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

Envisioning A Chemical-Safe World

Chapter 5 of 12

The environmental, human health and economic impacts of pesticides

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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 "The environmental, human health and economic impacts of pesticides" is the 5th 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

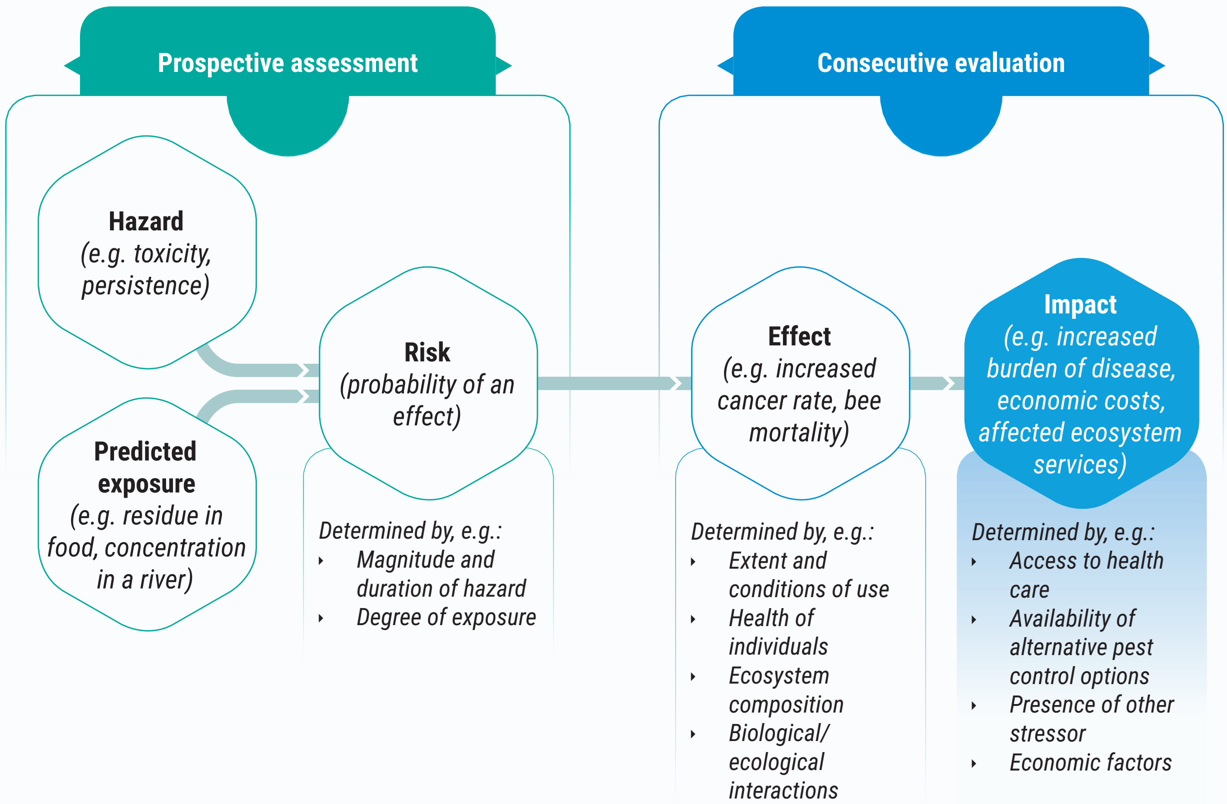
1 The Synthesis report is available at https://www.unep.org/resources/report/environmental-and-health-impacts-pesticides-and-fertilizers-and-ways-minimizing.

The environmental, human health and economic impacts of pesticides

5.1 Overview

In Chapter 4, steps in pesticide evaluation (Figure 5.1-1) were described, from the estimation of hazard and exposure to risk assessment, to impact evaluation. The effects of pesticides on the environment, health and agricultural sustainability were reviewed in that chapter. In this chapter available data about the ultimate impacts of pesticides on the environment and health are evaluated from three different perspectives:

Figure 5.1-1 The environmental and health impact of pesticide use consists of any durable changes in the condition of people or their environment brought about by the (adverse) effect(s) of a pesticide.



the burden of disease; monetary costs; and effects on ecosystem services. The impact of pesticides is defined as a durable change in the condition of the environment or people brought about by their (adverse) effect(s) (Chapter 4, Box 4.2-1).

