Agricultural intensification and climate change are rapidly decreasing insect biodiversity

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Major declines in insect biomass and diversity, reviewed here, have become obvious and well documented since the end of World War II. Here, we conclude that the spread and intensification of agriculture during the past half century is directly related to these losses. In addition, many areas, including tropical mountains, are suffering serious losses because of climate change as well. Crops currently occupy about 11% of the world's land surface, with active grazing taking place over an additional 30%. The industrialization of agriculture during the second half of the 20th century involved farming on greatly expanded scales, monoculturing, the application of increasing amounts of pesticides and fertilizers, and the elimination of interspersed hedgerows and other wildlife habitat fragments, all practices that are destructive to insect and other biodiversity in and near the fields. Some of the insects that we are destroying, including pollinators and predators of crop pests, are directly beneficial to the crops. In the tropics generally, natural vegetation is being destroyed rapidly and often replaced with export crops such as oil palm and soybeans. To mitigate the effects of the Sixth Mass Extinction event that we have caused and are experiencing now, the following will be necessary: a stable (and almost certainly lower) human population, sustainable levels of consumption, and social justice that empowers the less wealthy people and nations of the world, where the vast majority of us live, will be necessary.

biological extinction | insect loss | sustainable agriculture | agriculture intensification | climate change

Considering the recent history of human beings and their impact on terrestrial ecosystems, it is difficult to understand why anyone would ever have doubted that the number of insects (and indeed most other terrestrial, freshwater, and marine organisms) has diminished at an accelerating rate over the past half century. That is of course different from having actual measurements of the numbers involved, but it would be miraculous in the face of our exploding numbers and increasing levels of consumption if insects were as abundant as they were a century ago, when the global human population was less than a quarter of its present level. To imagine that an extra 6 billion people could find places to live and feed themselves without causing decreases in biodiversity defies reason and is a relationship that we shall discuss below.

Global Impact of Human Beings

In terms of deep history, land plants and insects originated at about the same time, some 475 million years ago, in the Ordovician Period (1). Glaciation and falling sea levels about 30 million years later resulted in the extinction of an estimated 86% of all marine species on Earth at the Ordovician-Silurian boundary (2). Three major extinction events followed, the most recent of them at the end of the Cretaceous Period some 66 my ago. From that time onward, diverse ecosystems have evolved as regional climates changed, providing a variety of niches into which insects, flowering plants, terrestrial vertebrates, and other kinds of organisms evolved and diversified. By the time our species, *Homo sapiens*, appeared in Africa, at least 300,000 y ago, other members of our genus had reached Eurasia but not migrated beyond it.

There is some evidence that *H. sapiens* migrated to Eurasia as much as 120,000 y ago (3), but the signs of our presence there do not become frequent and unmistakable until about 70,000 y ago. The major migration to the north and subsequent development of our species took place during a cool period of glacial expansion that lasted from 110,000 to about 10,000 y ago. Modern humans reached Australia more than

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60,000 y ago and North America probably no more than 17,500 y ago. From there, they migrated over the course of several thousand years to the southern reaches of South America (4). As they arrived in these areas and in northern Eurasia for the first time, they hunted and soon exterminated many of the large animals that were initially present in these new areas.

When our ancestors developed agriculture, about 11,000 y ago, the entire human population of the Earth, which by then had migrated to all of the habitable continents, consisted of about one million people. The population of Europe amounted to only about 100,000 people—about the number that could fit into one of today's large sports stadiums. With crop agriculture and the domestication of animals, however, people were able to form villages, towns, and ultimately cities, since they did not need to move about constantly seeking food, being able to produce and store food surpluses. Starting then, human numbers grew, their impact on the Earth increasing substantially. By about 3,000 y ago, pastoralists, agriculturists, and hunter-gatherers had transformed large stretches of the planet as their numbers increased (5). These numbers continued to grow steadily, reaching about 200 million people at the time of the Roman Empire; 500 million in 1500 as the Renaissance got underway; a billion by Napoleonic times; and a rapidly growing 7.8 billion today, with our numbers projected to reach nearly 10 billion 30 years from now at midcentury (2050).

