organisms[241,242]. Countries with invaluable biodiversity need to rethink critically the way they are doing agriculture and revaluate local and native sustainable practices[243,244]. Understanding that native pollinator species are unique "resource biota" (see Appendix 1) already contributing to current crop yield is to be aware of a strategic advantage compared to agriculture food production in non-WBH regions. Native pollinators are AE internal inputs that cannot be replaced by IA technological packages or external inputs[245]. Coexisting with our threatened biodiversity and valuing its cultural and biological wealth within productive ecosystems will protect the future of pollination services as well as contribute to food security and sovereignty. Here we focus on the development of agriculture schemes in WBHs considering native biodiversity, and compile a strategy summarized in four pillars based on agroecological thinking as well as First Nations' knowledge: (1) sharing, restoring and protecting the land; (2) AE as the paradigm of sustainable agriculture and pollinator protection; (3) localized research and technology; and (4) territorial planning and AE policies (Figure 1B).

1. **Sharing, restoring and protecting the land**

Natural ecosystems are far from simple, and to achieve sustainable agriculture there is a need to maintain their complexity[40]. Polycultures and florally diverse environments have been found to support native pollinator diversity due to a continuous supply of food resources[246]. Agricultural practices need to consider that pollinator functional diversity relies on these native habitats and that biodiversity hotspots by definition are already threatened, thus need to be considered with special care when conducting productive and extractive activities. A sustainable complex landscape matrix is needed to protect hotspots and ensure the delivery of pollination services to crops. This pillar should integrate restoration and protection of large areas of natural habitat and restoration of native land patches within agroecosystems to increase habitat quality (*i.e.* land sharing)[247]. Pollination services delivered by native insects have shown to rely strongly on their proximity to natural habitats [109,248,249]. Protected natural areas host higher biodiversity[250], but are not enough to sustain ecological stability[251]. To achieve stability, habitats that have been altered by human activities, including urban zones and areas utilized for productive activities, need to be restored as much as possible[252], leading to effective conservation outcomes by assessing their coverage (*i.e.* the number and types of species included within their limits) and management[253]. Restoring native patches of anthropized land improves habitat quality within agroecosystems, maintaining and securing native insects[254]. Native patches buffer the negative effects of pesticide application on pollinators[153,255], offer greater flower diversity and nesting sites[256] and are correlated with higher pollinator density[257]. In farmlands these patches also serve as wildlife corridors[114,181,258–260], promoting heterogeneous landscapes[261] and stabilizing crop pollination[262]. These patches could be implemented at field edges and should have mixed native plants with partial overlap in floral phenology as a way to provide resources for bees during the whole flowering season[256]. Pollinators benefit from florally diverse environments due to a continuous supply of food resources[246], which are critical for ensuring their reproduction[124]. The size of these patches could be dependent on the crop type that they surround, and research should be carried out to define the appropriate cost-effective sizes within specific agroecosystems[101,263].

2. AE for sustainability and pollinator protection

Among the core principles of AE science and practice is the preservation and use of local diversity as natural inputs contributing to crop yield[264]. This approach also advocates for food sovereignty while reducing the negative effects of agriculture on the environment and society[265]. Monocultures, organic or not, reduce the functional diversity of pollinators[115]. Under an agroecological strategy (AES), biodiversity is incorporated into agroecosystems to mimic natural ecological processes[28]. With higher biodiversity, agroecosystem inner complexity grows and reduces the dependence of crops on destructive external inputs, allowing the system to maintain its own soil fertility, productivity and protect itself from pests[266], benefiting insects and attracting pollinators[101]. All this allows native pollinators to visit crops safely and thrive in an agroecosystem with food and nesting resources free of pesticides. This higher pollinator biodiversity could even reduce the need to incorporate large numbers of managed pollinators within crops as additional external input. Nonetheless, the aforementioned falls short of defining AE, as not only are academic, political and cultural perspectives tightly knitted to this model, AE places small farmers and local knowledge as the key for food sovereignty[267] and does not agree with the new Green Revolution approach, which seeks to perpetuate an IA system for food production[268]. Instead, AE focuses on the dissemination of knowledge from farmer to farmer based on their historical backgrounds and on reviving their ancestral farming roots[269], strengthening communities and allowing them to become autonomous, securing local food production[268]. Mexican and Bolivian farmers are examples of how traditional low-intensity agriculture allows native bee species to provide successful pollination service[270,271]. There is no need for a new Green Revolution, as social vulnerability and income inequities are the main cause of hunger[5]. AES, summarized in this review, aim to protects pollinators not only by its effects in agroecosystems, but also by reducing poverty and improving people's livelihoods, by both recovering local knowledges and developing local research technologies as well as implementing territorial planning and AE policies considering the needs of local communities (Explained further in following sections, Figure 1B)[32]. People can only protect or be concerned about biodiversity and its conservation once their basic needs have been met. Thus, the world does not need more food commodities to be traded globally; it needs equal access to nutritive food and production not focused only on market and profits[272,273].

