Environmental and Health Impacts of Pesticides and Fertilizers and Ways of Minimizing Them

Envisioning A Chemical-Safe World

Chapter 2 of 12

Status and trends of pesticide use

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About

In December 2017, Resolution 4 of the 3rd Session of the United Nations Environment Assembly (UNEA 3) requested "the Executive Director to present a report on the environmental and health impacts of pesticides and fertilizers and ways of minimizing them, given the lack of data in that regard, in collaboration with the World Health Organization (WHO), the Food and Agriculture Organization of the United Nations (FAO) and other relevant organizations by the fifth session of the United Nations Environment Assembly". In response to this request, UNEP published a *Synthesis Report on the Environmental and Health Impacts of Pesticides and Fertilizers and Ways to Minimize Them*[1] in February 2022 (United Nations Environment Programme [UNEP] 2022).

The overall goal of the synthesis report is to provide the information base to enable other advocacy actions to be taken by stakeholders to minimize the adverse impacts of pesticides and fertilizers. Specific objectives of the synthesis report are to:

- Update understanding of current pesticide and fertilizer use practices;
- Present major environmental and health effects of pesticides and fertilizers, during their life cycle, and identify key knowledge gaps;
- Review current management practices, legislation and policies aimed at reducing risks in the context of the global chemicals, environmental and health agenda;
- Identify opportunities to minimize environmental and health impacts, including proven and innovative approaches.

This chapter on "Status and trends of pesticide use" is the 2nd in a series of 12 chapters that make up a comprehensive compilation of scientific information. The chapters were developed to both inform and further elaborate on the information provided in the synthesis report. Please note that the disclaimers and copyright from the synthesis report apply

1 The Synthesis report is available at https://www.unep.org/resources/report/environmental-and-health-impacts-pesticides-and-fertilizers-and-ways-minimizing.

Status and trends of pesticide use

2

2.1 Overview

In this report the term pest designates any type of organism targeted by a pesticide. When specific groups of pesticides such as insecticides or herbicides are addressed, they are identified as such. Pesticides are used to control arthropod (invertebrate) pests such as insects and mites, as well as diseases caused by fungi and bacteria. They are also used to control weeds, molluscs, nematodes, rodents, and other organisms that may damage crops or trees, transmit human diseases, overgrow roads, damage buildings, or are otherwise considered a nuisance or danger (Matthews 2018; Philipps McDougal 2018a).

Pesticide use has steadily increased since the introduction of synthetic organic pesticides in the 1940s (Matthews 2018). By 2016 about 4.1 million tons of pesticide active ingredients per year were used globally, double the quantity applied in 1990 (FAOSTAT 2019). The total value of the pesticide market was estimated at about United States dollars (USD) 65 billion in 2018 (Agrow 2019). The most pesticides by volume are used in Asia and South and Central America, the regions that have shown the highest growth in use during the last 25 years (FAO 2019a). [Chapters 2.4.2 and 2.4.3]

The large majority of pesticides are used in agriculture. Non-agricultural uses, including domestic or industrial applications and vector control, represent only 10-15 per cent of the global market by value (Phillips McDougal2017); Agrow 2019; Agrow 2020). About 60 per cent of the volume of all agricultural pesticides applied consists of herbicides, with the other 40 per cent almost equally divided between fungicides and insecticides (Phillips McDougal 2018b). [Chapter 2.4.3] Biological pest control agents (or bioprotectants) represent about 7 per cent of the value of the total crop protection market (Agrow 2018). Although this is a small fraction of the total pesticide market, sales of bioprotectants are growing rapidly (at 15-20 per cent per year), considerably faster than sales of synthetic chemical pesticides (Glare *et al*. 2012; DunhamTrimmer 2019). [Chapter 2.4.4]

The intensity of global agricultural pesticide use, measured as kilogram (kg) of pesticide active ingredient applied per hectare (ha) of cropland, increased by about 75 per cent between 1990 and 2016. Agricultural productivity has also increased in the same period. As a result, the quantity of pesticide required per unit agricultural production has remained approximately unchanged. Nevertheless, the biological activity ("pest control power per unit product") of modern pesticides is significantly higher than that of the older groups of pesticides (FAO 2019a). Pesticide use intensity per ha cropland and per unit agricultural production is positively correlated with per capita gross domestic product: the richer the country, the more pesticides are used. A slight decrease in use intensity per hectare (but not in pesticide use intensity per unit production) has been seen in the world's richest countries. High income countries therefore do not appear to use pesticides more efficiently than lower income countries. However, differences exist between crops and between regions (Schreinemachers and Tipraqsa 2012). [Chapter 2.4.5]

The pesticide industry has experienced important mergers and acquisitions during the last decade. Currently four (conglomerates of) companies represent about 60 per cent of the global agricultural pesticide market. The same companies often also have important activities involving seeds and biotech crops, leading to a concentration of research, development and marketing capacities with regard to agricultural inputs (Yuan 2019). At the same time, the share of off-patent ("generic") pesticides has increased from about 40 per cent of the global value of the pesticide market in the early 2000s to about 70 per cent today (AgbioInvestor 2019). [Chapters 2.5.1 and 2.7.9]. The growth of the global pesticide market has been accompanied by an important rise in the trade of illegal pesticides. They include banned or otherwise non-authorized pesticides, as well as counterfeit, fake, and illegally labelled or packaged products. Illegal pesticides can damage crops, harm human health and contaminate the environment. Although no precise estimates are available, the value of illegal pesticide sales is believed to represent 10-15 per cent of the legitimate global pesticide market (United Nations Interregional Crime and Justice Research Institute [UNICRI] 2016). [Chapter 2.5.3]

Application equipment and methods can greatly influence environmental and human exposure to a pesticide, as can the way pesticides are formulated and marketed. Developments in pesticide application technology have resulted in vehicle-mounted and tractor sprayers with various engineering controls which minimize occupational and environmental exposure (Jensen and Olesen 2014; Matthews 2020). Such technology is not available or much used in low and middle income countries, where simple hand-held sprayers dominate with associated higher risks for operators and the environment (Matthews, Bateman and Miller 2014; Horne 2019). [Chapter 2.6]

Many factors influence the use of pesticides, either positively or negatively. Drivers can be agronomic, economic or regulatory. Pesticide use can also be influenced by public health, environmental or information considerations. Key drivers that tend to increase pesticide use are current practices of agricultural intensification, pesticide resistance, genetically modified crops (mainly for herbicide resistance), pesticide marketing practices, and commodity prices. Pesticide use is limited mainly by national legislation and policies, as well as by environmental and human health (including food safety) concerns. The type of information and training provided to pesticide users can lead to increasing or decreasing use of pesticides. [Chapter 2.7]

2.2 Types of pesticides

2.2.1 Pesticide definitions

An internationally agreed definition of pesticide is provided in the International Code of Conduct on Pesticide Management. It defines a pesticide as "any substance, or mixture of substances of chemical or biological ingredients intended for repelling, destroying or controlling any pest, or regulating plant growth", where a pest is defined as: "any species, strain or biotype of plant, animal or pathogenic agent injurious to plants and plant products, materials or environments and includes vectors of parasites or pathogens of human and animal disease and animals causing public health nuisance" (Food and Agriculture Organization of the United Nations [FAO] and World Health Organization [WHO] 2014). According to the definition in the International Code of Conduct, pesticides can be of chemical or biological origin; they may not only kill pests, but also repel or otherwise influence them, and they may include plant growth regulators.

Table 2.2-1 **Specific groups of pesticides included in countries' pesticide definitions.** Based on an analysis by the Secretariat of the Rotterdam Convention (Rotterdam Convention 2019).

Pesticide group		Intended uses	Number of countries (out of a total of 122)
A	Pesticides used on plants	a. Prevent, destroy or control undesirable species b. Promote or inhibit plant growth, modify physiology, or influence the life processes of plants c. Protect commodities from deterioration during storage and transport by application to crops prior to or following harvest	114 (93 per cent)
B	Pesticides used on animals	a. Prevent, destroy or control insects, arachnids or other pests in or on animals b. Prevent, destroy or control pests on hosts' bodies (ectoparasites) c. Prevent, destroy or control vectors/transmitters of animal disease	83 (68 per cent)
C	Pesticides used in public health and hygiene	a. Control vectors of human disease/ectoparasites on humans b. Domestic/household use	76 (62 per cent)
D	Pesticides used on inanimate objects or in the environment	a. Protect food, feed and fodder b. Protect wood, clothes, textiles and fabrics c Prevent or control organisms harmful to roadways, railways, dams, airports, ports, vessels, floats, buildings or, for example, in industrial or aquatic environments	72 (59 per cent)

Included in the survey were 122 Parties to the Convention. In most cases the term pesticide was defined in national legislation.

While the term pesticide is generic in the sense that it covers all types of pests, several other terms are regularly used which tend to refer to specific pesticide uses. These include plant protection product, agrochemical, agricultural remedy and phytosanitary product (for pesticides used in agriculture), and biocide, public health pesticide and domestic pesticide (for non-agricultural pesticides).

Pesticides are defined differently by individual countries, often influenced by the ways they are intended to be used. A recent review by the Secretariat of the Rotterdam Convention of definitions of the term pesticide showed that a large majority of pesticide definitions referred to products intended for use in protecting plant health (Rotterdam Convention 2019) (Table 2.2-1). However, pesticide definitions in 30-40 per cent of the countries included in the review did not include products intended to protect animal or human health, or to protect inanimate objects or the environment. As many of these definitions are part of pesticide legislation, the review suggested that non-agricultural pesticides are less well regulated than agricultural pest control products, particularly in low and middle income countries (see also Chapter 3.4).

2.2.2 Pesticide categories

It is common to categorize pesticides according to the target organisms they are intended control. These categories include insecticides, fungicides, herbicides and rodenticides (Figure 2.2-1).

Pesticides can also be categorized according to their origin (chemical, biological or plant-incorporated).

Chemical pesticides

Some chemical pesticides (e.g., sulphur- and copper-based fungicides) are inorganic. However, a large majority of chemical pesticides on the market are synthetic organic compounds

Figure 2.2-1 Categorization of pesticides according to the target organisms they are intended control

Type of pesticide	Target pest organism
Herbicide	Weeds, algae
Insecticide	Insects
Acaricide	Mites
Fungicide	Fungi
Bactericide	Bacteria
Nematicide	Nematodes
Molluscicide	Snails, molluscs
Avicide	Birds
Wood preservative	Mainly fungi and insects
Antifoulant	Mainly barnacles (e.g. on ship hulls or other undersea surfaces)
Antimicrobial	Microbiological organisms in general, such as bacteria and viruses

Note: The definition of pesticides under the International Code of Conduct on Pesticide Management includes plant growth regulators, however this is not included in this figure as this group of pesticides does not target pest organisms

designed, synthesized and manufactured by the specialized pesticides industry. These pesticides are generally categorized according to the chemical groups to which they belong (e.g., organophosphates, neonicotinoids, triazoles and dinitroanilines) (Table 2.2-2) or their mode of action (e.g., cholinesterase inhibitors, fumigants, photosynthesis inhibitors).

Bioprotectants

Bioprotectants are products that originate in nature, can be sourced from nature, or are identical to their natural origin if synthesized (International Biocontrol Manufacturers Association [IBMA] 2019). They are also referred to as biological pest control agents (FAO and WHO 2017). Bioprotectants include semiochemicals (e.g., pheromones) and microbials (e.g., bacteria, fungi and viruses); natural substances such as botanical products; and invertebrate biocontrol agents (Figure 2.2-2). The environmental and human health risks of invertebrate biocontrol agents (or macrobials) in pest control are not covered in this report (but see, for example, van Lenteren *et al*. 2006; van Lenteren *et al*. 2018).

The term biopesticide is used to describe bioprotectants formulated and applied similarly to a conventional chemical pesticide (FAO and WHO 2017). Unlike chemical pesticides, many (although not all) biopesticides are very target-specific and will generally only control a limited range of pests, diseases or weeds (Table 2.2-2).

2.2.3 Components of a pesticide

A pesticide placed on the market is generally referred to as a pesticide product, pesticide

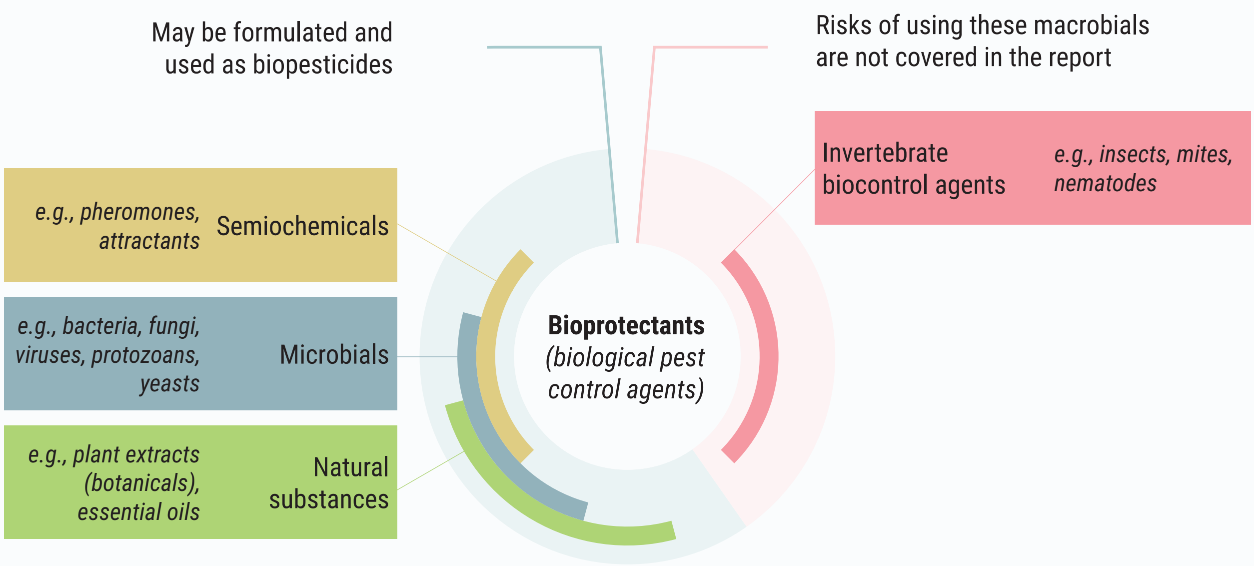
Table 2.2-2 **Major classes of synthetic chemical insecticides, herbicides and fungicides and examples of well-known individual compounds.** Adapted from Matthews (2018); Philipps McDougal (2018a); Wood (2019).

Insecticides	Herbicides	Fungicides
Organochlorines	Triazines	Dithiocarbamates
dichlorodiphenyltrichloroethane (DDT)	ametryn	mancozeb
endosulfan	atrazine	maneb
	cyanazine	thiram
Organophosphates	Phenoxy herbicides	Triazoles
chlorpyrifos-ethyl	2,4-D	difenoconazole
malathion	fluazifop-P	hexaconazole
pirimiphos-methyl	MCPA	tetraconazole
Carbamates	Chloroacetanilides	Strobilurines
bendiocarb	acetochlor	azoxystrobin
carbofuran	metolachlor	pyraclostrobin
oxamyl		
Pyrethroids	Dinitroanilines	Imidazoles
deltamethrin	pendimethalin	iprodione
tralomethrin	trifluralin	imazalil
Neonicotinoids	Quaternary ammonium herbicides	Carbamates
clothianidin	diquat	thiophanate-methyl
imidacloprid	paraquat	
thiamethoxam		
Pyrazoles	Organophosphonate herbicides	Benzimidazoles
fipronil	glyphosate	carbendazim
Diamides	Phenylureas	Aromatic fungicides
chlorantraniliprole	diuron	chlorothalonil
Avermectins	Sulfonylureas	Amides
abamectin	bensulfuron-methyl	metalaxyl
	metsulfuron	
	nicosulfuron	
Pyrroles		
chlorfenapyr		
Juvenile hormone mimics		
pyriproxifen		

formulation or formulated product. It consists of an active ingredient (or active substance) and one or more co-formulants. The active ingredient is the part of the product that provides the pesticidal action (FAO and WHO 2014). The manufactured active ingredient (known as the technical material) consists of the active ingredient, together with associated impurities, and sometimes small amounts of necessary additives (FAO and WHO 2016).

Apart from active ingredients, plant protection products contain co-formulants which give the product the necessary properties for application. These are the non-active ingredient components of a formulated product (FAO and WHO 2014), sometimes also referred to as inert ingredients or inerts. Co-formulants make plant protection products easy to handle, apply and store. They can improve operator safety, help disperse the active ingredient evenly in the spray liquid,

Figure 2.2-2 **Bioprotectants covered in this report include semiochemicals, microbials and natural substances, but not invertebrate control agents. Some bioprotectants may be formulated and used similarly to chemical pesticides, in which case they are sometimes referred to as biopesticides.**
Based on DunhamTrimmer (2019); IBMA (2019).



or facilitate spreading on plants. Examples of co-formulants are wetting agents, solvents, emulsifiers, carriers, anti-evaporants, synergists, dyes, stabilizers and safeners (German Federal Office of Consumer Protection and Food Safety 2019). However, co-formulants can be hazardous substances whose risks also need to be evaluated. Some co-formulants have been shown to be more toxic than the pesticide active ingredient, and certain regulatory agencies have established lists of prohibited co-formulants.

Chemicals added to a pesticide formulation to increase its effectiveness are referred to as adjuvants; these are generally added separately to the pesticide product in the spray tank.

Table 2.2-3 **Examples of common biopesticides on the market.** Adapted from DunhamTrimmer (2019); IBMA (2019).

Biochemicals			Microbials		
Example	Group	Target organism	Example	Group	Target organism
Trimedlure	Pheromone	*Mediterranean fruit fly*	*Bacillus thuringiensis subsp. kurstaki*	Bacteria	Lepidopteran larvae
(E,Z)-tetradeca-9, 12-dienyl acetate	Pheromone	Beet armyworm	*Bacillus thuringiensis subsp. israelensis*	Bacteria	Mosquito larvae
Azadirachtin A	Botanical	Wide range of insects	*Metarhizium anisopliae (various strains)*	Fungi	E.g. Coleoptera larvae, termites)
			Metarhizium acridum strain IMI 330189	Fungi	Locusts and grasshoppers
			Trichoderma atroviride	Fungi	Various fungal pathogens
			Helicoverpa zea single-enveloped nucleopolyhedrovirus (HzSNVP)	Virus	American cotton bollworm
			Bacillus amyloliquefaciens D747	Bacteria	Fungal pathogens

2.3 History of pesticide development

Since the early stages of agriculture, pesticides have been used to protect crops. Reportedly, the first known pesticide was elemental sulphur used about 4,500 years ago in Mesopotamia. The Rig Veda, an ancient Indian collection of Vedic Sanskrit hymns composed some 3,500 years ago, mentions the use of poisonous plants for pest control (Pandya 2018). The Greek poet Homer described the benefits of sulphur 3,000 years ago as a "pest averting" substance. Pyrethrum was known in Persia around 400 B.C., where it is thought to have been used to protect stored agricultural products (Matthews 2018).

In the 17th and 18th centuries substances such as vinegar, brine, tobacco extracts, sulphur, oil soap, arsenic and copper were used as pesticides. In the 19th century Bordeaux mixture (copper sulphate, water and lime) was, apparently accidentally, found to be effective against downy mildew on grapevines. Paris green (or Schweinfurt green), containing copper acetoarsenite, was used from about 1860 onwards as an insecticide and rodenticide (Matthews 2018).

In the early 20th century plant extracts such as pyrethrum, tobacco and rotenone, and inorganic chemicals such as arsenic, copper and sulphur were the main compounds used as insecticides and fungicides.

Until the 1940s pest management was mainly based on agronomic measures such as crop rotation, intercropping, mechanical measures (e.g., hand picking of pest insects), field hygiene (e.g., removal of crop residues), and promotion of pests' natural enemies (Chittenden 1899; Vayssière and Mimeur 1926). Pesticides only played a limited role.

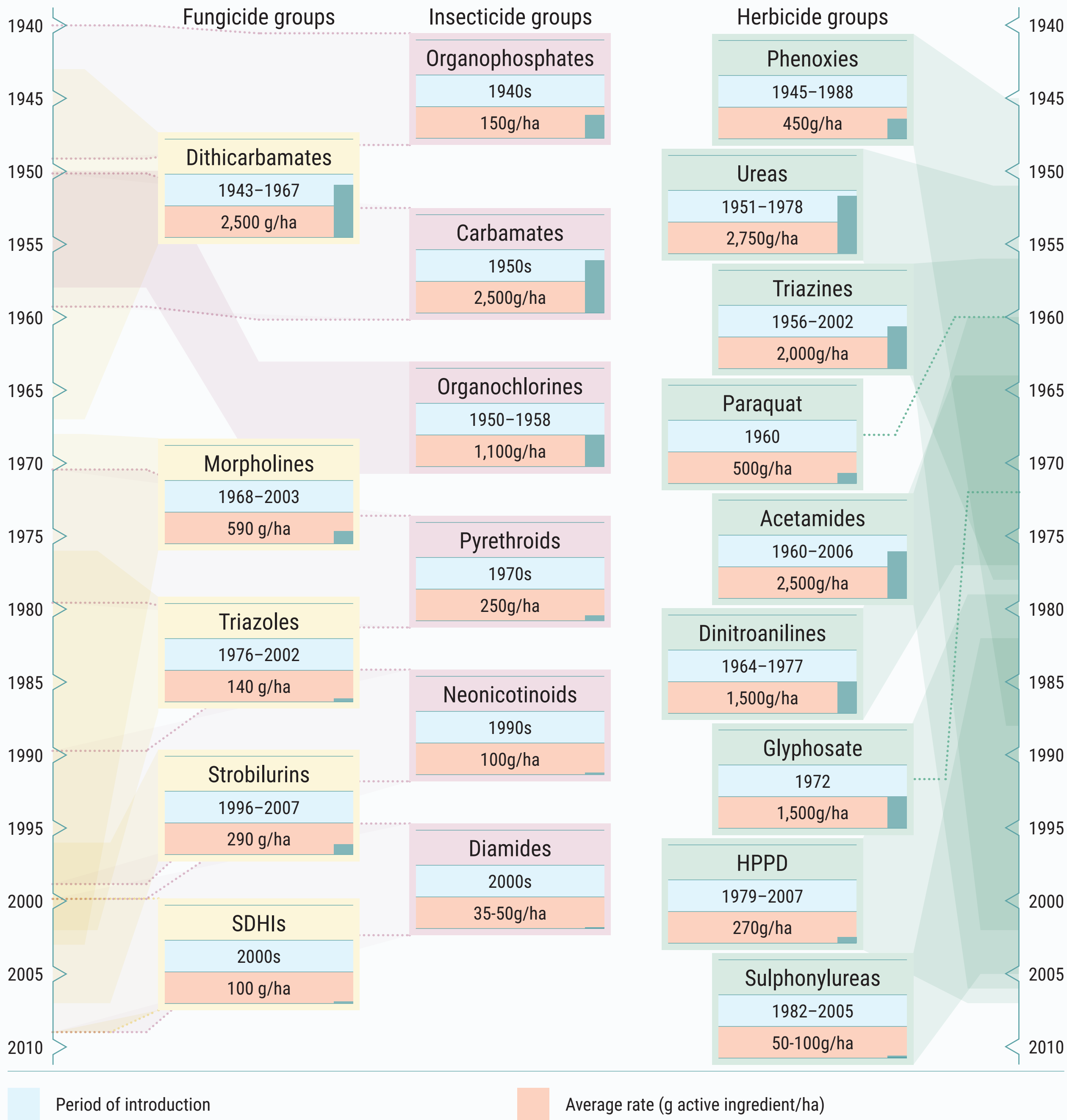
In the 1940s organic chemicals began to be synthesized which could be used as insecticides, herbicides and fungicides, representing a revolutionary change in pesticide development. Organochlorine and organophosphorus insecticides and acaricides, phenoxy herbicides, and dithiocarbamate fungicides all came on the market in the 1940s and 1950s. Some of these chemicals are still used today. Many other synthetic organic pesticides followed (Matthews 2018; Phillips McDougal 2018a).

More recently developed classes of insecticides include neonicotinoids, phenyl-pyrazoles, pyrroles, diamides, spinosyns, avermectins and ketoneols. Modern fungicides belong to groups such as the strobilurins and carboximides (succinate dehydrogenase [SDH] inhibitors). On the other hand, few new herbicide groups have come on the market in the last 30 years, and more recently developed herbicides belong to already known groups such as the pyrimidindiones, triazolones and benzoylpyrazoles (4-Hydroxyphenylpyruvate dioxygenase [HPPD] targeting herbicides) (Matthews 2018; Phillips McDougal 2018a) (Figure 2.3-1).

Over time new pesticide groups have become more effective for each gram of active ingredient used. Application rates in the 1950s averaged 1,000-2,500 grams of active ingredient per hectare (g/ha); by the 2000s they fell to 40-100 g/ha (Lamberth *et al*. 2013; Phillips McDougal 2018a) (Figure 2.3-1). Greater biological efficacy means farmers need a lower volume of pesticides to control the same pests. However, with the increased bioefficacy of modern pesticides has come higher toxicity to certain groups of non-target organisms.

In the 1960s there were about 100 active ingredients on the market, compared with some 600 synthetic chemical active ingredients today. In addition, there are currently around 300 biopesticide active substances and organisms (Phillips McDougal 2018a). The number of introductions of new pesticide active ingredients increased until the 1990s, but these introductions have significantly declined during the last two decades (Figure 2.3-2). While major companies annually invest 7-10 per cent of their sales in research and development (R&D), it has become increasingly difficult to develop and register new pesticide active ingredients. This is partly due to stricter environmental and human health requirements in large economies such as those

Figure 2.3-1 Chronology and application rates of the main fungicide, insecticide and herbicide groups.
Phillips McDougall (2018a).



in North America and the European Union [EU]). However, the number of compounds that need to be synthesized and screened to deliver one new market introduction has also increased considerably, from around 52,500 in 1995 to around 140,000 in 2005 (Lamberth *et al.* 2013).

For example, following the introduction of the EU-wide registration system for plant protection products in 1991 the authorizations of more than half the 1,000 active ingredients on the market were not renewed (European Union [EU] n.d.). This was partly because the pesticides did not meet the more stringent environmental and human health criteria, and partly because the pesticide industry did not consider the generation of additional data economically worthwhile and therefore withdrew applications for renewal.

Figure 2.3-2 **Number of new pesticide active ingredients introduced globally per decade.** Phillips McDougal (2018a).

