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Insect decline: immediate action is needed

Le déclin des Insectes : il est urgent d'agir

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Abstract. Insects appeared more than 400 million years ago and they represent the richest and most diverse taxonomic group with several million species. Yet, under the combined effect of the loss of natural habitats, the intensification of agriculture with massive use of pesticides, global warming and biological invasions, insects show alarming signs of decline. Although difficult to quantify, species extinction and population reductions are confirmed for many ecosystems. This results in a loss of services such as the pollination of plants, including food crops, the recycling of organic matter, the supply of goods such as honey and the stability of food webs. It is therefore urgent to halt the decline of Insects. We recommend implementing long-term monitoring of populations, tackling the

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causes of insect decline by reducing the use of synthetic insecticides, preserving natural habitats, and reinventing a positive relationship between humans and insects.

Résumé. Apparus il y a plus de 400 millions d'années, les Insectes représentent le groupe taxonomique le plus riche et diversifié, avec plusieurs millions d'espèces. Sous l'effet de la disparition des habitats, de l'intensification de l'agriculture avec l'usage massif des pesticides, du réchauffement climatique et des invasions biologiques, les Insectes montrent des signes alarmants de déclin. Bien que difficiles à quantifier, la disparition des espèces et la réduction de leurs populations sont avérées et communes à de nombreux écosystèmes. Elles se traduisent par une perte des services rendus, comme la pollinisation des plantes vivrières, le recyclage de la matière organique, la fourniture de biens comme le miel, et l'équilibre des réseaux trophiques. Il est donc urgent de freiner le déclin des Insectes. Pour cela, il faut mettre en œuvre des suivis à long terme des populations, réduire l'usage des insecticides de synthèse, préserver les habitats naturels, et réinventer la relation de l'Homme à l'Insecte en revalorisant son image et ses usages.

Keywords. Biodiversity, Insect, Decline, Global change, Conservation.

Mots-clés. Biodiversité, Insecte, Déclin, Changements globaux, Conservation.

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1. Introduction

Insects account for about 80% of living species and their impact on humanity is manifold. It includes not only ecological services essential to agriculture such as pollination, but also serious animal and human health problems through the transmission of pathogenic microorganisms. Insects also play a key role in biogeochemical cycles and the maintenance of vertebrate populations. They represent a model of general interest for basic and applied biology studies, particularly in the biomedical field. Insect biodiversity constitutes an invaluable natural heritage.

Appeared more than 400 million years ago, insects were among the first animals to colonize terrestrial ecosystems. Their evolution underwent considerable radiations, marked by major innovations such as flight and social life. Today, Insects are strongly affected by environmental changes and the decline of their populations is a scientifically established fact. It is therefore urgent for society to take the measure of the erosion of the biodiversity of Insects and its possible consequences for vitally important ecosystems.

This article aims to provide a balanced and up-to-date insight into the phenomenon of insect decline. It begins with a brief description of the classification of insects and their various roles in ecosystems before presenting an overview of the decline of insect populations, its probable causes and its ecological consequences. The paper concludes with a set of recommendations for halting this decline.

2. The position of Insects in the tree of life

More than one million one hundred thousand species of insects have been identified, making it one of the most diverse groups of macroorganisms on Earth, mainly in terrestrial and freshwater environments. The actual diversity of the group is estimated five to ten times higher. Its evolutionary history is very old, with an emergence as early as in the Devonian, about 410 million years ago, long before the appearance of the first dinosaurs [1]. Insects originate within a group of organisms, the Arthropods, nowadays considered as a phylum [2]. Insects are the most species-rich class of this phylum. Other well-known classes within Arthropods are the Crustaceans, of which Insects are probably the closest relatives, and also the Arachnids (spiders, mites, scorpions) and the Myriapods (centipedes).

Arthropods are metamerized animals (organized in segments), with articulated appendages and a chitin-rich carapace (exoskeleton) that determines a general cavity where organs and hemolymph (a circulatory fluid analogous for many functions to the blood of vertebrates) are located. Their development goes through successive moults that allow their bodies to increase in size. Their nervous system is structured as a chain with ganglia and with several "brains". Within the Arthropods, Hexapods have three groups of segments (head, thorax and abdomen), three pairs of thoracic legs and tracheal respiration (without lungs). Hexapods include groups of small apterous organisms (e.g. Collembola, Diplura, Protura) and the Insects themselves including two