3. Localized research and technology

Science has proven that IA is leading a steady biodiversity decline and exceeding the planetary boundaries that allow humans to survive on Earth[89]. The IA production and market scheme keeps low-income WBH countries of the world relying on the import of technological packages and depending on globalized markets to achieve their productivity goals. Technological packages should not be imported without knowing their consequences to ecosystems, local communities and economies[274,275]. Critical knowledge gaps still exist

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regarding taxonomy, ecosystem services and socio-ecological vulnerability in order to implement production alternatives considering native pollinators[276]. This is especially urgent in WBH countries risking their biodiversity, food sovereignty and human wellbeing[277].

Localized studies need to be conducted in regions where biodiversity knowledge is scarce and nature is heavily under threat due to industrialized food production activities[80]. As a starting point it is necessary to fill the current knowledge gap on species and their ecological associations[278]. There are still a great number of organisms and ecological interactions left to describe[279], largely in WBH zones. Taxonomy is one of the foundations of the applied sciences. If species have not been described, it becomes challenging to understand how they respond to ecological changes and be able to monitor them[280]. This is especially urgent for insects, a group underrepresented in conservation research[281] and under global decline[8]. Research in WBH countries is also key to assess native pollinator contribution to crop and native plant species reproduction, their nesting needs and different behaviors. Pollinator species have diverse life histories and traits, responding differently to the same threats[83,114]. Assessing how pollinators respond to potential dangers will allow for the modeling of proper AE production programs. To illustrate the urgent need of information we use the Apoidea, highly charismatic native pollinators. It has been estimated the number of native bee species in the Neotropical Region would be above 15,100, stressing that current knowledge on actual species richness would represent roughly one third of this total[9]. This is worrisome considering the high rates of biodiversity and ecosystem services losses reported for this region of the world [80], largely composed of WBHs focused on agriculture exports[4]. This may imply the potential extinction of many pollinators before even their description, “Centinelan Extintion” [282], and its neglect represents a threat to both local and global food security[283]. Therefore, the local study of bee biodiversity and conservation in these regions must be a global concern. Local farmers and first nations have been recognized as “local knowledge holders” for already possessing the understanding regarding their pollinators and their pollination services in their local food production[284–286]. This wisdom needs to be recovered and applied, as they are key to implement and ensure AES allowing a gradual transition towards a sustainable global food production scheme[287].

Research will improve our understanding on how insect pollinators respond to agricultural practices in WBH countries and provide alternatives with the goal to advance towards the sustainability of socio-ecological systems, allowing for the development of AE tools and technology as part of the production chain as well as conservation in several food and plant-derived goods needed by our species. Developing local AE knowledge will not only protect biodiversity (*e.g*. native pollinating insects) and agricultural productivity but also reduce the dependency on IA external drivers and inputs and contribute to the coupling of ecosystems and human wellbeing[277]. With this design, pollinator conservation will not be considered a trade-off against agroecosystems or society but as a partnership for our coexistence.