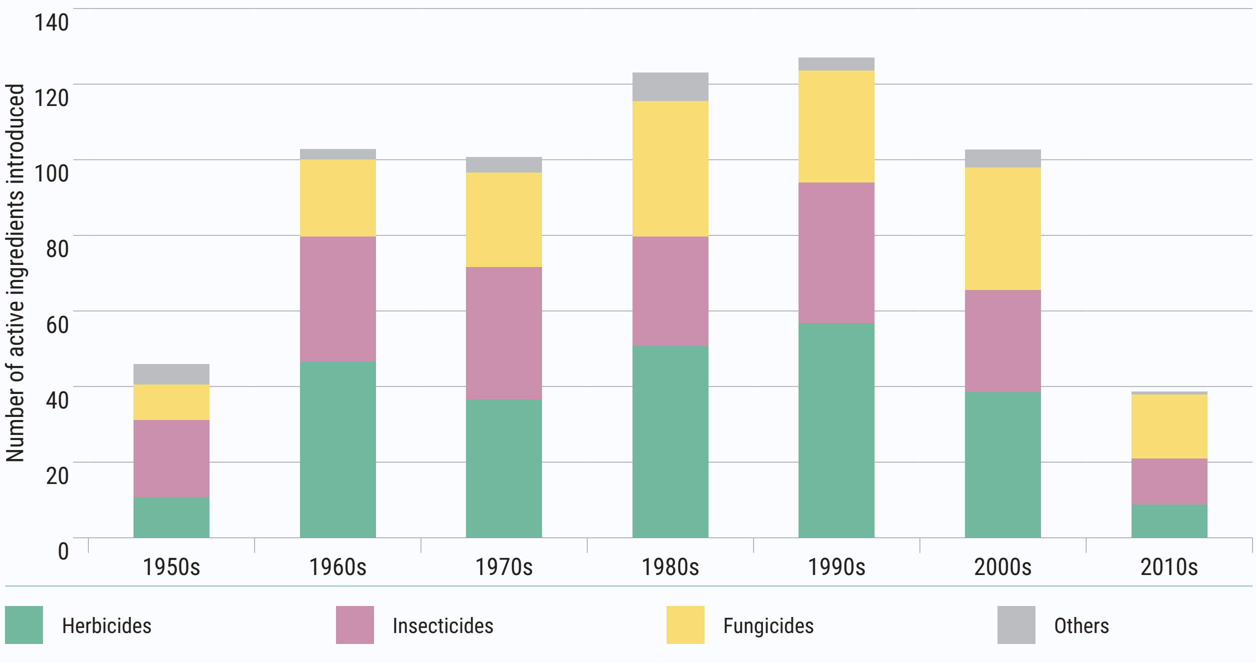
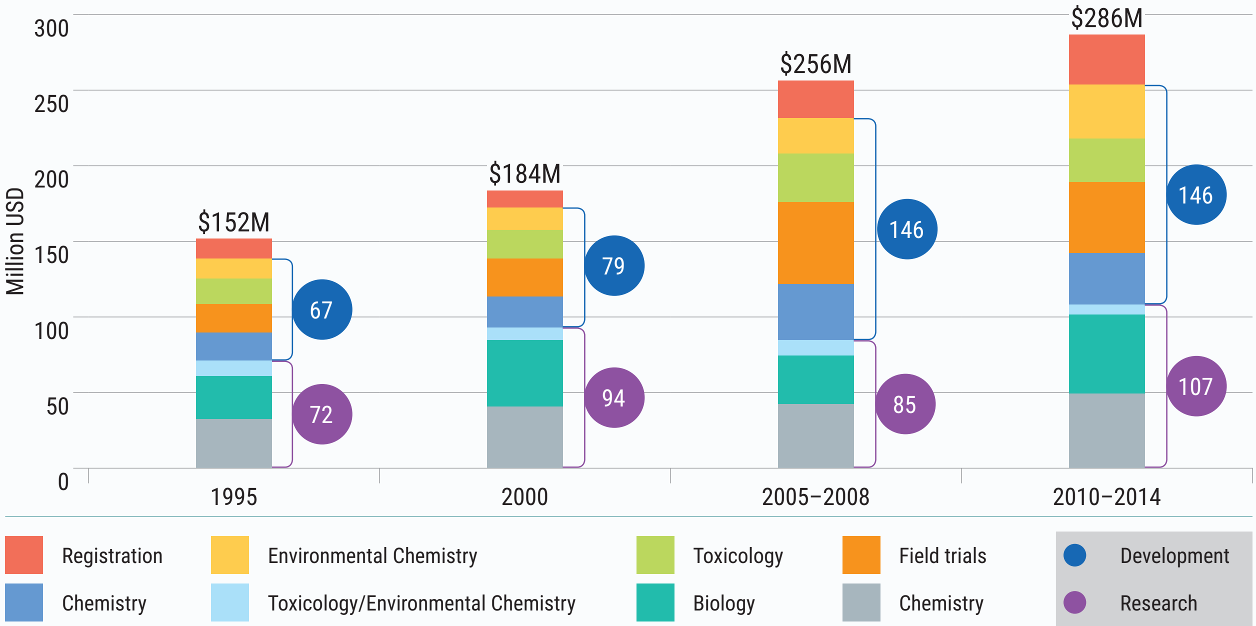


Figure 2.3-3 **Discovery and development costs (nominal values, i.e. not adjusted for inflation) of a crop protection product based on a new active ingredient increased almost 90 per cent between 1995 and 2014.** Phillips McDougal (2018a).



Note: Estimates are for five leading multinational pesticide companies. As a comparison, USD cumulative inflation over the same period was about 55% (CPI 2019).

As a result of the above and other factors, the overall nominal costs of the discovery and development of a new active ingredient intended for use in crop protection almost doubled between 1995 and 2010-2014, from United States dollars (USD) 152 million to USD 286 million (Figure 2.3-3).

About one-third of these costs are regulatory, i.e., related to registration of the pesticide (represented in the figure as the combined costs of registration, environmental chemistry and toxicology). In the same period the time required to develop and introduce a new pesticide active ingredient increased from about eight to about 11 years (Phillips McDougal 2018a).

In the last 20 years the number of new biopesticide introductions has frequently exceeded introductions of conventional pesticides. This trend is likely to continue. 2017 was the first year in which there were more patents for biopesticides than for conventional crop protection products: 173 compared with 117 (Phillips McDougal 2018a). At the same time, it should be remembered that not all patents result in a commercial product.

2.4 Historical and current use of pesticides

2.4.1 Pesticide manufacturing

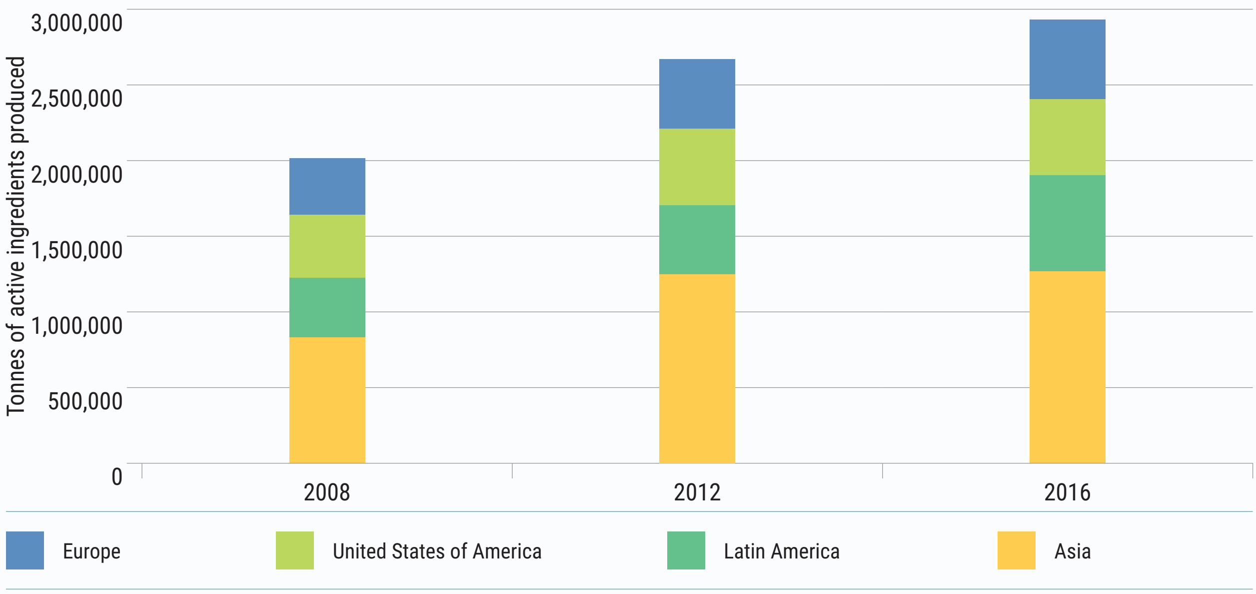
Global manufacturing of pesticide active ingredients has shown continuous growth in the last decade (Figure 2.4-1). Asia is the largest pesticide producer, with the greatest manufacturing capacity in China (where production more than doubled between 2008 and 2016). Growth of manufacturing during this period was highest in China (10 per cent compound annual growth rate), India (8 per cent), other parts of Asia (6 per cent) and Latin America (6 per cent). Pesticide production in other regions also increased, albeit at a slower pace (Oliver 2018).

2.4.2 Global pesticide use trends – volume

Pesticide use increased steadily following the introduction of synthetic organic pesticides in the 1940s and 1950s. Since the early 1990s global pesticide use in agriculture has almost doubled (Figure 2.4-2), amounting in 2016 to 4.1 million tons of active ingredients (FAOSTAT 2019).

Marked differences exist among world regions. The highest overall growth in pesticide consumption is in South and Central America and the Caribbean (an almost four-fold increase over

Figure 2.4-1 Global manufacturing of pesticides has increased steadily. Based on Oliver (2018).



25 years) (Figures 2.4-3 and 2.4-4). Asia uses more pesticides than any other region and has experienced the highest absolute growth in volume. Oceania has the lowest use of pesticides, but has shown the second highest growth rate. Pesticide use in northern America has only increased by about 10 per cent, while in Europe a slight decrease has been seen.

Estimates of pesticide use (Figure 2.4-2) are 25-40 per cent higher than those of pesticide manufacturing (Figure 2.4-1). This may be attributable to reliance on different sources: data from the FAO's FAOSTAT database for pesticide use and United Nations (UN) trade statistics and industry data for manufacturing, which have somewhat different geographical coverage.

Difference in pesticide use is also associated with per capita gross domestic product (GDP). Between 1991 and 1995 the majority of the volume of pesticides was used by what were then low income and high income countries, while in 2012-2016 the majority was used by upper-middle income countries (Figure 2.4-5). This change has been heavily influenced by China's development from a low income country in 1995 to an upper-middle income country in 2016. Even without taking into account pesticide use in China, however, upper-middle income

Figure 2.4-2 **Global use of pesticides in agriculture increased from about 2.3 million tons of active ingredient in the early 1990s to more than 4 million tons in 2016.** FAO (2019a).

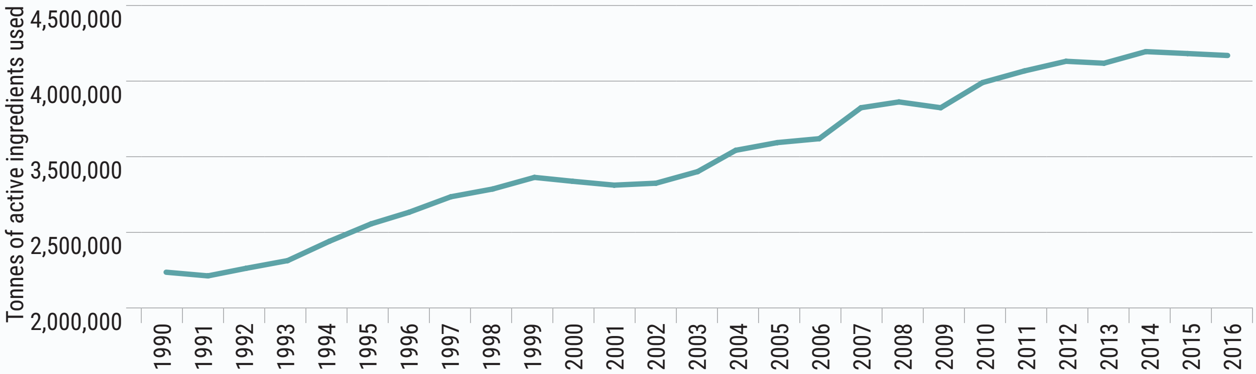


Figure 2.4-3 **Pesticide use in agriculture has exhibited different trends in the major regions of the world.** FAO (2019a).

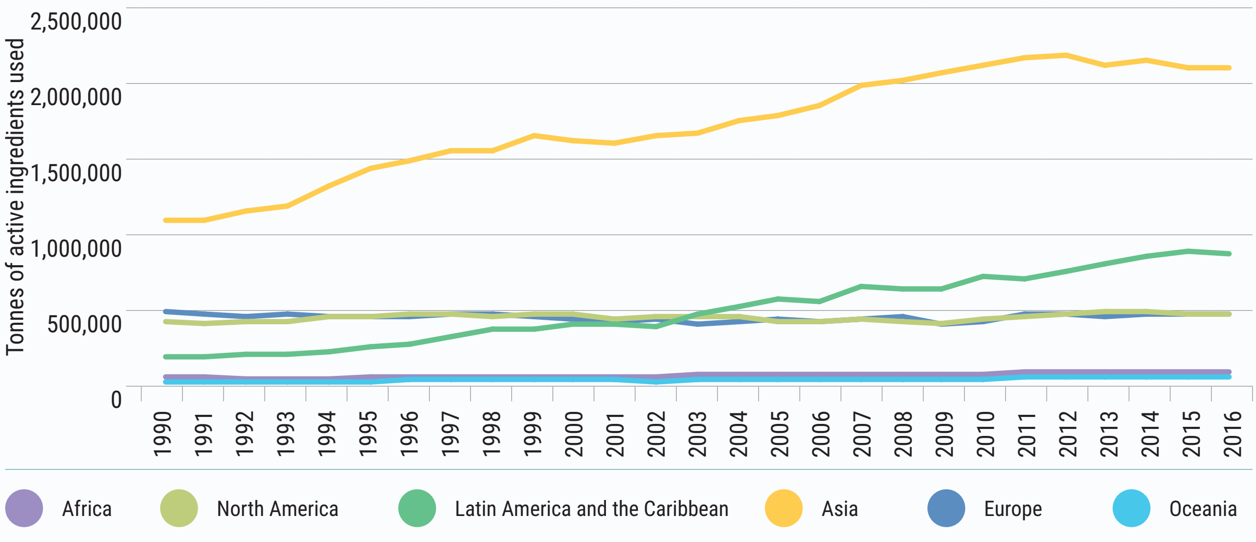


Figure 2.4-4 Overall growth in agricultural pesticide use (volumes of active ingredient) between 1990 and 2016 was highest in Latin America and the Caribbean. It was relatively stable in northern America and Europe. FAO (2019a).

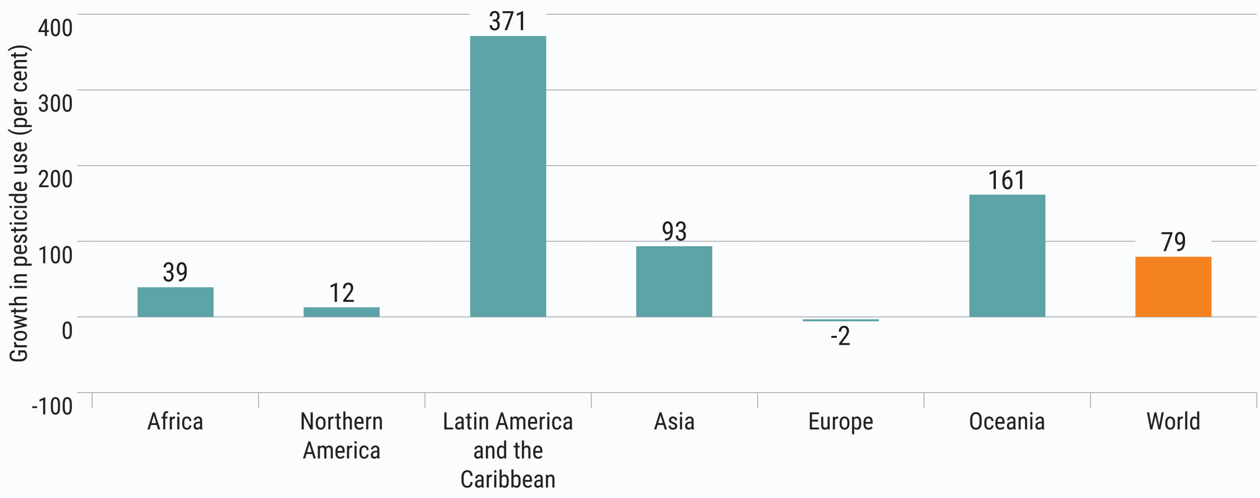
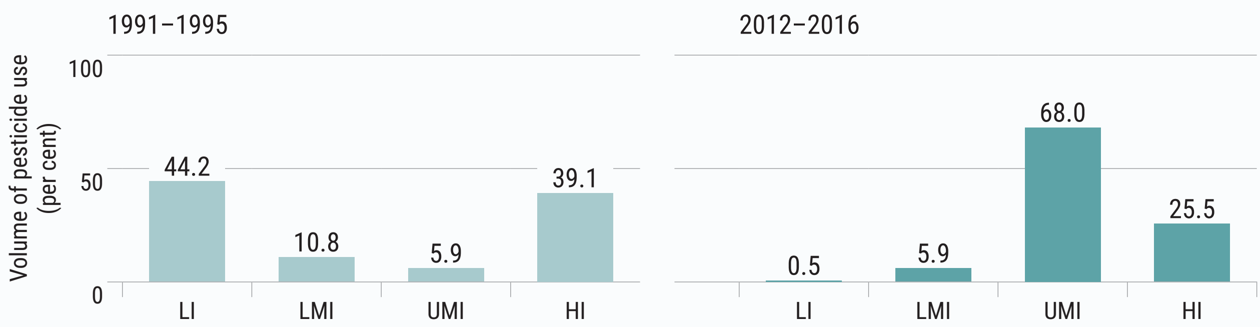
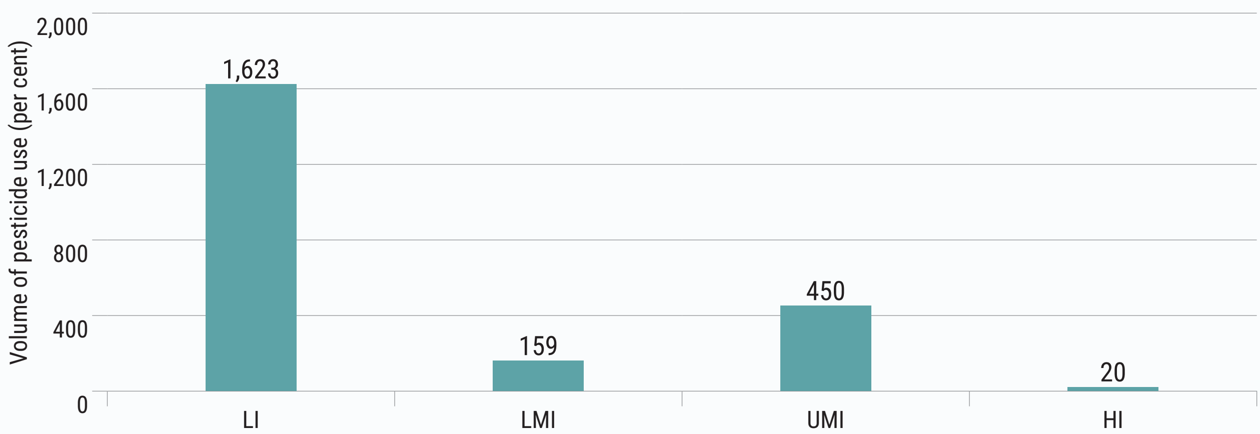


Figure 2.4-5 Share of the total volume of pesticides used by countries according to income group in 1991-1995 and 2012-2016. FAO (2019a).



LI = Low-income countries; LMI = Lower Middle-income countries; UMI = Upper Middle-income countries; HI = High-income countries
Note: For this analysis, 101 countries are included for which pesticide use data were updated on a regular basis in FAOSTAT (FAO 2019a); countries were omitted from the analysis if pesticide use data had not been updated for any 10 years or more during the 26 year time series. Income groups are as classified by World Bank (2020a) for calendar years 1995 and 2016

Figure 2.4-6 Average increase in the volumes of pesticides used in countries according to income group between 1991-1995 and 2012-2016. FAO (2019a).



Note: Data and abbreviations as in Figure 2.4-5.

countries are responsible for a major share of global pesticide use, likely linked to large-scale agricultural extension and intensification in these countries. Use in low income and lower-middle income countries in 2012-2016 did not exceed 7 per cent of total global pesticide use.

Despite the relatively limited use of pesticides in low income countries, it is in those countries that the relative increase in pesticide use since the early 1990s has been greatest (Figure 2.4-6).

2.4.3 Global pesticide use trends

Value

The total value of the pesticide market in 2018 was estimated at USD 65 billion, of which USD 57.6 billion (88 per cent) for crop protection products and USD 7.5 billion for non-crop protection purposes (e.g., home and garden, pasture, wood preservatives, public health, industrial) (Agrow 2019). The nominal value of the pesticide market (sales) has shown an overall steady increase since 2006 for crop protection products and non-crop pesticides (Figure 2.4-7). Over time, crop protection products represent a stable share (86-90 per cent) of the total pesticide market.

Although the value of the pesticide market has fluctuated from year to year, during the last decade there has never been a shrinking market for more than two years in a row (Figure 2.4-8). Between 2006 and 2018 the pesticide market grew by 4.8 per cent per year on average in both nominal and real terms.

In 2019 the largest regional markets for crop protection products were Asia and the Pacific and Latin America (Figure 2.4-9). The highest compound annual growth rate (2018 to 2019) was in Latin America (8 per cent). All other regions experienced a shrinking crop protection market.

Targets

The majority of pesticides used are herbicides, which amounted to some 61 per cent of the total volume of crop protection products applied globally in 2016. The share of herbicides has been growing since the 2000s (Figure 2.4-10). Fungicide use has also increased in the last few decades because of growing demand for fruits and vegetables, among other reasons. Insecticide use has remained fairly stable in volume terms, but has decreased as a percentage of the total crop protection product market.

Figure 2.4-7 The nominal value of global pesticide sales has increased steadily since 2006. Agrow (2016); Phillips McDougal (2017); Agrow (2019); Agrow (2020).

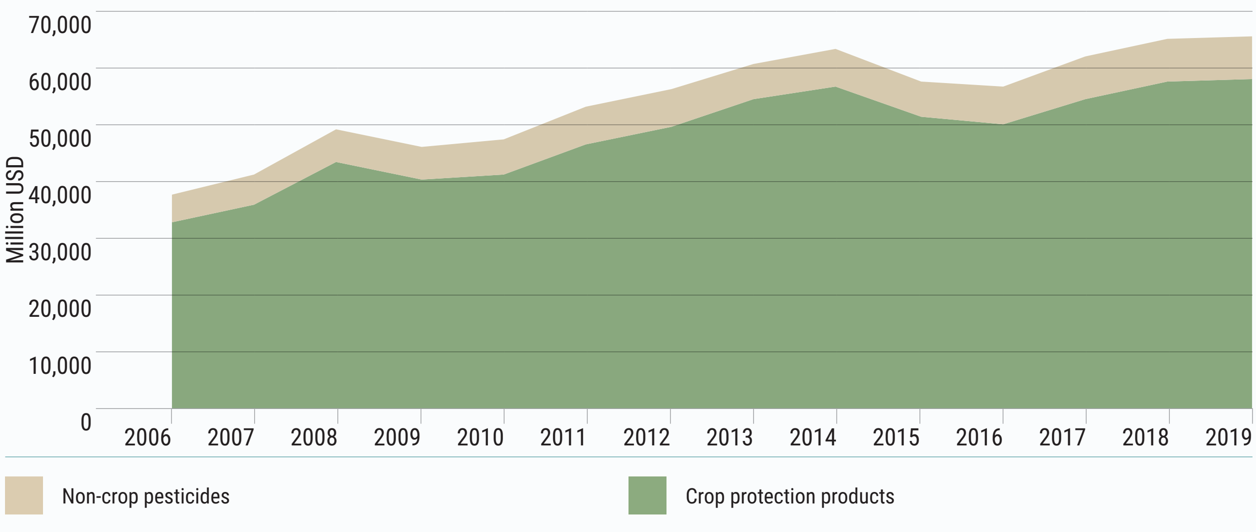
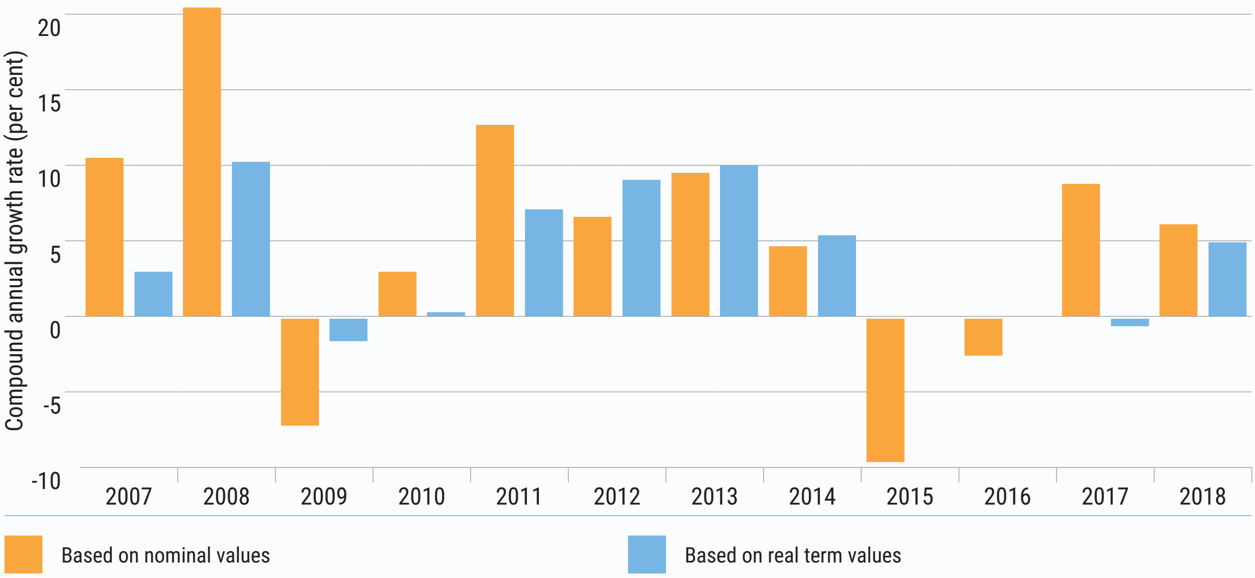


Figure 2.4-8 Compound annual growth rates for the global pesticides market, based on nominal and real term values (adjusted for variations in USD exchange rates and inflation). Agrow (2016); Phillips McDougal (2017); Phillips McDougal (2018a); Agrow (2019).



Note: Real term values for 2015 and 2016 are missing.

As an example of changing pesticide use patterns, farmers in the United States used very different types of pesticides on major crops in 2008 compared with 1960 (Figure 2.4-11). The growth of herbicide use in that country is also illustrated by the percentage of crop area treated. Approximately 5-10 per cent of corn (maize), wheat and cotton crops were treated with herbicides in

Figure 2.4-9 Regional markets for crop protection products and annual growth rates. Market value is expressed as USD million and percentage year-on-year change is from 2018 to 2019. Phillips McDougal (2019a), IHS Markit (personal communication).

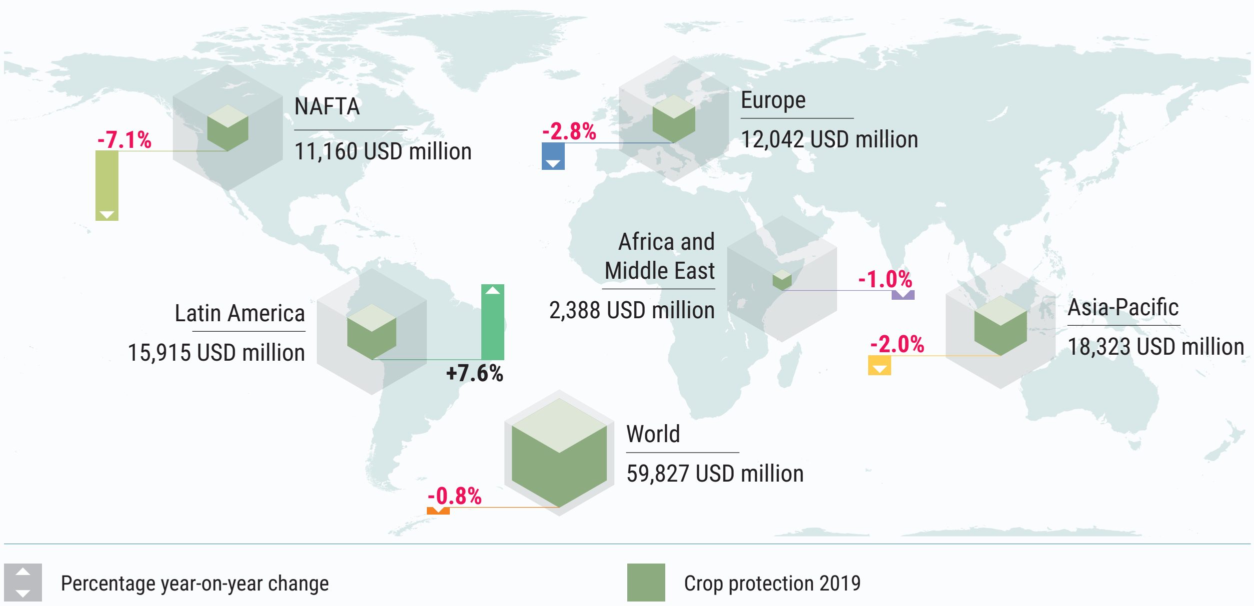


Figure 2.4-10 Major groups of crop protection pesticides as percentage of the total volume used globally.
Based on Phillips McDougal (2018b).