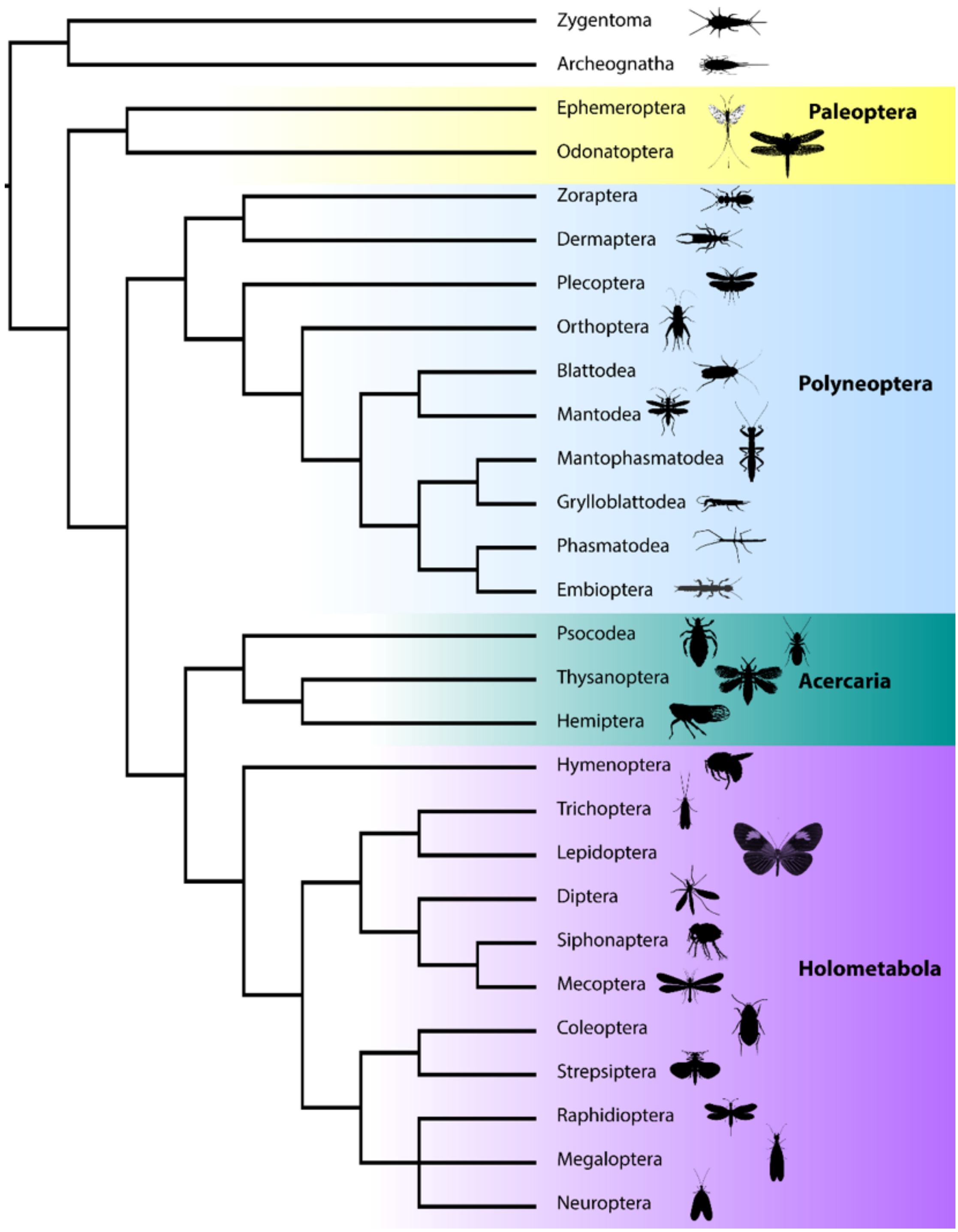

Figure 1. Synthetic phylogenetic tree of the 28 current insect orders (after [3, 4] and other studies).

Figure 2. Hymenopteran insects provide pollination functions ((a) wild bee) and honey production ((b) honey bee) but can also be formidable predators ((c) Asian hornet) (Photographs Romain Garrouste and Quentin Rome).

apterous orders (Zygentoma, Archeognatha) and the Pterygots with two pairs of thoracic wings (originally three).

Insects evolved with many diversification events, underwent moderate extinction crises and radiated even more strongly for many periods [5]. It is generally considered that Insect species are distributed into 38 different orders, of which ten are only known as fossils; the orders are sometimes themselves grouped in super-orders (Figure 1). Some orders are well known, such as Diptera (flies and mosquitoes), Lepidoptera (butterflies), Coleoptera (beetles, ladybugs, leaf beetles, weevils, etc.), Hymenoptera (bees, wasps, ants), Orthoptera (locusts, crickets, grasshoppers), Dictyoptera super-order (cockroaches, termites and mantids), Odonatoptera super-order (dragonflies, damselflies), and Hemiptera (cicadas, bugs) [3]. The best known of the super-orders is that of the Holometaboles, which appeared at the end of the Carboniferous period (300 million years ago, [6]). It groups together the majority of present-day insect species, which all develop by metamorphosis during an intermediate stage (nymph) between very different juvenile and adult stages (e.g. between caterpillars and butterflies, maggots and flies, etc.) [7]. It is often considered that the appearance and diversification of flowering plants in the Cretaceous period (100 million years ago) had major effects on the diversification of insects and in particular, on Holometabolous insects [8]. Apart from extraordinarily diversified wings and flight, one of the most significant sets of functional traits of insects concerns the mouth parts, transformed many times into chewing, siphoning, sponging, piercing and sucking etc. devices, in relation to extremely diverse diets [7].