Global Footprint Network (6) presents a useful analysis, based on United Nations statistics, of our global and local levels of consumption of potentially sustainable productivity. Their global analysis shows that over the past half century, we have gone from consuming about 70% of the total available in 1970 to about 175% today. Thus, by July 28, 2019, we had used up all of the sustainable productivity available that year. This level of consumption, which we clearly cannot maintain, also involves great inequality among nations. The rich nations are consuming far more than they can produce sustainably, and the poorest ones are increasingly sinking into what has been termed an "environmental poverty trap," with their individual incomes falling and their sustainable productivity continuously overexploited (7). Humans, together with our domesticated mammals, make up 95% of all mammalian biomass on the planet; all wild mammals amount to only 5% of total mammalian biomass today (8). With such an extraordinary degree of human dominance, it is no wonder that insect biodiversity is vanishing rapidly (9, 10).

The Spread of Agriculture

Paralleling the growth in human population numbers, the spread of agriculture began slowly and has accelerated, especially during the most recent five centuries (11). Particularly for Eurasia, the recorded rate of forest clearing provides a guide to that spread; it proceeded relatively steadily until about 1500 A.D., at the start of the Renaissance. At that time, the global population was about 500 million, supported by extensive fields of crops and pastures in Europe, the Near East, and East Asia. Over the next three centuries, the human population doubled; at the end of this period, the Industrial Revolution began and our impact on the Earth intensified even more rapidly. Until about 1840, wood provided the primary source of energy everywhere—most European forests had been cut by that time. With the adoption of coal as a primary fuel, and later other sources of energy, the forests gradually regrew to their present extent, while once predominantly agricultural societies became increasingly industrialized and urban. The transcontinental railroad, the cotton gin, electricity, internal combustion engine, and other inventions changed society.

As large industrialized cities grew, fewer and fewer people practiced agriculture; those who did often farmed on a much larger scale than previously, and more intensively. In the United States, there is about a third less forested land than there was in 1630, and we cultivate much of the cleared land, especially on the former prairies. Over much of Europe, farms were managed by single families, and included much natural vegetation and habitat for wildlife: fallow fields, coppices and hedgerows, wet meadows, and unmanaged ditches. Lightly grazed pasturelands can be rich in successional plant and insect diversity. The expansion of farms into large commercial enterprises, especially after World War II, was accompanied by a changed emphasis to monoculturing, and the application of increasing inputs of fertilizers and synthetic pesticides. Collectively, these practices drastically reduced the refuges available for insects, herbaceous plants, vertebrate insectivores, and other organisms—a direct consequence of increasing crop scale and productivity.

Currently, about 11% of the Earth's land area is devoted to crops, with about 30% more used for grazing. Most of that grazing takes place in areas that are still partly natural, almost all of it at stocking densities that are damaging or unsustainable. Over the entire agricultural area of the world, species are being lost rapidly and continuously (12). A recent review by Zabel et al. (13) discusses well the tradeoff that we face between the food needs of our rapidly growing population and biodiversity. Certainly, the solution will be a very difficult one, with 2.1 billion additional people projected to be added to the global total over the next 30 y, and yet, many people are starving or lack one or more essential nutrients even now.

In the tropical and subtropical regions of the world, where most people live, agriculture is continuing to spread rapidly. In these areas, the destruction of natural vegetation for crops (Fig. 1)—often for export crops such as oil palm—has become very rapid, and we seem not to be succeeding in our efforts to slow it down. Since the ratification of the Convention on Biological Diversity in 1992, more than a quarter of the tropical forests that were standing then have been cut; many experts predict that there will be no substantial stands of tropical forest remaining by the end of this century. In Sub-Saharan Africa, the current population of 1.1 billion people is projected to grow to 2.1 billion over the next 30 y, with an extra 90,000 people added, on the average, each day (14). The current GNP per capita in the region is about $4,000, a quarter of the global average. By the end of the century, it is projected that there will be about 4.4 billion people living in this region. In the light of those figures, one can readily see why few believe that any of the Congolese or other African rainforests will survive to the year 2100. For much of Indo-Malaysia, the future seems equally bleak (e.g., ref. 15). Growing numbers of people lead inevitably to more clearing for agriculture and direct uses of the forest for other purposes (16), resulting in the rapid loss of biodiversity, both in species numbers and in biomass.