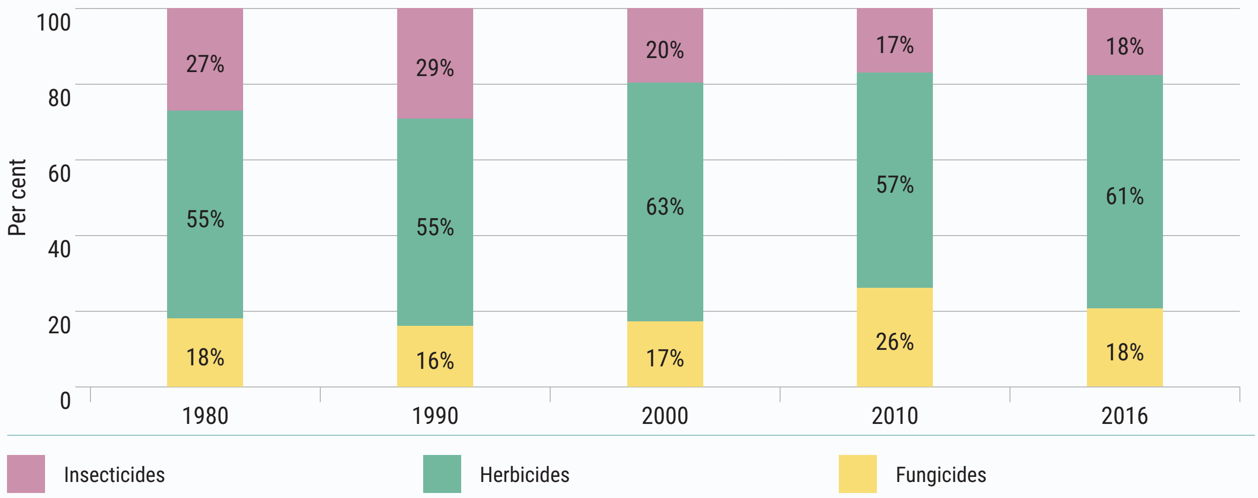
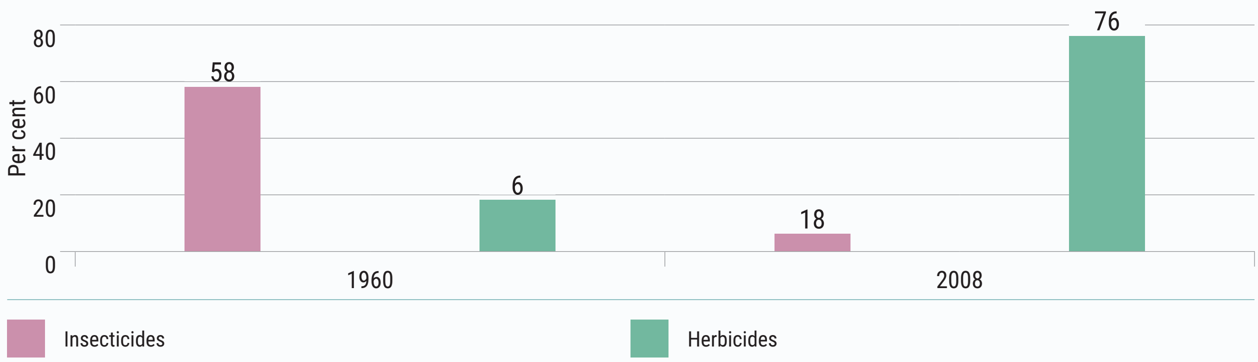


Figure 2.4-11 A major shift has occurred in pesticide use in the United States. Insecticides accounted for 58 per cent of pesticide volume applied in 1960, but only 6 per cent in 2008. Herbicides accounted for 18 per cent of the volume applied in 1960, compared with 76 per cent by 2008. Fernandez-Cornejo *et al.* (2014).



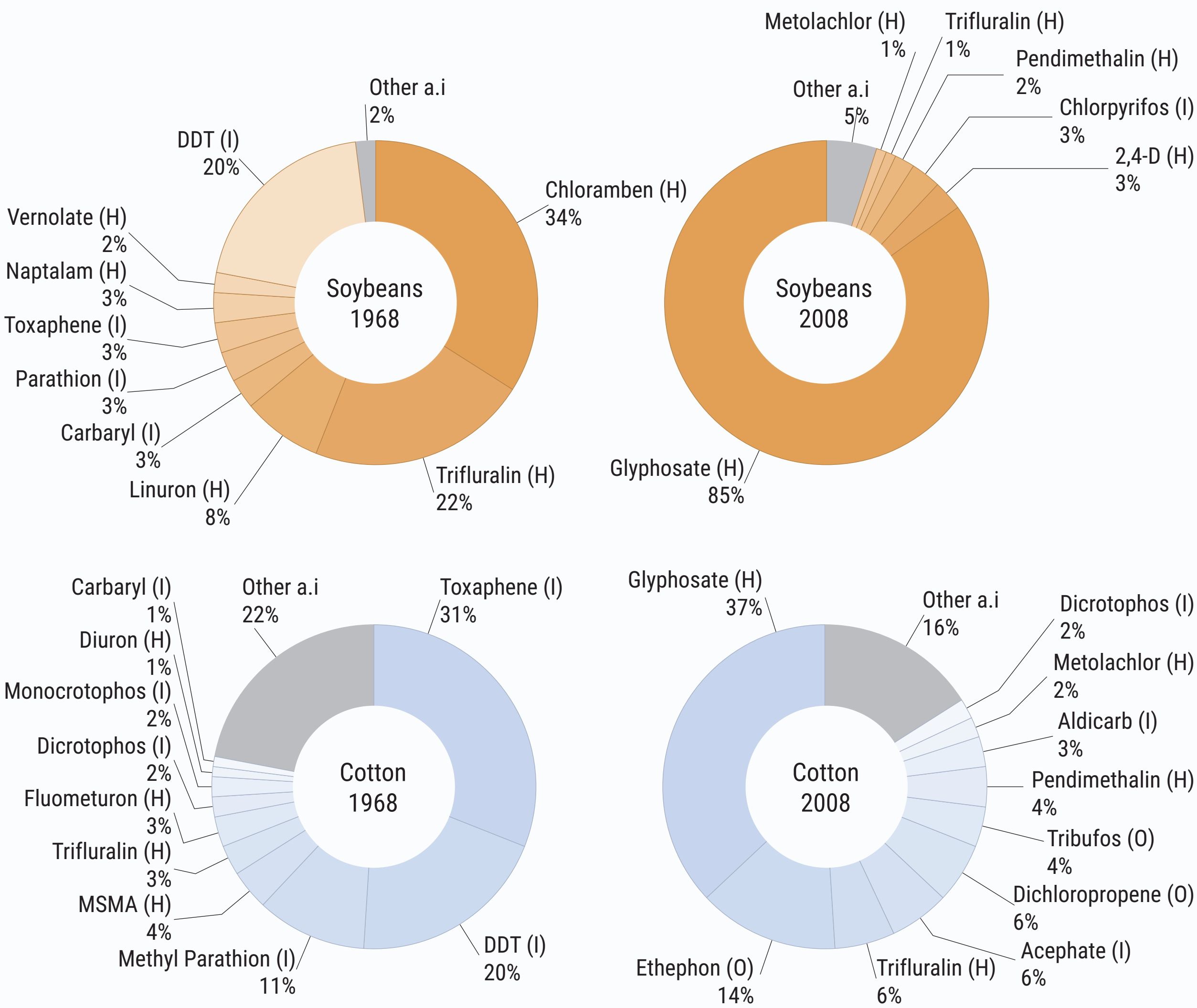
the early 1950s; by 1980 herbicides were used on 90-99 per cent of the area planted with corn, cotton and soybeans (Fernandez-Cornejo *et al.* 2014). This is further supported by another study which shows that between 1993 and 2015 the total applied mass of insecticides has decreased while the total applied mass of herbicides has increased in the United States (Schulz *et al.* 2021). These changing use patterns affect the environmental and human health risks posed by crop protection products (Chapter 4).

The spectrum of pesticide active ingredients used today is also very different from a few decades ago. For example, the dominant pesticides in soybean production in the United States in 1968 were the herbicides chloramben and trifluralin and the insecticide dichlorodiphenyltrichloroethane (DDT), while in 2008 the herbicide glyphosate dominated pesticide inputs (Figure 2.4-12). Similarly, the predominant pesticides used on cotton in 1968 were the insecticides toxaphene, DDT and methyl parathion; 40 years later they were the herbicide glyphosate and the plant growth regulator ethephon. Of the 17 active ingredients listed for 1968 in Figure 2.4-12, the use of eight had been prohibited in the United States by 2008.

Crops

Although pesticides are applied on many different crops, a large share of their use is concentrated

Figure 2.4-12 Change in pesticide use on soybeans and cotton in the United States between 1968 and 2008 (based on total volume of active ingredients applied). Fernandez-Cornejo *et al.* (2014).



a.i. = active ingredient; (H) = herbicide; (I) = insecticide; (O) = other.

on a limited number crop groups (Figure 2.4-13). Cereals are the largest market for pesticides globally, with maize, rice and other cereals representing 38 per cent of sales value. Fruits and vegetables represent one-quarter of the market and soybean another 15 per cent.

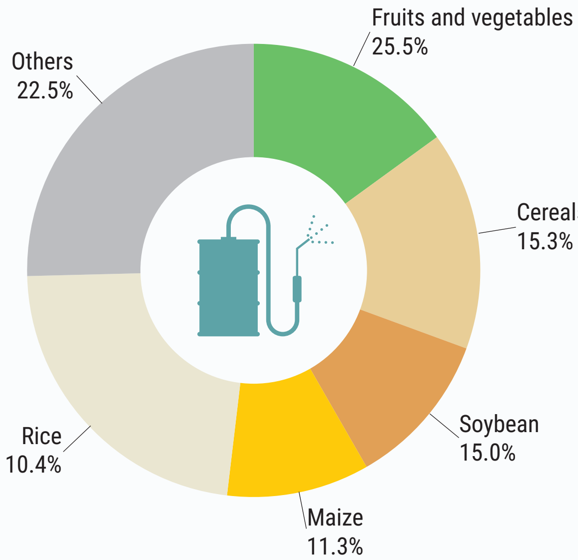
Non-agricultural pesticides

Non-agricultural pesticides include household and garden products, public health pesticides, products for disinfection of aircraft, hospitals and restaurants, and industrial pesticides, among others.

While both the sales and use of agricultural pesticides are relatively well monitored, much less is known about the use of non-agricultural pesticides. Such products tend to be used in or close to human habitations and therefore pose different (and sometimes higher) risks than agricultural pesticides. This is especially the case for domestic and public health pesticides (mainly pesticides used for vector control, in and around households, and by professional pest control operators). Sensitive groups such as children may also be exposed to such pesticides.

Non-agricultural pesticides represent about 12 per cent of the value of the global pesticide market (Figure 2.4-7). A considerable share of these pesticides is applied domestically, although no recent estimates of use volumes are available.

Figure 2.4-13 **Pesticide use on different crop groups in 2018, based on global sales value.** Phillips McDougal (2019a).



The World Health Organization (WHO) monitors the use of pesticides for the control of human disease vectors such as malaria, dengue, zika, leishmaniasis and Chagas disease. The latest review available is for the period 2000-2009 (WHO 2011; Van den Berg *et al*. 2012). On average during this period, 7,100 tons of pesticides were used annually for vector control, the equivalent of about 0.2 per cent of total agricultural pesticide use in those years. Of the total volume of pesticides applied for vector control, most was used in Southeast Asia (Table 2.4-1).

DDT, the only organochlorine pesticide covered in the WHO review, was used in larger quantities than any other insecticide class. It was exclusively applied for indoor residual spraying for malaria control. Of the global use of DDT in the period 2015-2017, 95 per cent was in India alone; the remainder was used in Africa

Table 2.4-1 **Average reported insecticide use for vector control according to method of application and class of insecticide by WHO region (2000–2009), in metric tons of active ingredient per year.** van den Berg *et al*. (2012).

WHO region[a]	Residual spraying				Space spraying		Treatment of nets (PY)[b]	Larviciding[c]	
	OC	OP	C	PY	OP	PY		OP	PY
Africa	805	19	19	24	0	0	12	1	0
Americas	0	97	4	164	276	66	0	82	0
Eastern Mediterranean	0	26	5	15	2	5	1	20	1
Europe	0	2	0	1	0	1	0	1	0
South-East Asia	3,623	483	2	39	15	1	4	49	0
Western Pacific	0	1	0	39	292	27	14	9	0
All	4,429	627	30	282	584	100	31	163	2

Abbreviations: C, carbamates; OC, organochlorines (DDT only); OP, organophosphates; PY, pyrethroids. ***a*** Canada and the United States (Americas region) and Australia and Japan (Western Pacific region) were not targeted, whereas in the European region, only Armenia, Azerbaijan, Georgia, Kyrgyzstan, Tajikistan, Turkey, Turkmenistan, and Uzbekistan were targeted. ***b*** Conventional application of insecticides to treat bed nets or curtains (excluding insecticides used in factory-made LNs). ***c*** The use of insecticides to treat aquatic breeding sites of mosquitoes.

Figure 2.4-14 **Trend in global use of vector control insecticides.** Based on van den Berg *et al.* (2012).

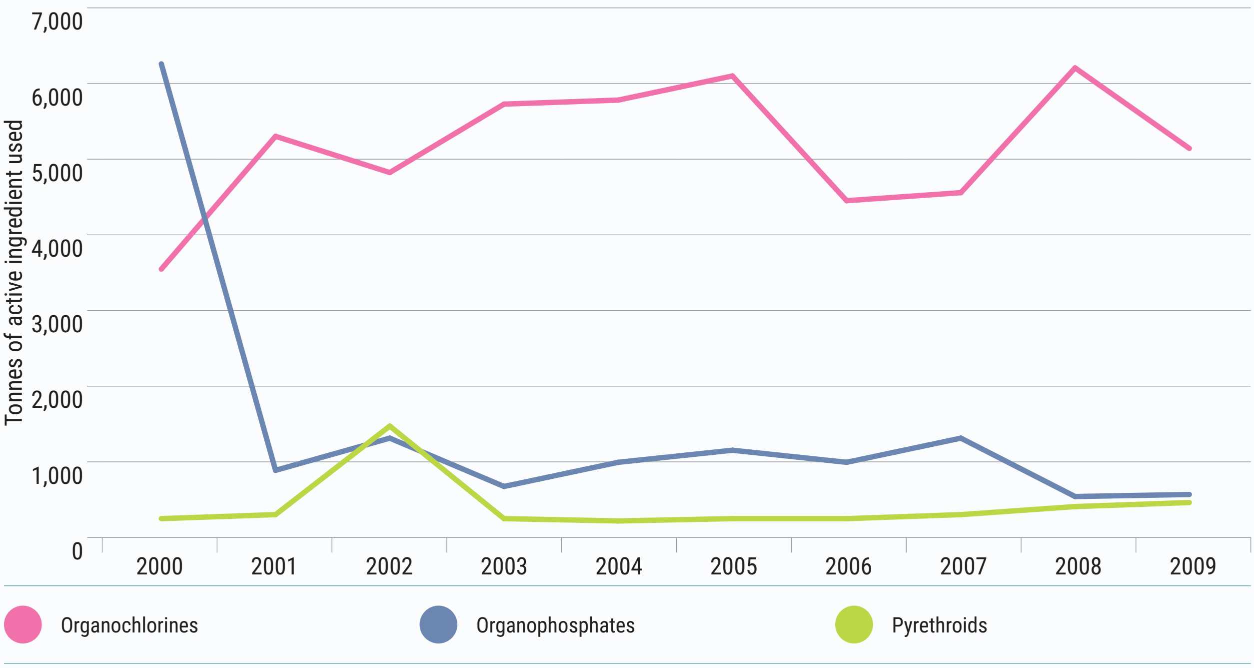
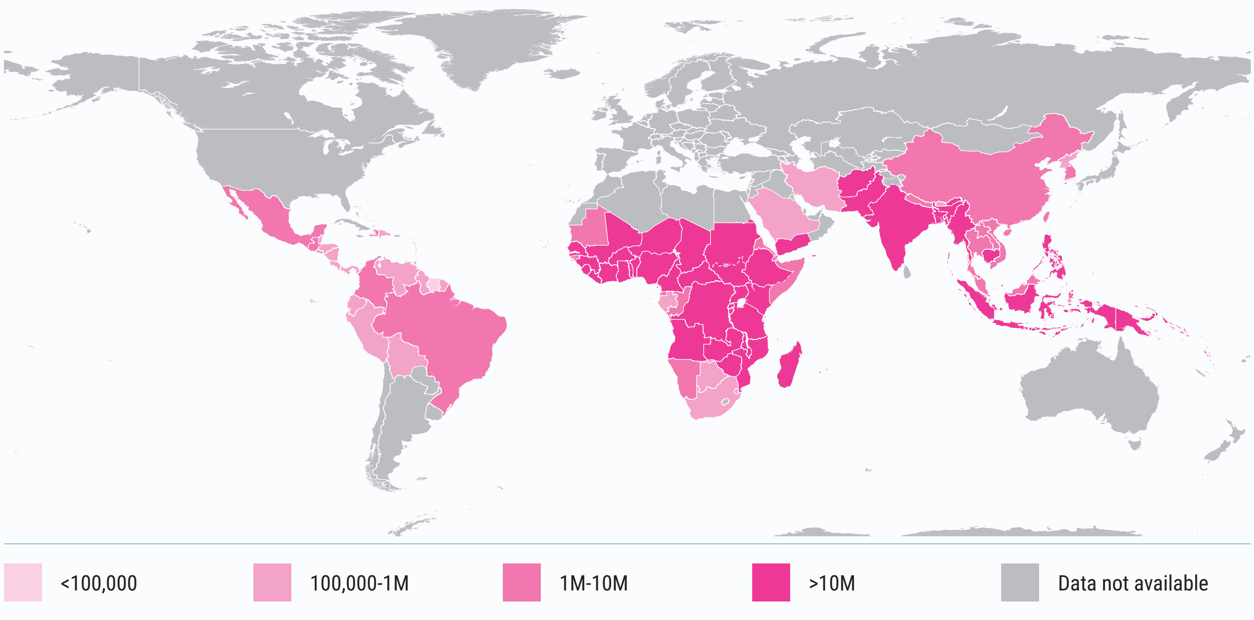


Figure 2.4-15 **Cumulative number of insecticide-treated nets delivered globally from 2004-2019 in sub-Saharan Africa and 2009-2019 in other countries. Almost 2.1 billion insecticide-treated nets were delivered in this period.** Alliance for Malaria Prevention (2020).



(United Nations Environment Programme [UNEP] 2019). Use of DDT, while much lower than in earlier decades, remained fairly stable in the period 2000-2010 (UNEP 2017 and Figure 2.4-14), but declined by about 50 per cent between 2010 and 2017 (UNEP 2019). Use of organophosphates had decreased considerably since the 1990s. Pyrethroids did not constitute a major global share in terms of tons applied. Due to their higher biological activity and much lower effective dosage against mosquito vectors, however, pyrethroids accounted for 81 per cent of the global spray utility in vector control (i.e., the surface area covered by an active ingredient) (WHO 2011; Van den Berg *et al*. 2012).

In addition, pyrethroids are used almost exclusively in insecticide-treated bed nets. The above estimates of vector control insecticides do not include ready-for-use, long-lasting insecticidal nets (LLINs), more than 2 billion of which have been distributed in malaria endemic countries over the last 15 years (Alliance for Malaria Prevention 2020) (Figure 2.4-15).

2.4.4 Bioprotectants

In 2018 global sales of all bioprotectants were estimated at about USD 3.8 billion, almost 7 per cent of the total crop protection product market (DunhamTrimmer 2019). Although they represent only a small share of the total pesticide market, sales of biocontrol products are growing rapidly at 15-20 per cent per year (Glare *et al*. 2012; DunhamTrimmer 2019) (Figure 2.4-16).

Figure 2.4-16 The global biopesticide market is a small but rapidly increasing part of the total market for crop protection products (nominal values: USD million per year). Based on Phillips McDougal (2018a); Agrow (2019); DunhamTrimmer (2019).

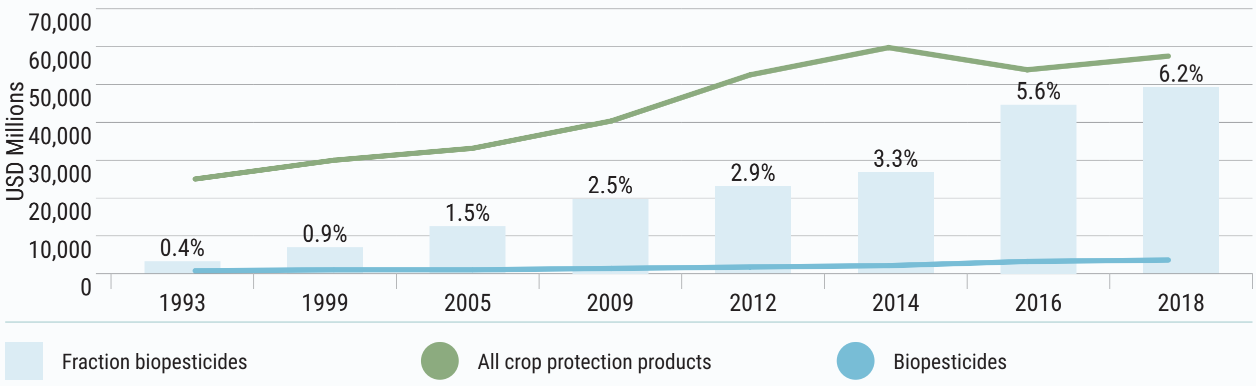
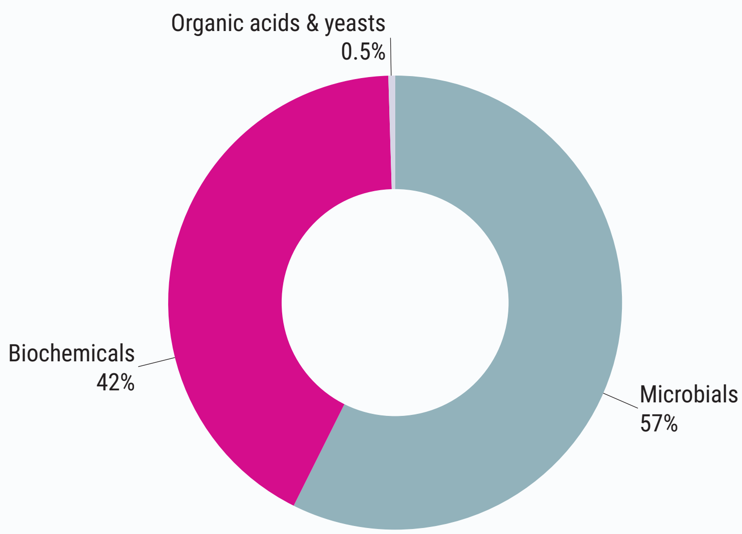


Figure 2.4-17 The biopesticide market is dominated by microorganisms, followed by biochemicals such as pheromones and plant extracts. Sales of organic acids and yeasts are relatively small. DunhamTrimmer (2019).



Biopesticides represent about 93 per cent of the bioprotectant market. The remainder consists of macrobials and non-formulated bioprotectants. Microorganisms account for more than half the biopesticide market; the rest is made up almost entirely of biochemicals (plant extracts and semiochemicals) (Figure 2.4-17). Bioinsecticides and biofungicides dominate the biopesticide market (DunhamTrimmer 2019).

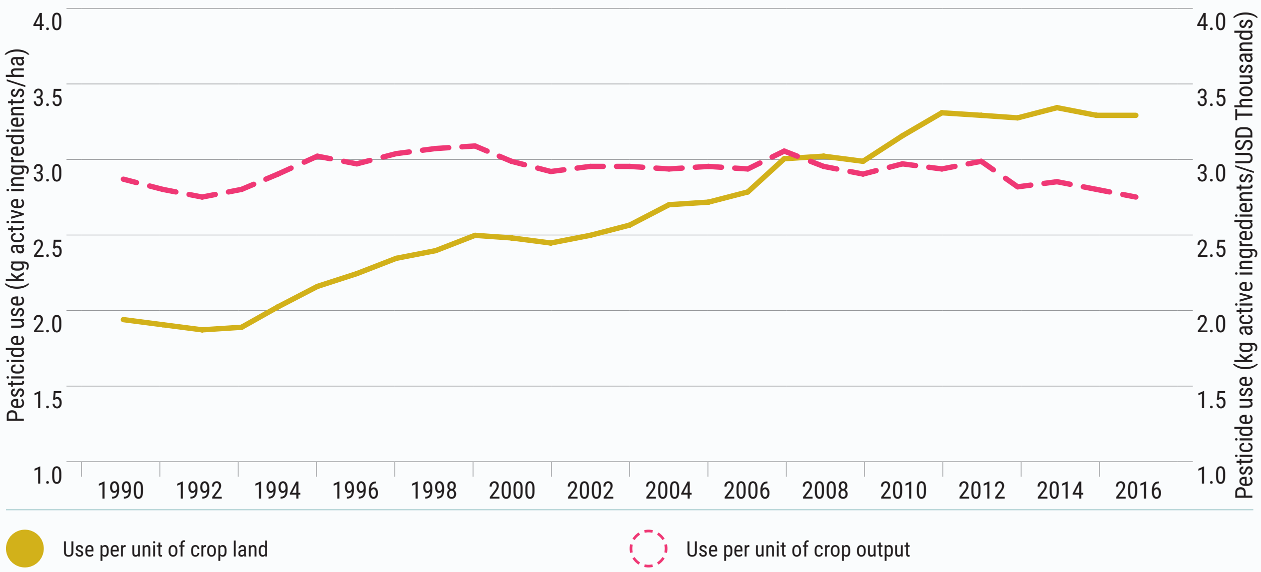
About three-quarters of the total bioprotectant market is accounted for by fruit and vegetable production. In this sector biocontrol (biopesticides and macrobials) represents about 18 per cent of the total crop protection market, considerably higher than the overall share of 7 per cent of the total crop protection product market. North America and Europe account for two-thirds of the biopesticide market, followed by Asia and the Pacific. Latin America is the fastest growing region for biopesticide sales (Agrow 2018).

The United States has long led in biopesticides registration, with over 350 biopesticide active ingredients presently registered. However, other world regions appear to be catching up (e.g., in Brazil only one biopesticide was registered in 2009 compared with almost 80 in 2018) (Agrow 2018). Europe has lagged behind in authorizing new biopesticides, but recently the number of new introductions of biopesticides has surpassed those of conventional chemical pesticides. Between 2011 and 2018 the number of registered biopesticides grew from 123 to 182, an increase of 48 per cent compared to 13 per cent for conventional pesticides in the same period (Robin and Marchand 2018).

2.4.5 Agricultural pesticide use intensity

While global pesticide use has steadily increased in the last 25 years, from an agronomic and environmental point of view it is more relevant to assess trends in pesticide use intensity (e.g., changes in pesticide use per unit area of cropland or per unit of agricultural output). Pesticide use per unit cropland is particularly relevant for environmental and human health risks. Pesticide use per unit crop output, on the other

Figure 2.4-18 Global agricultural pesticide use per unit cropland increased by 75 per cent between 1990 and 2016. FAOSTAT (2019a).



Note: *Continuous line:* overall pesticide use intensity in kg a.i. per ha crop land, for 108 countries for which pesticide use data were updated on a regular basis in FAOSTAT (2019a); countries were omitted from the analysis if pesticide use data had not been updated for any 10 years or more during the 27 year time series. *Hatched line:* overall pesticide use intensity in kg a.i. per 1000 constant International dollars of crop output, for the same countries. Be aware that this graph will be different from the pesticide sustainability indicator shown in FAOSTAT because of the larger number of countries included in the latter.

hand, is a more relevant indicator for agricultural production and intensification.

Figure 2.4-18 shows steady growth in pesticide use intensity. While an average of 1.9 kg active ingredient (a.i.) per ha of cropland was applied globally in the early 1990s, this increased to about 3.3 kg a.i./ha in the mid-2010s, a rise of almost 75 per cent. That global average is based on total area cropland. It disregards the fact that larger quantities of pesticides will be used on certain crops, while little or none will be used on others. This means the global average use intensity shown here underestimates real pesticide use per unit cropland for the crops on which they are actually applied.

Pesticide use per unit crop output has remained stable during the last 25 years, at approximately 2.9 kg a.i. of pesticide applied for every 1,000 International dollars of crop production (Figure 2.4-18). International dollars are often used as a proxy for the volume of crop production, which allows aggregating different crops (FAO 2019a). This indicator shows that the increase in pesticide use per unit cropland, on average, was associated with a similar increase in crop production. However, as indicated in Chapter 2.3, every kilogram of pesticide active ingredient has become more biologically active over time. While pesticide use intensity per unit output remained stable, the active load of pesticides on target pests (and non-target organisms sensitive to the same pesticide mode of action) is continuing to increase.

It is important to note that global average pesticide use per unit output does not represent an evaluation of the costs and benefits of pesticide use (Chapter 5).