3. Services provided and damages caused by insects to ecosystems and humans

Beyond the ethical need for recognizing insect biodiversity for its intrinsic value with its millions of species and hundreds of millions of years of evolution, we need to consider the services and contributions they provide to humanity (service value). We also need to take into account those that may occur in the future but that we do not know about or that will depend on the further evolution of ecosystems (option value). Insects indeed play an important role in providing services for human well-being [9]. They contribute to natural regulations: three quarters of our crops depend on pollinators (Figure 2), mostly insects (e.g. apples, almonds, strawberries, onions, squashes, etc. [10]). Insects (e.g. termites, dung beetles) also contribute strongly to the recycling of dead organic matter, by digesting humus or dead wood, or by burying and consuming vertebrate feces. These actions are fundamental to the functioning of ecosystems and biogeochemical cycles that make Insects true ecosystem engineers. Without these actions, soils would lose their fertility and dead matter would accumulate without being recycled. Insects are also sources of food for many species of vertebrates (such as birds or insectivorous bats), which in turn can regulate other species harmful to the human species (such as mosquitoes). Many other services are rendered by insects: for example, the human supply of honey (by bees, Figure 2), natural silk (silkworm) and dyes (cochineal red), the dispersal of certain seeds, for example by ants, or the reduction of gastrointestinal parasites of vertebrates via the burial of their excrements by beetles. Finally, insects represent a significant source of protein, part of the diets of certain peoples and increasingly used for the feeding of livestock or fish in aquaculture. They also serve as indicators for biodiversity conservation, and are used for education, recreation, etc. All these services have a considerable monetary value, amounting to hundreds of billions of euros per year [11]. On the other hand, some insects have negative aspects and can be responsible for harm, notably all those that are vectors of pathogens responsible for diseases for animals and humans, such as tsetse flies transmitting parasites responsible for sleeping sickness or mosquitoes that are vectors of infectious diseases (malaria, dengue, Zika, etc.) Although previously confined to tropical regions, insect vectors are now spreading to temperate countries under the effect of global change, which combines an increase in good trades and rising temperatures, both favorable to the introduction and then acclimatization of these invasive exotic organisms. Non-native insect species also threaten local biodiversity through competitive or predation processes (e.g. the Asian Hornet, *Vespa velutina*, Figure 2). Other herbivorous (plant-feeding) insects are considered pests on our crops, sometimes causing significant reductions in yield or quality of agricultural products, including post-harvest, with losses estimated at 70 billion euros per year worldwide [12]. However, other insects develop at the expense of these herbivores, whether predators or parasitoids (parasites that inevitably cause the death of the host), contributing to the natural regulation of the populations of insect pests [13].

4. The actual decline of Insect Populations

4.1. *The decline of insect fauna: facts and perceptions*

Over the last twenty years, field observations and compared analyses of biodiversity databases have shown a decrease in the number of insects [14]. The global significance of these observations, often made under non-standardized conditions and limited to a place and/or a family of insects, was however not established in a consensual way [15]. Furthermore, while the announced loss of bees or butterflies may have moved the public, the general perception of the importance of the decline of Insects is blurred by the negative image associated with certain harmful insects and by the threat of invasive species such as the tiger mosquito *Aedes albopictus*, vector of human viruses such as dengue fever, or crop pests such as the swarms of locusts that threaten East Africa, the Middle East and Asia [12, 16]. Vectors of human pathogens, however, account for only 1% of mosquito species, and only 1% of insects are considered crop pests.

In recent years, several published studies have confirmed a decline in insect fauna, both in terms of abundance and species extinction in temperate regions, but also in the tropics and even the Arctic [17]. Decreases in insect biomass of up to 75% have been reported in protected areas in Germany [18, 19] and in a tropical forest in Puerto Rico [20]. Radar monitoring of the flight of mayfly swarms over large American lakes showed a decline of more than 50% since the beginning of the 2000s [21]. Significant losses of up to 55% have also been measured for pollinating insects in Great Britain since 1980 [22]. The confirmation of a decline in insects and the extent of the phenomenon have resulted in a strong media response, associated with the use of an alarmist vocabulary ("insect apocalypse", "collapse", "global extinction").

However, while these studies provide a worrying signal about the reduction of the number of insect species and their abundance, particularly in Western and Northern Europe, we do not yet have sufficient data to assess the overall phenomenon and its magnitude on a global scale. The decline of insects is indeed a complex phenomenon and nuances are beginning to emerge [23].

4.2. *A complex phenomenon*

The best documented studies on the decline of insects concern European countries, where the anthropic footprint on landscapes (agricultural intensification, urbanization, road networks) is particularly marked. The studies are more fragmentary for North America, and especially incomplete for tropical regions, which are home to most of the biodiversity of insects. There is therefore a significant geographical bias in the published studies and, as a result, it is still difficult today to produce global conclusions on the observed decline. Indeed, regional differences have been observed, with some areas appearing to be only slightly affected by the decline of the insects [17].

Taxonomic differences have also been observed [23] and a global analysis of the literature on insect decline indicates that only 40% of taxa would be affected [24]. There are indeed several examples of insect species whose numbers or geographical distribution is increasing [22, 25–27], notably non-native species (Figure 3). A recent in-depth study, analyzing 166 studies including more than 1600 sites and covering the period 1925–2018, observed, for example, opposite dynamics for terrestrial insects, whose abundance is indeed decreasing, but less than in previous studies (9% per decade), and aquatic insects whose abundance would be increasing [25] but the analysis and the selection of data sets have recently been strongly criticized [28, 29] and the conclusions of the authors are then dubious.

