A Fair Share: Doing the Math on Individual Consumption and Global Warming

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20.2 Pesticides: herbicides and insecticides

- Synthetic pesticides came into widespread use following World War II, another technology of the Green Revolution. Since 1960, absolute pesticide use in the US dramatically increased through about 1980 but has since declined slightly, with most current pesticide use *herb*icide, rather than *insect*icide.
- Insecticides are generally far more toxic to all animal life than herbicides, and there also is greater potential to reduce insecticide use without compromising agricultural productivity. Pesticide use, overall, can probably be reduced by as much 50% with no or minimal effect on productivity. Complete abstinence may lead to significant crop losses.
- Pesticide production and application generates few carbon-equivalent emissions directly, perhaps 7.5 million $MgCO_2e$ per annum in the US, but pesticides do have multiple negative effects upon ecosystem health and productivity, as well as human health. These include direct wildlife kills, chronic toxicity, loss of both vegetable and insect food sources, widespread loss of pollinators, and increased cancer and immunologic disorders in humans exposed to pesticides.
- The effect of pesticides upon crop yields is probably smaller than that of fertilizers, but generally does increase productivity (at least short-term), and also enables highly productive cropping systems that are relatively vulnerable to pests and weed competition. It is therefore possible that, by increasing yield, pesticides reduce agricultural land-use and associated habitat loss and other agricultural input use. Thus, determining the balance of effects upon both general ecological health and CO_2e emissions is not a wholly straightforward calculus.
- Conventional fruits and vegetables are exposed to much higher pesticide spraying intensities than commodity crops such as corn and soy.
- Household pesticide use for purely aesthetic reasons ("healthy" lawns) harms both urban wildlife and humans, and is therefore generally an inexcusable practice.

20.2.1 Overview and history

Crop protection, *broadly speaking*, is profoundly important to agricultural production, and we may broadly divide crop "pests" into four major groups: pathogens (fungi such as powdery mildew, bacteria, etc.), viruses (also a pathogen, but considered as a separate category in some literature), animal pests (various insects, mites, and other arthropods, nematodes, snails/slugs, mammals, and birds), and weeds, which compete for space, light, and nutrients. Of these, weeds are by far the most important, accounting for over half of *potential* pest losses [357]. A variety of non-pesticide means exist to counter pests, such as crop rotation and mechanical weeding/tilling, but the era since World War II has seen a massive expansion in the use of synthetic pesticides targeting all categories of crop pest (mainly insecticides, fungicides, and herbicides), both globally and within the US. This expansion helped shape modern cropping systems by enabling simpler crop rotations, the use of higher-yielding but more vulnerable crop strains [357], decreased tillage for weed control, and, most recently, the widespread use of herbicide-resistant (mainly glyphosate-resistant) transgenic (GMO) crops [361].

Herbicides, rather than insecticides, are the primary pesticide class in use today (about 85% of US pesticides by mass), and, especially in the US, this category is now dominated by a single agent, glyphosate (the active ingredient in Roundup, the most common commercial version), which came into widespread use following the almost universal adoption of glyphosate-resistant corn, soy, and cotton GMO seeds since the mid-1990s [361]. Glyphosate and its various commercial formulations (which contain many poorly studied "adjuvants" that enhance the toxicity of glyphosate) may be less toxic to animal life than many other agents, but this molecule, and its intimate connection to GMOs, has been of great controversy, especially in popular environmental literature.

While global crop losses to pests, as a *percentage* of potential yield, from 1960 to about 2000 actually remained *constant*, the more modern cropping systems which are (at least partially) enabled by chemical suppression of pests are also intrinsically higher yielding, and so pesticide use has likely increased *absolute* agricultural productivity [357]. From a global warming perspective, the emissions directly attributable to pesticide production and application are fairly trivial, but their larger effects upon the agriculture system, e.g. possible land-sparing from higher yields, and modified cropping (simpler crop rotations with higher yielding varieties) and tilling patterns (decreased dependence upon mechanical tilling of weeds), are almost certainly significant. Of course, pesticides also have numerous ecosystem toxicities, and thus the overall balance of benefits and harms remains unclear. Pesticide intensity and agents also vary by both crop and farm, and it is probably possible to appreciably reduce use while maintaining yield. Finally, it should be noted that organic farming does not eschew all pesticides, just *synthetic* pesticides, and several "natural" pesticides can have significant toxicities, especially those containing copper (e.g. copper sulfate).