As was already explained, AES for WBHs must consider the political and cultural perspectives along with the research program. Therefore, the rediscovery of AE must link human wellbeing and ecosystem integrity, thus the collecting of information about the ecological vulnerability of pollination services needs to be coupled with gathering information on social inequalities in this food-producing WBH[277], as a link between economic vulnerability and biodiversity loss has been demonstrated[288]. Integrating all this will allow the development of local AE research and technology in consideration of the societal and ecological conditions of different WBH regions of the planet[276,289,290], providing AE schemes for each socio-agroecosystem[37].

Territorial Planning and AE policies

World Biodiversity Hotspots are strongly threatened by the loss of their species and resource depletion (*e.g.* water scarcity) due to IA schemes, currently representing sacrifice zones that provide food and goods to global markets, so the developed side of the world can "go green"[6]. This needs to change. AE's local biodiversity "internal inputs" such as native pollination services[73] cannot be labeled as commodities (*e.g.* "natural capital"[73]), as its "exchange" threatens the sustainability of food production and commerce[4]. This is likely currently happening in a "Centinelan" pollination consumption (not a "trade"), as native bees cannot be replaced or recovered once species go extinct. Moreover, there is not a fair planetary-level exchange and interdependency between WBH exporters and international food commerce, as the resulting benefits have been demonstrated to be distributed globally in a both socially and economically unequal way[4]. For instance, in Chile IA is coupled with sustained social inequalities and unrest, local communities driven to unsanitary water deficit and unique biomes shrinking as IA expands, leading pollinating species to decline before having a chance to be studied[207,211,291]. These are the challenges policy makers need to face; if we want to keep the remaining biodiversity of native pollinators in food-producing countries, intensive industrialized agriculture schemes must be first buffered by AES and gradually replaced by true sustainable food production[9,72].

In order to translate knowledge into policies, first the gathering of information needs to be supported. Science and local knowledge holders can provide a roadmap to make well-informed decisions (Figure 1B), but their work needs to be properly funded and listened to[292]. These policies can provide the data science and technology need to assess, propose and apply the best cost-effective strategy for pollinator conservation, food security and sovereignty[293]. This is already happening in main food consumer countries of the European Union and the

United States[8]. Unfortunately, this is not true for most WBH countries[80], where not taking the steps in this direction will have global consequences.

Strong environmental governments will be required in order to change IA schemes and prioritize the conservation of native pollinators and wildlife. Ecosystems, especially those belonging to biodiversity hotspots, need to be within an international legal framework of protection that starts by recognizing the context-specific complexity of agricultural systems and the irreplaceable relevance of local diversity, both biological and cultural[286]. Local deterioration of biodiversity due to extractivism has global consequences on the health of the Earth's system and food security[89]. Small-scale farming applying AE schemes, such as that proposed in this work, must be prioritized in WBH [69]. Agricultural businesses should be required to follow AES and sustainability standards[273], including: coherence with crop and climatic conditions of local biomes, diversified farming and to prioritize the use of AE's internal inputs. As a complement, rural and urban public awareness policies and AE education must be considered to provide tools towards conservation and food sovereignty[294]. Traditional ecological knowledge of local agricultural practice and native pollinators must be outreached to the public and applied, preferring small diversified AE farms instead of large monocrop IA. Moreover, urban AE initiatives and native plant gardening must be promoted as additional patches for native reforestation[33,273,295]. All these urgently need to be assessed and overseen, to ensure sustainable management practices and the conservation of biodiversity[213].

Agroecological management reduces the need for pesticide use and their undesirable consequences (Appendix 2), which is an opportunity for WBH countries to ban harmful pesticides, already done in main food consumer countries[8]. Given that insect decline is a global threat, taking sustainable measures in richer countries will not make this crisis disappear without a global commitment[60]. WBH governments also urgently need to implement AE-inspired territorial management plans, including the protection of people's livelihoods over large corporately owned agricultural areas (*e.g.* in Chile watering avocado orchards owned by a few cannot hamper entire communities' access to water).