The complexity of measuring insect decline is amplified by the difficulty of assessing the number and diversity of insects in their environment. In addition to their small size, they are often restricted to specific micro-habitats, with strong differences at ground level depending on the presence of rocks, dead wood and associated plant species, but also according to forest strata with different species on the ground and in the canopy, or according to depth in freshwater environments. Insects are also distributed according to day time with nocturnal and diurnal species, or to seasons with several generations per year or, on the contrary, underground or benthic larval cycles over periods of up to several years [30]. Such spatial and temporal specificities can lead to sampling inaccuracies or biases since there is no standard method to record population changes of all insect species at a given location [27, 31]. This probably explains the dominance of certain emblematic species such as bees, beetles and butterflies in studies monitoring insect populations and their diversity.

4.3. *The decline of Insects, a phenomenon that remains poorly documented*

While the studies published in recent years have played an invaluable role in alerting the society on an emerging issue, we do not yet have sufficient quantitative and reliable data to assess globally the severity of insect decline and its spatial or taxonomic variations.

It is therefore necessary to multiply studies with standardized protocols that take into account the lessons learned from pioneering work in this field. Thus, population changes should be studied over periods long enough to identify significant trends, rather than by comparison between different periods [31]. Indeed, the number of insects fluctuates naturally from generation to generation, sometimes significantly, and one-shot comparisons can therefore be misleading [26, 31, 32]. The available studies also show the importance of monitoring several sites, if possible the same ones repeatedly, as considerable variations in trend may exist between distant sites. Finally, particular attention must be paid to the variables measured (biomass, abundance or number of species), which often provide different or even contradictory information on insect diversity, and to the sampling methods used, which must remain comparable over time and adapted to the target taxa [27]. Exhaustive surveys are complicated by the fact that insect populations tend to be composed of few common species and many rare species [30]. Thus, maintaining the abundance of individuals within a community may mask the loss of rare species due to the dominance of a small number of very abundant species in the sample, as has been shown for pollinating insects in Great Britain. An alternative can be provided by the use of natural history collections that offer ancient reference points and thus allow the detection of significant long-term variations [33].

The rigorous monitoring of insect populations, the only way to establish a robust evaluation of their conservation status, therefore represents a significant investment of time and resources. The task is all the more difficult since (i) only a fraction of the species is described, their total number remaining unknown, (ii) little is known about the life cycle and ecology of most species, and (iii) the number of taxonomists and the means to finance their work remain insufficient.

However, some trends are emerging with regard to the most affected species. For example, it is apparent that Insects with highly specialized diets are more affected than generalist insects, which may occupy wider niches to build up populations and expand their geographical distribution. Univoltine (only one generation per year) or sedentary species also appear to be more at risk than multivoltine (several generations per year), species that are more mobile or have wider ranges. These observations provide first insights for studying further the causes of the decline.