Climate change poses a number of additional problems for agriculture and, thus, for biodiversity. The location of favored regions for crops will certainly shift drastically if we allow climate change to proceed at its current rate. The Earth's mean temperature has increased by 1 °C over preindustrial temperatures, and unless we collectively take serious steps to rein in the increase, will have climbed by 1.5 °C, which is supposed to be the point of no return, within a decade (2030)—and keep climbing (17). Some areas have already reached that level. Indeed, an overall increase

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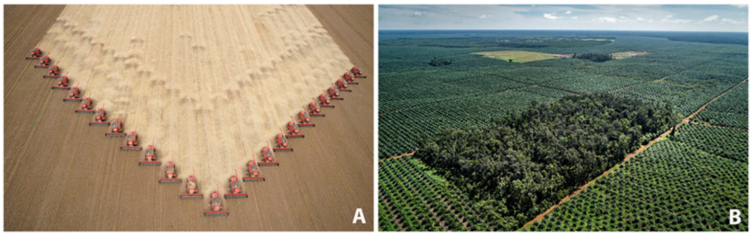

Fig. 1. Agricultural intensification in the tropics. The scale and intensity of agriculture continues to increase at the expense of grasslands and forests worldwide, with the tropics increasingly impacted. Developing productive monocultures allows us to feed our rapidly growing population but leaves little habitat for pollinators, natural enemies, and other wildlife within the cultivated areas. In any case, it theoretically spares more natural and partly developed habitats. In either case, tropical forests, which likely support more than 70% of the global insect species diversity, are rapidly being lost to agriculture, fuel consumption, logging, and increasingly, fires. (*A*) Soybean harvest near Tangara da Serra in western Brazil. Image credit: Reuters Pictures/Paulo Whitaker. (*B*) Oil palm plantation (PT Agriprima Cipta Persada Palm Oil Concession) in Papua, Indonesia. Image credit: Greenpeace/Ulet Ifansasti.

of 3 °C by 2060, clearly disastrous, is now regarded as possible—depending, of course, on how effectively we address the problem. If such an increase is allowed to happen, it would become almost impossible to alleviate poverty, to preserve most of the existing planetary biodiversity, and possibly even to maintain civilization as we know it (18–20).

The agriculture of the future, too, will need to diminish its own greenhouse gas emissions if we are to be successful in controlling climate change (21). Overall, a complete transformation of the global energy system will definitely be required to lessen the magnitude and effects of the Sixth Mass Extinction. Inevitably, some of our crops will need to be moved to new areas as a result of climate change over the next few decades; in doing so, much additional biodiversity is certain to be lost.

Extinction Rates

To estimate extinction rates, we need to understand as completely as possible the dimensions of life on Earth: How many species exist? We have named fewer than 2 million species of eukaryotic organisms to date, and we know very little about the vast majority of even these. Estimates of the total number that exist vary, but some suggest totals of at least 10 million species. Many groups, such as fungi, mites, and nematodes, are unknown to a large extent, and we are making relatively little effort to learn more about them. Clearly, we shall never know how many species exist on Earth, although the widespread application of genetic methods will eventually give us an improved idea of this matter (e.g., refs. 22 and 23). For the numbers of prokaryotes—bacteria and archaea—we can scarcely even make an educated guess, but it seems clear that millions of species-like lineages must exist, with only a few thousand of them named to date.