Developed main food consumer countries need to consider that being climate neutral at the expense of importing food crops from underdeveloped countries does little to solve the negative effects of IA and completely ignores that the loss of ecosystem services will not make distinctions between geopolitical borders[296]. When trading with other nations, developed countries need to have policies that hold the same standards of sustainable production (including bans on GMOs and pesticides) as those applied to their own countries, and not insist on requiring "yield increases in many low-income countries"[297].These low-income areas are often also world reservoirs of biodiversity (including pollinators). To consider WBS as sacrifice zones, for the sake of meeting current market needs, are putting in peril not only biodiversity itself, but also global food security and Earth system health[6].

Conclusion

A new deal considering AE approaches must be implemented globally, considering WBH as key areas both for the preservation of native pollinator biodiversity and rights and wellbeing of local communities. The implementation of agroecological strategies in WBHs as starting point and buffer for IA may facilitate the transition towards a true sustainable food production. AES will improve our understanding of ecological dynamics in agroecosystems, allowing sustainable development over time, ensuring local development and food sovereignty of WBH, for the sake of keeping native pollinator biodiversity and the wellbeing of the whole planet[88,89].

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Figures

Figure 1. A: Industrial agriculture (IA) scheme rely on agricultural intensification, this is mainly done by the simplification of rural ecosystems due to increased landscape homogenization (LH). In addition IA depends, for the production of crop yield (CY), on the application of external inputs (EI), such as: pesticides, GMOs and managed exotic pollinators. Nonetheless LH and EI are also causing a decline of biodiversity including wild pollinators like native bees (NB). This is exemplified in this illustration, from large to small, by genera: *Bombus*, *Anthidium* and *Lasioglosum* native species. This problem is especially critical at world biodiversity hotspots (WBHs) like central Chile, where relatively larger species have been found to be more likely affected by LH and EI (represented in gray in Figure A). **B** An agroecological strategy (AES) to counteract the effects of current IA intensification at world biodiversity hotspots (WBHs) by incorporating: Land Sharing, Restoration and Preservation (LS R&P), the use of Internal Inputs (II) derived from local biodiversity, including microorganisms, native plants and animals. AES also propose the development of localized research and technology (LR&T) as well as Territorial Planning and Implementation of Agroecological policies (TP&AP). We propose that these AES pillars may contribute to the survival and performance of native pollinators such as wild bees, NB contribute directly to crop yield as well as indirectly by its influences on AES (e.g. helping LS R&P, II and LR&T). We suggest AES may be able to buffer current LH and EE from IA, as a start point towards a gradual change towards the implementation of an agroecological food production system; not focused on international market needs only, but on food sovereignty and safety as the base for a true global sustainable food production. Illustration

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by Cristian Villagra.

Figure 2. Giant bumblebee: *Bombus dalhbomii* (Hymenoptera), native from Chile and Argentina, legitimately visiting blueberry flowers in November, 2015, Villarica, X Region, Chile (scale: 1cm). This species has been categorized as “endangered” by the IUCN Red List. Photography by Marianela Castillo Arias.