Pesticides are sold and used because of the benefits they are expected to provide. The potential benefits of pest control (of which pesticides are an instrument) include reduced crop losses, reduced prevalence of human vector-borne diseases, longer shelf life of agricultural commodities, greater livestock yields, reduced soil disturbance, and better protection of wooden structures.

The overall adverse human health impact of pesticides can be quantified as burden of disease. So far, no international estimates are available of the burden of disease caused by pesticides, with the exception of self-poisoning (Prüss-Ustün *et al*. 2016a; Prüss-Ustün *et al*. 2016b; WHO 2016; Landrigan *et al*. 2018; WHO 2019). [Chapter 5.2]

No recent independent global or regional reviews of the economic benefits of pesticide use are available (Dobson 2007; Wiese and Steinman 2020). While the pesticide industry certainly collects information about the costs and benefits of their products internally, such data do not seem to be publicly available for systematic review and independent analysis. [Chapter 5.3.1]

Pesticide use has different types of costs: direct costs, which are all the monetary and non-monetary expenses borne by farmers and other pesticide users; indirect or hidden costs (e.g., occupational health effects, development of pest resistance, or reduction in crop pollination); and external costs or externalities, which are the costs of pesticide use borne by society as a whole (e.g., pesticide regulation, treatment of polluted water, or clean-up of stocks of obsolete pesticides) (Ajayi *et al*. 2002; Bourguet and Guillemaud 2016).

Despite great uncertainties associated with estimates of the indirect environmental and health costs of pesticide use, these costs are likely to be high. The most recent review of annual indirect environmental and health costs, published in 2016, found that they ranged from USD 5.5 million in Niger in 1996 to almost USD 12 billion in the United States in 2005. However, these were considered to be underestimates and to be based on outdated information (Bourguet and Guillemaud 2016). More recent estimates of the health costs of endocrine disrupting pesticides amount to tens of billions US dollars, in both Europe (Trasande *et al*. 2015; Trasande *et al*. 2016) and the United States (Attina *et al*. 2016). [Chapter 5.3.2]

Very few comprehensive assessments are available comparing the overall costs of pesticide use with their estimated benefits (Bourguet and Guillemaud 2016). If indirect costs are not taken into account, benefit-cost ratios at farm level tend to average between 3 and 6 (i.e., USD 1 in expenditure on pesticides and their application yields USD 3-6 in benefits to the farmer) (Fernandez-Cornejo, Jans and Smith 1998; Zilberman *et al*. 1991; Popp, Pető and Nagy 2013; Fernandez-Cornejo *et al*. 2014; Bourguet and Guillemaud 2016). If hidden private costs and externalities are included, benefit-cost ratios are much reduced and in some cases are below 1 (Bourguet and Guillemaud 2016). Most indirect costs are borne by society as a whole. They are generally not taken into account in decision-making about pest control at either the private or government level. [Chapter 5.3.3]

Pesticide use may affect ecosystem services, in particular pollination, soil function, pest regulation, food production and maintenance of future options. There is clear evidence that pesticides adversely affect the natural regulation of pests and other detrimental organisms (MA 2005). High levels of pesticide use also impact pollination (Dainese *et al*. 2019), although it is less clear whether sublethal exposure of pollinators leads to a reduction in pollination services (Kovács-Hostyánszki *et al*. 2016). The circumstances under which pesticide use affects soil functions are currently unclear and require further research (Dornbush and von Haden 2017). Food and feed production can be positively or negatively influenced by pesticides, depending on the circumstances of their use.

Relatively few studies have been conducted on pesticides' impact on biodiversity and the associated capacity of (agro-)ecosystems to adapt to change. Where such studies have been carried out, biodiversity was generally shown to be adversely affected by pesticide use (Potts, Imperatriz-Fonseca and Ngo 2016; Stavi, Bel and Zaady 2016; Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [IPBES] 2019). [Chapter 5.4]

Large gaps still exist in our understanding of pesticides' ultimate environmental, health and economic impact under current conditions of use. Thus, informed decision-making about the best and most sustainable forms of pest and vector management, and the role of pesticides therein, is handicapped by lack of the comprehensive knowledge needed to develop sound national and regional policies.