Early history

From the late 1800s, a variety of mainly copper, lime, and sulfur-based compounds were used in small amounts as general fungicides [358], but the modern era of crop protection via industrially produced pesticides largely began in the early 1940s with the rapid advance of the chemical industry during the War Years. A variety of antifungals were introduced in this period, while that most famous and controversial of insecticides, DDT, was first synthesized in 1939 by Paul Müller, a feat which would earn him the 1948 Nobel Prize in Physiology or Medicine; DDT entered commercial production in 1942 [359]. During the war, it was used on the European continent to control potato beetle plagues, while the American armed forces widely deployed the agent for malaria control in the Pacific theater [359]. Entering into civilian use in late 1945, DDT was soon hailed as a miracle compound, yet toxicity to fish and birds was recognized as early as 1946 [359]. A wide variety of new fungicides, herbicides, and insecticides would be synthesized and brought into use over the following decades.

In 1962, Rachel Carson published Silent Spring, a fierce critique of pesticide overuse and the chemical industry, focusing particularly upon DDT. The book sparked national and international debate, helped usher in the fledgling environmental movement, and has been widely credited as the major impetus for the formation of the Environmental Protection Agency (EPA), in 1970, and the subsequent banning of DDT for agricultural use in 1972 (in the US). It is notable that Carson herself explicitly *did not* call for an outright ban even on DDT, but for a more limited and rational use of these agents that takes into account their harms.

A common misconception (and one, apparently it seems, intentionally promoted by pesticide advocates) is that Rachel Carson and the DDT ban caused the deaths of perhaps millions of (mainly African) children by undermining malaria control efforts. In fact, DDT was never (and has never been) banned for malaria control, and the World Health Organization's (WHO's) Global Malaria Eradication Programme, which was indeed based largely spraying highly persistent pesticides indoors, such as DDT ("indoor residual spraying"), was disbanded due to futility in 1969. In subsequent years, newly independent African governments abandoned pesticide-based strategies largely because of evolving pesticide resistance in mosquitoes, among other reasons [360].

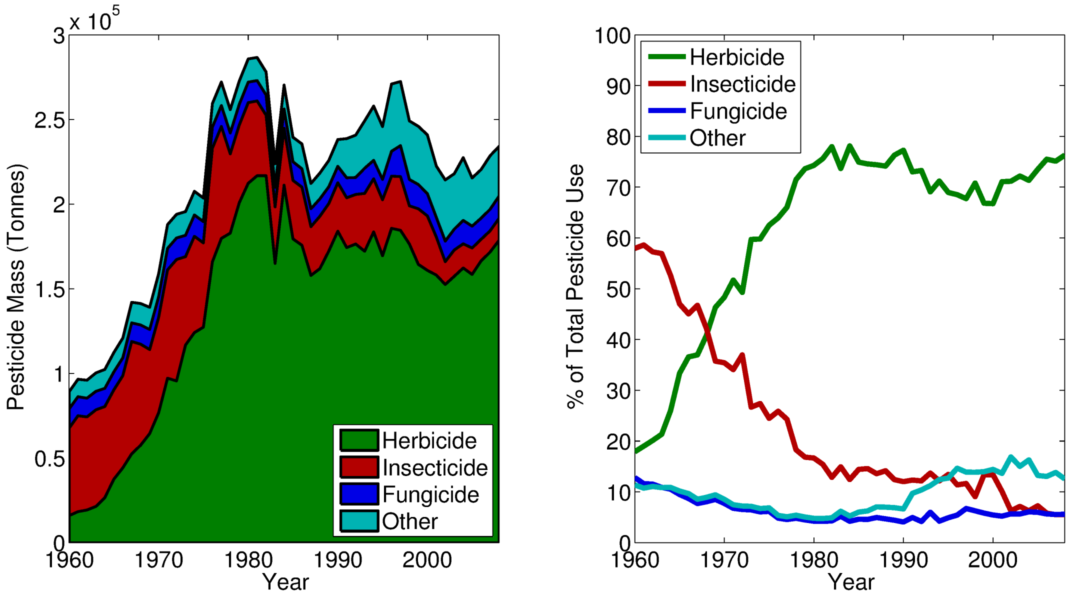

Figure 20.4: Broad trends in pesticide use from 1960 to 2008, based on 21 selected crops that represent about 70% of US pesticide use [361] (note then, that total pesticide use for the US as a whole is about 40% higher than the numbers given here would indicate).