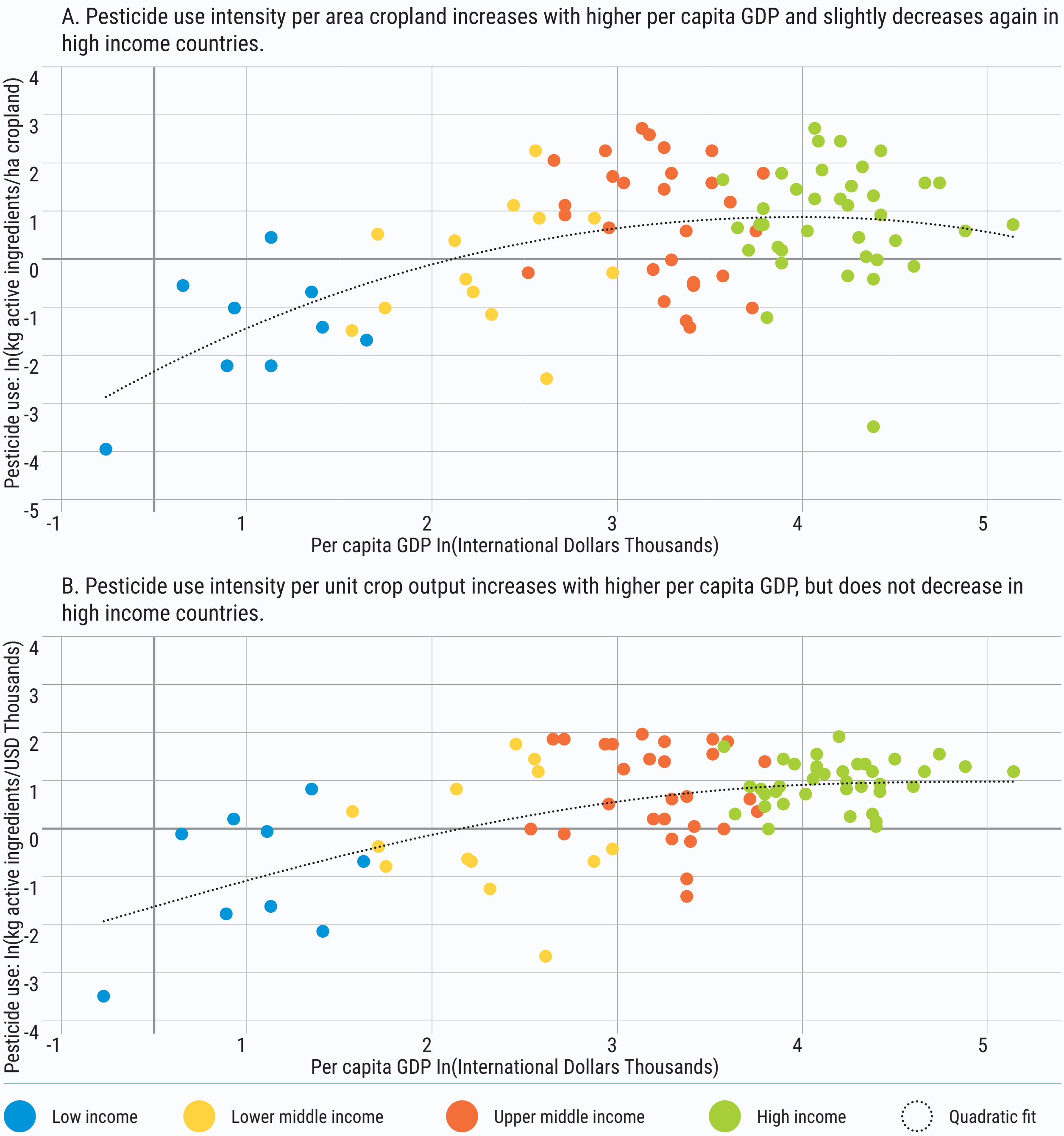
Pesticide use can be very different between countries and regions. Schreinemachers and Tipraqsa (2012) analysed pesticide use data from the mid-1990s to the mid-2000s. They found that pesticide use increased with the income group to which a country belongs (i.e., there was higher pesticide use, both per unit of cropland and per unit of crop output, in countries with higher income levels). Only at the highest per capita GDP did pesticide use intensity appear to level off.

Based on a similar approach, pesticide use intensity was assessed for the most recent period on which data were available in FAOSTAT (2019a). Pesticide use per ha cropland increased with a country's per capita GDP and then showed a slightly decreasing trend for high income countries (Figure 2.4-19a). This may be explained by the fact that in certain high income countries, especially in Europe, there have recently been significant reductions in pesticide sales (Eurostat 2018), partly as a result of specific policies to reduce reliance on pesticides in agriculture (Chapter 3.4). Another explanation for apparent reductions in use intensity in high income countries is that they may be introducing new active ingredients, with lower application rates, more rapidly than lower income countries.

Similarly, pesticide use per unit crop output increases with per capita GDP and levels off in high income countries, but does not show a clear reduction (Figure 2.4-19b). More pesticides are thus applied per unit of crop production in richer than in poorer countries. It has been suggested that pesticide use intensity will decrease in high income countries, where pest management is most effective and environmental and health measures limit the use of pest control products. Somewhat surprisingly, this does not appear to be the case, nor does the situation seem to have changed since the assessment by Schreinemachers and Tipraqsa (2012).

It is not entirely clear why higher income countries should apply more pesticides per unit crop output than lower income ones. This might partly be explained by relatively higher commodity prices, which are known to stimulate pesticide use (Chapter 2.7.10). Agricultural production in high income countries may also be more intense (e.g., larger areas of monocropping, limited genetic variety in crops), which can increase pest pressure and subsequent pesticide use. A longer history of relatively high levels of pesticide use may also increase pest resistance and resurgence, leading to increased use of pesticides (Chapter 4.4.3). However, this analysis seems to suggest that, contrary to expectation, the effectiveness of pesticide use in increasing or maintaining crop outputs in higher income countries is lower than in lower income countries.

Figure 2.4.19 Pesticide use intensity correlates positively with the level of a country's economic development. FAOSTAT (2019a).



Pesticide use, areas of cropland and crop output are annual average values for the period 2014-2016 in FAOSTAT (FAO 2019a); pesticide use intensity per surface area is expressed as kg a.i./ha cropland; pesticide use intensity per unit crop output is expressed as kg a.i./1,000 international dollars of crop output; per capita GDP (in current International dollars) is for 2015 (World Bank 2020b).

This assessment is global and will very likely be different in specific cropping systems. Trends in pesticide use intensity and pesticides' associated effectiveness in specific crops or regions merit further research.

2.5 Pesticide distribution mechanisms

2.5.1 Organization of the pesticide industry

The pesticide industry has traditionally been divided into two main groups of companies, those developing and marketing new pesticide active ingredients (research and development [R&D] companies) and those marketing generic off-patent or post-patent pesticides ("generics companies"). R&D companies invest a considerable part of their profits in discovering and developing new molecules and products; generics companies may develop new products, but on the basis of off-patent active ingredients.

Currently that dichotomy is no longer as strict as in the past. R&D companies attempt to maintain off-patent pesticides as proprietary products by developing new innovative formulations or introducing new uses. The combination of pesticides, seeds and biotech crops in the same company, which has been a trend during the last 10-15 years, has opened up new market possibilities for R&D companies. More recently, small biocontrol companies are being acquired by the larger agrochemical firms. Furthermore, some of the main R&D companies have acquired producers of generics with the aim of servicing a broader market.

At the same time, generics companies are investing in developing new formulations and some have entered the field of identification and development of new or modified active ingredients.

The broader plant science industry (including pesticides, biotechnology, seeds and biocontrol) has been much in flux over the last decade. Several important and many more smaller mergers and acquisitions have taken place. For instance, Bayer CropScience acquired Monsanto; United Phosphorus Ltd (UPL) acquired what used to be Arysta LifeScience; ChemChina acquired both Syngenta and ADAMA (and will be merging its agricultural assets with Sinochem); and Dow AgroSciences merged with DuPont to become Corteva Agriscience. (See Phillips McDougal 2019b for a graphical representation of key agrochemical mergers and acquisitions.)

This activity has led to a concentration of pesticide manufacturing and marketing. Today the global pesticide market is dominated by four major conglomerates or companies: ChemChina (with subsidiaries Syngenta and ADAMA), Bayer Crop Science, BASF and Corteva Agriscience, which together represent about 60 per cent of the agricultural pesticide market (Table 2.5-1).

Table 2.5-1 Top 10 pesticide companies and their share of the total agricultural pesticide market in 2018. Yuan (2019).

Company	Agricultural pesticide sales in 2018	Share of total agricultural pesticide market in 2018
Syngenta	9,909	17%
Bayer CropScience	9,641	17%
BASF	6,916	12%
Corteva AgriScience	6,445	11%
FMC	4,285	7.3%
ADAMA	3,617	6.3%
UPL	2,741	4.7%
Sumitomo Chemical	2,538	4.3%
Nufarm	2,332	4.0%
Huapont Life Sciences	935	1.7%

Figure 2.5-1 The pesticide industry collaborates in three major international associations representing R&D companies, producers of generic pesticides and biopesticide companies

Research-based pesticide companies

CropLife International

6 members + **8 regional associations**

6 members:
- BASF
- Bayer
- Corteva Agriscience
- FMC
- Sumitomo Chemical
- Syngenta

8 regional associations:
- CropLife Brazil
- CropLife America
- CropLife Asia
- CropLife Africa Middle East
- CropLife Canada
- CropLife Europe
- CropLife Latin America
- Japan Crop Protection Association

(+ several regional biotech associations)

▼ National associations in 91 countries

▼ Proprietary & proprietary off-patent pesticides
Chemical & biopesticides
(also covered: seeds, biotech)

Generic pesticide companies

AgroCare

4 regional associations
- AgroCare Latinoamérica
- European Crop Care Association
- China Crop Protection Industry Association
- Pesticides Manufacturers & Formulators Association of India

▼ Approximately 865 companies

▼ Off-patent – mainly chemical – pesticides

Biopesticide companies

BioProtection Global

9 regional associations
- Brazilian Association of Biological Control Companies
- Association of Natural Biocontrol Producers
- Asociación Colombiana de Bioinsumos
- Biological Products Industry Alliance
- Cámara Argentina de Bioinsumos
- International Biocontrol Manufacturers Association
- Japan BioControl Association
- Pesticides Manufacturers & Formulators Association of India
- South African Bioproduct Organisation

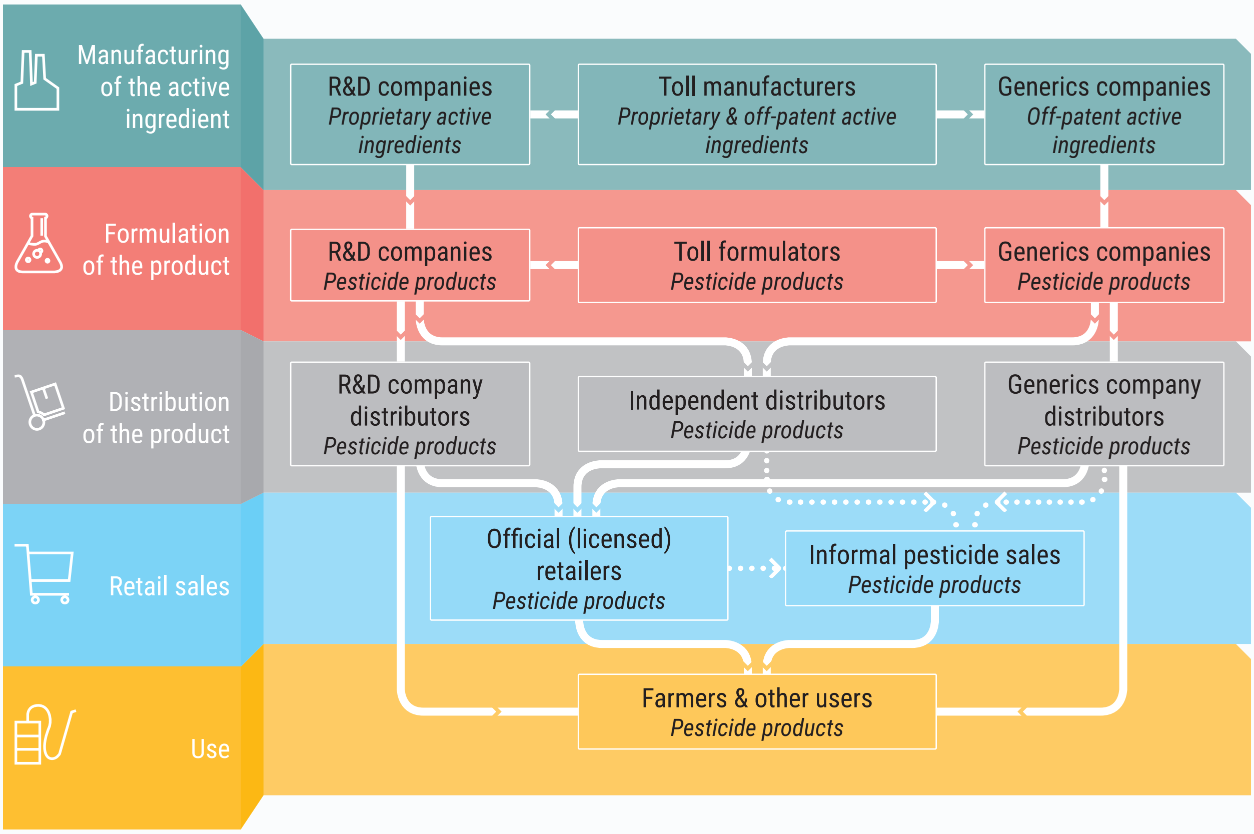
▼ Biopesticides
(also covered: macrobials, biostimulants, etc.)

In addition, the integration of pesticide, seed and biotech activities in the same companies has allowed the plant science industry to better develop and control combined agricultural inputs. This includes seeds and seed coatings, seeds and genetically modified (GM) traits, and GM traits and pesticides.

Proponents of mergers have argued that companies need to operate on a larger scale in order to invest in and support research, and that these mergers – by creating more balanced portfolios of seed and chemical businesses – would incite greater combined seed and chemical innovations. Opponents have pointed out that, with less competition, it is in the interests of combined firms to raise product prices. The resulting companies may also be less likely to invest in research and innovation once the degree of competition is less (MacDonald 2019). An important risk associated with mergers is further loss of crop diversity (an already ongoing process) and the associated increased susceptibility of crops to insect pests and diseases (FAO 2019b).

At global and regional levels, pesticide companies are collaborating in a number of industry associations (Figure 2.5-1). The mainly R&D companies collaborate in CropLife International, which consists of a number of regional associations and six major companies. A large number of generic pesticide companies are united under AgroCare, which is currently made up of four regional associations. Companies active in biological pest control are represented by BioProtection Global, which covers many types of bioprotectants including natural pest enemies and biopesticides.

▶ **Figure 2.5-2** Simplified pesticides supply chain, where pesticide products may originate from different sources.



2.5.2 Pesticide supply chains

A variety of pesticide supply chains exist. These supply chains often operate in parallel in a given country or region (Figure 2.5-2).

Pesticide technical materials (active ingredients) will be manufactured by R&D companies themselves, especially in the case of proprietary active ingredients still under patent. In some cases such materials are produced under contract by independent toll manufacturers, which are frequently specialized in particular chemistries. Off-patent technical materials can be manufactured by generic companies, R&D companies or toll manufacturers.

Commercial pesticide products are formulated by plants directly under the control of R&D or generic companies, or by specialized toll formulators. While technical materials for a given pesticide tend to be produced at a limited number of manufacturing locations, formulation plants may be more decentralized in specific parts of the world. In some countries relatively small formulators may also produce for the local market.

Pesticide distribution companies (national or international) ensure the importation and distribution of commercial pesticide products in a country or region. Some of these companies may be under the management of the pesticide manufacturers, but most are independent, distributing pesticide products under licence from one or more manufacturers or formulators. Distributors may sell pesticide products directly to (larger) pesticide users or governmental and non-governmental organizations, as well as supplying pesticide retailers.

Pesticides are sold to users by a variety of retail outlets, ranging from shops or dealers specialized in agricultural inputs, to supermarkets, household, garden and do-it-yourself retailers, general retail outlets, markets or travelling pesticide sellers. In many countries retail outlets need to be licensed to sell pesticides, while pesticide sales in supermarkets and other more general retailers tend to be limited to low-risk household and garden products. However, this is not always the case and more hazardous pesticides may be sold in general retail outlets. Recently, direct sales from manufacturers to local dealers or to end users appear to have become increasingly common in an attempt to better control the supply chain.

In some (mainly high income) countries restricted use pesticides (i.e., those which pose high risks) are sold only to professional pest control operators licensed to apply them. These operators generally carry liability protection for possible crop damage or other adverse effects. Such liability procedures are much less common in many low and middle income countries where, if they exist, they are rarely used effectively.

Pesticide sales in markets or by street sellers and travelling pesticide sellers are common, especially in low and lower-middle income countries, often constituting an informal, unregulated supply chain by means of which pesticides may be illegally repackaged into small quantities, not properly labelled, and with the quality unclear. Nevertheless, the informal supply chain is frequently a very important source of pesticides for farmers as well as for households in urban areas. This is because specialized retailers may not be present, especially in rural areas.

Sales of biopesticides can follow the above model, especially if products are relatively broad spectrum and can be stored easily. However, given the target specificity of many biopesticides, as well as specific storage requirements, they are often sold directly by the manufacturer or distributor to end users, which tend to be larger agricultural producers.

2.5.3 Illegal pesticides

The growth of global pesticide markets (Chapter 2.4) has been accompanied by an important increase in the trade of illegal or illicit pesticides. While illegal pesticides were hardly an issue in the late 1990s, they now form a significant fraction of pest control products sold (Food Chain Evaluation Consortium [FCEC] 2015).

Illegal pesticides can take many forms: they may never have been authorized for use in a given country; their legal use may have been cancelled or banned; they may be legal for use on one crop but not on another; or they may be counterfeit, fake, or illegitimately or illegally relabelled or (re) packaged (Box 2.5-1).

These illegal pesticides can damage crops, contaminate water and soil, and harm human health. They may erode public confidence in and perceptions of food safety, as well as confidence

Box 2.5-1 Illegal pesticides can take different forms. OECD (2019), UNICRI (2016).

Illegal pesticide	Any pesticide which, for whatever reason, is not legal in the country of destination. This includes the sub categories of counterfeits, fakes, obsolete and unauthorised pesticides.
Unauthorised pesticide	A pesticide that is not authorised for use by the regulatory authorities in the country in which it is being placed on the market.
Counterfeit pesticide	An illegal copy of a legitimate, branded pesticide which may be difficult to distinguish from the legal product due to the high quality branding and packaging.
Fake pesticide	An illegal copy of a legitimate, branded pesticide which may make some effort to imitate the original product but which can be identified with relative ease due to the poor quality of the product and packaging
Illegally (re-)packaged pesticide	A pesticide sold in an illegally (re-)filled pesticide container or a non-approved type of packaging, such as food or beverage containers.

Table 2.5-2 Recent reports on the scale of the trade in illegal pesticides.

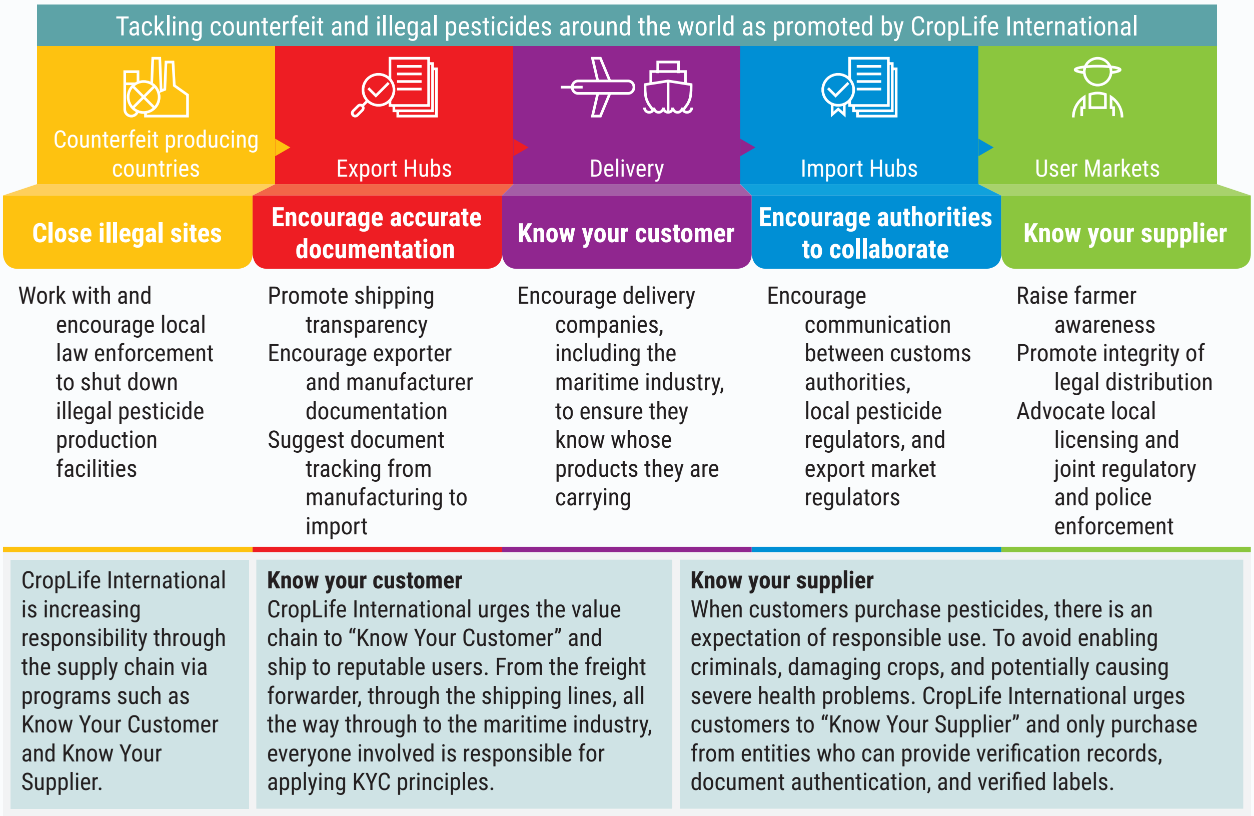
Region / country	Findings	Source
Global	Estimates of global trade in illegal and counterfeit pesticides range from 5 to 15 per cent of the total pesticide market.	UNICRI (2016)
Brazil	In 2015/2016 illegal pesticides represented about 24 per cent of the total crop protection product market.	Instituto de Desenvolvimento Econômico e Social de Fronteiras (IDESF) (2019)
Mali	45 per cent of glyphosate products from national retailers sampled were unregistered or counterfeit.	Haggblade *et al*. (2019)
Africa	Most national pesticide industry associations reported that counterfeit or illegal pesticides represented about 15-20 per cent of total markets.	Guyer and Davreux (2012)
EU	Illegal plant protection products (PPP) represented approximately 10 per cent of the EU's PPP market in 2014, compared with about 7.5 per cent in 2008.	FCEC (2015)
EU	It is estimated that the legitimate industry loses approximately EUR 1.3 billion in revenue annually due to the presence of counterfeit pesticides in the EU marketplace, corresponding to 13.8 per cent of sales in this sector.	European Union Intellectual Property Office (EUIPO) (2017)
	If knock-on effects on other industries and on government revenue are added (and both direct and indirect effects are considered), counterfeiting in this sector causes approximately EUR 2.8 billion in lost sales to the EU economy, leading in turn to the loss of about 11,700 jobs and of EUR 238 million in government revenues.	
India	Non-genuine and illegal pesticides represented approximately 25 per cent by value and 30 per cent by volume of domestic pesticide industry in 2013.	Federation of Indian Chambers of Commerce and Industry (FICCI) (2015)
	Non-genuine and illegal pesticides included products not registered in India, pesticides with low/incorrect active ingredients, products containing substances banned in India, counterfeits, and products laced with chemicals allegedly sold as biopesticides.	
Ukraine	Share of illegal pesticides represents 19 to 25 per cent of the national pesticides market	UNEP and GRID-Arendal (2020)

in reputable agricultural producers and producing countries. They may also cause reputational damage to established pesticide manufacturers and distributors or undermine the authority of national regulators. (UNICRI 2016; United Nations Environment Programme [UNEP] and GRID-Arendal 2020; European Crop Protection Association n.d.).

Owing to its nature, the importance of the trade in illegal pesticides is difficult to quantify (UNEP and GRID-Arendal 2020). Various recent estimates indicate that, depending on the region or country, illegal pesticides represent between 10 and 25 per cent of national pesticide markets, with even higher estimates for selected countries (Table 2.5-2). Based on the global UNICRI estimate of 10-15 per cent illegal pesticides, and a total market for legal pesticides of USD 65 billion in 2018 (Chapter 2.4.3), the value of trade in illegal pesticides would amount to USD 7-11 billion annually.

National enforcement authorities are increasingly clamping down on trade in illegal pesticides. Recent examples are the Silver Axe operations which seized over 550 tons of illegal pesticides throughout Europe in 2019 (European Union Agency for Law Enforcement Cooperation [Europol] 2019); anti-counterfeiting operations in Indonesia (Tribun Jateng 2020);

Figure 2.5-3 **Countering the illegal trade in pesticides should address all stages of the pesticide distribution chain to be effective.** CropLife International (CLI) (n.d.).



and the confiscation of illegal pesticides worth USD 1.5 million in Brazil in December 2019 (Betancur 2020). Competent authorities' level of awareness of illegal trade in pesticides, together with the resources made available for addressing it, appear to be key factors determining the success of initiatives in this area (FCEC 2015).

The legitimate pesticide industry has been very active in creating awareness of illegal trade in pesticides, with activities along the entire pesticide distribution chain. These activities include training programmes for enforcement agencies, "know your customer" approaches for pesticide manufacturers and distributors, and "know your supplier" programmes for pesticide users (Figure 2.5-3). A study recently commissioned by CropLife International (CLI) resulted in concrete recommendations for improved supply chain traceability of agrochemicals (Accenture 2019).

UNEP and GRID-Arendal (2020) have recommended – at national and regional level – improving the monitoring and understanding of the pesticide supply chain (e.g., national reporting of chemical movements from source to end use and disposal); more cross-border cooperation among national authorities regulating and controlling the trade in pesticides; and the development of joint regional action plans to fight illegal trade in chemicals and waste. At the global level they urge stronger coordination among United Nations agencies and others involved in preventing illegal trade in chemicals.

At the international level, the Organisation for Economic Co-operation and Development (OECD) has established the Network on Illegal Trade of Pesticides (ONIP), in which governments and the private sector collaborate, and a Rapid Alert System (RAS) for suspected illegal international trade in pesticides. In 2019 the OECD Council issued a Recommendation on Countering the Illegal Trade of Pesticides, accompanied by a best practice guidance document (OECD 2019).

2.6 Pesticide application technology

2.6.1 Application techniques

Application equipment and methods affect both environmental and human exposure to a pesticide. Using the right equipment in the right way goes a long way towards minimizing exposure and the associated risks. On the other hand, using equipment which is of bad quality, faulty or inappropriate – or applying pesticides under improper environmental conditions – tend to greatly increase exposure and therefore environmental and human health risks.

Most pesticides are applied in the form of sprays, using equipment such as boom sprayers, orchard sprayers, foggers, spray aircraft, backpack sprayers, and other manually carried sprayers. In solid form pesticides may be applied as granular formulations (e.g., to the soil), baits (e.g., for rodent control) or dusts. Fumigation is carried out using pesticides in gaseous form. For seed treatments, crop seeds are coated with a pesticide before planting to create a protective zone of active ingredient in the soil against soil-borne pathogens and insects, while systemic seed treatments also provide additional protection against early-season foliar diseases and insects (Nuyttens *et al*. 2013).

In many instances the plant foliage is the intended target for sprayed herbicides, fungicides and insecticides. Sometimes the soil is targeted (e.g., for pre-emergence herbicides) or insects may be targeted directly (e.g., for locust swarm control). During spray applications only a fraction of the applied pesticide reaches the intended target, generally the leaf canopy. As most pesticides are applied using hydraulic nozzles that produce a spray containing droplets that vary in size, the smallest droplets can be carried by air currents/wind and drift outside the target area while the largest may be deposited on the soil. Additional losses occur when pesticides deposited on the target are washed off by rain or volatize (if the pesticide is relatively volatile).

In the case of pesticides intentionally applied to soil, a large fraction may run off during rainstorms or drain into the soil. When treated seeds are drilled into the soil, the pesticide can be abraded and lost as dust drift (Nuyttens *et al*. 2013; Jensen and Olesen 2014). Recently seed coatings have been improved and drilling equipment adapted to reduce the risk of dust drift. The share of the applied dose that does not reach the intended target is a loss to the farmer and a potential source of environmental pollution.

Pesticide losses during and after application are extremely variable, depending on crop cover, application method, type of nozzle, pesticide formulation and environmental conditions. Jensen and Olesen (2014) reviewed pesticide spray mass balances for vehicle-mounted sprayers. They found that on average 66 per cent of the applied pesticide reached the foliage when applied by boom sprayers, 46 per cent when applied by orchard sprayers and 55 per cent when applied by tunnel sprayers, all crops and growth stages combined. The rest of the sprayed product was deposited on soil, drifted outside plots or was not accounted for.