5.2 Burden of disease

The overall health impacts of pesticides can be quantified as the burden of disease attributable to pesticides. The burden of disease is generally expressed as deaths or as disability-adjusted life years (DALYs). One DALY can be thought of as one lost year of "healthy life". The sum of these DALYs across the population, or the burden of disease, is considered a measurement of the gap between current health status and an ideal health situation in which the entire population lives to an advanced age free of disease and disability. DALYs are calculated as the sum of the "years of life lost" due to premature mortality in the population and the "years lost due to disability" for people living with the health condition or its consequences (World Health Organization [WHO] n.d.).

The use of pesticides may also lower the burden of disease, for instance when used in the control of vectors of human disease such as malaria, or to reduce the production of mycotoxins on certain crops.

WHO has published global assessments of the burden of disease from environmental risks and environmental determinants of health, as well as the public health impact of chemicals (Prüss-Ustün *et al*. 2016a; Prüss-Ustün *et al*. 2016b; WHO 2016; WHO 2019). Estimates of unintentional poisoning with chemicals are provided, but so far have not been disaggregated for pesticides. The only pesticide-specific estimate in the WHO burden of disease publications is for intentional self-poisoning by pesticides (Chapter 4.4.4). The *Lancet* Commission on Pollution and Health (Landrigan *et al*. 2018) noted that the contribution of pesticides to the global burden of disease is not quantified despite their widespread use and potential effects on human health.

Fantke, Friedrich and Jolliet (2012) modelled the consumer health impact of 133 pesticides applied in 2003 in 24 European countries. They estimated that dietary exposure to these pesticides resulted in an overall burden of disease of 1,959 DALYs per year, for all 24 countries combined, corresponding to 2.3 minutes per person per year. They concluded that dietary pesticide exposure contributed little to the overall burden of disease in Europe. Just 13 pesticide active ingredients contributed to 90 per cent of the total number of DALYs; in early 2020 only three of these were still approved in the EU (European Union [EU] 2020).

Bellanger *et al*. (2015) and Attina *et al*. (2016) estimated the number of cases of disease resulting from exposure to endocrine disrupting chemicals in the EU and the United States in 2010 (Table 5.2-1). Prenatal exposure to organophosphate pesticides was associated with almost 60,000 cases of IQ loss and intellectual disability in Europe, but many fewer in the United States. Tens of thousands of cases of adult diabetes and fibroids in women were estimated

Table 5.2-1 Human disease burden associated with certain pesticides in the EU and the United States in 2010. Bellanger *et al*. (2015); Attina *et al*. (2016).

Pesticide or pesticide metabolite	Adverse health effect	Annual number cases	
		EU	United States
Organophosphate pesticides	IQ loss and intellectual disability	59,300	7,500
DDE	Childhood obesity	1,555	857
DDE	Adult diabetes	28,200	24,900
DDE	Fibroids	56,700	37,000

to have been caused by exposure to DDE on both continents. These estimates have come under criticism as being insufficiently based on toxicological evidence (Bond and Dittrich 2017), but so far alternative assessments have not been published.

In conclusion, the impact of exposure to pesticides on the burden of disease has barely been quantified so far, although certain pesticides are known to cause chronic disease while others are strongly associated with it (Chapter 4.4.3).

5.3 Monetary costs

5.3.1 The benefits of pesticide use

Pesticides are considered a critical component for the growth of agricultural productivity and food supply (National Research Council 2000; Pingali 2012; Popp, Pető and Nagy 2013; Organisation for Economic Co-operation and Development and Food and Agriculture Organization of the United Nations 2019). They are sold and used because of the benefits they are expected to provide. The potential benefits of pesticide use include reduced crop losses, prevention of the introduction of harmful pests, lower costs of agricultural production, contribution to food security, reduced prevalence of human vector-borne diseases, longer shelf life of agricultural commodities, greater livestock yields, reduced soil disturbance, and better protection of wooden structures.

Cooper and Dobson (2007) list almost 60 primary and secondary benefits of pesticides. These benefits are economic, social and environmental. However, it has been argued that this analysis confuses benefits that derive from control of a pest with those deriving from the use of a pesticide. As there are often several possible ways to control damage caused by pests, it is misleading to attribute all the benefits of pest control to pesticides (Edwards-Jones 2007). In many situations, pesticides offer advantages over other control methods, associated with characteristics such as ease of use, speed and consistency of control, and reduction of pest and disease risks. However, that does not mean pesticides necessarily offer greater net benefits than other control methods. It is only by comparing the costs and benefits of each control method in a given situation that the relative merits of different pest management options can be assessed (Edwards-Jones 2007; Waterfield and Zilberman 2012).