Recent trends in US pesticide use

Since 1960, overall pesticide use in the US, as measured by total pesticide mass, increased dramatically until peaking in 1981, with the subsequent decades showing a slow but uneven overall decline [361]. Between 1960 and 1981, the overall increase in pesticide use was driven entirely by increased herbicide use, which peaked in the early 1980s and has since remained relatively constant, but with a recent uptick, especially in glyphosate (the active ingredient in Monsanto's Roundup), which now makes up at least 50% of all herbicide applications. Insecticide use, on the other hand, has declined appreciably over the last few decades.

Broadly speaking, we can divide 49 years spanning from 1960 to 2008 (the most recent year for which comprehensive USDA data is available) into three pesticide eras, following Fernandez-Cornejo et al. [361]. The expansion of herbicide use in the 1960 to 1981 period represented a broad shift away from tillage and cultivation as the primary weed control strategy and towards chemical suppression. From 1982 to 1995 was a quasi-stable era, while the period from 1996 onward has been strongly influenced by the adoption of genetically engineered corn, soy, and cotton varieties that either express the naturally occurring Bt insecticide (Bt trait) or are resistant to the broad-spectrum herbicide glyphosate. This era has seen a slow *decline* in total applied pesticide mass, while glyphosate has rapidly displaced other herbicides to become by far the most used single agent. The overall toxicity, and not just mass, of applied pesticides has declined as well, as the most toxic insecticides have declined in use or been banned [361].

Pesticide intensity on major crops today

As shown in Figure 20.5, most pesticides are applied to several commodity crops, especially corn and soy. However, this is mainly attributable to the massive land area devoted to these crops, not use intensity. Indeed, as also shown in Figure 20.5, use intensity (i.e kg of pesticide per hectare) is generally much higher for fruits and vegetables, with potatoes by far the most intensely sprayed crop (this particular crop is fairly unique in that it is subject to extensive soil