Biological extinction is proceeding so rapidly that most biologists agree that we have entered the early stages of a Sixth Major Extinction event and have already crossed the point of no return (e.g. refs. 24–26). In estimating extinction rates, we can do best by concentrating on groups of organisms with a rich relatively continuous fossil record, such as terrestrial vertebrates and mollusks. Using this information, we have calculated that over the past 66 million years we have lost about 0.1 species per million species per year; currently the rate is about 1,000 times higher (27). We can then compare this rate with the estimated proportions of endangerment in land plants and other groups for which the existing species are relatively well known. Considering both kinds of evidence, it appears likely that about a fifth of all species of eukaryotes will disappear within the next few decades and, perhaps, even twice that proportion by the end of the century (28–31). Even more powerful evidence that extinction is proceeding rapidly comes from observations of the disappearance of populations, which is occurring much more rapidly than the loss of species (18). In Mexico, for example, Ceballos et al. (32) have estimated that some 60% of all vertebrate populations have disappeared since 1950.

What Is Happening to Insects

We have been slow to recognize that insects, too, are declining rapidly. Their losses have been documented by numerous reports from western and northern Europe (e.g., refs. 33–38)—most of which identify agricultural spread and intensification as a principal stressor. Agriculture is also the primary contributing factor in insect losses reported in California and Ohio (39, 40). Four of the papers in this collection link agriculture to insect declines. Two reports, both concerning butterflies (41, 42)—the most familiar and best assessed terrestrial insects—indicate clearly that the declines in Europe began long ago, and that they were linked to agriculture as their primary driver. Butterfly diversity in southwest Germany began declining as much as two centuries ago, and the rate of decline remained more or less constant until after World War II, when steeper rates of loss developed (35). For moths in Great Britain over the past half century, there have been increases and decreases, but two-thirds of the widespread, common species are decreasing in number (43). The long-term abundance trends in the same region have been analyzed by Bell et al. (44), who documented that moth abundances had decreased by 31% over the past five decades.

Agriculture has changed greatly since World War II, when pesticides, fertilizers, and tractors became available, allowing greatly increased industrialization of farming methods. Following the war, traditional family farms gave way to commercial operations. Today's farmlands are larger in scope than their predecessors, more apt to be monocultures, and more reliant on fertilizer, insecticide, and herbicide input. Greater emphasis is now placed on the elimination of weeds, filling ditches, and cutting down hedgerows. Low-lying wet areas are tiled to increase arable acreage. These sweeping reductions in habitat diversity and heterogeneity have left little room for wildlife in many modern-day farming operations.

To a degree, Europe has maintained the traditional character of its farms by importing a great deal of its food, while North America, where large fields are the mode, is a major food exporter. As Europe moves forward with agricultural "reform," however, the preservation of biodiversity is likely to become

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increasingly difficult (45). In all parts of the world, agricultural intensification seems to be a prime driver in insect population declines (9, 10), although climate change is also playing an increasingly important role in the process of extinction. As this situation develops, we should keep in mind the reciprocal importance of biodiversity for successful agriculture in providing pollination services, and many other ways as well (ref. 46 provides a timely review of this area).

Grasslands and prairies worldwide have been converted into croplands and plantations. As a result of this extensive conversion, grassland habitats and their autochthonous biota have become one of the most threatened biomes on the planet. The tallgrass prairie of central North America once extended from Manitoba to northern Texas, covering some 60 million hectares. Less than a tenth of this ecosystem remains; virtually all of the remainder has been given to agriculture. The grasslands, open fields, and vernal pools of the Central Valley of California have been converted into some of the most productive farmlands anywhere in the world. Parallels occur across Europe's anthropogenic grasslands—the product of centuries of unmechanized, low intensity agriculture—following their post-World War conversion to industrialized agriculture.

The insect faunas of grasslands are experiencing elevated rates of loss. Taxa that are especially diverse in these ecosystems include butterflies and noctuid moths (Lepidoptera); ants, bees, and wasps (Hymenoptera); scarab and ground beetles (Coleoptera); crickets, grasshoppers, and katydids (Orthoptera); leaf and plant hoppers, seed bugs, and their kin (Heteroptera). Of these, only butterflies have been well studied; across Europe, grassland butterflies rank among the most imperiled insects (35, 36, 47, 48).