The economic benefits of pesticide use can be expressed in monetary terms. Such assessments may be made for individual pesticide-pest-crop situations and, more broadly, at the level of cropping systems or regions/countries. Deloitte (2018) estimated that Australian dollars (AUD) 20.6 billion of Australian agricultural output in 2015-16 was attributable to the use of crop protection products, or 73 per cent of the total value of crop production that year. Mark Goodwin Consulting Ltd. (n.d.), which assessed the value of increased yield and quality of field crops, nut/

fruit crops and vegetables in the United States between 2008 and 2010, estimated that using crop protection products added USD 81.8 billion in crop value or about 36 per cent of the total value of these crops.

Both of these studies calculated the share of agricultural output value attributable to pesticides on the basis of crop losses that would occur if pesticides were not used (based on Gianessi 2009 for insecticides). However, such assessments may overestimate losses due to pests, diseases and weeds since farmers will use alternative pest management options to compensate at least in part for the absence of pesticides (Chapters 2.7.2 and 2.7.5). On the other hand, there can also be an opportunity cost for alternatives such as labour that could have been spent on other income generating activities, children kept out of school (in some countries) to perform labour, or more contamination with mycotoxins.

The United States Environmental Protection Agency evaluates the benefits of new active ingredients or significant new uses of a pesticide as part of the registration process. It assesses potential advantages that can lead to greater flexibility of use for growers, better outcomes or lower costs (United States Environmental Protection Agency [US EPA] 2018)

No independent global or regional reviews appear to have been made of studies on the economic benefits of pesticide use at either individual pesticide level or a larger geographical scale. Cooper and Dobson (2007) noted that the economic benefits of pesticide use were not well documented in the scientific literature. Recently, Wiese and Steinman (2020) concluded that even in the case of glyphosate (currently the most widely used pesticide globally) no scientific basis exists for published economic calculations of its yield benefits in non-GMO arable farming in the European Union (EU). Only limited advances appear to have been made since Sexton, Lei and Zilberman (2007) reviewed the economics of pesticides and pest control and reported that "only now we are beginning to understand the productivity of pesticides, how productivity changes over time, and how environmental factors affect productivity".

While the pesticide industry certainly collects information about the costs and benefits of their products internally, such data do not appear to be systematically reviewed and independently analysed. Furthermore, such studies tend not to take into account other pest management options or the costs of externalities.

5.3.2 The costs of pesticide use

The use of pesticides may have different types of costs (Ajayi *et al.* 2002; Bourguet and Guillemaud 2016):

- *Direct costs*. These are all the monetary and non-monetary expenses incurred by a farmer or other pesticide user which are noticeably related to applying a pesticide (e.g., cost of the pesticide product and spray equipment, labour costs for application, pesticide registration costs insofar as they are included in the price of the pesticide product).

- *Indirect or hidden costs*. Pesticide use may cause indirect effects, such as occupational health effects, development of pest resistance leading to increased pesticide use, and reduction of crop pollination due to honeybee kills. The costs of such indirect or hidden effects are (mainly) borne by the pesticide user, either in the short or long term.

- *External costs or externalities.* These are costs of pesticide use borne by society as a whole (e.g., part of or all costs of regulatory control, increased costs of water treatment because of pesticide pollution, costs due to environmental effects of pesticides outside treated areas, health effects on residents or bystanders, clean-up costs for obsolete pesticide stocks).

A more extensive list of these types of costs is provided in Table 5.3-1.

Indirect costs and externalities of pesticide use are often not taken into account when farmers or other pesticide users decide to apply a pesticide. Such costs also tend not to be considered when national governments develop pest and pest management policies, although this is changing in some parts of the world.

Table 5.3-1 Direct and indirect costs of pesticide use, as they may be borne by the pesticide user or society as a whole. Based on Ajayi *et al.* (2002); Bourguet and Guillemaud (2016).