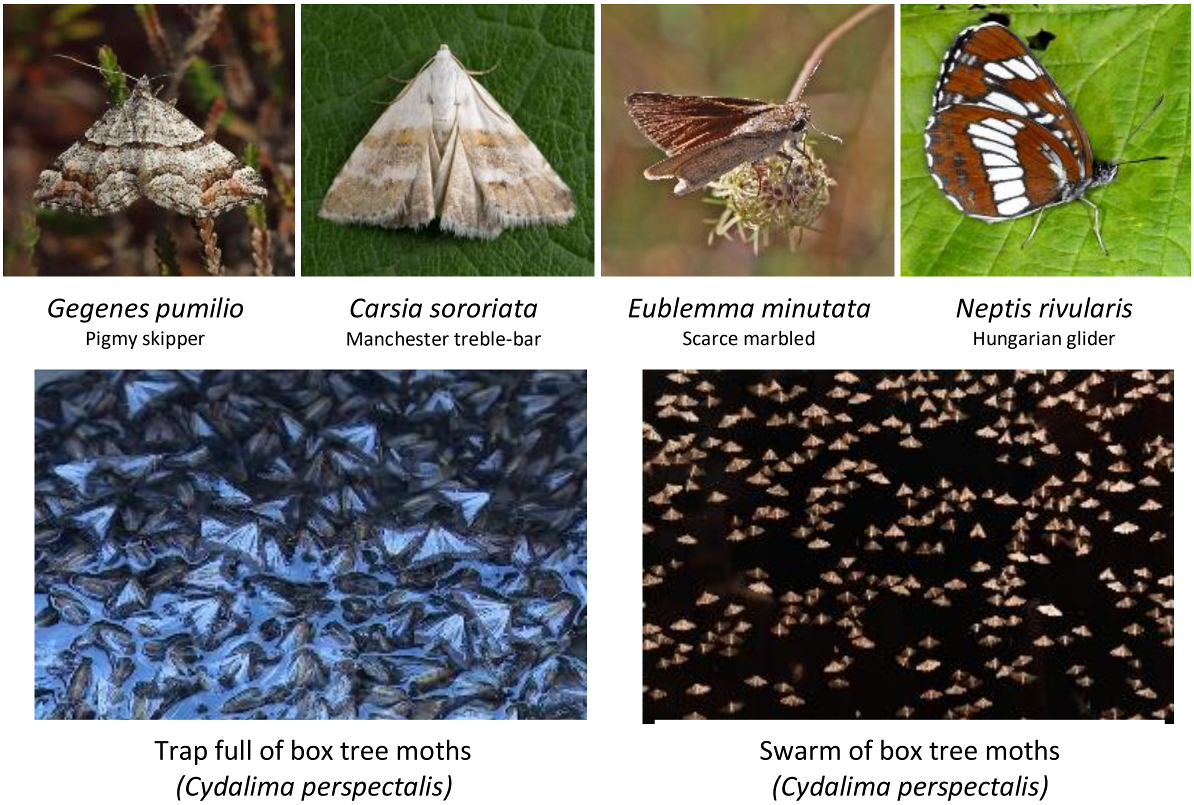

Figure 3. Four species of butterflies (Lepidoptera) declared extinct in France ((a) source INPN) and an invasive exotic butterfly species whose populations are increasing, the box tree moth ((b), Photos Marc Chaumeil and France 3 Occitanie of August 23, 2017).

5. Probable causes of insect decline

The five main causes of biodiversity loss are well known, ranked in descending order of importance by the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) [10] as (1) land use change and conversion, (2) direct exploitation of organisms, (3) climate change, (4) pollution, and (5) invasive alien species. For Insects, not concerned with fishing or hunting, direct exploitation cannot be incriminated. The other four drivers of change are clearly implicated in the reduction of insect biodiversity [17, 30] although in a different importance order as shown below [24].

5.1. *Land use change*

The first cause of Insect decline is the destruction or degradation of their habitats. The conversion of natural areas for agricultural use or for the extension of urban areas, which now occupy half of the land surface [10], results in a continuous decrease in naturally forested surface (loss of about 5 million hectares per year [34]), grasslands (70% have disappeared in developed countries, MEA 2005) or wetlands (87% destroyed [10]). Yet forests, often covering very large surfaces, composed of long-lived tree species, with complex vertical stratification and buffered climates, offer an extraordinary variety of habitats sheltering a multitude of insect species [35], notably beetles living in dead wood (3000 species in France). Similarly, the loss of grassland habitats has harmful consequences for the abundance and diversity of butterflies [36] and pollinating insects (notably Hymenoptera). The drying up of lakes, ponds and rivers results in heavy losses for aquatic insects.

In addition to the decrease in the surface area of habitats favorable to insects, land conversion and the accompanying transport infrastructure increase the fragmentation of landscapes. Inhabiting smaller, more isolated patches of habitats, less well connected by ecological corridors (hedges, grassy strips) that are disappearing, insect populations tend to decline due to lack of resources or reduced reproductive success [19, 30, 37].

5.2. *Pollutions*

The most important pollution affecting Insects comes from the use of insecticides. Toxic by definition, chemical insecticides have been developed during the 20th century to fight against crop pests (herbivorous insects) but their lack of specificity (broad spectrum of action) has led to collateral mortality of many non-target insects [38]. The deleterious effects of massive DDT applications on insect populations have been known for a long time (see Rachel Carlson's Silent Spring 1962 or [39]). More recently, awareness of the major impacts of neonicotinoid use on insect fauna, especially pollinators [40], has led to their ban in France in 2018 (but exemptions are granted). An important discovery in recent years is that insecticides can lead to the decline of insects even at sublethal doses because they disrupt their behavior, making them unable to feed, reproduce or defend themselves against infections [41, 42]. The coating of seeds with these insecticides, proposed as a simple prophylactic solution, is furthermore contradictory to a sustainable strategy of treating crops only in case of potential damage. Finally, the persistence of many synthetic molecules poses a problem beyond the short term of their application [43].

Other types of pollution have negative effects on Insects. The use of herbicides or fertilizers in agriculture, by impoverishing the flora, leads to a decrease in the diversity of herbivorous insects [30]. Air pollution also affects insects [44], as does light pollution [45], especially in cities [17] because artificial light sources act as traps.

5.3. *Climate change*

The effect of climate change is more difficult to discern [17] because its components are multiple and their consequences are sometimes opposite. As organisms that do not regulate their temperature (poikilothermic), insects are generally favored by the increase in temperature; developing faster, they can, for example, multiply the number of generations per year or even extend their geographical range. But they are also more sensitive to thermal shocks and heat waves, especially when temperatures exceed lethal thresholds [46, 47]. The desynchronization of insect emergence and the flowering or leaf flush period in their host plants can lead to starvation of herbivorous insects [30].

Global warming is linked to the increase in carbon dioxide concentrations, which indirectly results in a deterioration of the nutritional quality of plants, with a negative effect on the survival of herbivorous insects [17, 48]. Intensified droughts are harmful to insects because they are organisms with a low weight-to-surface area ratio, making them more sensitive to desiccation [17]. Large-scale wildfire following periods of drought and high temperatures destroy large areas of habitats favorable to insects, such as forests in Mediterranean climatic regions. On the contrary, the increase in the intensity of storms leads to an increase in the volume of dead wood favorable to the biodiversity of forest insects.