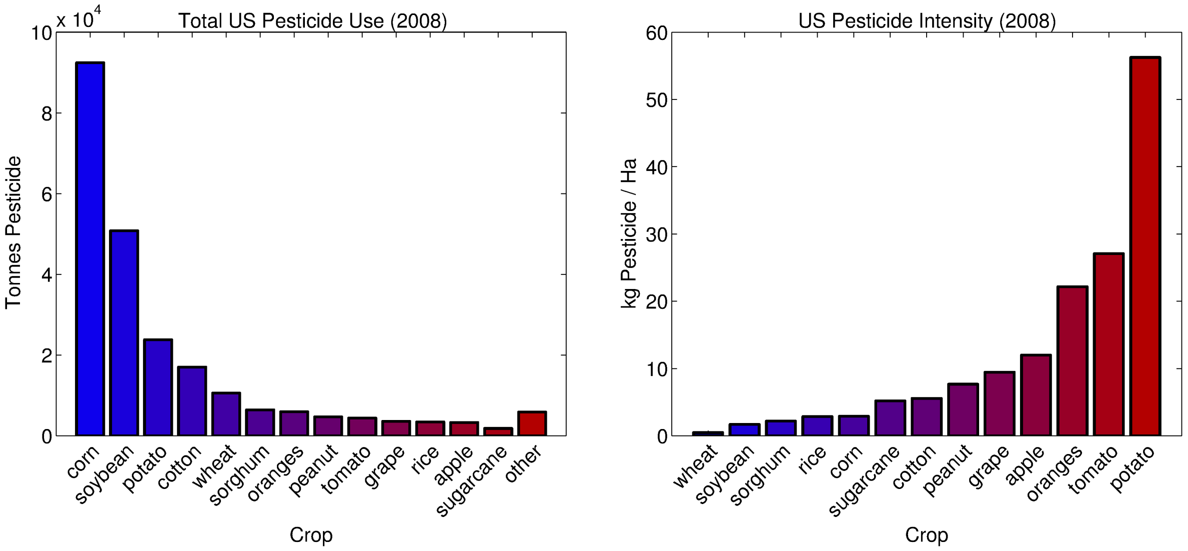

Figure 20.5: Total mass of pesticides used on 21 selected crops that account for about 70% of US pesticide use, along with use intensity for the top 13 crops; data is from Fernandex-Cornejo et al. [361]. As seen in the left panel, corn and soy account for most pesticide use overall, but pesticides are used at relatively low intensity on these crops (right panel). Fruits, vegetables, and especially potatoes, are subject to more spraying. Note that, dissimilar to other crops, fumigants accounted for 83% of all pesticide application, by weight, on potatoes.

fumigation).

20.2.2 Direct production emissions

On a per-kg basis, the production of various pesticides is much more energy/emissions-intensive than fertilizer production. However, since the total mass of pesticide applied in the US (241,000 tonnes in 2008) is about two orders of magnitude lower than the fertilizer mass, the net direct global warming impact of these substances is relatively small. Lal [501] compiled a number of emissions factors for these substances, and gave ranges of 6.23–46.2, 4.4–29.7, and 4.4–29.3 kgCO_2e/kg for herbicides, pesticides, and fungicides, respectively. The respective unweighted means (i.e. mean across many different particular substances, not weighted according to use) were 23.1 (herbicide), 18.7 (pesticide), and 14.3 (fungicides) kgCO_2e/kg. However, as glyphosate accounts for 50% of herbicide use, and its production is relatively carbon-intensive (33.4 kgCO_2e/kg in [501]), when weighting by actual herbicide use we get about 25.6 kgCO_2e/kg for herbicides, a slight increase over the unweighted average.

Now, using the above mean estimates for carbon intensity, and pesticide use-rates in 2008 (per the USDA), we arrive at about 7.6 million MgCO_2e attributable to all pesticide production, with about 85% of this due to herbicides. For major crops, then, as an overall average, about 2.5 kg of pesticide is applied per hectare, equating to around 50 kgCO_2e. On a per-kg basis, pesticide production is a trivial component of the carbon footprint for major commodity crops (corn, soy, wheat), adding, using corn as an example, less than <0.01 kgCO_2e/kg corn. The impact is somewhat larger for the highly fumigated potatoes, at perhaps 0.02–0.035 kgCO_2e/kg potato, or around 5–10% of this tuber's production carbon footprint; for highly sprayed fruits, such as oranges, apples, and grapes, pesticides may account for about 3–5% of the production carbon impact (which is generally on the order of 0.5 kgCO_2e/kg produce).

It follows in conclusion that most significant global warming effects attributable to pesticide will be downstream, mainly in the form of altered yields and/or land management (e.g. no-till or reduced-till systems). Increased yields for similar levels of non-pesticide inputs would obviously decrease the carbon impact of food production (at least on a direct per-kg basis) and may decrease the agricultural land-base, while reduced-till systems can reduce soil carbon losses. On the other hand, ecosystem toxicities are an independent axis of harm that must be considered. This is further complicated by the fact that it may be better to poison the forest than to cut it down outright for crops (a fate possibly avoided if pesticides do indeed decrease land-use).

20.2.3 Effectiveness and ecological effects

A basic question that must be answered is, simply, how effective are pesticides in increasing agricultural productivity? The answer is not straightforward, as pesticides help shape the overall cropping system, and there are also secondary effects that may undermine pesticide effectiveness. Quantifying overall effectiveness and detrimental ecological effects is difficult, but I review many of the qualitative patterns and arguments here.

Yield, crop protection, and cropping systems

Pesticides do appear to increase the productivity of conventional cropping systems, although the magnitude of benefit is unclear, and there is likely the potential to significantly reduce, if not completely eliminate, pesticide application without negatively impacting yields. We must also be clear that while “crop protection” is absolutely essential to adequate agricultural productivity, this term is *not* synonymous with pesticide use. Various diseases and pathogens, animal pests, and weeds all affect crop productivity, and may be subject to different control measures.