Category of costs	Type of costs	Direct private costs	Indirect costs	
			“hidden” private	“externalities”
		Borne by pesticide user	Borne by pesticide user	Borne by society as a whole
Pesticide application	Product	●		●[1]
	Transport	●		
	Labour	●		
	Equipment	●		●[1]
	Storage	●		
	Personal protective equipment	●		
Environmental costs	Pesticide resistance, leading to greater difficulty and/or expenses to manage pests		●	●[2]
	Decrease of pollination, resulting in crop yield/quality reduction and/or rental of bee colonies		●	●[2]
	Decrease in natural enemies, leading to pest resurgence or new pests		●	●[2]
	Decreased soil fertility leading to reduced yields		●	
	Adverse effects on livestock and domestic animals		●	●
	Impact on other economic activities (e.g. fisheries, beekeeping, silk production, organic food production) resulting from pesticide exposure			●
	Loss of biodiversity; effects on non-target organisms			●
	Environmental pollution: treatment or clean-up costs (e.g. drinking water treatment)			●
	Clean-up of pesticide spills, obsolete pesticide stocks and empty pesticide containers	●		●
Health costs	Medical costs after occupational poisoning		●	●[3]
	Loss of productivity after occupational poisoning of applicators and other workers.		●	●
	Medical costs after bystander/residential poisoning			●
	Loss of productivity after bystander/residential poisoning			●
	Health costs due to dietary exposure (pesticide residues in food or water)			●
Regulatory costs	Public research, communication, expertise on pesticides			●
	Pesticide regulation, registration, control, enforcement			●
	Mandatory pesticide handling practices (e.g. storage, disposal)		●	

1 In the case of subsidies or tax exemptions.
2 Pesticide resistance, pest resurgence and pollinator declines tend to develop area-wide and are not limited to the farmer’s field.
3 In the case of government support to the health sector.

Examples of authoritative studies on the environmental, health and economic development costs of pesticide use include those conducted in the United States by Pimentel and colleagues at Cornell University (Pimentel and Burgess 2014) and work done in Africa, Asia, Europe and South America under the Pesticide Policy Project by Hermann Waibel and colleagues at the University of Hannover, Germany (Leibniz University Hannover n.d.), among others.

The UNEP report *Costs of Inaction on the Sound Management of Chemicals reviewed* studies that quantified indirect costs of the production and use of chemicals (United Nations Environment Programme [UNEP] 2013). It revealed that there were limited monetized and quantified data ready for use in policy decision-making. Nevertheless, a relatively a large fraction of available studies that are reasonably disaggregated with respect to chemicals tend to address pesticides.

Based on several studies from Sub-Saharan Africa (SSA), UNEP (2013) estimated the costs of lost work, medical treatment and hospitalizations due to pesticide poisoning among smallholder farm workers in 37 SSA countries at USD 4.4 billion in 2005 (range USD 1.4 billion- USD 8.1 billion). This would mean the health costs associated with pesticide use in Africa amounted to almost double the market value of crop protection products sold in the region (see Chapter 2, Figure 2.4-9). The UNEP study was limited to acute health and lost work costs resulting directly from working with pesticides on small landholdings. No attempt was made to estimate other costs. However, these other costs are likely to be substantial (e.g., the costs of bystander effects, suicide and self-poisoning, chronic health effects, lost livelihoods and lives, environmental impact and effects on farm animals).

Bourguet and Guillemaud (2016) conducted an extensive review of studies on the indirect environmental and health costs of pesticides. This review included 61 articles published between 1980 and 2014. Most studies that monetized adverse pesticide impacts concerned acute human health effects. Studies on the environmental costs of pesticides were much more limited. Only 10 independent data sets were available which combined estimates of environmental, health and regulatory costs at the national level (Table 5.3-2). Overall, indirect costs of pesticide use ranged from about USD 5.5 million in Niger in 1996 to almost USD 12 billion in the United States in 2005.

Bourguet and Guillemaud (2016) noted that the indirect costs of pesticide use were underestimated due to the fact that several costs had never been evaluated. In addition, they pointed out that these estimates were almost all outdated since the current impact of pesticide use was probably very different from that during the 1980s and 1990s. This is because of the difficulties of estimating the economic costs of unintentional impacts of pesticide use, particularly for goods without market values. Most estimates of external costs to date must therefore be considered as minimum costs. UNEP (2013) also stressed that monetized environmental and health effects are often underestimated, only cover one or a few types of costs, and hardly ever address costs with respect to human welfare.

Trasande *et al*. (2015, 2016) assessed the human health costs that could reasonably be attributed to exposure to endocrine disrupting chemicals in the EU. They focused on nine chemicals or groups of chemicals for which they considered there was sufficient evidence of adverse human health effects. Organophosphates and dichlorodiphenyldichloroethylene (DDE), a metabolite of dichlorodiphenyltrichloroethane (DDT), were the pesticides included in their evaluation. Attina *et al*. (2016) conducted a study that applied the same methodology in the United States.