2.6.2 Reducing environmental and occupational exposure

Continuous progress is being made in the development of more precise pesticide application technology and engineering controls to reduce environmental and occupational exposure. However, when compared with the development of new pesticide products, application technology has received relatively little attention from the private sector or from governments (International Pesticide Application Research Consortium [IPARC] 2020; Matthews 2020).

Occupational exposure has been minimized though technologies such as enclosed and ventilated tractor cabins, low-level induction bowls to facilitate placing the pesticide product in the tank, triple-rinse pesticide containers, closed pesticide transfer systems, and modular-mix-on-demand (MMOD) systems whereby the pesticide is mixed on demand from concentrate to avoid pre-mixing or disposal of unused chemicals (Matthews, Bateman and Miller 2014).

Environmental exposure, especially through pesticide drift, has been reduced by using specific application technologies. Air induction nozzles have been introduced to minimize the proportion of small droplets to reduce drift, while rotary atomizers provide more uniform droplet size. Other technologies that have been introduced include spray boom shields or shrouds, self-levelling spray booms to maintain the right distance above the crop canopy and minimize drift, and orchard sprayers using sensor systems to detect gaps in the tree canopy and reduce spray delivery when there is no crop to intercept it (Matthews, Bateman and Miller 2014; IPARC 2020).

A reduction in environmental exposure to applied pesticides can also be realized through mitigation measures not directly related to the equipment. In many countries buffer zones are required in order to minimize drift to surface waters, neighbouring fields or human dwellings. They can be strips of unsprayed crops adjacent to field boundaries or vegetated areas which partly intercept spray drift (Matthews, Bateman and Miller 2014). Buffer zones tend not to be very popular with farmers, particularly when relatively wide zones are involved, as cropland is lost and such zones are a potential source of pests, diseases and weeds. Buffer zones are virtually impossible to implement in regions with many small adjacent crop fields, for example paddy rice or horticultural systems, where they would take up an unrealistically large fraction of individual fields.

2.6.3 Improving the precision of pesticide applications

Since much pesticide is lost during application, increasing the precision and efficacy of pesticide application equipment and techniques has received particular attention.

Global positioning system (GPS) equipment has been used in spray aircraft for some time. More recently, it has been built into tractors. Combining GPS with in-cab controls (e.g., to adapt flow rates) and a geographic information system (GIS) that contains cartographic information about a crop or pest provides detailed information to the driver and enables individual applications to be recorded (Matthews, Bateman and Miller 2014). On-off switching sprayers and canopy-optimized distribution sprayers, using 3D sensing systems able to detect the shape and volume of the sprayed canopy, allow more precise application and minimize losses and drift (Tona, Calcante and Oberti 2018).

Unmanned aerial vehicles (UAVs), also known as drones or remotely piloted aircraft (RPA), are increasingly used in some parts of the world (e.g., Brazil, China, Japan and North America). Originally, UAVs were primarily employed to monitor the presence of weeds, pests and diseases in crops through a variety of sensors. More recently, drone-based systems have also been developed for aerial pesticide applications (Iost Filho *et al*. 2020).

UAVs are useful, in particular, for spraying relatively small fields or complex terrains that are not easily accessible by personnel or large machinery. They are also replacing back-pack spraying in some countries (He 2018; Carvalho *et al*. 2020). Spraying with UAVs has the advantage that the airflow which keeps the drone airborne can blow the spray into the crop canopy. Furthermore, UAVs operate at a much slower speed than traditional spray aircraft, so that they can be used closer to the crop, reducing the risk of drift, especially when rotary nozzles are used (Matthews, G.A., personal communication).

Further studies are needed to provide data on droplet deposition, spray coverage and drift when spraying with UAVs. The next step for agricultural UAVs is to use them in an integrated system for pest control comprising complementary components: one for remote sensing, detection and mapping of weed, pest or disease infestations and another with precision spraying capability (Hunter *et al*. 2020).

2.6.4 Pesticide formulation

Pesticide active ingredients are generally not applied in their pure form, but are formulated into a commercial product. The main objective of formulation is to ensure that the active ingredient remains stable and effective from manufacture through application to its final target (Bullock 2020a). This includes the following aspects:

- product stability during manufacture, packaging, storage and application, as well as after it has been applied;
- compatibility with the application equipment and process, as well as with other products and diluents;
- effective delivery to the target, e.g., by reducing volatilization, improving wetting and adhesion, aiding penetration and uptake of the active ingredient, and improving rain fastness.

In addition, formulation technology can reduce (and sometimes even eliminate) exposure of the pesticide user and bystanders and reduce exposure of non-target organisms and the environment, e.g., by reducing spray drift (Bullock 2020a).

In the past, most formulations were based on simple solutions in water (SL), emulsifiable concentrates (EC) in petroleum-based solvents, or dusts (DP) and wettable powders (WP). The presence of solvents in EC formulations, and fine dusts in DP and WP formulations, may cause occupational health risks during use and adverse effects on the environment (Knowles 2008). Therefore, newer formulations have been developed which are safer for the user, have less impact on the environment, and can be applied at minimum effective dose rates.

Examples of more recent formulation types which generally present lower environmental or health risks are (Knowles 2008; Bullock 2020a):

- water dispersible granules (or dry flowables) – as a replacement for WP – because they are non-dusty, free-flowing granules which disperse quickly when added to water in the spray tank;
- water-soluble packs or sachets which can be added directly to a spray tank, thus minimizing exposure of the user and pack disposal problems;
- microencapsulated controlled release formulations, which may reduce mammalian and fish toxicity, lower application rates, and reduce leaching to groundwater and surface water;
- oil-in-water emulsions – as a replacement for EC – as a way to reduce or eliminate volatile organic solvents and reduce handling risks.

Use of nanopesticides is a novel approach to formulation which has been the topic of recent research and patent activity. Nanopesticides are generally classified into two types (Kookana *et al*. 2014; Li *et al*. 2019):

- very small particles of a (generally inorganic) pesticide active ingredient, such as nanometals (e.g., silver, copper) or nanoclays, which are biologically active against a disease or pest;
- engineered (often organic) nanocarrier particles (e.g., polymers, solid lipids) which contain a pesticide active ingredient – the nanocarrier may be designed, for instance, to protect the active ingredient or enhance its delivery to the pest or disease.

Nanopesticides are an emerging technology that potentially offers a range of benefits, including increased efficacy and/or a reduced amount of the active ingredient to be applied (e.g., through improved solubility/dispersibility, controlled release, targeted delivery, enhanced bioavailability, increased leaf adhesion, or improved stability in the environment) (Kah *et al*. 2018). A reduction in the amount of pesticide active ingredient applied may reduce environmental and human health risks.

Since nanopesticides will have both benefits and risks for pest management, the environment and human health, careful and comprehensive assessments of these products need to be made before they are marketed (Kah 2015; Li *et al*. 2019). Important data gaps continue to exist with regard to the interactions and behaviours of nanomaterials in the human body, methods to determine such interactions and behaviours, and the relevance of these types of data for risk assessment (FAO and WHO 2013). If nanopesticides become "emerging contaminants" rather than "emerging solutions", potential useful tools for pest control may be lost (Kah 2015).

While newer formulations have increasingly come on the market, they have by no means replaced the more conventional formulation types such as EC, WP or granular (GR), which, in 2016-2018, represented two-thirds of the total number of products on the market and more than 50 per cent of total market value (Bullock 2020b). So far, commercial adoption of recent innovations in pesticide formulation has been relatively modest. Nevertheless, because the market is expected to continue its drive towards safer, environmentally acceptable and economically efficient solutions, the demand for novel formulations can be expected to grow (Bullock 2020a; Bullock 2020b).

2.6.5 Regional differences in pesticide application innovations

While improvements in pesticide application and formulation technology over the last few decades have led to more effective and safer pesticide application, innovations have not been evenly applied across the world.

There is a striking difference in the availability and use of modern pesticide application technology between countries with large-scale industrialized agriculture and those where small-scale subsistence farming predominates. In the former, tractor-mounted sprayers and aircraft tend to be used, often with modern technology. In most low and lower-middle income countries, knapsack sprayers and other types of relatively simple hand-carried pesticide application equipment prevail, for which many of the innovations discussed above do not apply (Matthews, Bateman and Miller 2014; Horne 2019).

Hand-held sprayers have a relatively high risk of operator exposure to pesticides when the sprayer is filled and when the pesticide is applied (Matthews 2020). Since engineering controls to reduce exposure have primarily been developed for modern tractor-mounted sprayers, users of knapsack sprayers are particularly dependent on the use of appropriate personal protective equipment (PPE) to reduce the risk of exposure. However, such PPE is often not accessible for smallholder farmers (Chapter 4.4.5). In addition, training in the correct use of hand-held sprayers is of great importance even if the equipment is relatively simple.

The Food and Agriculture Organization of the United Nations (FAO) has published guidelines on procedures for the registration, certification and testing of new pesticide application equipment (FAO 2020a), and the International Organization for Standardization (ISO) has published standards for testing and equipment (Matthews, Bateman and Miller 2014). However, quality control and certification of pesticide application equipment is legally required and/or systematically conducted in only a few countries.

Innovations in pesticide formulation have mainly been marketed in high and upper-middle income countries, where more expensive specialized formulations are being used. Conventional formulation types, often posing higher occupational risks, dominate the markets in low and lower-middle income countries, probably since many of them are cheaper generic products (Bullock 2020a).

2.7 Drivers of pesticide use

Global pesticide use, and pesticide use intensity, have increased considerably during the last decades (Chapter 2.4). Many drivers influence the use of pesticides in agriculture, as well as public health and domestic uses. Some drivers tend to increase the use of pesticides while others may lower it (Box 2.7-1). To identify future policies to reduce the risks of pesticides, knowledge of the main drivers influencing pesticide use is essential. Therefore, this chapter discusses important current drivers of pesticide use and how they can

Box 2.7-1 **Key current drivers of pesticide use. The predominant ways in which these drivers tend to influence pesticide use are presented. However, it is recognized that such influences may be more subtle, as is discussed in the referenced chapters.**

Driver	Tends to increase use	Tends to lower use	Chapter
Agronomic			
Agricultural production growth	All pesticides		2.7.1
Crop losses	All pesticides		2.7.2
Agricultural intensification	All pesticides		2.7.3
Pesticide resistance	All pesticides		4.4.3
Genetically modified crops	Mainly herbicides	Mainly insecticides	2.7.4
Integrated pest and vector management	Biopesticides	Synthetic pesticides	2.7.5
Organic production	Biopesticides	Synthetic pesticides	2.7.6
Regulatory			
Pesticide legislation and policy	Low risk pesticides	High risk pesticides	2.7.7; Chapter 3
Health and environmental policy and legislation	Low risk pesticides	High risk pesticides	2.7.7; Chapter 3
Economic			
Pesticide marketing	All pesticides		2.7.8
Pesticide prices	If low: all pesticides		2.7.9
Commodity prices	If high: all pesticides	If low: all pesticides	2.7.10
Fiscal policies	If tax breaks or subsidies: all implicated pesticides	If taxes: all implicated pesticides	2.7.11
Voluntary sustainability standards	Biopesticides	Synthetic pesticides	2.7.12
Public health			
Food safety		Synthetic pesticides	2.7.13
Public concerns about health		Synthetic pesticides	2.7.14
Vector-borne diseases	Public health pesticides		2.7.15
Environmental			
Climate change	All pesticides		2.7.16
Invasive species and pest outbreaks	All pesticides		2.7.17
Public environmental concerns		Synthetic pesticides	2.7.18
Information			
Information sources	Depends on type of source	Depends on type of source	2.7.19
Knowledge, awareness and attitudes		Limited impact	2.7.20
Training		Limited impact	2.7.21

affect the extent and manner in which pesticides are applied.

The drivers of pesticide use are described here as if they were generally applicable everywhere in the world and in all crops or pesticide use situations. However, the extent to which individual drivers influence pesticide use is greatly influenced by local agronomic, regulatory, economic and social conditions.

In some cases drivers are mentioned only briefly in this chapter, but are reviewed in more detail elsewhere in the report.

Agronomic drivers

2.7.1 Growth in agricultural production

Global agricultural production is projected to increase by around 20 per cent between 2018 and 2027, with considerable variation across regions (Figure 2.7-1). Strong growth is expected in sub-Saharan Africa, South and East Asia, and the Middle East and North Africa. By contrast, production growth in industrialized countries is expected to be much lower, especially in Western Europe, where agricultural and fish production are projected to increase by only around 3 per cent during this period (Organisation for Economic Co-operation and Development and Food and Agriculture Organization of the United Nations [OECD/FAO] 2018).

Owing to population growth and higher per capita income, food consumption will continue to expand with regard to most commodities. Low and middle income countries will be the source of most demand growth in the next ten years, with sub-Saharan Africa and India accounting for a large share of additional food demand for cereals (OECD/FAO 2018).

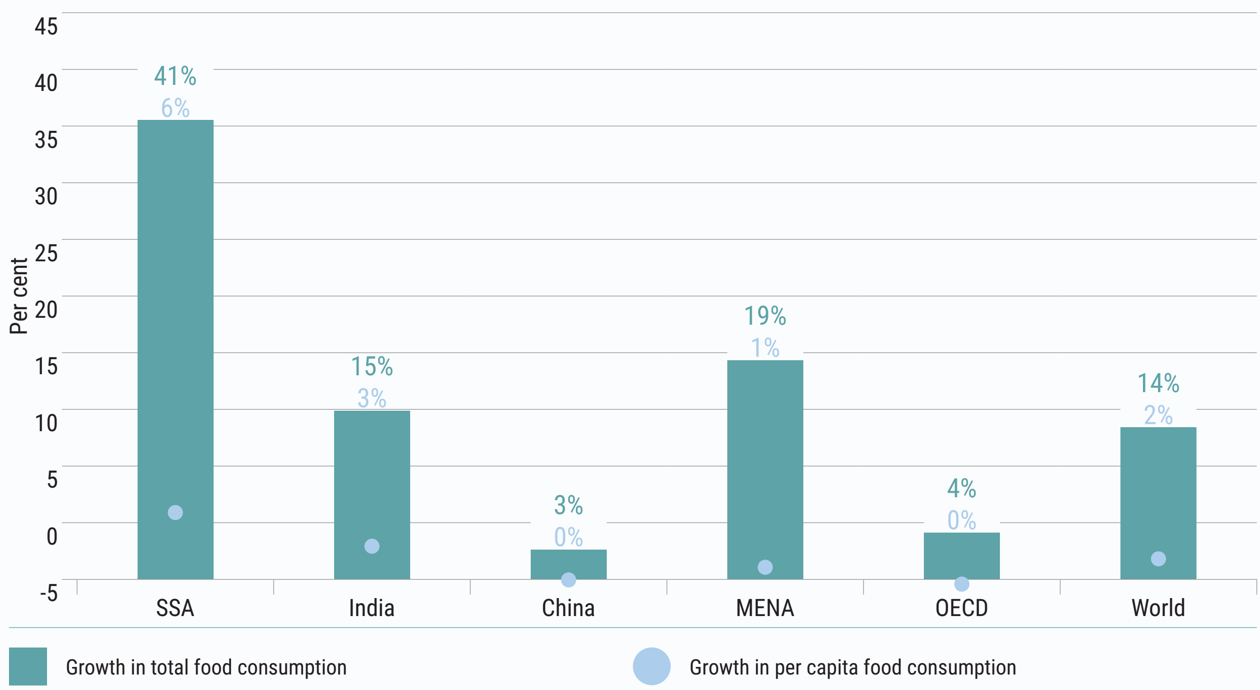
Growth in production will be achieved primarily by (preferably sustainable) intensification and efficiency gains, and partially by enlargement of the production base through herd expansion and conversion of pasture to cropland (OECD/FAO 2018).

In the past, growth in agricultural production has been accompanied by increased use of pesticides. Without changes in environmental and agricultural development policies, as well as pest management practices, it is expected that pesticide use will continue to grow (McIntyre *et al*. 2009).

2.7.2 Crop and post-harvest losses due to weeds, pests and diseases

The main rationale for using pesticides in agriculture is to minimize economic losses. Pests, diseases and weeds may lead to crop injuries which result in crop damage or losses that cause economic losses. However, these

Figure 2.7-1 Growth rates of total and per capita food consumption, 2018-2027. OECD and FAO (2011).



Note: SSA = Sub-Saharan Africa; MENA = Middle East and North Africa; OECD = Organisation for Economic Co-operation and Development countries

Table 2.7-1 Estimates of global yield losses in major crops caused by pests, diseases and weeds.

	Average actual yield loss as % of attainable yield (global range)				
Crop	Weeds	Animal pests*	Diseases	Total	Source
Wheat	**7.7** (3 – 13)	**7.9** (5 – 10)	**12.6** (7 – 16)	**28.2** (14 – 40)	1
	not assessed	**2.0** (0 – 4)	**19.5** (10 – 24)	--	2
Maize	**10.5** (5 – 19)	**9.6** (6 – 19)	**11.2** (6 – 20)	**31.2** (18 – 58)	1
	not assessed	**4.7** (4 – 11)	**17.7** (14 – 37)	--	2
Rice	**10.2** (6 – 16)	**15.1** (7 – 18)	**12.2** (8 – 19)	**37.4** (22 – 51)	1
	not assessed	**9.1** (6 – 12)	**21.0** (20 – 30)		2
Potato	**8.3** (4 – 14)	**10.9** (7 – 13)	**21.1** (12 – 33)	**40.3** (24 – 59)	1
	not assessed	**2.8** (1 – 4)	**14.5** (6 – 19)		2
Soybean	**7.5** (5 – 16)	**8.8** (3 – 16)	**10.1** (3 – 18)	**26.3** (11 – 49)	1
	not assessed	**5.7** (2 – 10)	**15.6** (9 – 24)		2
Cotton	**8.6** (3 – 13)	**12.3** (5 – 22)	**7.9** (5 – 15)	**28.8** (12- 48)	1

* primarily insects, mites and nematodes.
1: Oerke 2006;
2: Savary *et al*. 2019 (only assessed losses by pests and diseases; loss percentages were disaggregated on the basis of Supplementary Table 3)

relationships are not linear or automatic: pest, disease or weed infestations do not always lead to measurable crop injuries, nor do injuries necessarily lead to crop losses, while crop losses do not always lead to economic losses (Savary *et al*. 2012) (Box 2.7-2). This makes assessments of economic losses due to crop pests, diseases and weeds complicated.

It would be logical to expect that estimates of crop losses and subsequent economic losses due to pests, diseases and weeds are based on thorough science, as these estimates form the basis for pest management decisions including use of pesticides. However, perhaps surprisingly, many projections of the costs and benefits of pesticide interventions lack corroborating data on actual field losses in the geographical areas concerned (Savary *et al*. 2012; Institut national de la recherche agronomique 2017; Savary *et al*. 2019) (see also Chapter 5).

Over the years many estimates have been made of crop losses due to Pests, diseases and weeds, and associated economic losses. Estimates of crop losses show high variability, depending on crop variety, geographical area, agronomic and environmental factors, the estimation methods used, and baselines selected for crop damage and yield. The most recent reviews, while using different methods, show similar overall crop losses of 20-40 per cent of attainable yields (Oerke 2006; Savary *et al*. 2019) (Table 2.7-1).

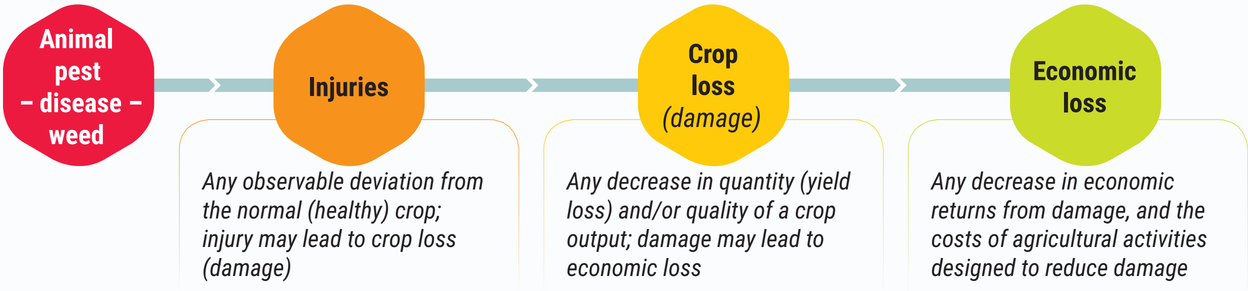
Very large regional differences exist, however, in crop losses across the world. High losses – relative to per capita production – have been found in sub-Saharan Africa and on the Indian subcontinent and for certain crops in China. Relatively lower losses are seen in some regions of high crop production, such as North America and southern South America (Savary *et al*. 2019). Crop losses appear to be more important in food insecure regions than in regions with production surpluses. Such regional variations are partly explained by environmental (climatic, social and economic) differences, but also by differences in the efficiency of crop health management practices, with regard to which scope for improvement may be indicated (Savary *et al*. 2019).

2.7.3 Agricultural intensification

Growth in agricultural production will, to a large extent, need to be achieved through the intensification of production processes (i.e., increasing production per unit land, preferably sustainably).

Box 2.7-2 **Concepts of crop yield and crop loss.** Savary *et al.* (2006); Savary *et al.* (2012); Esker, Savary and McRoberts (2013); Boote (2017)

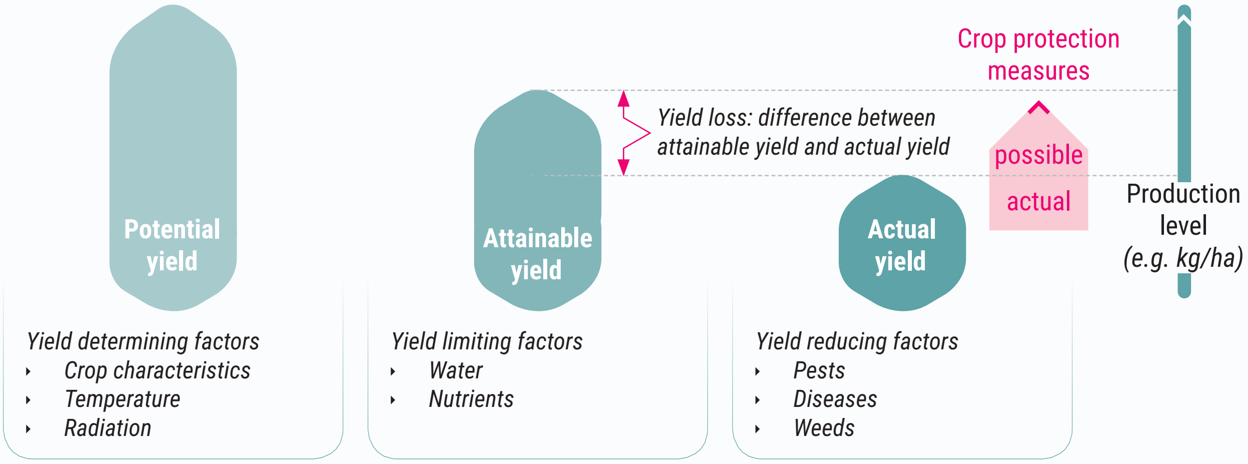
Pests, diseases and weeds may cause injuries to the plant, such as lesions on fruits or leaves, reduction of turgor, or effects on photosynthesis. Such injuries may lead to crop damage or crop loss, either decreased yield or adverse effects on the quality of the crop. The production of aflatoxins by fungal diseases is an example of an effect on crop quality. Whether or not injuries lead to crop loss depends on crop management, environmental conditions and crop protection measures and is often locally specific. Crop loss can result in economic loss for the farmer. Economic loss depends on the magnitude of the crop loss, but also on the costs of pest management measures and pesticides and the price elasticity of the crop.



The yield concepts below are generally used in crop loss assessments. The potential (or theoretical) yield of a crop is determined by the genetic makeup of the plant, as well as by temperature and radiation. Potential yield is achieved if there are no limitations of nutrients and water, or any injury by pests, diseases or weeds. The attainable yield is the potential yield, less any effect of water or nutrient shortages (or excesses) in the local production situation. The actual yield is the yield actually harvested; it incorporates the yield reducing effects on the attainable yield by pests, diseases, weeds (and possibly pollutants), as well as actual crop protection measures.

Yield loss by pests, diseases and weeds is defined as the difference between attainable yield and actual yield.

Crop protection measures aim to increase actual yields as much as possible towards attainable yields. Generally, crop protection measures will not fully achieve attainable yields, as this this is not economically affordable.



Intensification of crop production to meet increasing demand for food and fodder began in earnest in the 1950s in North America and Europe and expanded in the 1960s with the Green Revolution in Asia and Latin America. The production model focused initially on the introduction of improved, genetically uniform crops grown in large homogeneous areas with high levels of complementary inputs such as irrigation, fertilizers and pesticides. Green Revolution technologies are estimated to have fed more than a billion extra persons. The Green Revolution is credited, especially in Asia, with alleviating rural poverty, saving large areas of fragile land from conversion to extensive farming, and helping to reduce hunger (FAO 2011; Fresco 2016).

However, these large gains in agricultural production were often accompanied by negative effects on the environment, human health, and agriculture's natural resource base. For instance, pest and disease pressure increased due to monocultures of high-yielding but pest-sensitive crop varieties, reduction of fallow and crop rotation, and high use of fertilizers. This led to increased pesticide use, resulting in the development of pesticide resistance, the resurgence of existing pests, and upsurges of secondary pests – leading in turn to further repeated use of pesticides. A "pesticide treadmill" was the result (van den Bosch 1989).

Many of the adverse effects of this type of intensification have been mitigated, at least partly. Nevertheless, current agricultural intensification processes may still lead to large increases in the use of agricultural inputs and associated environmental and health impacts. For example, Riwthong *et al*. (2015) found that intensification of smallholder agriculture in northern Thailand resulted in higher productivity (expressed as gross margins at the farm gate) by up to a factor 13, but also increased pesticide use intensity by a factor 16.

It is widely recognized that meeting future demand for food will require different, more sustainable approaches. As stated by Godfray and Garnett (2014): Sustainability is a "must have" not a "nice to have". Further production optimization and intensification has been described in different ways, including sustainable crop production intensification, ecological intensification and agroecology, among others (FAO 2011; Bommarco, Kleijn and Potts 2013; Pretty 2018; Garibaldi *et al*. 2019; High Level Panel of Experts on Food Security and Nutrition 2019)..

2.7.4 Genetically modified crops

The global area of genetically modified (GM) crops (also referred to as biotech crops) increased more than 100-fold, from 1.7 million ha at the time of their commercial introduction in 1996 to 192 million hectares in 2018. In that year GM crops were grown in 26 countries; 54 per cent of the global GM crop area was in developing and 46 per cent in industrialized countries (International Service for the Acquisition of Agri-biotech Applications [ISAAA] 2019).

In 2018 about half the global acreage of GM crops consisted of soybean, followed by maize (21 per cent), cotton (13 per cent) and canola (5 per cent). Worldwide, 78 per cent of soybean, 76 per cent of cotton, 30 per cent of maize and 29 per cent of canola were GM crops (ISAAA 2019).

Overall, almost 80 per cent of all GM crop approvals involve traits which affect weed, pest and disease control and therefore potentially influence pesticide use (Table 2.7-2). Herbicide tolerance (HT) in soybeans, canola, maize, alfalfa and cotton is the dominant trait, representing 42 per cent of approvals for cultivation and 46 per cent of the global GM crop area in 2018

Table 2.7-2 **Global share of approvals for cultivation of genetically modified crops according to the main commercial GM traits. Approved events may be single traits or combinations of traits.** ISAAA (2020).