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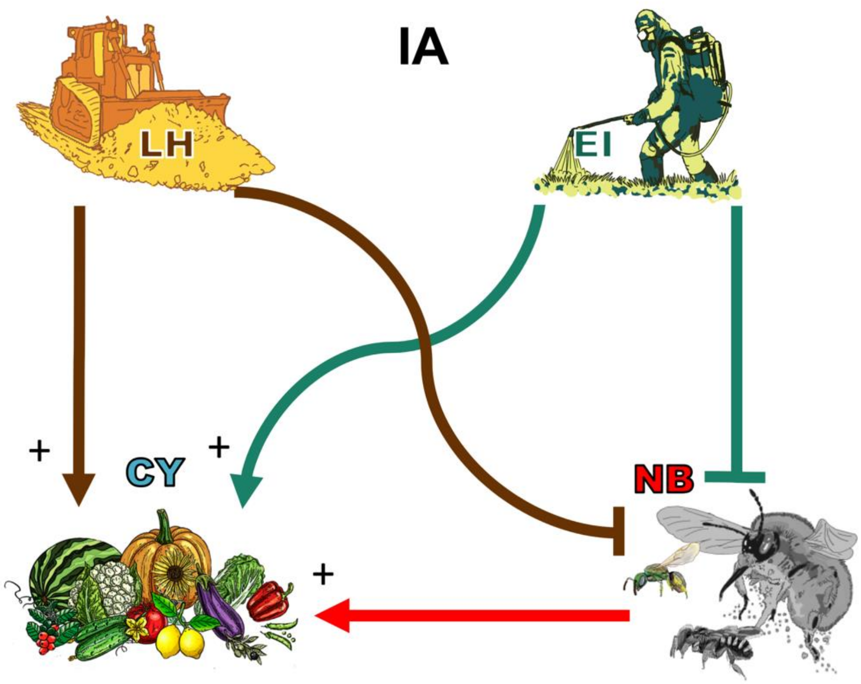
Figure 1

A



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B

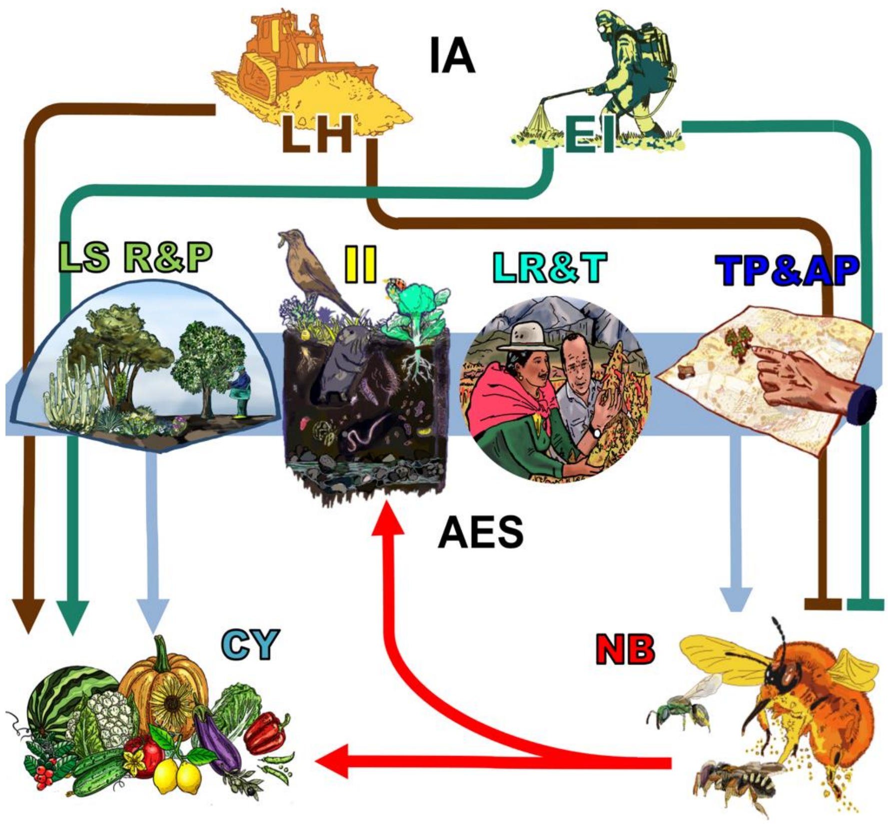

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Figure 2.

Appendix 1. Glossary

Agroecology: agronomic discipline focused on an environmental and socially responsible agricultural management. This is achieved through the study of ecological processes inside agroecosystems and the application of this knowledge to agricultural practices.

Agricultural intensification: agricultural scheme that seeks to maximize crop yield per unit of area through the use of external inputs.

Ecological intensification: replacement of external inputs used in intensive agriculture (*e.g.* insecticides, fertilizers, growth regulators, etc.) by ecosystems services to maximize crop yield with minimum environmental impacts.