In the EU the health costs of exposure to DDE ranged from several tens to hundreds of millions of euros (Table 5.3-3); prenatal exposure to organophosphates was costed at 47 billion to 195 billion euros, the highest cost of all nine groups of chemicals evaluated. In the United States health costs associated with organophosphate pesticide exposure were about USD 34 billion, about a quarter of those in the EU. This was due to lower exposure of the population to organophosphates, reportedly resulting from stricter regulations of this group of pesticides.

Table 5.3-2 **Estimates of overall indirect costs of pesticide use.** Bourguet and Guillemaud (2016).

Country	Year	Estimated annual costs in USD (2013) million			
		Health effects	Regulatory actions	Environmental effects	Total
Thailand	1995	1.26	558	5.58	565
Germany	1996	18	168	9.3	195
Niger	1996	4.40	0.15	0.89	5.44
United Kingdom	1996	2.3	319	63	384
Mali	1999	3.71	1.58	38.1	43.4
Pakistan	2002	78.1	9.71	815	903
United States*	1986	245-487	3,203	204-4,029	3,652-7,719
United States*	2002	1,309	4,989	1,470-1,508	7,768-7,806
United States*	2005	1,493	4,229	5,974	11,696
Thailand	2010	2.99	357	16.9	377

* Estimates for the United States are from independent authors and data sets.

The costs of adult diabetes as a result of DDE exposure, on the other hand, were almost double in the United States compared with the EU.

Based on these estimates, it was concluded that there is a substantial probability of very high disease costs across the human lifespan associated with exposure to certain pesticides, both in the EU and the United States. Given the limited number of pesticides that have been evaluated in this manner, however, the total health costs of pesticide exposure are likely to be considerably underestimated (Grandjean and Bellanger 2017). The reanalysis by Bourguet and Guillemaud (2016) of North American data published earlier suggested that each per cent of cancers attributable to pesticides was associated with a cost of about USD 20 billion annually,

Table 5.3-3 **Estimates of the economic cost of exposure to certain endocrine disrupting pesticides in the EU** (Trasande *et al*. 2015; Trasande *et al*. 2016) **and the United States** (Attina *et al*. 2016). **Costs consisted of hospitalization, physicians' services, nursing home care, medical appliances and related items.**

Pesticide or pesticide metabolite	Adverse health effect	Costs		
		Low estimate	Base estimate	High estimate
European Union		EUR million		
Organophosphates	IQ loss and intellectual disability	46,800	146,000	195,000
DDE	Childhood obesity	24.6	24.6	86.4
DDE	Adult diabetes	835	835	16,700
DDE	Fibroids	163	163	163
United States		USD million		
Organophosphates	IQ loss and intellectual disability	14,300	33,700	59,500
DDE	Childhood obesity	n.a.	29.6	57.3
DDE	Adult diabetes	n.a.	1,800	13,500
DDE	Fibroids	n.a.	259	595

n.a. = not available

confirming the very high costs of chronic illness to society.

Estimates of environmental costs of pesticide use are much more limited. Bourguet and Guillemaud (2016) found only five studies based on data recorded after 2000 and only one article published since 2006. Most estimates of environmental costs referred to losses of natural enemies and bees. However, this does not mean that environmental costs are less important than human health costs from a monetary point of view. Of the 10 data sets presenting the overall indirect costs of pesticides listed in Table 5.3-1, eight estimated (considerably) higher environmental than human health costs.

In the future, owing to various initiatives concerning the economic valuation of ecosystem services and biodiversity, better information will likely become available with which to estimate the environmental costs of pesticide use. For instance, the Economics of Ecosystems and Biodiversity (TEEB) Initiative is attempting to "make nature's values visible" and mainstream the values of biodiversity and ecosystem services into decision-making. TEEB follows a structured approach to valuation that is intended to help decision-makers recognize the benefits provided by ecosystems and biodiversity and demonstrate their values in economic terms.

As part of TEEB, the AgriFood programme seeks to provide a comprehensive economic evaluation of the "eco-agri-food systems" complex, and assess to what extent the economic environment in which farmers operate is distorted by significant externalities, both negative and positive (TEEB 2015). To date, no economic studies on the costs of pesticides with regard to biodiversity and ecosystems services have been conducted under TEEB. It is expected that data on this topic will become available in the near future.