There also have been increasing numbers of reports of declines of wild bees, again mostly from northwestern Europe (33, 38, 49, 50). The importance of maintaining pollinator diversity can scarcely be overexaggerated: The value of wild and managed bee pollination to global crop production was estimated as $518 billion per annum (51). Agricultural intensification was identified as the principal threat to bees and their ecosystem services in the studies cited above. Likely the fate of butterflies and bees is indicative of most grassland lineages. Grasshoppers in particular (52), perhaps because of their susceptibility to tilling practices, appear to be faring poorly. Ironically, the Rocky Mountain locust, at one time believed to be one of the most abundant and destructive insects on the planet, was the first insect known to have been driven to extinction in the New World (53).

Two recent studies also link bat declines to modern agriculture (54, 55). Not surprisingly, the insectivorous birds of grasslands are among the most rapidly declining bird guilds (56, 57). In general, it is clear for birds in the United States and worldwide that populations and species are disappearing rapidly, with decreases in insect abundance potentially contributing to their declines (58, 59).

In the tropics, the clearing of forests for crops, pasture, and wood fuel is proceeding at alarming rates in Central Africa, Central America, many parts of South America, and Southeast Asia (Fig. 1). Between 2001 and 2015, an average of 5 million acres of tropical forest were lost annually to industrial-scale agriculture (16, 60). In 2018, 12 million acres of tropical forest were cleared, one-third of which mapped as previously intact primary forest (61). Deforestation on larger scales has the potential to change local and regional weather and, in particular, alter rainfall patterns (62, 63). Given that the great majority of insect species diversity is found in tropics (64), deforestation there surely ranks among the greatest threats to the world's insect biodiversity. With probably less than 15% of tropical insects named as yet, it seems certain that the tropical insect species that are being driven to extinction by anthropogenic stressors will never be seen by any human before they pass into oblivion.

Where spreading and increasingly intense agriculture is not a significant factor, climate change is starting to play a primary role in driving insects, along with most other kinds of organisms, to extinction. Two recent reports from Costa Rica document steep declines of Lepidoptera from lowland and cloud forests (65, 66). Given the apparent fragility of many ecosystems, including tropical rainforests, in the face of climate change, we may expect widespread extinction there even where forests remain standing. It is urgent that we find ways to come together and collectively arrest climate change soon if we are to stem losses from the Earth's great cradles of diversity and global ecosystem function; e.g., the planet's tropical forests.

Dealing with Global Extinction Threats

In theory, we are protecting biodiversity throughout the world in parks and other reserves, and the global treaties we have put in place are intended to accomplish just that. Most conservation organizations have similar goals, and it is certainly a worthy objective for us to attempt to preserve as much as possible. The Half Earth strategy championed so effectively by Wilson (67) presents a goal that, if realized, would play an important role in protecting planetary biodiversity. The extent to which such efforts are focused on areas particularly rich in biodiversity, however, will make a major difference in their effectiveness. Considering the relatively weak international efforts to stop climate change that we have been able to organize so far—when its dangers are obvious to everyone who pays attention to the demonstrated facts—it is going to take a very strong effort to muster an effective response to the even more serious, and lasting, problem of biodiversity extinction. In any case, the greater the amount of natural habitat that we succeed in preserving now, the more options that we will have in the future. In and around the reserves, the restoration of ecosystems will be another important way to address the problem of slowing extinction (e.g., refs. 68 and 69). In view of climate change, it will be important to selectively preserve lands with elevational complexity, since in them organisms have more options for movement and dispersal—thus enhancing the possibility of their survival.