Ecosystem services: ecological functions that benefit and are essential for human beings.

Habitat: environment inhabited by a particular species.

Landscape homogenization: simplification and reduction of biotic components inside an area of land, which leads to a community of similar functional and structural traits.

Natural habitat: pristine environment inhabited by native species.

Organic agriculture: agricultural scheme that does not use fertilizers and pesticides.

Patch: area of land with the same characteristics, regardless of its size.

Seminatural habitat: a native environment partially modified by human activities.

Sustainable agriculture: agricultural scheme that efficiently maximizes production while protecting the habitat and natural resources from which it depends, safeguarding biodiversity in the long term.

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Appendix 2. Active ingredients with effects in bees still used in Chile and not approved by the European Union.

Use Classification in Chile[1]	Active Ingredient [2]	Pesticide class	[3]Effect	Reference
I, R, A	Acephate	Organophosphate	Highly toxic to bees and other beneficial insects.	Christiansen *et al*. 2011
H	Atrazine	Triazine	Oxidative stress responses and alteration acetylcholinesterase activity in honeybees; pesticide detected in native bee tissue; found in stored pollen of honeybees; decreases survival, reduces food consumption, and negatively affects behavior in stingless bees.	Bernal et al. 2010; Boily et al. 2013; Hladik et al. 2016; Williams 2016; dos Santos Araújo et al., 2021
H	Atrazine/S-metolachlor	Triazine/Chloroacetamide	Oxidative stress responses and alteration acetylcholinesterase activity in honeybees; pesticide detected in native bee tissue; found in stored pollen of honeybees; decreases survival, reduces food consumption, and negatively affects behavior in stingless bees.	Bernal et al. 2010; Boily et al. 2013; Hladik et al. 2016; Williams 2016; dos Santos Araújo et al., 2021
F, B	Benomyl	Benzimidazole	Moderatly toxic to honeybees	N.C. Agriculture 2016
I, R, A	Cadusafos	Organophosphate	Highly toxic to bees	EFSA 2006
I, R, A	Carbaryl	Carbamate	Highly toxic to honeybees; found in stored pollen of honeybees	Bernal et al. 2010; Bond et al. 2016
F, B	Carbendazim	Benzimidazole	May alter the immune response and P450-mediated detoxification of honeybees	Shi et al. 2018
F, B	Carbendazim/Epoxiconazole	Benzimidazole/Triazole	May alter the immune response and P450-mediated detoxification of honeybees; detected in corbicular pollen loads of honeybees	Böhme et al. 2018; Shi et al. 2018
F, B	Carbendazim/Mancozeb	Benzimidazole/Carbamate	May alter the immune response and P450-mediated detoxification of honeybees	Shi et al. 2018
F, B	Tebuconazole/Carbendazim	Triazole/Benzimidazole	May alter the immune response and P450-mediated detoxification of honeybees; pesticide detected in native bee tissue	Hladik et al. 2016; Shi et al. 2018
I, R, A	Cartap hydrochloride	Carbamate	Toxic to bumblebees	Marletto et al. 2003
I, R, A	Cartap monohydrochloride	Carbamate	Highly toxic to insects	Kegley et al. 2016
I, R, A	Chlorfenapyr	Pyrrole	Highly toxic to honeybees	Rhodes & Scott 2006
F, B	Chlorothalonil/Carbendazim	Chloronitrile/Benzimidazole	May alter the immune response and P450-mediated detoxification of honeybees; found in stored pollen of honeybees	Bernal et al. 2010; Shi et al. 2018
F, B	Copper 8-quinolinolate/Carbendazim	Organometallic compound/Benzimidazole	May alter the immune response and P450-mediated detoxification of honeybees	Shi et al. 2018
F, B	Copper oxychloride/Dibasic copper sulfate/Iprodione/Sulphur	Copper salt/Copper salt/Dicarboximide/Chalcogen	Decrease in honeybee's forager survival; found in stored pollen of honeybees	Bernal et al. 2010; Fisher et al. 2017
I, R, A	Diazinon	Organophosphate	Precocious foraging in honeybees; Impaired olfactory learning in honeybees; found in stored pollen of honeybees	MacKenzie & Winston 1989; Weick and Thorn