5.4. *Biological invasions*

The effects of biological invasions are multiple. The case of invasive alien plants is particular. They can replace local plants and thus destroy the habitats of the insects for which these plants are the exclusive source of food [32]. Exotic insect pests can also destroy host plants and thus threaten the native insects that depend on them [49]. The introduction of predatory insects for biological control purposes can also lead to significant risks for local fauna through competitive exclusion processes or direct predation when these natural enemies prove to be too generalists, as in the case of the Asian ladybug in Europe [24, 30]. Invasive alien species, sometimes introduced to promote pollination, may carry with them pathogens that they transmit to native insects, including viruses [49, 50], or promote the establishment of parasitoid insects that may change hosts and attack local species

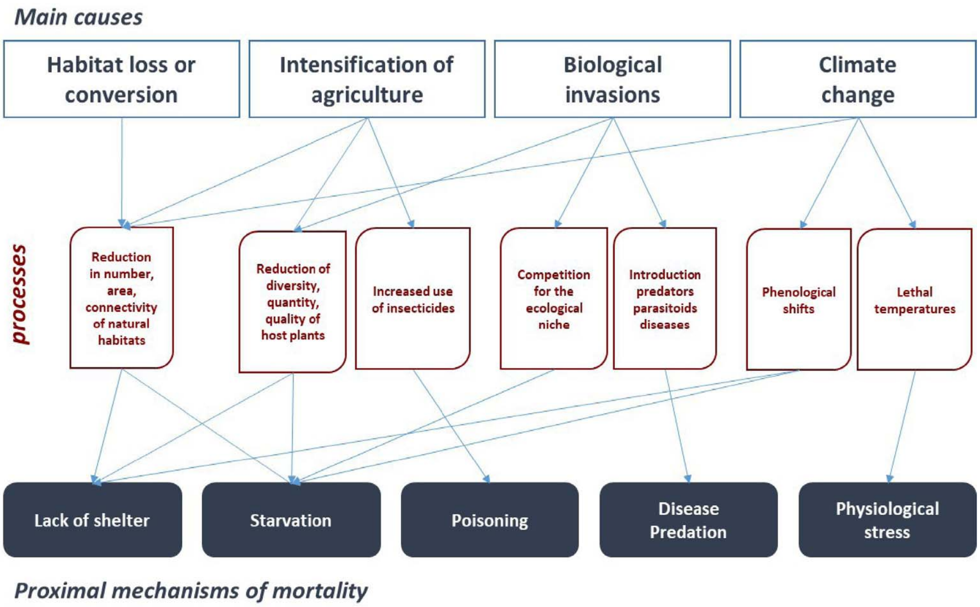

Figure 4. Main causes, processes and mechanisms of insect mortality.

(apparent competition [49]). Finally, the colonization of aquatic environments by particularly prolific or voracious exotic fish species can lead to a sharp decrease in the abundance of freshwater insects.

5.5. *Interactions between main causes and mechanisms involved*

Most of the factors determining the decline of Insects are in a dynamic of increase, such as agricultural intensification and urbanization, climate change and the rate of biological invasions, suggesting a worsening of the conservation status of Insect fauna. In addition, most of these degradation forces interact to reinforce each other. Changes in land use are accompanied by an increase in pollution risks, global warming favors the settlement and development of invasive species originating from subtropical regions, landscape fragmentation prevents the migration of species unsuited to new climatic conditions.

Deleterious or lethal mechanisms can also combine. Climatic stresses, toxic molecules, starvation linked to the loss of host plants act directly on the physiology and development of individuals, lowering their resilience threshold and triggering a spiral of decline. The death of individuals, the decrease in their reproductive success or the disruption of their dispersal behavior causes a decrease in their reproductive capacity and thus a decrease in the level of insect populations. Smaller populations have greater difficulties in ensuring, on the one hand, the meeting of breeding partners with risks of inbreeding and, on the other hand, group behavior in search of food or defense against predators (e.g. social insects), leading to their extinction (Allee effect). The progressive loss of populations leads to the extinction of the species (Figure 4).

6. Ecological consequences of insect decline

6.1. *Impact on pollination*

Many cultivated [51,52] or wild [53] plants depend on insects for their pollination. The spectacular decline of the honey bee *Apis mellifera* [24] should not make us forget the decline of many other pollinators, notably bumble bees, butterflies and hoverflies [54, 55].