Similarly, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) includes valuation of biodiversity and ecosystem services in its assessments. For instance, the IPBES assessment on pollinators, pollination and food production includes a detailed chapter on economic valuation of pollinator gains and losses (Gallai *et al.* 2016) which provides a summary of the economic values of pollination services from local to global scales.

5.3.3 Cost-benefit assessments

Agricultural pest management decisions are generally made at the farm level, although they may be constrained by government regulation and resource availability. The farmer's objective is assumed to be profit maximization, where profit is the revenue from selling output on the market after subtracting production costs (Waterfield and Zilberman 2012).

Determining a truly optimal pest control strategy requires full knowledge of locations-specific pest pressures, how pest pressure relates to crop damage, and the range of impacts of available pest control technologies including the use of specific pesticides. Farmers' decisions are further complicated by the dynamic changes in the cropping system, both over the course of the season and across seasons: current pest control decisions may have consequences far into the future (e.g., build-up of resistance, pest resurgence). Farmers also have different attitudes towards accepting risks respecting both the development of pests and diseases and investments needed for pest control. Deciding on an economically optimal pest control strategy is therefore very difficult for individual farmers (Waterfield and Zilberman 2012).

Ghimire and Woodward (2013) conducted a macro-economic analysis of under- and overuse of pesticides in 75 countries between 1990 and 2000. They found that, after correcting for agricultural and climatic variables, underuse of pesticides was predominant in low income countries while high income countries tended to overuse pesticides. More recent assessments appear to indicate that pesticide overuse occurs frequently in specific cropping systems in low and middle income countries, e.g., China (Zhang *et al.* 2015; Wu *et al.* 2018) and Thailand (Grovermann, Schreinemachers and Berger 2013; Schreinemachers *et al.* 2020) as well as high income countries, e.g., France (Lechenet *et al.* 2017), the Netherlands (Skevas, Stefanou and Oude Lansink 2014) and the

Table 5.2-4 Estimates of the net return of pesticide use, at farm level, without taking into account hidden costs and externalities.

Period	Region	Benefit-cost ratio	Source
1980-1991	Canada, France, United States	0.1-8.0	Fernandez-Cornejo, Jans and Smith (1998)
Before 1991	United States	3.0-6.5	Zilberman *et al*. (1991)
2002-2009	United States	6.5	Popp, Pető and Nagy (2013)
1980s-1990s	United States, Europe	1-8	Fernandez-Cornejo *et al*. (2014)
"most widely cited"	mainly United States	4	Bourguet and Guillemaud (2016)

Note: The benefit-cost ratio is the unit value increase in agricultural output for each unit value of aggregate pesticide expenditures (i.e. direct costs). A benefit-cost ratio >1 suggests that pesticide use is economically justified.

United States (US EPA 2014). No up-to-date comprehensive review is available. As a result, it has been argued that pesticide use reductions rarely cause yield losses (Vasileiadis 2017). Frisvold (2019), however, cautions against a possible bias associated with certain study methodologies and calls for the use of careful econometric assessments as the basis for reducing pesticide use.

Various evaluations exist of the net return, or net benefit, of pesticide use at farm level without taking into account hidden costs and externalities (Table 5.3-4). Benefit-cost ratios tend to average between 3 and 6, suggesting that USD 1 in pesticide expenditures yield USD 3-6 in benefits to the farmer. However, net benefits were highly variable, depending on crop, year and aggregation level (Fernandez-Cornejo, Jans and Smith 1998). Even the most recent review by Bourguet and Guillemaud (2016) mostly cites data that go back to the 1980s and 1990s. This is relevant since Fernandez-Cornejo, Jans and Smith (1998) and Fernandez-Cornejo *et al*. (2014) found that the net benefits of pesticide use fell between the 1950s and 1990s, while more recent independent economic data quantifying pesticide net benefits at farmer level do not seem to be available (see Chapter 5.3.1). Furthermore, most data appear to have been generated in North America.

It should be noted that the benefit-cost ratios reported here are comparisons of the average value of production (across all pesticides) against the average cost of (all) pesticides. In that respect, they are not necessarily a good representation of the private value of the use of a pesticide or of decision-making by the individual user. However, particular farmers' pesticide use decisions will generally not consider either the hidden costs to themselves or external costs imposed on society (Sexton, Lei and Zilberman 2007). These are many of the environmental, health and regulatory costs associated with pesticide use listed in Table 5.3-1. Calculating the net benefits to society

Table 5.2-5 Estimates of benefit-cost ratios of pesticide use, including hidden costs and externalities.
Based on Bourguet and Guillemaud (2016).