				2002; Bernal et al. 2010
I, R, A	Fenpropathrin	Pyrethroid	Highly toxic to honeybees	Gromisz 2001
I, R, A	Fenvalerate	Pyrethroid	Highly toxic to honeybees; hazardous to leafcutter bees	National Research Council of Canada 1981
I, R, A	Fipronil	Phenylpyrazole	Highly toxic to honeybees; Impaired olfactory learning in honeybees; toxic to leafcutter bees; pesticide detected in native bee tissue; found in stored pollen of honeybees; causes lethargy, motor difficulty, paralysis and hyperexcitation in stingless bees	Mayer & Lunden 1999; Hassani et al. 2005; Bernal et al. 2010; Pisa et al. 2015; Hladik et al. 2016; de Morais et al., 2018
H	Glufosinate-ammonium	Phosphinic acid	Low toxicity in honeybees	European Food Safety Authority 2005
H	Imazamox/Imazapyr	Imidazolinone/Imidazolinone	Low toxicity in honeybees	EPA 2005; European Food Safety Authority 2016
F, B	Iprodione	Dicarboximide	Decrease in honeybee's forager survival; found in stored pollen of honeybees	Bernal et al. 2010; Fisher et al. 2017
F, B	Iprodione/Propiconazole	Dicarboximide/Triazole	Decrease in honeybee's forager survival; pesticide detected in native bee tissue; detected in corbicular pollen loads of honeybees; found in stored pollen of honeybees	Bernal et al. 2010; Hladik et al. 2016; Fisher et al. 2017; Böhme et al. 2018
F, B	Iprodione/Sulphur	Dicarboximide/Chalcogen	Decrease in honeybee's forager survival; found in stored pollen of honeybees	Bernal et al. 2010; Fisher et al. 2017
H	Isoproturon	Phenylurea	High mortality in honeybees; detected in corbicular pollen loads of honeybees	Abrol & Andotra 2001; Böhme et al. 2018
I, R, A	Methidathion	Organophosphate	Highly toxic to honeybees; found in beeswax of honeybees	EPA 2006; Chauzat & Faucon 2007
I, R, A	Novaluron	Benzoylurea	Highly toxic to honeybees	Fine et al. 2017
H	Paraquat dichloride	Bipyridylium	Highly toxic to honeybees; changes the size of honeybee oenocytes	Moffett et al. 1972; Cousin et al. 2013
H	Paraquat dichloride/Diquat (dibromide)	Bipyridylium/Bipyridylium	Highly toxic to honeybees; changes the size of honeybee oenocytes	Moffett et al. 1972; Cousin et al. 2013
I, R, A	Permethrin	Pyrethroid	Highly toxic to honeybees; disorientation and disruption of normal behavior in honeybees; pesticide detected in native bee tissue	Hagler et al. 1989; Cox & Wilson 1984; Sanchez-Bayo & Goka 2014; Hladik et al. 2016
F, B	Tebuconazole/Propiconazole/Permethrin	Pyrethroid	Highly toxic to honeybees; disorientation and disruption of normal behavior in honeybees; pesticide detected in native bee tissue	Hagler et al. 1989; Cox & Wilson 1984; Sanchez-Bayo & Goka 2014; Hladik et al. 2016