A basic method for quantifying the impact of different pest categories, and the potential and actual impact of various crop protection strategies, is to quantify a crop’s *potential* yield in the absence of any pests, and then estimate the degree to which different pest categories reduce potential yield. Perhaps the most widely cited such work, a review by Oerke [357], concluded that there was no change at all in potential yield reduction as a *percentage* from 1960 to 2000. However, because pesticide-based crop protection enabled newer and simpler high-yielding, input-responsive agricultural systems, they still were of net benefit to productivity.

More complex cropping systems (i.e. greater crop variety, longer crop rotations) tend to better suppress weeds. Widespread herbicide use thus goes hand in hand with the broad shift to simpler cropping rotations and large scale monocultures [362]. On the other hand, herbicides have also facilitated reduced-till and no-till systems, which may decrease soil organic carbon losses.

Potential for reducing use

Multiple authors have examined the relationship between pesticide intensity and productivity, with an eye towards the potential for significant pesticide reduction. In general, it seems likely that, for conventional farms, appreciable reductions in use, probably on the order of 50% for major cereal and commodity crops, are possible with only a small or even no effect upon productivity. However, complete abstinence may lead to much more significant crop losses.

A review of earlier studies conducted mainly in experimental farms examining herbicides applied at below-label rates by Zhang et al. [363] concluded that low herbicide application rates generally yield good weed control, often at as little as 20–40% of the label rate, and especially if herbicide was combined with inter-row cultivation (mechanical weeding). While there was generally a trend towards improved weed control at higher application rates, the benefit was uniformly very small beyond about 60–80% of the label rate. A more recent meta-analysis [364] comparing organic, low-input, and conventional farming found no yield difference between the low-input and conventional systems for corn (mean 50% reduction in pesticides for the low-input systems) and only a small difference for wheat (70% reduction in pesticides), while organic systems that eschewed pesticide entirely were clearly less productive than either the low-input or conventional ones.

Several recent studies have focused on wheat yields in France, and similarly suggest 50% pesticide reductions are feasible. Most recently, Lechenet and colleagues [365] performed a regression analysis upon data from 946 farms in France relating treatment frequency index (TFI), various other farm parameters, and farm productivity, as measured by gross energy output per unit area (GJ Ha^{-1} yr^{-1}). The TFI is a lumped metric that summarizes the intensity of all pesticide use, and is defined as the sum of the ratio of applied to recommended dose across pesticide treatments, or more formally,

$$\sum_T \frac{\mathrm{AD}_T}{\mathrm{RD}_T} \tag{20.6}$$

where AD_T and RD_T are the applied dose and recommended doses of treatment T, respectively. These authors' results suggested that a majority of (but not all) farms could decrease pesticides without affecting productivity and that, overall, pesticide use could be reduced by 42% without affecting productivity. Herbicides had the least potential for reduction (37% overall), and the generally more harmful insecticides the greatest (60%).

Gaba and colleagues [366] were unable to detect any relationship between herbicide intensity and yield or overall weed control in 150 winter wheat fields divided between 30 farms in France. They did find, however, that herbicides suppressed rarer plants not the focus of suppression efforts, leading to the conclusion that reducing herbicide on the order of 50% would not affect yield and increase weed diversity. On the other hand, a regression analysis of 176 experimental wheat plots in France by Hossard et al. [367], which used the TFI index as an explanatory variable, concluded that a 50% drop in pesticide use from the mean would reduce wheat yields 5–12%, while complete avoidance would lead to more a dramatic 24–33% yield drop. However, beyond a TFI of about 6, there was no (or very little) apparent benefit to increased spraying, and thus this study would be consistent with the idea that heavier pesticide users, at least, could safely decrease use.

While the analyses above suggest that very significant pesticide sparing is possible without penalties to yield, it is important to note that variations in pesticide use at the farm level occur within a *landscape* that, as a whole, is subject to relatively intense pesticide application. Therefore, if a single farm or experimental plot experiences only a small or nonexistent reduction in yield upon reducing pesticides, this may not apply at a landscape scale, as our reduced pesticide plot may be indirectly benefitting from pest suppression in surrounding farms and fields. Several analyses also used data from French farms, where GMOs are generally prohibited, and thus may not be wholly generalizable to the US, where most commodity crops (except wheat) are GMO varieties that either produce insecticide (e.g. Bt corn) or are resistant to herbicide.