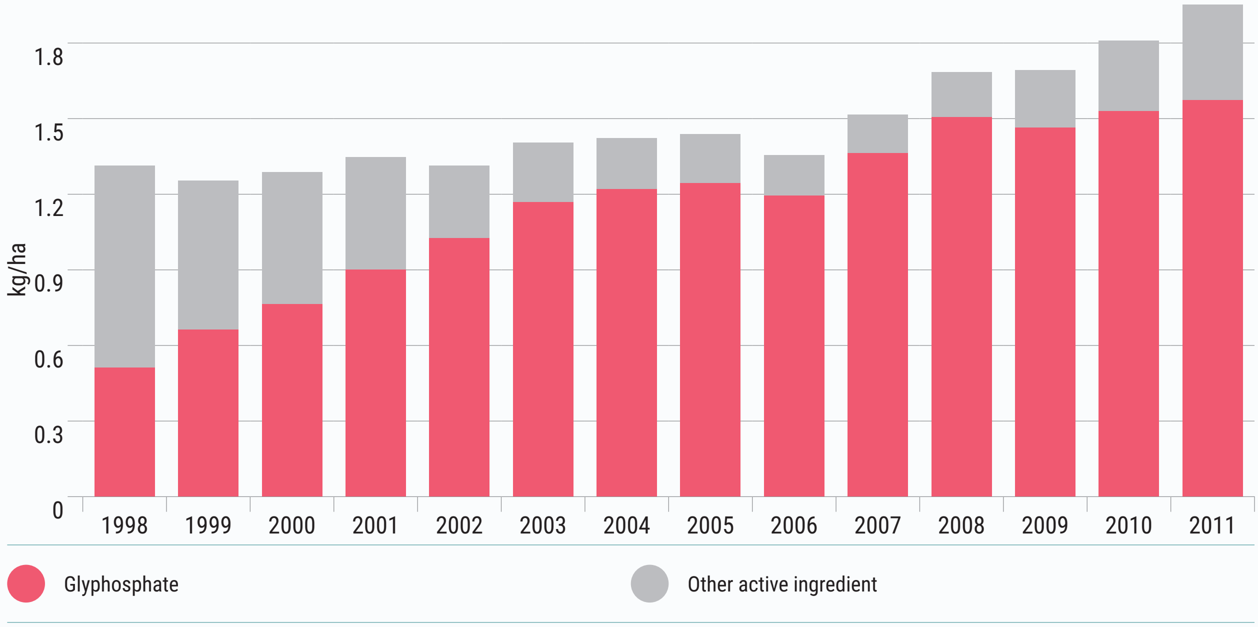
Commercial trait	Number of approvals for cultivation	Percentage of total
Herbicide tolerance	226	42%
Insect resistance	178	33%
Disease resistance	20	3.70%
Abiotic stress tolerance	10	1.90%
Altered growth/yield	3	0.50%
Modified product quality	76	14%
Pollination control system	26	5%

Table 2.7-3 Impact of growing genetically modified crops on volume of pesticide use.

Coverage	Assessment method	Study size	Effect of GM crop on pesticide use volume	Reference
Global	Comparison of GM crop pesticide use with typical application rates in non-GM crops	31 countries	Various HT crops: aggregate impact = 0-19 per cent reduction in a.i. per ha	Brookes and Barfoot (2018), partly reviewed in NAS (2016)
		12 countries	IR cotton and maize: aggregate impact = 30-60 per cent reduction in a.i. per ha	
Global	Systematic review (studies until 2015)	13 studies	In all cases, use of IR crops reduced application of insecticides	NAS 2016
		6 studies	Use of HT crops sometimes initially correlated with decreases in total amount of herbicide applied per hectare, but decreases were generally not sustained	
Global. HT soybean, maize and cotton; IR maize and cotton	Meta-analysis: differences in pesticide use between GM and non-GM crops. (studies 1996-2014)	31 data sets	IR crops: 42 per cent reduction in insecticide use	Klümper and Qaim (2014), reviewed in NAS (2016)
		7 data sets	HT crops: 2.4 per cent increase in herbicide use	
United States and global	Glyphosate use statistics from multiple sources from 1974 to 2014 in the United States and from 1994 to 2014 globally. ISAAA data for HT crops	Global, with special focus on the United States, Brazil and Argentina	Globally, glyphosate use has risen almost 15-fold since genetically engineered glyphosate tolerant (GT) crops were introduced in 1996. Genetically engineered HT crops account for about 56 per cent of global glyphosate use.	Benbrook (2016)
United States Maize, soybean, cotton, rice, wheat	United States Department of Agriculture (USDA) herbicide use data for individual a.i.'s: 1990-2015	National	Average number of herbicide treatments increased in all crops except soybean. Increases were similar in mainly HT crops (cotton, maize) compared to mainly non-HT crops (rice, wheat). In the majority of crops acute and/or chronic hazard quotients decreased over time, indicating potentially lower human health risks.	Kniss (2017)
United States Soybean and maize	Comparative study. Data 1998-2011	5,424 maize farmers	Adopters of IR maize used 11 per cent less insecticide than non-adopters. IR maize adopters used increasingly less insecticides over time than non-adopters.	Perry *et al.* (2016)
		5,029 soybean farmers	Adopters of GT soybeans used 28 per cent more herbicide than non-adopters. Adopters of GT maize used 1.2 per cent less herbicide than non-adopters. GT adopters used increasingly more herbicides over time relative to non-adopters.	
United States Soybean, corn and cotton	Pesticide use statistics 1992-2009 (no explicit distinction between GM and non-GM crops)	Surveys of more than 20,000 farm operations	Substantial decrease in the mass of insecticides applied since the introduction of Bt corn and cotton.	Coupe and Capel (2016)
			Rates of herbicide application to soybean, corn and cotton initially decreased after GT crop introductions. By the early 2000s herbicide rates started to increase in all crops. By 2009 herbicide rates in soybean were substantially higher than pre-GM.	
Bangladesh Eggplant	Pesticide use evaluation	Survey of 1,200 farm households	IR eggplant: 51 per cent reduction in the number of pesticide applications and 39 per cent reduction in the quantity of pesticides applied.	Ahmed *et al.* 2019

a.i. = active ingredient; GT = glyphosate tolerant; HT = herbicide tolerant; IR = insect resistant

Figure 2.7-2 **Herbicide use in soybean (kg/ha) in the United States following the introduction in 1996 of GM herbicide tolerant soybean. Glyphosate has progressively replaced other herbicides.** Perry *et al.* (2016).



(ISAAA 2019). HT crops are dominated by glyphosate tolerance and, to a lesser extent, tolerance to glufosinate, dicamba, sulfonylurea and oxynil herbicides. Insect resistance is the second most important trait being commercialized; insect resistant (IR) crops are virtually all based on the expression of Bacillus thuringiensis (Bt) toxins.

Insect and disease resistance in a crop can potentially reduce the use of insecticides and fungicides. There is general agreement that the growth of IR crops has significantly reduced the quantity of insecticides applied (Klümper and Qaim 2014; National Academy of Sciences, Engineering and Medicine [NAS] 2016). Reductions in the quantities of insecticides applied range from 11 to 60 per cent compared to non-IR crops, depending on the crop, country, and assessment method used (Table 2.7-3). In some cases the use of IR crop varieties has also been associated with reduced use of insecticides in fields where there are non-IR varieties of the crop, and even with reduced use in other crops, probably due to area-wide pest suppression (NAS 2016). However, in some regions pests have developed resistance to IR crops, leading to a renewed increase of insecticide use (Chapter 4.3.3).

Disease resistant GM crops are grown on a much more limited scale. No reviews were found concerning their impact on fungicide use. However, GM crops with disease resistant traits could potentially reduce the use of fungicides significantly (e.g., late blight resistant potato; Ghislain *et al.* 2018).

The impact of HT crops on the use of herbicides is more ambiguous. An obvious effect is that herbicides used after the introduction of an HT crop converge with those to which the crop is tolerant. Since most HT crops are currently glyphosate tolerant, use of this herbicide has experienced large growth (Figure 2.7-2).

Some studies and reviews show an increase of up to 30 per cent in herbicide use following the introduction of an HT crop, while others indicate declines (Table 2.7-3). Variability in the outcomes of studies appears to be influenced by the assessment methodology used, the HT crop, the time since introduction of the HT crop, and the types of herbicides used before and after introduction of the HT crop.

Several studies appear to indicate an initial decrease in the total rate of herbicide application following introduction of an HT crop, but (significant) increases of herbicide rates afterwards, sometimes reaching higher levels than was the case before its introduction (Coupe and

Capel 2016; NAS 2016; Perry *et al*. 2016). It is likely that this observed pattern of change in herbicide use over time is caused by the emergence of herbicide resistance in the weeds (Chapter 4.3.3). Benbrook (2016) calculated a 15-fold increase in glyphosate use following the commercial introduction of HT crops, considerably higher than in the case of non-HT crops.

2.7.5 Integrated pest and vector management

The concept of integrated pest management (IPM) originated in the late 1950s in the United States, in response to the increasing and indiscriminate use of pesticides. At that time IPM had a relatively narrow focus, combining biological and chemical control and applying economic thresholds before interventions would take place (Ehler 2006). From the 1970s onwards IPM developed into a more holistic ecosystem approach to crop production and protection, combining different management strategies and practices to grow healthy crops and reduce the use and/or risks of pesticides. IPM is a method for analysis of the agro-ecosystem and management of its different elements, in order to control pests and keep them at an acceptable level with regard to environmental, human health and economic requirements.

Many definitions of IPM exist, ranging from what has been referred to as integrated pesticide management (basically promoting judicious pesticide use) (Ehler 2006) to biointensive IPM, which mainly relies on enhancing plant health and conserving beneficial organisms and habitats to limit pest populations (Box 2.7-3). IPM can take different forms that vary in time and space. It is shaped according to site-specific factors such as cropping patterns, cultivation practices, pest pressure, field size, the broader landscape, R&D efforts, availability of training, and farmer attitudes. Furthermore, farmers do not adopt IPM strategies based solely on technical parameters; the social and economic environment in which they operate is also critical (Barzman *et al*. 2017).

Table 2.7-4 Integrated pest management (IPM) and integrated vector management (IVM) have become central policies for pest and vector management at national and international levels: some examples.

Entity	Policy instrument	
International organizations		
FAO	*Save and Grow – A Policymaker's Guide to the Sustainable Intensification of Smallholder Crop Production*	FAO (2011)
FAO and WHO	International Code of Conduct on Pesticide Management	FAO/WHO (2014)
WHO	Global Vector Control Response 2017-2030	WHO (2017)
World Bank	Environmental and Social Standards No. 3: Resource Efficiency and Pollution Prevention and Management	World Bank (2018)
European Union and national governments		
European Union	EU Framework Directive on the sustainable use of pesticides, and EU Regulation on the placing of plant protection products on the market	EU (2009a; 2009b)
United States	National roadmap for integrated pest management	United States Department of Agriculture (USDA) (2018)
Morocco	National vector control plan 2019-2025	Direction de l'Epidémiologie et de la Lutte contre les Maladies (DELM) (2019)
Pesticide industry		
CropLife International	Crop protection industry supports FAO on IPM	CropLife International (CLI) (2017)
Voluntary sustainability standards		
Rainforest Alliance	Sustainable agriculture standards	Rainforest Alliance (2020)

Box 2.7-3 Aspects of integrated pest management (IPM). IPM as a continuum scheme adapted from Benbrook *et al.* (1996)

IPM and IVM defined

IPM and IVM have been defined in many ways. FAO and WHO currently use the following definitions (FAO/WHO 2014; FAO 2020):

Integrated pest management (IPM) means the careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified and reduce or minimize risks to human health and the environment. IPM emphasizes the growth of a healthy crop with the least possible disruption to agro-ecosystems and encourages natural pest control mechanisms.

Integrated vector management (IVM) means the rational decision-making process for the optimal use of resources for disease vector control. It aims to improve efficacy, cost-effectiveness, ecological soundness and sustainability of disease vector control interventions for control of vector-borne diseases.

Principles of IPM

The EU has identified eight general principles of IPM which should be implemented by professional pesticide users in all Member States (EU 2009a; as summarized by Creissen *et al.* 2019)

Principle	Components
1. Prevention and suppression	Crop rotation, cultivation techniques, varietal resistance, phytosanitary measures, beneficial organisms ("grow a healthy crop"; FAO 2020)
2. Monitoring	Field monitoring, forecasting, seeking expert advice
3. Informed decision making	Protection measures based on expert advice, action thresholds
4. Non-chemical methods	Preference for biological and physical control methods over chemical ones
5. Pesticide selection	Using pesticides that minimize negative effects on human health and the environment
6. Reduced pesticide use	Reduced doses, reduced application frequency considering the risk for development of pesticide resistance
7. Anti-resistance management	Alternation/mixing pesticides containing multiple modes of action
8. Evaluation	Assessment of the efficacy of measures used to inform future management decisions

IPM as a continuum

Benbrook *et al.* (1996) proposed that IPM systems could be thought of as falling along a continuum. In the shift from chemical-intensive to biointensive IPM, reliance on interventions with pesticides drops and reliance on prevention-based biological practices increases.

→ *Shifting reliance from treatments with pesticides to prevention* →

No IPM	Low level IPM	Medium level IPM	Biointensive IPM
Typical elements of IPM systems (examples)			
‣ Proper calibration of spray equipment ‣ Good application practices ‣ Pest monitoring ‣ Good agronomic practices ‣ Field sanitation	‣ Pest monitoring followed by threshold based pesticide treatments ‣ Delay resistance and secondary pest development ‣ Optimally time pesticide applications ‣ Preventive practices, e.g. resistant varieties, mechanical control	Multi-tactic approaches to: ‣ Limit pest habitats ‣ Enhance beneficial organisms ‣ Grow resistant varieties ‣ Use of cover crops ‣ Use of longer rotations ‣ Apply disease forecasting models	Reliance on preventive measures to limit pest pressure and enhance beneficial: ‣ Enhance plant health and soil quality ‣ Focus on conservation of beneficials and their habitats ‣ Use of biocontrol methods

Table 2.7-5 Effects of integrated pest management (IPM) on pesticide use (global and regional reviews conducted since 2010).

Region	Review coverage	Economic effects	Effect on pesticide use and risks	Reference
Global (mainly low and middle income countries)	Meta-analysis IPM Farmer field schools (FFS) compared to non-FFS farmers 15 studies with medium or low risk of bias	13 per cent average increase in yields 19 per cent average increase in net profits	23 per cent average reduction in pesticide use for IPM and IPPM FFS farmers compared with other farmers Significant increase in adoption of other beneficial practices 39 per cent average reduction in environmental impact quotient (EIQ) score as a result of reduced pesticide use among FFS farmers compared with other farmers No valid estimates possible of impacts on farmer health outcomes	Waddington *et al*. 2014
Global (mainly low and middle income countries)	Systematic review IPM and other FFS compared to non-FFS farmers 7 "more rigorous" studies, published after Waddington *et al*. 2014	9 per cent average increase in yields 28 per cent increase in profits (one study)	35 per cent reduction in insecticide expenditure (one study) 32 per cent increase in adoption of recommended practices	Rejesus 2019
Africa and Asia	Quantitative review 85 IPM projects in 24 countries implemented from 1990 to 2014	Average yield increase of 41 per cent	Average pesticide reduction of 31 per cent Under IPM, a total of 35 of 115 (30 per cent) crop combinations resulted in a transition to zero pesticide use.	Pretty and Bharucha (2015); Pretty (2018)
Western United States	Narrative review Pest management studies and survey published since 2000	IPM programmes have contributed to increased agricultural productivity	IPM programmes have reduced some environmental and human health risks due to decreases in pesticide use. Risks from potential carcinogens and toxic air contaminants may have increased. Pesticide use has declined 40-90 per cent in hazelnut production in the State of Oregon, almond and fresh-market grape production in the State of California, and pear production in California, Oregon and the State of Washington. Significant reductions in insecticide use against pink bollworm and 70 per cent reduction of foliar insecticides against whitefly observed in cotton (includes the effect of Bt cotton)	Farrar, Baur and Elliott (2015; 2016a; 2016b)
United States	Systematic review for various key arable crops (excluding fruits and vegetables) in the period 1996-2005	Not assessed	Pesticide cost per acre was used a proxy for pesticide use. On average throughout the United States, IPM adoption and pest management training led to slightly greater pesticide spending by farmers.	Maupin and Norton (2010)

IPM has become the official policy for pest management, as part of sustainable intensification of crop production, of international organizations and many national governments, as well as of the crop protection industry and standard-setting bodies. Similarly, integrated vector management (IVM) is currently the central paradigm for disease vector control (Table 2.7-4). IPM is thus an important part of sustainable intensification of crop production. Through enhancing ecosystem function and making the agricultural ecosystem healthier, more ecosystem services are provided: in this case pest control (FAO 2020b). In EU Member States applying the principles of IPM has become an obligation for farmers (Box 2.7-3).

Measuring the level of IPM implementation has been difficult, as crop production and protection are site-specific, dynamic, and influenced by economic, agronomic and social parameters (Barzman *et al*. 2015). Despite considerable investment in IPM-related research and broad political support for IPM (at least on paper) over several decades, the adoption of IPM has generally been considered to be relatively low (IAASTD 2009) both in higher income countries (Ehler 2006 for the United States; Hokkanen 2015 and European Commission [EC] 2020a for Europe; Zalucki, Adamson and Furlong 2009 for Australia), as well as in lower income economies (Parsa *et al*. 2014; Bottrell and Schoenly 2018; Alwang *et al*. 2019).

Nevertheless, IPM has been highly successful and cost-effective in many crops and countries, where over time pest management systems have been implemented that are more sustainable from both an agronomic and economic point of view (e.g., pears in California [Weddle, Welter and Thomson 2009], cotton in Arizona [Naranjo and Ellsworth 2009], various crops in the western United States [Farrar, Baur and Elliott 2015], tomatoes in New Zealand [Cameron *et al*. 2009], rice in Indonesia in the 1990s [Thorburn 2015] and cotton in Mali [Settle *et al*. 2014], among many others).

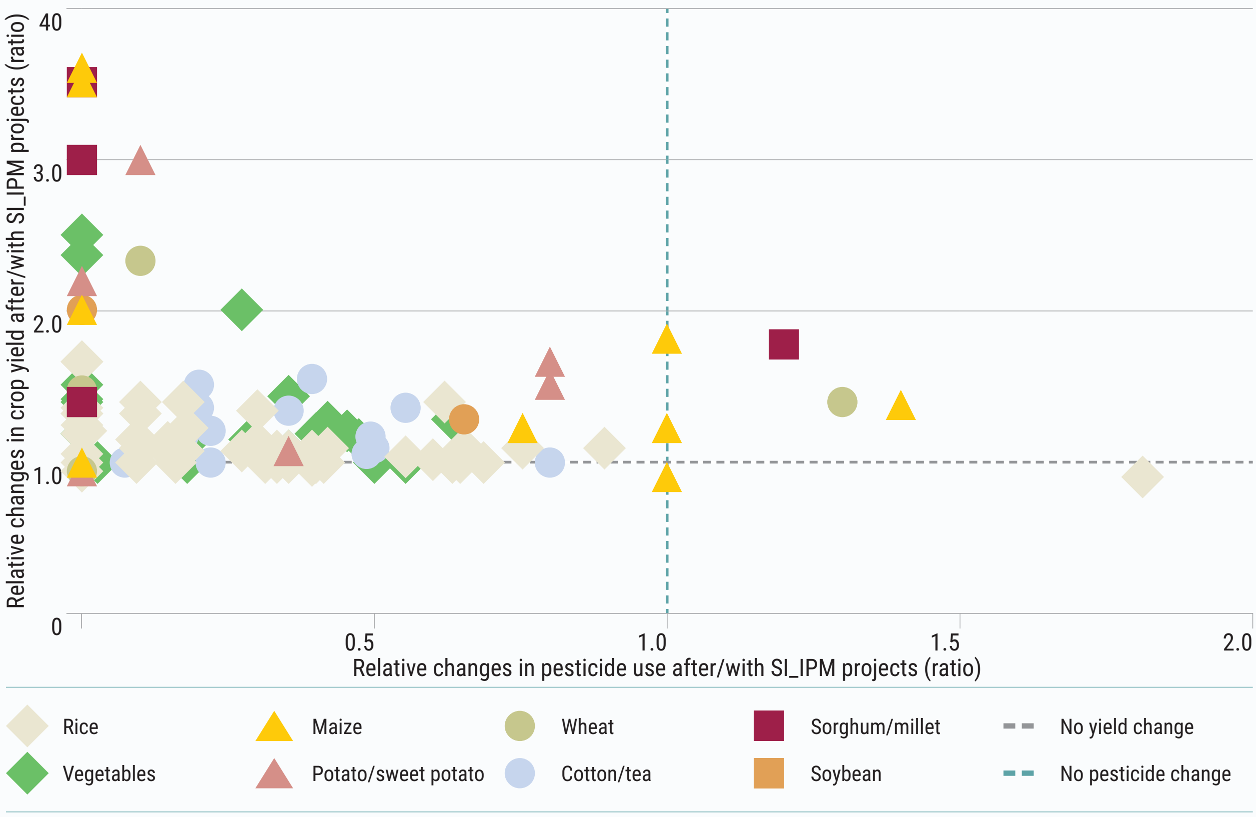
To some extent the degree of adoption of IPM by farmers depends on their understanding of what constitutes IPM. Most farmers will apply one or more crop production and protection measures which can be part of an IPM approach (e.g., resistant cultivars, crop rotation, regular cleaning of machinery, balanced fertilization, pest monitoring), often without being recognized as such, but they may not apply all the practices which would constitute "ideal" (ecological or biointensive) IPM (Maupin and Norton 2010; Barzman *et al*. 2015). For example, Creissen *et al*. (2019) surveyed arable farmers in the United Kingdom and found that all of them had adopted IPM to some extent (an average 65 per cent adoption rate) but only 6 per cent had adopted more than 85 per cent of the measures that were theoretically possible. Although simpler practices may be adopted more rapidly than more complex ones, that does not imply that partial adoption of IPM is a poor investment (Norton *et al*. 2019).

It is important to emphasize, however, that IPM implementation does not mean choosing a number of measures "randomly" based on personal preferences, cost or ease of implementation. As proposed by Benbrook *et al*. (1996), IPM systems can be thought of as falling along a continuum. In the shift from chemical-intensive to biointensive IPM, reliance on interventions with pesticides should drop and reliance on prevention-based biological practices should increase (Box 2.7-3).

While it may be pragmatic to accept incomplete adoption of IPM, especially if it still leads to reduced pesticide risks, this does not solve the problem of ensuring long-term sustainability, let alone long-term sustainable intensification. More fundamental changes in agricultural production are then needed.

An important question to be addressed in this report is whether IPM adoption (irrespective of the exact definition) will lead to a reduction in the use of pesticides, their risks to the environment and human health, or farmers' dependency on pesticides. Most recent reviews indicate that farmers use less pesticides if they apply IPM (Table 2.7-5, Figure 2.7-3). Furthermore, pesticide use reductions generally do not result in reduced crop yields; on the contrary, in most cases (limited) increases in yields have been observed. The only exception is a review by Maupin and Norton (2010) for the United States, where on average a slight increase in pesticide expenditures was observed in

Figure 2.7-3 IPM projects and programmes in Asia and Africa result in increased crop yields and reduced pesticide use. Shown are 85 projects in 24 countries. Pretty (2018)



the case of farmers who adopted either partial or complete IPM measures. Overall, it seems justified to conclude that IPM practices, if effectively adopted and implemented, generally reduce the use of pesticides in cropping systems.

One argument for IPM adoption has been that it leads to a reduction in environmental and human health risks as a result of reduced application of pesticides, expanded use of reduced risk products, improved pesticide application practices, or better use of precautionary measures such as PPE.

Waddington *et al*. (2014) found a considerable reduction in environmental and health risks following IPM adoption in a review of three studies, as measured through an aggregate environmental impact indicator (Table 2.7-5). In individual studies it has often been shown that implementation of IPM reduces human health effects observed in farmers, e.g., in India (Mancini *et al*. 2009), Cambodia and Viet Nam (FAO 2013), Bolivia (Jørs *et al*. 2014) and Costa Rica (Fuhrimann *et al*. 2020). However, this is not always the case, e.g., in Uganda (Clausen *et al*. 2017) or Bangladesh (Gautam *et al*. 2017) where no clear impacts on risk reduction could be determined. This variability in results is at least partly explained by the complexity of measuring pesticide exposure and effects (Fuhrimann *et al*. 2020). So far, no systematic review appears to have been conducted assessing the empirical relationship between IPM adoption and the reduction of environmental and health effects.

Despite successful local application of IPM, its impact on pesticide use has not been visible at global or continental scale due to its limited large-scale adoption. Peshin and Zhang (2014) analysed IPM and pesticide use in the United States, Europe and Asia and concluded that pesticides were and are the primary pest management tools. Low-volume pesticides and insect resistant transgenic crops both decreased and stabilized pesticide use in the 1990s and early 2000s. Since then, pesticide sales have regained an upward trajectory and their use in agriculture has increased. In Australia, Zalucki, Adamson and

Furlong (2009) found that during the previous 30 years insecticide input costs per hectare had increased faster than the price index, indicating that insecticide inputs had actually increased.

Overall, global pesticide use per unit cropland has steadily increased since the early 1990s, while use per unit crop output has remained stable despite the increased crop protection potency of more modern pesticides (Figure 2.4-18).

It can be concluded that IPM, however defined, reduces the use and risk of pesticides locally. However, its implementation is limited in both lower and high income countries. The overall impact of IPM has therefore not resulted in reduced global dependence on pesticides in crop protection.

2.7.6 Organic production

There are many definitions of organic agriculture, but all converge to characterize it as a system that relies on ecosystem management rather than external agricultural inputs. Organic agriculture begins to consider potential environmental and social impacts by eliminating the use of inputs such as synthetic fertilizers and pesticides, veterinary drugs, genetically modified seeds and breeds, preservatives, additives and irradiation. Use of these inputs is replaced by site-specific management practices that maintain and increase long-term soil fertility and prevent pest and diseases (FAO 2020c).

The Codex Alimentarius Commission has defined organic agriculture as “a holistic production management system which promotes and enhances agro-ecosystem health, including biodiversity, biological cycles, and soil biological activity. It emphasizes the use of management practices in preference to the use of off-farm inputs, taking into account that regional conditions require locally adapted systems. This is accomplished by using, where possible, agronomic, biological, and mechanical methods,

Figure 2.7-4 **Distribution of main organic land use types and crop categories in 2018. Globally, 71.5 million ha were under organic production in 2018.** Schlatter *et al.* (2020).

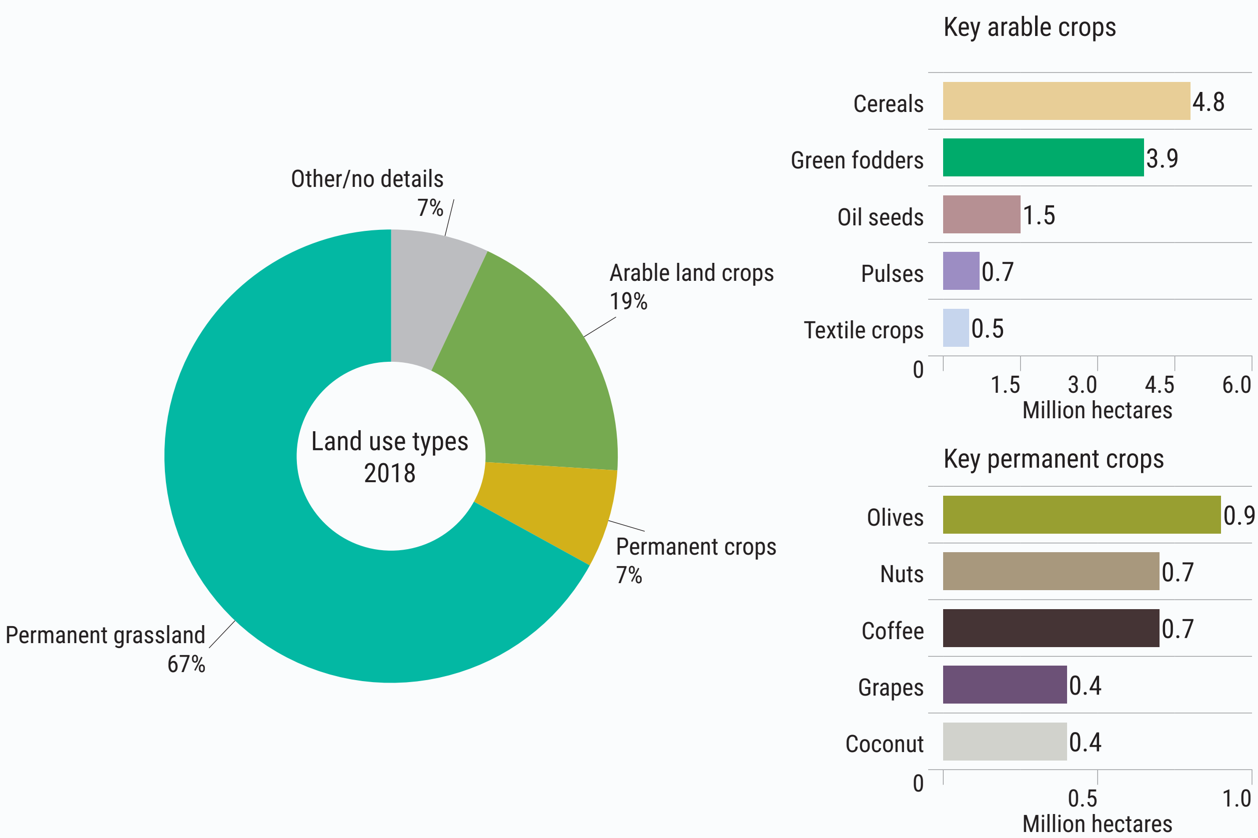


Table 2.7-6 **Examples of pesticides allowed in organic agriculture.** IFOAM – Organics International (2014)

Substances of plant or animal origin	Substances of mineral origin	Microorganisms
Chitin nematicides (natural origin)	Copper salts	Fungal preparations (e.g. spinosad)
Natural acids	Diatomaceous earth	Bacterial preparations (e.g. *Bacillus thuringiensis*)
Neem	Light mineral oils (paraffin)	**Others**
Pyrethrum	Sulfur	Iron phosphates (as molluscicide)
		Soft soap

as opposed to using synthetic materials, to fulfil any specific function within the system" (Codex Alimentarius Commission 2013).