F, B	Procymidone	Dicarboximide	Low toxicity to bees; found in stored pollen and beeswax of honeybees	FAO 2001; Chauzat & Faucon 2007; Bernal et al. 2010
I, R, A	Profenofos	Organophosphate	Highly toxic to honeybees; high mortality in honeybees	Melisie et al. 2015; Stanley et al. 2015
H	Saflufenacil	Pyrimidinedione	Low toxicity to honeybees	APVMA 2012
I, R, A	Thiocyclam hydrogen oxalate	Oxalate salt	Highly toxic to bees	Jiménez & Cure 2016
I, R, A	Acetamiprid/Novaluron	Neonicotinoid/Benzoylurea	Highly toxic to honeybees; detected in corbicular pollen loads of honeybees; impaired long-term retention of olfactory learning and increased locomotor activity in honeybees; ataxia in bees; slow to no movements and ataxia in bumble bees and leafcutter bees; occur in sufficient quantities in natural bee food to have adverse effects on bees.	Hassani et al. 2008; Fine et al. 2017; Baines et al. 2017; Böhme et al. 2018
I, R, A	Dinotefuran	Neonicotinoid	Highly toxic to honeybees; higher number of bouts of behaviour in honeybees	EPA, 2004; Williamson et al. 2014
I, R, A	Fipronil/Imidacloprid	Phenylpyrazole/Neonicotinoid	Highly toxic to honeybees; Impaired olfactory learning in honeybees; honeybees line up in perfect rows or clusters; pesticide detected in native bee tissue; found in stored pollen of honeybees; honeybees loose postural control and spent more time laying on their backs; inhibited grooming, reduced walking and lower righting reflex in honeybees; increased foraging and homing flight times in honeybees; detected in corbicular pollen loads of honeybees; trembling, excessive grooming, uncontrolled proboscis extension, slow to no movements, ataxia and reduced survival in bumble bees and leafcutter bees; toxic to leafcutter bees; occur in sufficient quantities in natural bee food to have adverse effects on bees.	Mayer & Lunden 1999; Hassani et al. 2005; Bernal et al. 2010; Schneider et al. 2012; Williamson et al. 2014; Pisa et al. 2015; Hladik et al. 2016; Baines et al. 2017; Böhme et al. 2018
I, R, A	Fipronil/Thiamethoxam	Phenylpyrazole/Neonicotinoid	Highly toxic to honeybees; Impaired olfactory learning in honeybees; toxic to leafcutter bees; pesticide detected in native bee tissue; found in stored pollen of honeybees; honeybees loss postural control and spent more time laying on their backs; honeybees spend more time grooming; impaired homing ability in honeybees; hyperactivity, ataxia, excessive grooming, permanent late-onset neuromuscular dysfunction and reduced survival in bumble bees and leafcutter bees; occur in sufficient quantities in natural bee food to have adverse effects on bees.	Mayer & Lunden 1999; Hassani et al. 2005; Bernal et al. 2010; Henry et al. 2012; Williamson et al. 2014; Pisa et al. 2015; Hladik et al. 2016; Baines et al. 2017
F, B	Orthoboric acid/Borax	Inorganic compound/Inorganic compound	Toxic to honeybees	Taylor et al. 2007
F, B	Orthoboric acid/Fenpropimorph/Propiconazole	Inorganic compound/Morpholine/Triazole	Toxic to honeybees; detected in corbicular pollen loads of honeybees; found in stored pollen of honeybees	Taylor et al. 2007; Bernal et al. 2010; Böhme et al. 2018
F, B	Picoxystrobin/Cyproconazole	Strobilurin/Triazole	Decreased survival, slight changes in pericardial cells and fat bodies in africanized honeybees; detected in corbicular pollen loads of honeybees	Domingues et al. 2017; Böhme et al. 2018

F, B	Tributyltin naphthenate/Permethrin	Organotin/Pyrethroid	Highly toxic to honeybees; found in honeybees and beeswax; associated with winter losses of honeybee colonies; disorientation and disruption of normal behavior in honeybees; pesticide detected in native bee tissue	Kalnins & Detroy 1984; Hagler et al. 1989; Cox & Wilson 1984; Sanchez-Bayo & Goka 2014; Hladik et al. 2016

[1]A=acaricide; B=bactericide; F=fungicide; H=herbicide; I=insecticide; R=rodencitide
[2]Mixed active ingredients where considered not approved with one active ingredient not approved by the EU.
[3]Effect can correspond to one or more of the mixed active ingredients.
NA = Not Applicable

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