Some general systemic drawbacks

Wilson and Tisdell [368], among others, have described how insecticide use may initially increase agricultural productivity, but eventually lead to overall decreased productivity and/or increased pest epidemics later in time. Initially, target pests are destroyed by insecticide application.

However, this has the side-effect of destroying many natural predators that normally check pest populations, as well as other insect competitor species. Furthermore, as resistance evolves, ever more pesticide must be used, with ever diminished agricultural and economic returns. Eventually, it becomes uneconomical to use the pesticide, and pest populations *rebound* beyond their initial population size, now that natural controls are reduced.

This pattern whereby the natural predator-prey is undermined can lead to pest epidemics that cannot be controlled by predation, nor, once sufficient pesticide resistance is evolved, can they be controlled by chemical means. A related phenomenon, termed *secondary pest outbreak*, occurs when pesticide use targeting one pest species leads to outbreaks of other pest species that were previously not problematic. Similar to rebound, potential mechanisms include elimination of pest predators and/or other competing insect species, as well as induced changes in non-target species.

Even if they increase the productivity of the fields to which they are applied, pesticides can decrease productivity in other food production systems. For example, aquatic ecosystems are sensitive to pesticide exposure, which may lead to both outright large-scale fish kills, as well as reduced fishery productivity. An older estimate gives 6–14 million fish kills annually attributable to direct pesticide exposure [368], and one study concluded that common pesticide exposure is sufficient to reduce wild salmon productivity [369].

20.2.4 (Some) ecosystem toxicities

Pesticides affect ecosystems via at least three major mechanism: (1) direct, acute poisonings causing either death or impaired development and/or reproductive success, (2) chronic toxicity, also decreasing survival, development, or reproduction, and (3) direct or indirect elimination of food resources (i.e. direct and indirect plant and insect declines).

There is no such thing as a truly selective insecticide: all insecticides affect both the target insect as well as non-target insects and other invertebrates, and every class of vertebrate animal, i.e. fish, amphibians, reptiles, birds, and mammals. Herbicides, which target an entirely different kingdom of life, are generally much less toxic but can still directly affect a broad range of animal species, and can have important indirect effects upon food sources and ecologies. Acute insecticide exposure can result in mass deaths; this is best documented in fish and birds, and was largely the focus of Silent Spring and early attempts at regulating pesticide use. With increased regulation and broad shifts in pesticide use patterns (decreasing insecticide use and a withdrawal from the market of some of the most toxic and persistent insecticides), acute poisonings have probably declined in the developed world, but may still be quite substantial.

Quantifying direct avian mortality from insecticides is challenging, although at their peak, insecticides almost certainly killed at least several tens of millions of birds annually and perhaps hundreds of millions (in the US) [371]. Mineau [372] estimated that a single pesticide, carbofuran, killed between 17–91 million birds in US cornfields at its peak of popularity, although this particular agent is now effectively banned in the US. Rather remarkably, Mineau and Whiteside [371] found that the risk of lethal insecticide exposure was the best predictor of grassland bird species decline from 1980–2003, more so even than changes in land area under crop cultivation. With the phasing out of more toxic insecticides, there has been some signal of a concomitant reduction in bird declines [371].

Even if they do not directly poison certain animals, pesticides can affect their populations by altering species interactions. For example, herbicide application reduces plant cover and "weed" species that are important food sources for some birds and many insects. In turn, other birds rely on the herbivorous insects and their invertebrate predators, e.g. spiders, as a food source. Furthermore, intensive herbicide helps facilitate large-scale monocultures, and the loss of diversity in plant species also reduces food sources. Therefore, one sees an overall decline in bird populations and diversity as an indirect consequence of herbicide use via multiple causal cascades [370]. Insecticides also directly reduce insect food resources as well. Space limits a more thorough discussion, but other orders of animal life, such as fish and amphibians, also likely suffer greatly from man's pesticidal activity.