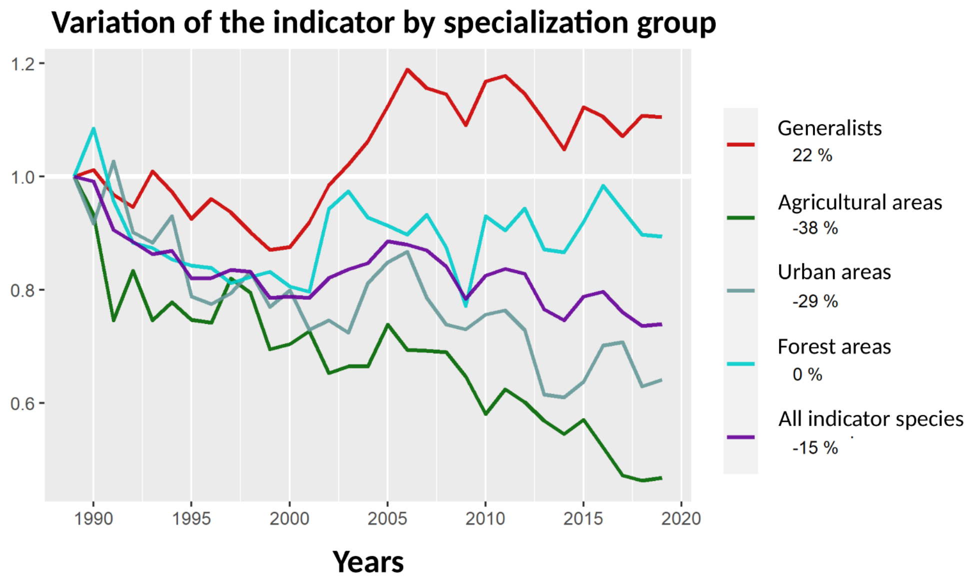

Figure 5. Evolution over the last 30 years of the indicator of common birds abundance, by habitat specialization group (http://www.vigienature.fr/fr/observatoires/suivi-temporel-oiseaux-communs-stoc/resultats-3413). The value of this indicator corresponds to the rate of change in the abundance index (number of individuals per km^2) of 75 species of common birds (14 generalist species, 24 specialists in agricultural environments, 24 specialists in forest environments, and 13 specialists in urban areas). The rate of change is equal to the slope of the regression line between the abundance indices per year and the number of years since the monitoring began in 1989.

The importance and complexity of insect-plant pollination networks is only just beginning to be deciphered [56, 57]. Correlative analyses [58] clearly show an association between the decline of some pollinators and of the plants that depend on them. Various observational [59] and experimental [60, 61] studies on detailed mechanisms, such as the number of pollinator visits to flowers, demonstrate a causal link between pollinator decline and crop yield reduction.

However, a widespread impact of insect decline on agricultural production has not yet been demonstrated [62], which may be explained by the resilience induced by the complexity of pollination networks, interactions with multiple changes in agricultural practices and other limiting factors [63]. Still, the growth of crops dependent on pollinating insects [54, 62, 64] and the erosion of pollinator diversity [22] raise concern of irreversible threshold effects [65]. The economic consequences of insect decline have been evaluated many times [52, 66], with various examples of one-time losses of several million dollars [67]. The cost of renting hives for crop pollination has already increased in the USA due to the decline of bees [68]. The economic value of crops dependent on insect pollination amounts to hundreds of billions of dollars [67], even when weighted for partial dependence on such pollination [66].

6.2. *Impact on birds*

The concomitant decline of Insects and many species of birds in field crops has long attracted attention. The most documented case is that of the grey partridge. The survival of chicks depends on the abundance of their main prey insects, aphids, beetles, butterfly caterpillars, locusts, etc. [69]. An experimental increase in the proportion of aphids in the diet also markedly affects chick development [70]: the average body mass at 5 days of age increases from 14 g to 19 g when the proportion of aphids in the diet increases from 0 to 45%. Similar results have been demonstrated in several passerines [71], sometimes using a refined experimental approach [72], thus explaining the generalized decline of bird abundance in agricultural areas [73], in particular for insectivorous species [74]. This decline of the avifauna via a decrease in the abundance of prey insects results in particular from the use of neonicotinoid insecticides [75]. Although the avifauna can be directly contaminated by these substances, with individual effects, no direct demographic impact of this contamination has been detected to date [76]. Even if the decline of birds in agricultural areas in France (Figure 5) has several causes [77], ranging from changes in practices [78] and landscapes [79] to climate change [80], the decrease in insect populations appears to be the main one.

6.3. *General impacts on biodiversity and ecosystems*

With a cascade effect through food webs [81], the impact of insect decline spreads within ecosystems [30]. For example, the decrease in beneficial insects such as dragonflies, due to water pollution or the drying up of lakes and ponds, results in an increase in the abundance of mosquitoes that are usually part of their diet [24]. The decline of insects that are aquatic at some stage in their cycle [21, 75] also affects the fish populations that feed on them [82] just as the decline of terrestrial insects affects bird or bat populations. These cascade effects, both ecological and evolutionary, are thus multiple, complex and discrete, and it will take time to report and analyze them.

7. Recommendations to halt the decline of Insects

7.1. *Recommendation 1: Develop reliable methods for assessing the decline in insect diversity and abundance*

Just as the reality of climate change has taken shape in the common mind when ice cores from the poles and precise meteorological monitoring have made it possible to reconstitute long series of reliable temporal data, more precise measurement methods and instruments must be deployed to confirm quantitative changes in insect populations and diversity. Numerous sampling biases or problems with historical references have been identified, which should be resolved by implementing long-term monitoring with standardized methods adapted to the different functional groups of insects, if possible over at least 15 years and in many sites or large landscapes where the factors of decline can also be analyzed [83]. There is also an urgent need to develop statistical indicators of the evolution of the population based on museum collections, in order to establish historical reference points [33].