Certainly, designing agriculture in such a way as to preserve as much as possible of the existing biodiversity is another key strategy that we should adopt widely (70–72). We can, for example, maintain natural or restored areas within or beside the fields. Regionally, we will need to consider whether intensive or less-impactful agriculture will have the more damaging effects on biodiversity overall. This question has no simple answer, since we practice agriculture in so many different conditions all over the six habitable continents. In some areas, such as much of the Midwestern United States and parts of China, Chile, and Argentina, large-scale agriculture is highly productive and, in theory at least, leaves the greatest amount of uncultivated space for the maintenance of biodiversity. The inclusion of biodiverse communities in strips or patches within cultivated areas often has an unpredictable result on their yield (73), and experimental studies of this relationship should continue. Where fields are small or cultivation is less intense, we need to work out what will be the most productive and sustainable systems. The degree to which we are willing to subsidize the emplacement of sustainable agricultural

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systems and then expedite the most efficient movement of agricultural products around the world will also play an important role in preserving biodiversity. Some areas, like Western Europe, get by because the nations are so rich they do not need to satisfy their own requirements for food, but ultimately the food needs of our global community must be considered in an environmentally just manner.

Both the breeding of crop strains to be sustainable and productive under specific local conditions and the precise assessment of those conditions (precision farming) to find the best matches for them will be key to maximizing productivity and allow for the preservation of other lands for preserving regional biodiversity. In addition, the deployment of insect- and disease-resistant strains of crops will contribute to a reduction in the chemicals sprayed on the fields, with great benefit to nonpest organisms. When pesticides are applied, we must effectively restrict their application to the cultivated areas themselves and keep the biocidal chemicals from drifting into or washing out into neighboring areas and wildlands. The same is true for the application of fertilizers on fields, as there is increasing evidence that nitrification (from agriculture as well as atmospheric deposition) is an important driver of insect declines in Europe (10, 35, 74, 75).

Beyond our efforts to preserve natural areas, to restore them, and to design ways to combine them with agriculture sustainably, we will need to deploy additional strategies to achieve the greatest amount of biodiversity conservation possible. Some kinds of organisms, notably plants, can be preserved in living collections as seeds or tissue culture collections. Zoos, botanical gardens, and culture collections offer ways to avoid the extinction of selected kinds of organisms. None of these efforts will be successful for long, however, unless we agree on and adopt effective global approaches to climate change, which has the potential not only for driving large numbers of species to extinction while at the same time threatening our agriculture in many regions.

To create a global context in which these strategies would have lasting success, we would certainly need to find ways to limit our population growth, adopt sustainable standards for our consumption, and move away from global inequality and national selfishness. Under the existing conditions, it will become increasingly difficult for the poorer nations of the world to maintain their nature reserves or sustainable agricultural systems even if they succeed in developing them. Many currently protected areas are being invaded and damaged by the people living near them—often, poor people who have great needs. In the face of such trends, ecological restoration will become an obvious, effective, and essential strategy for preserving biodiversity in various parts of the world.

Few scientists have concluded that the Earth can remain a stable home for more than 2–3 billion people indefinitely; human population growth has been the greatest challenge for all natural systems. In rich countries like the United States, Japan, and those of Western Europe, we must strive to nourish an international outlook so that for reasons of morality or love we begin to care about and assist the people who live in the other, poorer nations of Earth. We cannot and must not simply just keep scooping as much money as possible into our own national pockets, so to speak, until nature, our planet, has been exhausted, extinguished. Social justice is not an option, but a necessity, if we wish to forge a sustainable future for our children and grandchildren.

Despite all of these obstacles, our efforts now—whatever we can do—will help to make the world a better place for all nations, and for the extraordinary biological diversity that has shared our evolutionary journey over millennia. To preserve life's variety on which we depend, for the quality of our atmosphere, clean water, soil, and our food, we face an enormous challenge. Stork (64) estimated that there were 5.5 million species of insects, but we think the number likely to be closer to 10 million or more (76). Insects are very much the little things that run our world. By preserving insect diversity, we are helping to secure manifold benefits to our own civilization while enhancing our prospects for the future. Insects don't get to argue for their own future or vote in elections, so we must find ways to give them voice, protect them—our actions over the next few decades will determine how many will still be alongside us, in their own unending struggles for existence at the century's end. Let's resolve to accomplish this goal as well as we possibly can.

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