Pollinator decline and pesticides

Pesticides, particularly the neonicotinoid insecticides, have been widely implicated in global declines in pollinator insects, especially bees. This has been best studied in the (semi-) domesticated European honey bee (*Apis mellifera*), colonies of which are commercially raised at large scales for honey production and orchard pollination services, and subject to the colony collapse disorder (CCD) featured so prominently in the media in the last few years. One must, however, understand that outside of Eurasia and Africa, the honey bee is an introduced, domesticated species (including in the US), and (usually solitary, non-honey producing) wild bee populations are far more important to both natural ecologies and human agriculture [377].

Pollinator insects play a pervasive role in supporting most natural ecosystems, and are thus of profound, if somewhat indirect, importance to human civilization as well. Angiosperms, or flowering plants, are by far the dominant form of plant life on planet Earth, with nearly 90% of extant land species belonging to this phylum [373], and Ollerton and colleagues [374] have calculated that 87.5% of all angiosperm species are pollinated by animals (although not all necessarily *require* biotic pollination). Similarly, a majority of the world's food crop *species* depend at least partly upon animal pollination, and one of the most cited sources has been interpreted as stating that humans depend upon pollinators for about one-third of all their food: Klein et al. [375] reported that, of 115 leading global crops, 87 of these species (76% of the total) rely upon animal pollination, with these species accounting for 35% of all global food production.

Note however, that a disproportionate amount of agriculture production comes from crops that depend upon pollinators not at all. The world's major staple grains, including maize, wheat, soy, rice, and barely, are all wind-pollinated, while tubers (e.g. potatoes), also major staples, do not require pollination (as tubers are not fruits, but specialized roots, and these plants are typically propagated from the root). Furthermore, while animal pollinators *enhance* the productivity of many food crops, only a small minority of these are absolutely dependent upon animals (less than 10%), and thus Aizen et al. [376] calculated that a complete loss of pollinators would reduce global agricultural output (in terms of weight) by "just" 5–8%; significant to be sure, but much less than one-third. Nevertheless, because insect pollinated crops tend to have lower yields than others, compensating for pollinator losses could disproportionately increase agricultural land requirements [376]. Moreover, the share of pollinator-dependent crops has increased dramatically in recent decades, with demand for pollinators outstripping supply. Finally, even if the effects on grain-based agriculture are comparatively minor or manageable (at a global scale), pollinator decline has potentially dire ramifications for the larger global ecology.

Returning to pesticides and pollinators, Europe and North American have seen severe declines in managed honey bee populations in recent decades, although increased bee-keeping in Asia has led to a net global honey bee increase [377]. Data is far sparser for wild bee populations, but it is clear that both Europe and North America have also suffered severe bumblebee (which form small colonies) and other wild bee (which are generally solitary) losses over the last century or so. This is actually even more worrisome than honey bee loss, as wild pollinators perform most crop pollination globally, and wild bees support ecosystem services more generally.

Multiple anthropogenic stressors, including habitat loss, introduced pathogens, and chronic agrochemical exposure all undoubtedly interact to drive bee declines [377]. Massive losses of flower-rich grasslands to farmland historically drove major bee declines, and agricultural intensification continues to eliminate habitat, while monocultures provide very limited diets. Long-distance transport of commercial bees has contributed to the spread of pathogens and disease, especially the parasitic mite, *Varroa destructor*, a major cause of colony collapse; commercially raised bees at high densities can also introduce devastating diseases into wild bee populations. Finally, pesticides play a significant role: broad herbicide applications kill many food sources, but most focus has been on the more direct effects of insecticides, particularly the neonicotinoids. These agents are applied as seed treatments, and are present throughout the mature plant. They can directly kill bees, and have a variety of sublethal effects, including decreased learning, foraging, and reproduction, and they likely increase vulnerability to disease and other stressors. Such effects occur at very low doses, and bees living in farmed areas are likely routinely exposed to doses sufficient for harm. An extensive scientific literature, partially reviewed in [377], confirms the hazard of insecticides to bees, although there remains great uncertainty.

20.2.5 Household pesticide use

Pesticides are widely used by residential households and on commercial properties, largely for purely aesthetic landscaping and gardening. This, I believe, is inexcusable. We may have a serious debate over the merits of pesticide use in agriculture, given the potential environmen-tal benefit of improved yields, but to use these products that clearly affect both human and ecosystem health towards no end other than a “nice” lawn is, again, inexcusable.