In 2018, 71.5 million ha of certified organic agricultural land was recorded (two-thirds grazing land). Arable land comprised 13.3 million ha and permanent crops 4.7 million ha (Figure 2.7-4). The area under organic agriculture is steadily increasing globally, having doubled since 2010. Organic agriculture represents about 1.5 per cent of the world's total agricultural land, while organic arable and permanent crops are grown on 1.2 per cent of total global cropland (Schlatter *et al.* 2020; FAOSTAT 2020).

In organic agriculture the use of almost all synthetic pesticides is prohibited, but some biological pest control agents and inorganic compounds are allowed (Table 2.7-6).

Given the limited area of cropland currently under organic agriculture, its contribution to a reduction in pesticide use at the global scale is still small. However, certain principles of organic agriculture have been adopted in more mainstream forms of agriculture.

Regulatory drivers

2.7.7 Pesticide legislation and policies

Pesticide legislation[1] and policies, as well as legislation and policy that address public health, the environment and trade more generally, can greatly influence pest and pesticide management, including production and use. This is true not only nationally, but also in the case of regional and international instruments.

Overall, legislation concerned with pesticide management – but also public health and environmental legislation – aims to reduce the risks and sometimes the use of pesticides. The promotion of international trade in agricultural commodities is increasingly accompanied by policies that encourage the sound management of pesticides and reduction of pesticide residues in commodities.

Agricultural policies, on the other hand, have the potential either to increase or limit pesticide use. Pesticide dependency may grow, especially if policies exclusively emphasize production growth in specific crops; or it may decrease if policies focus on supporting production approaches which are agronomically and environmentally sustainable in the long term and/or promote more integrative farming (e.g., rice plus fish plus ducks plus vegetables).

[1] Throughout this report references to legislation are understood to refer to legal and other measures adopted by a country, including both primary and secondary legislation.

Legislation and policies that directly affect pesticide production, management and use are discussed in detail in Chapter 3.

Economic drivers

2.7.8 Pesticide marketing

In low income countries, pesticide distributors and retailers are farmers' main source of information. Agricultural extension services and private advisory services have only limited coverage. This appears to be a consistent pattern across low and middle income regions of the world (Anang and Amikuzuno 2015; Haj-Younes, Huici and Jørs 2015; Okonya and Kroschel 2015; Schreinemachers *et al*. 2017), but it is also encountered in some high income economies (Oleksa Vanzant 2014-2015). As a result, there is a high likelihood that farmers and other pesticide users will receive information in which pesticides are proposed as the predominant pest management option. Schreinemachers *et al*. (2017) found that farmers in Cambodia, Laos and Viet Nam who sought advice from pesticide shopkeepers used 251 per cent more pesticide than the average.

While public and private sector initiatives to train retailers in more comprehensive pest management advice may lead to increased use of lower risk pesticides by farmers (Lekei, Ngowi and London 2014), they cannot be expected to result in overall reduced pesticide sales.

Furthermore, widespread pesticide advertising in some parts of the world exposes potential pesticide users to constant information and incentives encouraging them to purchase and use pesticides. Article 11 in the International Code of Conduct on Pesticide Management addresses pesticide advertising in all media (FAO and WHO 2014). It has been endorsed by major pesticide industry associations. However, a report by the Special United Nations Rapporteur on the right to food has suggested that "aggressive, unethical marketing tactics" are still used by pesticide and agroindustry (United Nations [UN] 2017).

Continuous pesticide advertising using radio and television in the mid-2000s was identified as a key reason why rice farmers in Viet Nam discontinued IPM practices, even though rice yields were maintained with a reduced number of insecticide applications (Escalada *et al*. 2009). No independent reviews are available of the impact of current pesticide advertising on pest management practices in different parts of the world.

2.7.9 Pesticide prices

The price of a pesticide at the sales outlet depends on many factors. They include the cost of the manufacturing and formulation process, the size of the market in a given country of region, exchange rate factors, the level of national taxation, the purchasing power of farmers and other pesticide users, the expected benefits of the pesticide for a farmer, and competition between manufacturers.

Competition based on whether an active ingredient is under patent or off-patent has markedly influenced pesticide pricing in the last few decades. Production and sales of off-patent, non-proprietary pesticides, also referred to as generic pesticides, has greatly increased over the last 20 years or so. Off-patent, non-proprietary pesticides currently represent around 70 per cent of the total market for crop protection products (AgbioInvestor 2019). This situation has increased competition and reduced sales prices.

For example, glyphosate, the most used herbicide in the world (UNEP 2020a), was introduced on the market in 1974 and the last global patent protection of the Roundup (the first product containing glyphosate) expired in 2000. Subsequently, large-scale generic production got under way, especially in China. Prices of glyphosate products in the United States dropped by almost 60 per cent between 2000 and 2014; similarly, glyphosate prices in Mali in 2015 were 35 per cent lower than in 2008 (Benbrook 2016; Diarra and Haggblade 2017).

Lower pesticide prices increase access to such products by farmers and other users. The presence of cheap generic products on the market also complicates the introduction of newer, low-risk chemical products and biopesticides, as well as non-pesticide alternative pest management options.

2.7.10 Commodity prices

Pesticides tend to be used more in the case of high-value agricultural commodities than in that of low-value subsistence crops. Furthermore, the structure of the value chain can influence commodity prices, as the prices paid to a farmer for her/his crop may be higher when value chains are more direct. Investments in pest management are considered worthwhile if potential revenues are higher, which often translates into use of pesticides. When commodity prices are high, farmers tend to spend more on pesticides (Waterfield and Zilberman 2012; AgbioInvestor 2019).

2.7.11 Fiscal policies

Fiscal instruments that can affect pesticide use have been adopted by countries, such as direct subsidies, taxes, charges and fees, implicit subsidies, and various tax exemptions and reductions.

Direct subsidies

Agricultural input subsidies are used to meet policy objectives ranging from short-term responses (to enhance food security and income and avoid poverty traps, maintain affordable prices for major crops, and avoid high costs of agricultural inputs) to more long-term structural objectives such as addressing market imperfections and supporting the adoption of new technologies. In general, input subsidies lower costs to producers, which increases the risk of their over- or misuse, with potentially harmful consequences for the environment and the health of farmers and consumers (UNEP 2020b).

In the 1980s and 1990s the majority of developing countries provided financial incentives to farmers to use pesticides; in particular, they directly and indirectly subsidized pesticide imports, domestic manufacture, and local sales and use with a combination of mechanisms (Farah 1994).

Direct subsidization of pesticides has virtually been abandoned in OECD countries (UNEP 2020b). It is also becoming less common in low and middle income countries (unlike subsidization of fertilizers; see Chapter 7.4). On the other hand, subsidies increasingly appear to be provided for biopesticides or other low risk pest control tools as a way to promote IPM and biocontrol (Box 2.7-4).

Implicit subsidies

Much more common than direct subsidies are fiscal measures that implicitly subsidize pesticide use. Agricultural inputs are subject to general ad-valorem taxes as applied to other commodities, such as an import tax, value added tax (VAT) or other general taxes. Many high income countries and an increasing number of lower income countries currently exempt or reduce (i.e., set at zero rate) general and import taxes on pesticides. Without specific conditions, such tax exemptions act as an implicit or hidden subsidy (UNEP 2020b). Given their dominant share of the pesticide market, the use of conventional chemical pesticides tends to profit most from tax reductions/exemptions. However, some countries also offer fiscal incentives to encourage, for instance, organic farming practices, thus facilitating pest management with lower environmental and health risks.

Pesticide taxes

Taxes on pesticides are generally imposed to create incentives for producers and consumers to shift towards less polluting products or substances, stimulate innovation and raise additional fiscal revenues. Countries use revenues obtained from pesticide taxes in different ways. These revenues may simply accrue to the state budget, but in some countries they are used to compensate farmers, cover the costs of pesticide inspection and enforcement, provide training, support projects promoting more sustainable pest control, or fund research on innovative practices (UNEP 2020b).

Despite this potential, beyond general ad valorem taxes only a few countries (mainly in Europe) have so far levied taxes on pesticides with the clear intention to reduce pollution (Box. 2.7-4).

Box 2.7-4 Examples of fiscal instruments that may influence pesticide use.

Direct pesticide subsidies

The number of countries with direct subsidies on pesticides has declined over time (UNEP 2020). Some examples of current pesticide subsidies are:

- **Botswana:** Integrated Support Programme for Arable Agriculture Development (ISPAAD) (since 2013). Subsidy on herbicides for emerging and commercial farmers [30-35 per cent of costs of pesticide] and horticultural enterprises [40-60 per cent of costs] (ISPAAD 2013).
- **State of Hawaii, United States:** Coffee Berry Borer (CBB) Pesticide Subsidy Program (since 2014). To assist Hawaii coffee farmers with the cost of biopesticides containing the fungus, Beauveria bassiana. [up to 50 per cent of cost of the pesticide]. (State of Hawaii Department of Agriculture 2019).
- **China (Beijing Municipality):** "Green Pest Control" subsidy programme (since 2009). Products are subsidized at different rates prioritizing natural enemies, pollinating insects, biopesticides and plant protection tools, and finally by least toxic/residual synthetic pesticides [50-90 per cent of the cost of the product] (Wei *et al*. 2019).

Indirect pesticide subsidies

A considerable number of both high and low income countries currently apply exemptions or zero rates on VAT and general taxes on pesticides (UNEP 2020). These include:

All pesticides

- **European countries:** standard VAT rate on goods ranges from 17 – 25 per cent. Italy applies a reduced VAT rate at 4 per cent on pesticides; Cyprus, Poland, Portugal, Romania, Slovenia and Spain all apply a reduced VAT rates; and Switzerland a reduced VAT rate on pesticides at 2.5 per cent.
- **Republic of Korea:** Pesticides are VAT exempted.
- **United States:** Complex set of exemptions from sales taxes for pesticides.
- **Thailand, Kenya, India:** General and import taxes on pesticides exempted or at zero rate.

Pesticides for organic agriculture

- **Norway:** Pesticide product applicable under organic farming practices are fully tax exempted.
- **Denmark:** Organic farms are entitled to receive benefits from tax revenues.
- **France:** Introduced a combined tax system with preferential treatment of organic farming practices, whereby a reduced tax rate on "organic pesticides" is applied.

Pesticide taxes

Few countries currently impose specific taxes on pesticides (UNEP 2020):

- **Denmark:** Since 1996. A new tax system was introduced in 2013, based on the "environmental load index" and sales volumes: the higher the potential risk of a pesticide, the higher the tax, amounting up to 100 per cent of the sales price for high risk pesticides (Hansen 2017).
- **France:** Since 2000. Pesticide tax was updated in 2008, based on the toxicity of the pesticide and its sales volume, ranging from 0.9 – 5.1 EUR/tonne, amounting to up to 5-6 per cent of the sales price for the most toxic pesticides (OECD 2017)
- **Norway:** Since 1988. Tax rate is based on environmental and human health risks of the pesticide, and recommended use per hectare; in 2015 it ranged from 1 – 21 EUR/ha for farming, and higher for domestic use (Böcker & Finger 2016).
- **Sweden:** Since 1984. Flat rate of (in 2015) 3.6 EUR/kg of active ingredient (Böcker & Finger 2016).
- **Mexico:** Since 2014. Tax rate of 6 – 9 per cent based on acute toxicity, classified according to the GHS (Servicio de Administración Tributaria 2020).
- **Mozambique:** Import fee varying according the pesticide acute toxicity class, ranging from 0.15 – 0.2 per cent of the FOB value of the pesticides (Government of Mozambique 2007).
- **Kenya:** Import fee of 0.8 per cent of FOB value of the pesticides; part of the revenues is used for training and inspections (Pest Control Products Board 2020)

The adoption of pesticide taxes has been constrained primarily by concerns about the negative impact on competitiveness in global markets.

In terms of the tax rate applied, countries increasingly classify pesticides according to their public health and environmental risks or hazards and assign a specific tax rate accordingly. For instance, Denmark, France and Norway have adopted different tax rates per active substance, reflecting these substances' toxicity to the environment and human health and taking into the account characteristics such as degradability in soils, bioaccumulation and leaching potential. There is no international consensus on how to categorize such relative risks (UNEP 2020b) (Box 2.7-4).

The impact of pesticide subsidies and taxes on pesticide use and impacts

The available literature remains largely divided on the economic benefit-cost ratio of pesticide subsidy programmes. The drawbacks include high fiscal costs, mismanagement of funds, appropriation of subsidies by local elites, and ineffectiveness in reaching poor smallholder farmers. At the same time, agricultural input subsidies generally lower the per unit variable cost of pesticides and create incentives to increase the intensity of input use, with potentially harmful consequences for the environment and the health of farmers and consumers (UNEP 2020b).

Possibly due to their limited current use, few if any recent studies appear to have been conducted on the economic – as well as environmental and health – impacts of direct and indirect pesticide subsidies (unlike the impacts of fertilizer subsidies, which have been studied more widely). Neither does the effect on farmer revenues and agricultural production of abandoning pesticide subsidies seem to have been much studied; no examples of significant declines in production or higher food prices were found. Overall, the costs and benefits of pesticide subsidies are unclear.

It is also challenging to assess the impacts of pesticide taxes, given their relatively recent introduction in only a handful of countries. These impacts depend on tax design, including the structure of the incentives created, the tax rates adopted, demand price elasticity, and precision in targeting, among other factors. Moreover, as countries often introduce a complex package of policies to address the use and management of pesticides, it is difficult to disentangle the contributions of specific instruments from the impact of the wider policy package (Lee, den Uyl and Runhaar 2019; UNEP 2020b).

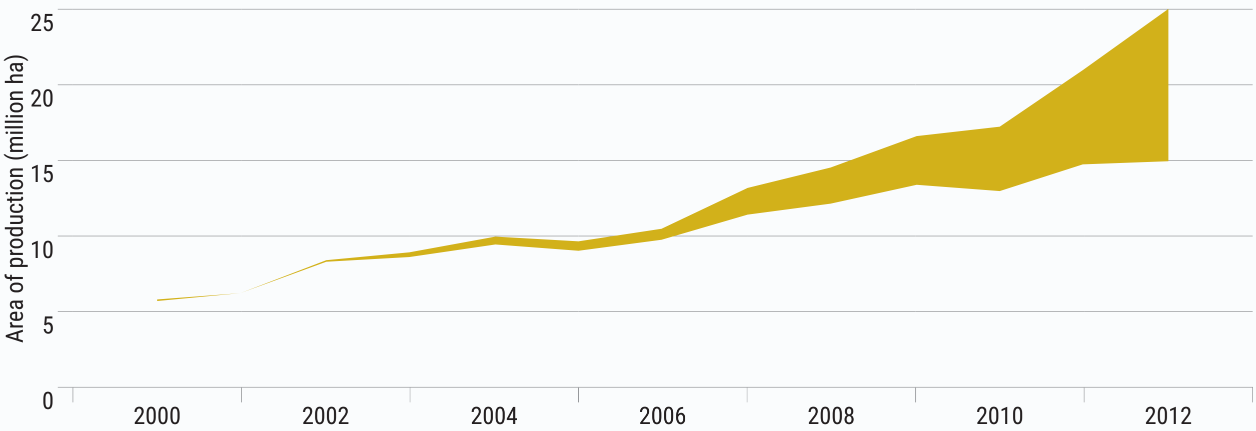
Several studies suggest that the overall impact of these taxes as currently designed has been rather limited, and that there is a broad perception that existing tax rates have been too low to foster significant changes in the use of pesticides or their environmental or health impacts (Böcker and Finger 2016; OECD 2017; UNEP 2020b). However, reductions in the risks of pesticide use have been associated with the introduction or strengthening of pesticide taxes in Denmark and Norway (Hansen 2017; UNEP 2020b).

The effectiveness of pesticide taxes in reducing the use of harmful products depends on various factors, including price elasticities which vary depending on the product type, time frame and type of farming. The elasticity of demand for pesticides is generally low (i.e., changes in pesticide purchasing by farmers are not very responsive to price changes). Experiences in European countries further highlight the importance of revenue redistribution mechanisms in ensuring acceptance of the tax (UNEP 2020b). In reviewing policy instruments for pesticide use reduction in Europe, Lee, den Uyl and Runhaer (2019) found that imposing pesticide taxes in isolation was not particularly effective. Dedicated taxes did result in pesticide use reductions in combination with one or two additional policy measures, such as training, advisory services or regulations.

2.7.12 Voluntary sustainability standards

Voluntary Sustainability Standards (VSS) (sometimes referred to as private standards) are standards that specify requirements for a product or a process that producers, traders or retailers need to meet in relation to sustainability indicators. These requirements can include respect

Figure 2.7-5 The global area of cropland under VSS certification has been increasing rapidly. Tayleur *et al.* (2017).



Note: Data are for 12 major certification standards; since multiple certifications can apply to the same area of land, the minimum and maximum range is shown.

for basic human rights, workers' health and safety, the environmental impacts of production, and land use planning (FAO 2017; United Nations Forum on Sustainability Standards 2020). VSS have been developed by the private sector, governments, non-governmental organizations, and through multi-stakeholder initiatives, often in response to pressures from consumers.

Contrary to mandatory governmental measures, a producer's decision to participate in and comply with VSS is voluntary, although demand-led pressure from buyers can make the producer's choice to adopt a VSS less discretionary. Compliance with these standards by producers and other market actors is normally monitored through third-party certification.

Rewards for adoption of VSS by producers range widely. They include price premiums for the production of certified products, greater market access, and training and support for production and marketing (Smith *et al.* 2019).

The total area under certification for VSS has been increasing rapidly (from approximately 5.7 million hectares in 2000 to 15-25 million hectares in 2012, or about 11.0 per cent annually) (Figure 2.7-5). Across all crops overall coverage has remained low, at just 1 per cent of global cropland (Potts *et al.* 2017; Tayleur *et al.* 2017). However, in the case of certain crops a relatively large percentage of production volume was certified in 2014: for example, cocoa (30 per cent), oil palm (20 per cent), coffee (19 per cent), tea (18 per cent) and bananas (12 per cent). On the other hand, for major crops such as wheat, rice, maize, soybean and cotton certification levels were at a maximum of 1 per cent of production volume (Potts *et al.* 2017).

Many standards include IPM, the prohibition of certain pesticides, and pesticide use monitoring as part of their requirements. They can therefore influence pesticide use and resulting risks (Table 2.7-7). Nevertheless, it has been argued that those who adopt voluntary standards are faced with the dilemma that pesticide inputs are often directly related to (increased) yields. Consequently, there appears to be some reluctance to explicitly require that pesticides are used only as a last resort. Potts *et al.* (2017) found that the degree of obligation to meet this requirement was only 48 per cent across the 15 VSS reviewed.

Most VSS have systems in place to monitor their success towards achieving sustainability goals. However, few published reports of these standards' economic, environmental or social effectiveness meet rigorous scientific requirements (DeFries *et al.* 2017; Oya, Schaefer and Skalidou 2018). Out of 24 cases

Table 2.7-7 **Selected pest and pesticide management requirements of major voluntary sustainability standards.**

Fairtrade (2014); IFOAM – Organics International (2014); DeFries *et al*. (2017); Potts *et al*. (2017); Tayleur *et al*. (2017); Better Cotton Initiative (2018); GlobalG.A.P. (2018); Fairtrade (2019); Rainforest Alliance (2020).

Standard	Major crops	Requirements			
		IPM as required approach (pest/ disease monitoring, pesticides used as last resort)	Pesticide restrictions (not all registered pesticides allowed for use)	Occupational health (e.g. PPE, training, washing facilities)	Pesticide use monitoring (record keeping for pesticide applications)
IFOAM – Organics International (organic)*	Bananas, cereals, coffee, cocoa, oilseeds	Organic production	Yes (all prohibited except those on the list of allowed crop protectants)	Yes	Yes
Rainforest Alliance/UTZ	Bananas, coffee, cocoa, tea, palm oils	Mostly	Yes (lists of prohibited and risk mitigation use pesticides]	Yes	Yes
Fairtrade	Bananas, coffee, cocoa, tea	Mostly	Yes (hazardous materials list: Red List = prohibited, Orange List = restricted, Yellow List = flagged)	Yes	Yes
Better Cotton Initiative (BCI)	Cotton	Partly	Yes (prohibition of Stockholm Convention, Rotterdam Convention and Montreal Protocol listed pesticides; phase out of pesticides with other Highly Hazardous Pesticide [HHP] criteria)	Yes	Yes
GlobalGAP	Bananas	Yes	No [national registration]	Yes	Yes

* In many countries organic production standards have been included in legislation, in which case they are no longer voluntary.

of implementation of sustainability standards reviewed by DeFries *et al*. (2017), 36 per cent of environmental impact indicators showed a positive effect while 64 per cent showed no significant effect. This study did not assess pest and pesticide management parameters.

It can be expected that even partial implementation of pest and pesticide management requirements will lead to a reduction in adverse effects on the environment and human health. So far, however, no systematic evaluations of the effects of VSS on pesticide use, or on pesticides' adverse effects, have been made.

Private food safety standards are a particular type of VSS. These standards are generally established by private firms (e.g., large retailers or brand owners) or standard-setting coalitions (e.g., GlobalG.A.P or SQF 1000) operated by retailer associations (Hensen and Humphrey 2009; Ecratum 2020).

Among the main drivers of private food safety standards are demonstration of due diligence by food chain operators to ensure food safety; global sourcing and the need for improved supply chain management; heightened consumer interest in food safety; and the possibility for individual food firms to distinguish themselves on the market (although there is general agreement that food safety should not be used by the food industry as a competitive tool) (Clarke 2010).

In general, collective private food standards refer to prevailing official pesticide residue regulation and do not set additional requirements. However, private pesticide residue provisions may also be stricter than corresponding Codex Alimentarius provisions and national regulations. In particular, private retail labels may impose more stringent maximum residue limits or impose limitations on the total number of residues present on the food, neither of which is generally based on scientific considerations (Clarke 2010). It is therefore not clear cut whether private food standards significantly reduce the risks of pesticide residues to consumers.

There is an ongoing debate about the impact of private standards on small producers that might be excluded from access to the market. It is easier for bigger producers to make the investments to meet certain requirements, putting small producers at a disadvantage. This is likely to lead to "winners" and "losers" in a world where increasingly strict food safety requirements – driven by both the public and private sectors – need to be complied with. In practice, it has been found difficult to separate out the specific impacts that private standards could have on developing countries' food commodity exports from a host of other factors (Hensen and Humphrey 2009).

Public health drivers

2.7.13 Food safety

Limiting the levels of pesticide residues in food and drinking water has been an important driver for regulating and restricting the use of pesticides. Maximum residue limits (MRLs) (or tolerances) have been established for many pesticide-commodity combinations, with the aim of enforcing good agricultural practices (Chapter 4.4.6). The establishment of MRLs in major importing countries, such as the EU Member States, the United States and Australia, has also had a wide influence on pesticide use in countries exporting agricultural commodities. This also holds true for countries where national MRLs may not have been established (yet) or are insufficiently enforced.

On the other hand, pesticides may also be used to increase food safety. This is the case, for instance, if they are used to control the production of mycotoxins such as aflatoxins and ochratoxin A in food. These mycotoxins, which may be formed by fungi (moulds) that grow on numerous foodstuffs such as cereals, dried fruits, nuts and spices, can cause severe acute and chronic health effects. Fungicides and insecticides may be applied to control fungi that produce mycotoxins, although the extent to which this results in major increases in pesticide use is not known.

Overall, food safety issues most likely lead to a reduction in pesticide use.

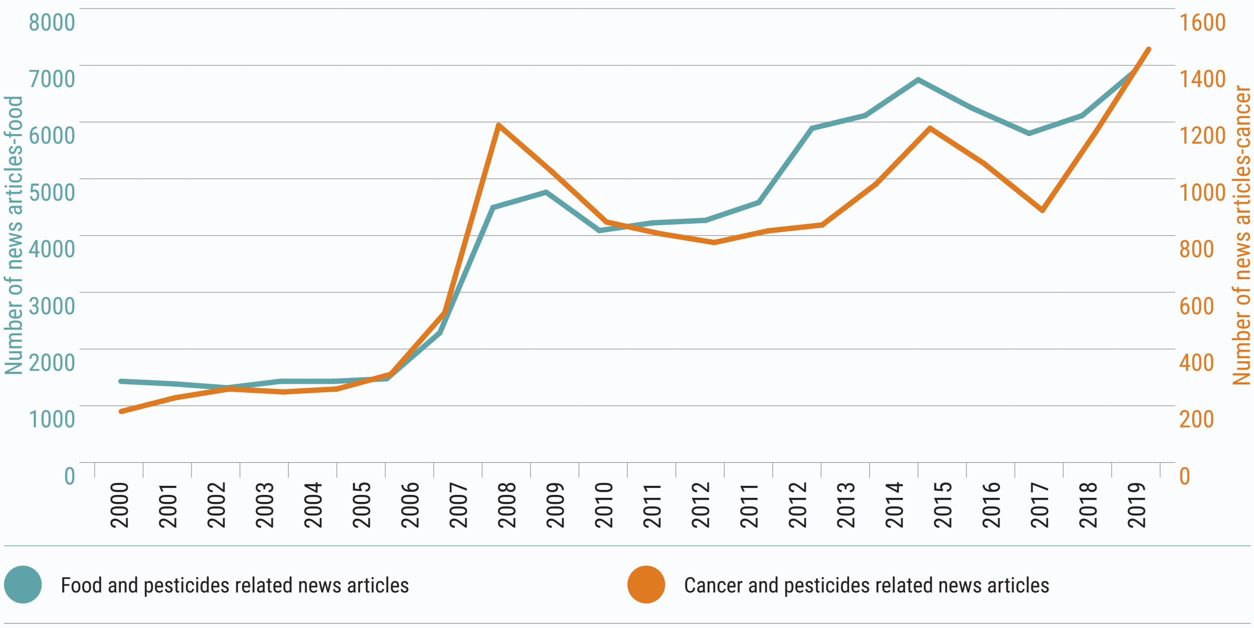
2.7.14 Public concerns about human health

Public concerns about the effects of pesticides on human health and food safety have been voiced almost as long as synthetic pesticides have been used (Dunlap and Beuss 1992).

The presence of pesticide residues in fruit, vegetables or cereals was found to be the overall highest concern in EU Member States in 2010: 31 per cent of citizens were very worried about this issue and 41 per cent were fairly worried, an increase compared to 2005 (EC 2010). In India, 62 per cent of respondents in a wide survey felt that pesticide residues were associated with high or medium human health risks (Khrishna and Qaim 2008). More recently, pesticides, chemicals and toxins were seen as the greatest threat to food safety by German consumers (Koch *et al.* 2017). In a national survey on perceptions of environmental public health risks in the United States, 31 per cent of adults indicated they were concerned about the health risks posed by pesticides (Shin *et al.* 2019).

Pesticides and food have also figured prominently in newspaper reports. Since the early 2000s the number of articles published globally on this topic in English has increased almost five-fold, from 1,400 to 6,200 per year (Figure 2.7-6).

Figure 2.7-6 Public health concerns in the news. Shown are the number of newspaper articles about food and pesticides as well as cancer and pesticides, published annually over the last 20 years.



Data obtained from the NexisUni database (LexisNexis 2020) using the search terms *pesticid* AND food and pesticide* AND cancer*, for newspaper articles published globally in English.

Health concerns that have received much public attention include pesticide drift to residential areas and chronic health effects such as cancer or neurotoxic reactions, both in high income countries (Horan 2015; BNNVARA 2019; Faux 2020) and low and middle income countries (Route to Food 2019). As an example of greater public interest in pesticides and public health, the number of newspaper articles about pesticides and cancer almost quadrupled over the last 20 years (Figure 2.7-6).

Increased public concerns about pesticides and health or food safety have clearly been an important incentive for governments around the world to tighten pesticide legislation and improve monitoring controls.

2.7.15 Vector-borne diseases

Vector-borne diseases, which account for an estimated 17 per cent of the global burden of communicable diseases, claim more than 700,000 lives every year. The burden is highest in tropical and subtropical areas, with malaria the most important disease. More than 80 per cent of the world population is also at risk of other vector-borne diseases such as dengue, chikungunya leishmaniasis, Chagas disease, schistosomiasis and lymphatic filariasis. Others such as Lyme disease and tick-borne encephalitis, are spreading rapidly in temperate regions (WHO 2017).