To increase the efficiency of measurement and to automate data recording, increased use of new technologies is needed [84]. These include in particular the detection of insects by radar or bioacoustics measurements as well as their automatic trapping, followed by an identification by meta-barcoding and environmental DNA analysis [35, 83]. To be validated and calibrated, however, these methods must be based on long-term maintenance of taxonomic competence and preservation of museum collections. In addition, the recent development of citizen science has shown that mobilizing the general public for obtaining naturalist data (via smartphone applications, for example) can provide valuable information on the major trends in biodiversity dynamics, particularly in the most anthropized environments (cities, gardens), while generating interest and understanding in society.

7.2. *Recommendation 2: Tackle the causes of insect decline and better preserve the natural heritage*

Urgent and comprehensive actions must be taken to halt the general erosion of biodiversity, such as fighting against climate change, halting land urbanization and deforestation, controlling trade and the biological invasions it causes. But more specifically, two main types of measures must be taken to halt the decline of insects and the services they provide to humanity.

The first major measure is to reduce the use of chemical insecticides in agriculture and to improve the specificity of their targets (spectrum reduction). The direct and indirect toxicity of these crop protection products, their poorly reasoned application, as well as their economic and environmental cost make their development and application less and less relevant. Alternative methods, based on the agroecological approach, must be sought and then disseminated, including, among others, biological control, elicitation of plant defenses, use of semiochemical compounds (pheromones, plant odors) and the diversification of crops and (micro)habitats at plot and landscape scales, in particular to restore and enhance the abundance and effectiveness of the natural enemies of insect pests, be they other insects, insectivorous birds or bats. In addition, the mutualization of harvests and losses caused by insect pests in a given region would greatly enhance the profitability of agricultural approaches based on reduced use of insecticides.

The second major measure is the preservation, or even improvement, of refuge habitats for Insects. Forests, natural meadows and freshwater aquatic environments are particularly important ecosystems to be protected because they offer numerous ecological niches for insects due to their plant diversity, heterogeneous structure and temporal permanence. But Insects must also be conserved in more anthropized territories such as agricultural areas or urban environments. In these cases, interstitial spaces (hedges, grassed strips), parks and gardens, and microhabitats (walls and roofs planted with vegetation, trees in hedgerows, "insect hotels") must be generalized and maintained [35, 85]. Beyond these particular environments, it is also the heterogeneity of landscapes and the connectivity between different types of habitat that must be improved, in particular to allow the exchange of genes and individuals between insect populations, for the long-term maintenance of the evolutionary potential and the adaptation of insects to global changes.

7.3. *Recommendation 3: Inventing a new relationship between Man and Insect*

Much of the disinterest to the fate of Insects stems from the repulsion or detestation they inspire to many people. This attitude is rooted in personal memories of mosquito or wasp bites but also in a collective imagination often using the strange morphology of Insects to embody the figure of Evil (many extraterrestrial "aliens" carry antennae, mandibles or a multitude of pairs of legs). If it remains difficult to explain this mainly Western aversion, it is clear that the conservation of insect fauna will only be fully supported by public opinion if the image and reputation of the Insects are rehabilitated.

A first approach to convince our fellow citizens to slow down the decline of Insects is to better explain their major contribution to human well-being, not only through the services they have always provided (pollination, pest control, honey and silk production, etc.) but also through new uses. Many companies have developed industrial insect farms for food, sometimes human but especially animal feed (flour for chicken farms, aquaculture), replacing soybean meal or fish fodder in a more efficient way, from an energy point of view, and more respectful of the environment. Another emerging contribution is their use in bioinspiration. The structure of the scales on the wings of the Morpho butterflies allowed the design of the most hydrophobic surface in the world (useful for self-cleaning glasses, Figure 6), the social behavior of ants or bees is being studied to develop the piloting of drone swarms, locomotion with three pairs of legs seems to be the most practical for robots, the mechanism by which flying insects avoid obstacles thanks to their retina has been elucidated, making it possible to envisage the development of innovative navigation instruments for aviation, the ventilation of termite mounds offers a very effective solution for the design of bioclimatic buildings, etc.

More symbolically, the image and perception of the insect should also be improved [35]. This undoubtedly involves focuses on iconic species (as the panda has become for mammals), and for this there is no lack of superb species of butterflies or dragonflies. But more than that, it is a new "story" that is needed, a story or stories to tell to the younger generations so that they will consider with interest and benevolence the world of insects. An important effort should therefore be made towards teachers and artists so that they convey the message of the usefulness but also the beauty of Insects.

To facilitate these efforts, together with the French Foundation for Biodiversity Research (FRB) (https://www.fondationbiodiversite.fr/) and the Office for Insects and their Environment (http://www.Insectes.org/opie/monde-des-Insectes.html) we propose to consider the creation of an Insect Foundation, intended to collect public and private funding to support educational, artistic and scientific projects on Insects, their knowledge, preservation and use.

Figure 6. Example of bio-inspiration found in the world of Insects with the microscopic structure of the scales of the wings of the *Morpho menelaus* butterfly, which gives it an impermeability unique in the world and can be used to develop particularly hydrophobic glass surfaces (Photographs Serge Berthier).

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