While the overall volume of insecticides used for human disease control seems to have decreased, this is largely due to the replacement of high volume organochlorines and organophosphate insecticides by low volume pyrethroids and neonicotinoids (Chapter 2.4.3).

Given the recent alarming resurgence of certain vector-borne diseases such as dengue and Zika, and the serious threat they pose to public health and economic development, the World Health Assembly adopted a Global Vector Control Response 2017-2030 (WHO 2017). It aims to reposition vector control as a key approach to reduce mortality and prevent, control and eliminate the burden of vector-borne diseases. One of the pillars of action of this strategy is to scale up and integrate vector control tools and approaches. It can therefore be expected that the use of insecticides for vector control, including insecticide-treated nets, will increase. The resurgence of some vector-borne diseases is exacerbated by the widespread increase in the frequency and intensity of insecticide resistance observed in several disease vectors, especially mosquitos, the world over (Chapter 4.3.3).

The volume of pesticides used for vector control equals less than 0.5 per cent of the volume of pesticides used in agriculture (Chapter 2.4.3). Thus even a considerable increase in their application will have a limited impact on the quantity of pesticides used globally. Nevertheless, since much vector control is conducted in or close to human habitations, the possible human health risks of vector control pesticides merit specific attention.

Environmental drivers

2.7.16 Climate change

The impact of climate change on agricultural The impact of climate change on agricultural production and food security has been an increasing focus of research. Climate change affects agriculture in many ways, which vary from one region to another. Increasing temperatures and changes in precipitation lead to shifts in the location and incidence of pest outbreaks, as well as the types of pests concerned. Assessing the consequences of climate change with regard to crop losses due to pests is complex, as these losses result from interactions among effects on plant vigouur (due to abiotic stressors), crop yields, pest population changes, and pests' natural enemies (Gregory *et al*. 2009).

Deutsch *et al*. (2018) modelled crop production losses for rice, maize and wheat due to insect pests and found that global yield losses of these grains would increase by 10-25 per cent per degree of global mean surface warming. Losses would be most acute in in temperate regions, where most of these cereals are produced.

Based on published observations of more than 600 insect pests and pathogens, Bebber *et al*. (2013) assessed global shifts in their latitudinal ranges since 1960. They found a significant trend of increasing numbers of pest and pathogen observations at higher latitudes, globally and in both the northern and southern hemispheres. The mean shift in detection since 1960 (26.6 km per decade) was more rapid than that reported for many wild species (17.6 km per decade), but was nearly identical to that expected as a result of temperature changes (27.3 km per decade).

The responses of forest insect pests to climate change were recently reviewed by Jactel, Koricheva,and Castagneyrol (2019), who noted that the complex interplay between abiotic stressors, host trees, insect herbivores and their natural enemies makes it very difficult to predict the overall consequences of climate change for forest health. However, most of the responses of forest insect herbivores to climate change were expected to be positive, with shorter generation time, higher fecundity and greater survival, leading to increased range expansion and outbreaks. The observed positive latitudinal trends in many taxa support the hypothesis of global warming-driven pest movement.

Wilke *et al*. (2019) argue that due to global warming arthropod vectors of human disease (e.g., mosquitos, ticks and sandflies) will expand their ranges, as they will be able to colonize new areas including urban environments and be present for extended periods during the year. This, in turn, will likely drive an increase in the incidence of vector-borne diseases.

Overall, among the main impacts of climate change on agriculture are increased incidence of drought and extreme weather events, more intense pest and disease pressures, and loss of biodiversity. Changes in pest-crop complexes mean there will be a need to better understand the changes that may occur in pest management methods, including management of both synthetic and biological pesticides. Moreover, climate change will increase the potential for movements of pests and diseases, as well as movements of products, from one country to another (FAO 2016).

It is likely that such climate change-driven changes in pest incidence will result in greater pesticide use in agriculture, especially in intensive agriculture environments, and to protect public health (Delcour, Spanoghe and Uyttendaele 2015; Deutsch *et al*. 2018).

2.7.17 Invasive species and pest outbreaks

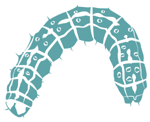
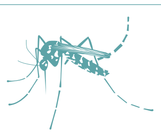
Invasive alien species are species that have been intentionally or accidentally introduced into a new ecosystem. They can become problematic for biodiversity, human health, and agriculture as well as other human activities. Invasive species are a driver of biodiversity loss (International Union for Conservation of Nature 2020) and can be a major cause of crop losses (Paini *et al*. 2016). Greater globalization and connectedness increase the threat that invasive species will arrive in countries where they were previously absent.

A recent review of the global threat to agriculture from invasive species indicated that countries which are large agricultural producers (e.g., Brazil, China, India, the United States) will experience the highest potential costs from invasive species. However, the countries with the highest costs from invasive species relative to their GDP were all developing ones, with the top six most vulnerable located in sub-Saharan Africa (Paini *et al*. 2016). Examples of recent serious invasive pests include the Asian tiger mosquito, Panama disease and parthenium weed (Table 2.7-8).

A much publicized case is the spread in Africa of the fall armyworm (Spodoptera frugiperda), a moth indigenous to the Americas which feeds on over 80 different crops including maize, rice, sorghum and sugarcane. The fall armyworm has been reported to cause potential maize yield losses estimated at between USD 2.5 billion and US 6.2 billion per year in just 12 of Africa's maize-producing countries (Day *et al*. 2018). Its invasion of Africa and massive crop losses have led to important government-sponsored control campaigns using large volumes of pesticides (Hruska 2019). In most cases, however, maize yield reductions tend to be much lower, typically ranging from 10 to 30 per cent, and more sustainable pest management approaches are now being developed and implemented (Hruska 2019).

The often sudden appearance of invasive species in agriculture, or in relation to public health, tends to lead to sharp increases in pesticide use in an

Table 2.7-8 Some examples of recent serious invasive pests. Centre for Agriculture and Bioscience International (CABI) (2020).

Species		Origin	Current presence	Economic importance
	Fall armyworm (*Spodoptera frugiperda*)	Tropical and subtropical Americas	Africa, Asia	Damage to maize, rice, sorghum, sugarcane and wheat, as well as other vegetable crops and cotton
	Asian tiger mosquito (*Aedes albopictus*)	Southeast Asia, the Pacific, China, Japan and Madagascar	North and South America, Africa, Australia and Europe	Transmission of many human viral diseases, including dengue, West Nile virus and Japanese encephalitis
	Panama disease (*Fusarium oxysporum* f.sp. *cubense*)	Southeast Asia	Asia, Africa, the Americas, Oceania	TR4 isolates of the pathogen threaten production of Cavendish banana cultivars, which produce the bulk of global exports
	Parthenium weed (*Parthenium hysterophorus*)	Americas	Africa, Asia, Europe Oceania	Major weed in rangeland and field crops
	Melon fly (*Bactrocera cucurbitae*)	India (Southeast Asia is its natural range)	Africa, Oceania, Hawaii	Very serious pest affecting cucurbit crops

Box 2.7-5 **The desert locust upsurge, 2019-2020.** FAO (2020d); Cressman, K., FAO (personal communication).

Desert locust upsurges are not a new phenomenon. Locusts are one of the oldest migratory pests in the world. They have wreaked havoc on crops across the globe for centuries. When large swarms infest many countries and spread across several regions or continents, it becomes a plague.

The recent desert locust upsurge (see map)

In **2018** two cyclones brought heavy rains that gave rise to favourable breeding conditions in the Empty Quarter of the southern Arabian Peninsula. As a result, three generations of desert locust breeding occurred, causing an 8,000-fold increase in locust numbers.

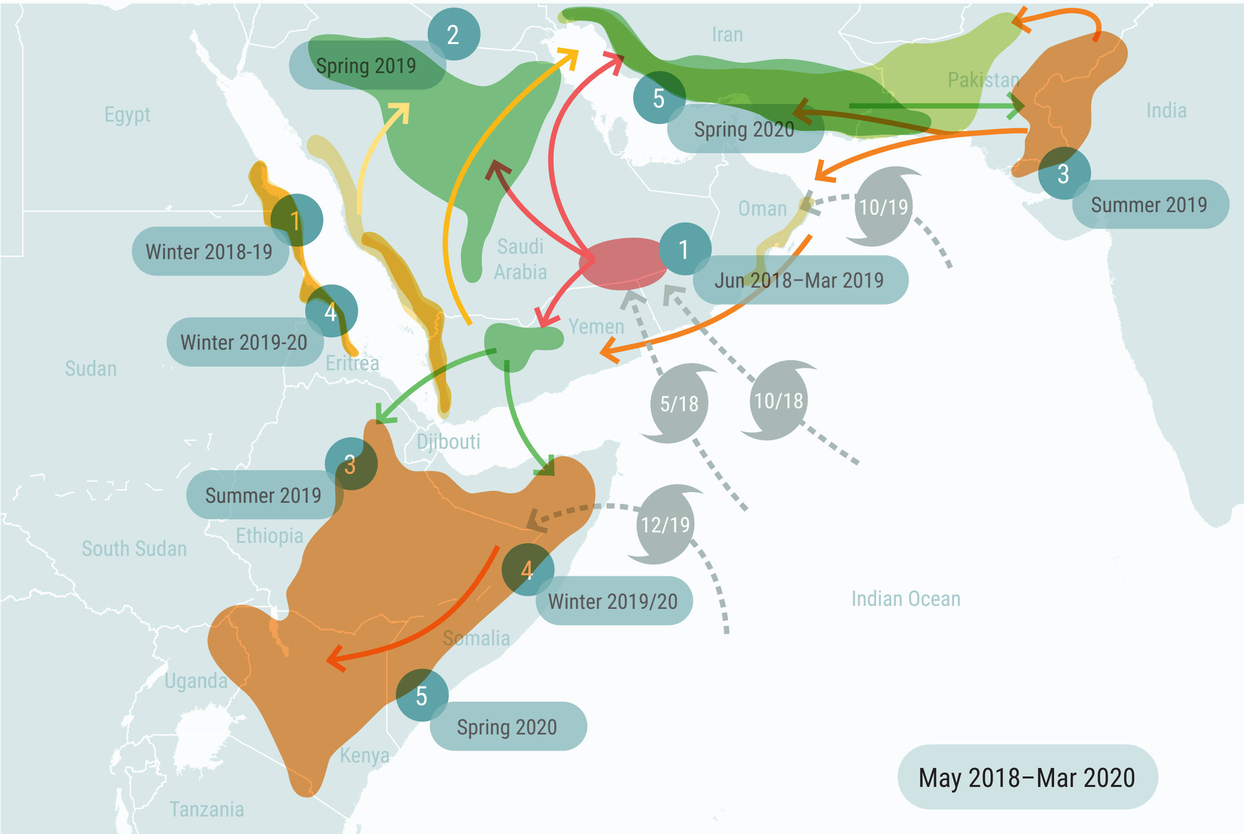
In **2019** locust swarms reached Saudi Arabia, Iran, and Yemen where widespread breeding occurred during the spring. Later that year, swarms invaded the Indo-Pakistan border and also migrated to Somalia and Ethiopia.

© FAO/Sven Torfinn, Walking through a Desert Locust swarm

Despite control operations, massive waves of swarms invaded Kenya in late 2019 and early 2020, and other swarms moved to Eritrea and Djibouti.

During the first half of 2020 two generations of breeding occurred in Ethiopia, Kenya and Somalia as well as in Iran and Pakistan. A few swarms invaded Uganda, the Democratic Republic of the Congo, and South Sudan. In June, swarms started to migrate from the spring to the summer breeding areas.

As a result of the desert locust upsurge, which affected parts of the Horn of Africa and South-West Asia, by mid-2020 an estimated 20 million people were facing severe acute food insecurity.



Given the scale of the locust outbreak, large control operations have been set up by the governments concerned, with support from bi- and multilateral donors and with technical support from FAO.

Between December 2019 and May 2020 approximately 1.4 million hectares were treated with insecticides. Most of these were synthetic chemical insecticides, primarily organophosphates and pyrethroids.

Biocontrol against locusts is conducted using the entomopathogenic fungus *Metarhizium acridum*. Insect growth regulators can also be used and are more target specific than broad-spectrum insecticides.

However, the scale of interventions with such less hazardous products is limited, primarily because they are applied only against the larval stages of the locust, and the operational logistics are more complex.

attempt to control these organisms. Chemical pesticides tend to be the first control measure of choice, as they can be procured and distributed rapidly and can bring about short-term reductions in pest populations. For instance, Pozebon *et al*. (2020) reviewed arthropod invasions in soybean in Brazil and concluded that the introduction of whitefly (Bemisia tabaci complex), two-spotted spider mite (Tetranychus urticae) and cotton bollworm (Helicoverpa armigera) likely led to significant increases in the total amount of insecticide and acaricide used in the country, as well as increased insecticide input per area. They also showed that depending solely on chemical control increased the likelihood of establishment of the invasive pests due to adverse effects on their natural enemies and the development of resistance.

Few invasive pests in agriculture have been controlled through the use of chemical pesticides alone. More sustainable and long-term control often involves the introduction of resistant crop varieties and biological control agents, or the development of integrated pest or vector control approaches. The spread of invasive species can therefore also be an opportunity for research on and development of non-chemical pest management techniques. This will occur especially after the emergency of the invasion has passed and/or the species has established itself to stay.

Endemic pests may also lead to pest outbreaks, even if such organisms have been present in a region for a long time. One of the best known examples is the desert locust (Schistocerca gregaria), which is endemic to semi-arid and arid deserts of northern Africa, the Near East and Southwest Asia where it generally does not pose any risks to crops. During outbreaks the desert locust becomes gregarious, increases in population size and invades much larger areas, where it can cause great damage to crops. The desert locust outbreak in 2019 spread to the Horn of Africa and Southwest Asia (Box 2.7-5). Although the quantities of insecticide used to control such locust upsurges are only a small fraction of global insecticide use, they may constitute a significant increase in pesticide consumption by the countries directly concerned. Furthermore, pest outbreaks such as that of the desert locust may require large numbers of pesticide applicators with no or limited training and experience to be recruited, increasing risks to human health as well as the environment.

2.7.18 Public environmental concerns

As in the case of public health, environmental concerns have also partly shaped the regulation and risk assessments of pesticides and, indirectly, the types and quantities of pesticides used.

The importance of the United States biologist Rachel Carson's path-breaking Silent Spring (Carson 1962), which described the environmental effects of DDT and other organochlorine pesticides, is well known. Public concerns about the environmental effects of many other groups of pesticides followed its publication. More than half a century later, recent scientific and public debates have concentrated on neonicotinoid insecticides and their effects on pollinators and aquatic organisms.

Surveys of the environmental concerns of European citizens show that agricultural pollution (defined as "the use of pesticides, fertilizers etc.") is consistently cited among the most important environmental issues, and that concerns about this issue have increased in the last decade (EC 2011; EC 2014; EC 2020b) (Figure 2.7-7).

There has been a clear and steady increase in the number of published newspaper articles about the environment and pesticides during the last two decades (Figure 2.7-8). A specific example is the steep rise in the number of articles about the environment and honeybees since about 2005, when colony collapse disorder began to be reported and pollinator population reductions were linked to pesticide use.

Public environmental concerns have contributed over time to increased scientific and regulatory scrutiny of certain pesticides and subsequent halting or restriction of their use. For example, local authorities in some countries are moving away from the use of herbicides in public spaces and adopting alternative approaches to control unwanted vegetation.

Figure 2.7-7 Environmental concerns of European citizens. The percentage of respondents who considered "the use of pesticides, fertilizers, etc" an important environmental issue has slightly increased since the mid-2000s. EC 2011; EC 2014; EC 2020b).

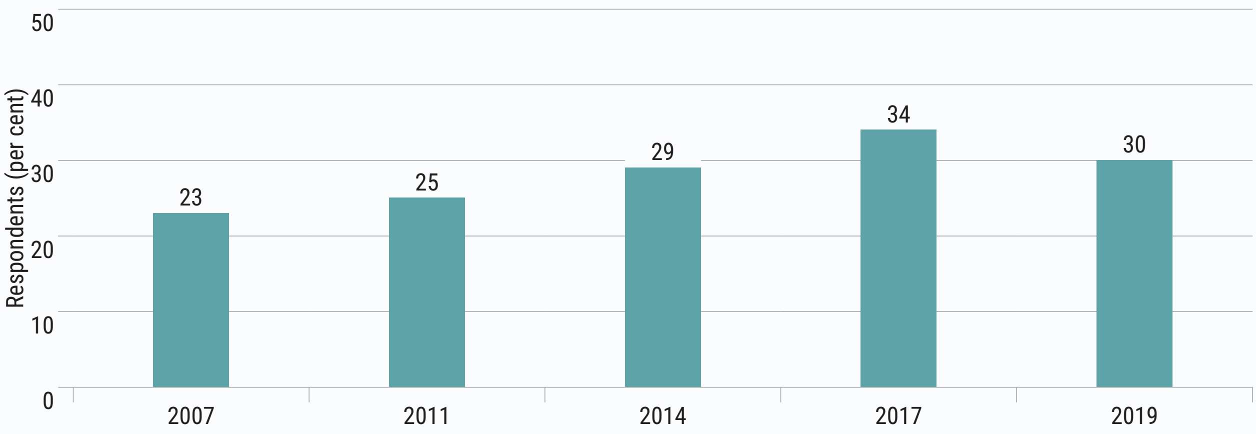
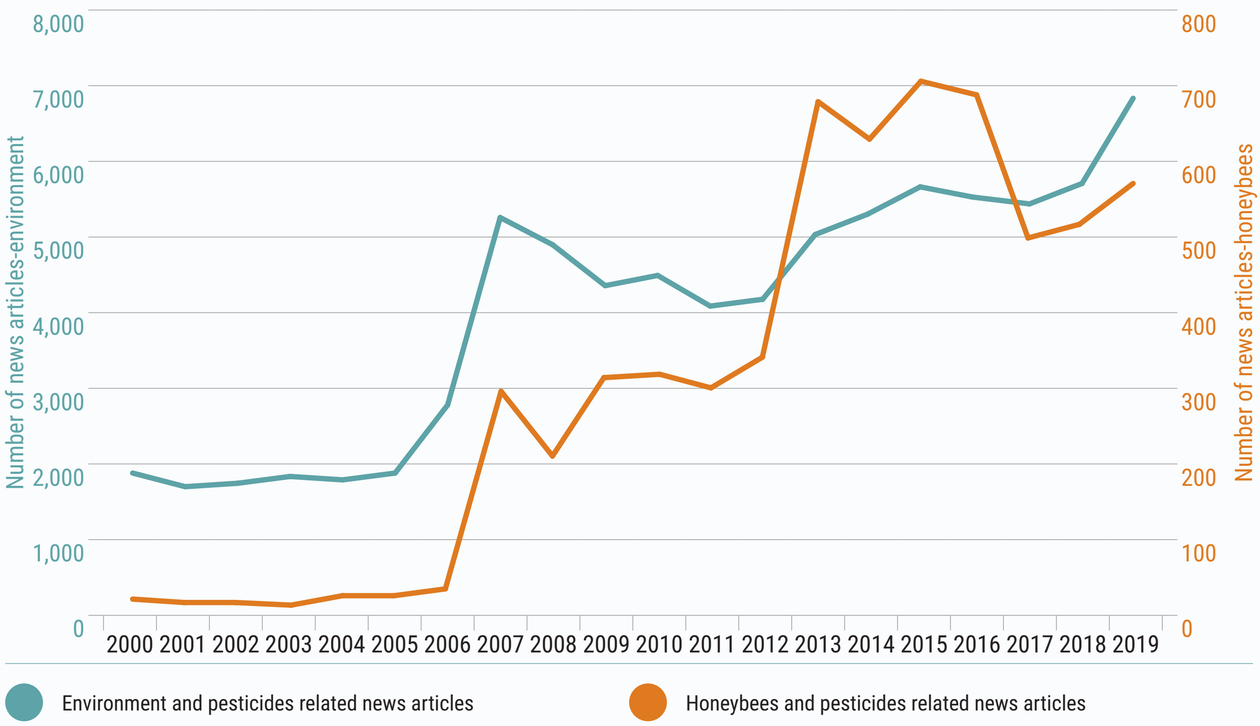


Figure 2.7-8 Environmental concerns in the news. Shown are the number of newspaper articles about the environment and pesticides, and honeybees and pesticides, published annually in the last 20 years.



Data obtained from the NexisUni database (LexisNexis 2020) using the search terms *pesticid* AND environment and pesticide* AND* (*honeybee* or* "*honey bee**"), for newspaper articles published globally in English.

Information drivers

The information that pesticide users and others have or lack, for example about whether it is necessary to use pesticides, other pest management options, pesticide risks, and precautionary measures, influences the use of pesticides and of alternative approaches.

2.7.19 Information sources

The information sources available to farmers and other pesticide users may increase or reduce pesticide use. Information about pest management and pesticides is obtained from various sources, including agricultural extension and advisory services, research institutions, pesticide retailers, pesticide distributors that conduct demonstrations and information sessions, other farmers, and (more recently) public and private digital information providers.

In many countries public extension and advisory services reach only a limited number of farmers, a situation which has worsened in recent decades due to government budget cutbacks and privatization policies. However, farmers increasingly receive technical information from private advisory services or from pesticide distributors and retailers. As most smallholder farmers in low and lower-middle income countries do not have access to private advisory services, information about pest management options in these countries is mainly obtained from pesticide shops and other retail outlets. Recent examples are provided by Haj-Younes, Huici and Jørs (2015) (Bolivia); Jin, Bluemling and Mol (2015) and Sun *et al*. (2019) (China); and Okonya and Kroschel (2015) (Uganda).

It is important for pesticide retailers to give adequate technical advice on the judicious handling and use of the products they sell. Nevertheless, if they are the main information sources influencing farmers' pest management choices, there is a risk that their advice will be biased towards the pesticides they sell rather than alternative pest management options. Independent advisory services may be likely to provide more objective information, including about different (integrated) pest management approaches.

The impact of information sources on the choice of pest management options has not been systematically reviewed, but various studies indicate that information bias does affect farmers' pesticide use. Schreinemachers *et al*. (2017), who studied vegetable farmers in Cambodia, Laos and Viet Nam, observed that those who sought advice from friends and neighbours used 45 per cent less pesticides, while those who sought advice from pesticide shopkeepers used 250 per cent more than the average. They also calculated that the risk of pesticide overuse was lower if farmers had received advice from extension agents and significantly higher if the advice came from pesticide retailers (Schreinemachers *et al*. 2020). In Ghana, Anang and Amikuzuno (2015) found that a higher number of extension contacts tended to reduce the use of pesticides in rice farming. In Hebei Province, China, 87 per cent of smallholder farmers used double or more the recommended amount of pesticides on cotton; farmers who received information mainly from pesticide retailers applied pesticides at 20-70 per cent higher rates than those who were part of a cooperative with extension support and also applied pesticides twice as often (Jin *et al*. 2015). Similar results were found in an analysis of pest management recommendations in Beijing Municipality, China. Although chemical pest management was emphasized by both business-linked and independent extension workers, business-linked advisors recommended the use of pesticides 18 per cent more often than advisors who were not business-linked (Wan *et al*. 2019).

2.7.20 Knowledge, awareness and attitudes

Improving pesticide users' knowledge about proper handling and application of pesticide products, and creating awareness of their risks to the environment and human health, are often considered essential for risk reduction. However, while training farmers and other pesticide users generally succeeds in increasing knowledge about good pesticide application and awareness of risks, knowing about precautionary measures and risks does not necessarily lead to effective changes in behaviour and use of good practices, as demonstrated in reviews by Remoundou *et al*. (2014) and Ricci *et al*. (2016). Schreinemachers *et al*. (2017) reported that in Cambodia, Laos and Viet Nam pesticide use was not reduced by previous training in pest management, greater awareness of adverse health effects, or good agricultural practices.

It is often found that despite farmers having considerable knowledge about (and a positive attitude towards) the use of personal protective equipment (PPE), they may use this equipment to a limited extent if at all (Pasiani *et al*. 2012; Remoundou *et al*. 2014; Yuantari *et al*. 2015;

Gesesew *et al*. 2016). The reasons include lack of availability, high cost, discomfort, habits of personal behaviour and limited social acceptability, among others).

Farmers' knowledge about pests and their natural enemies, and a basic understanding of pest ecology in a crop, have been shown to influence pesticide use. Wyckhuys *et al*. (2019) reviewed the "ecological literacy" of farmers (i.e., their understanding of insect pests and their natural enemies). They found that globally, across studies, farmers' dependency on synthetic insecticides showed a downward (although statistically non-significant) trend with increasing ecological literacy and increasing levels of technical knowledge. In a separate study on vegetable farmers in Cambodia, Laos and Viet Nam, Schreinemachers *et al*. (2017) found that greater knowledge of beneficial and harmful arthropods was associated with lower levels of pesticide use.

Gender differences in knowledge about pest management and pesticide use are also often observed. Women and men from the same community may perceive the identity and importance of pests in different ways; men and women may also apply different control methods; or women may not be invited to participate in training about the judicious pesticide use (Kawarazuka *et al*. 2020). For instance, Ochago (2018) found that men and women coffee farmers in Uganda were equally aware of the adverse effects of pesticides on human health, but more men than women were knowledgeable about pest control methods including IPM.

However, addressing gaps in women farmers' knowledge is not necessarily sufficient to improve pest management, as these may also be limited by gender-related socio-economic constraints. For instance, a study conducted in Ethiopia showed that women farmers were unable to spray their potato fields, primarily due to less access to financial resources than men; this in spite of having been included in training exercises (Damtew *et al*. 2020).

A focus on quick-fix solutions to pest and disease problems may lead to increased pesticide use. Farmers and other pesticide users throughout the world are inclined to choose rapidly acting pesticides, with clearly visible results, as a preferred pest management approach (Alwang, Norton and Larochelle 2019). This is especially the case if pest control is reactive, attempting to reduce crop damage, rather than preventive, focusing on minimizing the build-up of pest or disease populations. For instance, 66 per cent of vegetable farmers in Cambodia, Laos and Viet Nam agreed with the statement that good pesticides are those that kill all insects immediately (Schreinemachers *et al*. 2017).

In conclusion, information and knowledge are rarely the only drivers of pesticide use. Psychological, social, economic and environmental factors play important roles. Providing the right information and building pest management capacity are essential, but are insufficient to change behaviour.

2.7.21 Training

Different types of training are of relevance to pesticide use. Training may focus on reducing the occupational and environmental risks of handling and applying pesticides (sometimes referred to as "safe use training"). This type of training generally does not question the need to use pesticides, but attempts to ensure that they are handled and applied judiciously. At the other end of the spectrum, training is conducted on biointensive integrated pest management or agroecology, which explicitly aim to reduce reliance on pesticides and make maximum use of natural pest management processes.

In some parts of the world pesticide users and retailers are required to successfully complete training as a step towards certification. In many low and middle income countries training is not mandatory before pesticides can be sold or used. Therefore, the large majority of farmers and other pesticide users in those countries will not have had training on judicious pesticide use, let alone broader training on sustainable pest management.

In many cases training on the occupational health and safety of pesticide use has been shown to improve knowledge about pesticide risks, increase pesticide risk perception, and improve attitudes to good pesticide handling and application (Sam *et al*. 2008; LeProvost *et al*. 2014; Ricci *et al*. 2016; Schreinemachers *et al*. 2016; Vaidya *et al*. 2017). Training on pesticide application has sometimes also led to reductions in exposure or health effects. For instance, Levesque, Arif and Shen (2012) found that farm workers in North Carolina (United States) who had received short pesticide safety training were almost five times more likely to wear PPE than those who had not; nevertheless, more than a quarter of the farm workers studied would still not use PPE. Damalas and Koutroubas (2017) found that pesticide safety training not only improved the knowledge and attitudes of cotton farmers in Greece, but was also accompanied by better safety behaviours. Fuhriman *et al*. (2020) observed a 33 per cent reduction in the exposure scores of farm workers in Costa Rica who had received training compared to those who had not.

Reviews of training on (pesticide) occupational health and safety aimed at improving behaviours and reducing risks have generally concluded that the effectiveness of such interventions is low if they take place in isolation (Lehtola *et al*. 2008; Ricci *et al*. 2016). This may be due in part to the often incidental nature of the training and its short duration. Increased knowledge and better risk perception are generally not enough to change behaviours. The gap between knowledge and practice needs to be bridged using a more interactive and participatory training model (Yuantari *et al*. 2015).

A highly participatory model which has been applied to build capacity in integrated pest management is farmer field schools (FFS). This approach emphasizes hands-on learning to improve the skills and knowledge of groups of farmers in order to help them adapt practices to their specific context (FAO 2020e). While FFS have generally succeeded in changing the behaviours of farmers and reducing pesticide use, they are relatively resource and time intensive compared to “classroom” training, demonstrations and media messages. Upscaling of FFS programmes to cover the majority of farmers in a given country or region has taken place to only a limited extent (Waddington *et al*. 2014).

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