Year	Country	Annual costs or benefits, in USD million				Benefit-cost ratio
		Direct costs	Indirect costs (hidden and externalities)	Total costs	Benefits	
1996	Germany	1,309	196	1505	2199	1.46
2002	Pakistan	533	186	719	610	0.85
2005	United States	12,153	8,985	21,138	48,611	2.30
2013	United States	6,914	31,404	38,318	26,983	0.70

of pesticide use requires consideration of all costs and benefits.

Very few studies are available that compare the overall costs of pesticide use with their estimated benefits (Bourguet and Guillemaud 2016) (Table 5.3-5). When hidden costs and externalities are included in the calculations, benefit-cost ratios are much reduced compared with calculations based only on private costs. In the case from Pakistan and the 2013 re-estimation for the United States, the benefit-cost ratio was even below 1 (Bourguet and Guillemaud 2016).

Recently Lee *et al*. (2020) reviewed the cost-effectiveness of banning Highly Hazardous Pesticides (HHPs) to prevent suicides due to pesticide self-ingestion across 14 countries. They estimated that banning HHPs across these countries could result in up to 28,000 fewer suicide deaths per year at an annual cost of USD 0.007 per capita. National bans were found to be cost-effective in countries where a high proportion of suicides are attributable to pesticide self-poisoning.

It is important to bear in mind that rational decision-making on the use of pesticides requires a comparison of the costs and benefits of alternative farming systems in which different pest control methods are used. In this way farmers, and society, can decide which pest control method offers the most appropriate levels of costs and benefits (Edwards-Jones 2007; Bourguet and Guillemaud 2016). So far, comprehensive assessments of both the benefits and costs of pest control and pesticide use in specific farming systems have been rare.

5.4 Ecosystem services

5.4.1 Introduction

Ecosystem services have been defined as the benefits people obtain from ecosystems (Millennium Ecosystem Assessment [MA] 2005). The ways in which humans benefit from ecosystems and the consequences of ecosystem change for their well-being were reviewed globally for the first time by the Millennium Ecosystem Assessment, carried out between 2001 and 2005 (MA 2005). The presumption is that ecosystem service approaches provide a better basis for environmental decision-making than other approaches because they make explicit the connection between human well-being and ecosystem structures and processes (van Wensem *et al.* 2017)

Different typologies of ecosystem services have been proposed. The most common include the following (MA 2005; Food and Agriculture Organization of the United Nations and Secretariat of the Convention on Biological Diversity 2016):

- *Regulating services* are defined as the benefits obtained from the regulation of ecosystem processes such as climate regulation, natural hazard regulation, water purification and waste management, pollination and pest control.
- *Supporting services* are those that support the delivery of other services, such as soil formation and supplying habitat for species, which enable ecosystems to continue to supply provisioning and regulating services.
- *Provisioning services* refers to the goods and physical products obtained from ecosystems, such as food, freshwater, wood, fibre, genetic resources and medicines.
- *Cultural services* include non-material benefits that people obtain from ecosystems, such as spiritual enrichment, intellectual development, recreation and aesthetic values.

The MA mainly refers to pesticides as a threat to ecosystem services in general terms. It only mentions one service that, with high certainty, has been degraded by the use of pesticides: natural pest regulation. In many agricultural areas, pest control provided by natural enemies has been replaced by the use of pesticides. Such pesticide use has itself degraded the capacity of agroecosystems to provide pest control (MA 2005).

The MA was succeeded by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (Chapter 3.2.5). One of the more recent key elements of the IPBES conceptual framework is the notion of nature's contributions to people (NCP), which builds on the ecosystem service concept popularized by the MA. While ecosystem services were based primarily on ecology and economics, NCP more broadly attempt to incorporate social, cultural and indigenous elements and experiences. Moreover, many ecosystem services fit into more than one of the four original categories (Díaz *et al.* 2018). The ecosystem services concept is nevertheless still applied by many institutions today.

NCP are all the contributions, both positive and negative, of living nature (i.e., diversity of organisms, ecosystems, and their associated ecological and evolutionary processes) to the quality of life for people. Beneficial contributions from nature include food provision, water purification, flood control and artistic inspiration. Detrimental contributions include disease transmission and predation that damages people or their assets, among others. Many NCP may be perceived as benefits or detriments depending on the cultural, temporal or spatial context (Intergovernmental Science-Policy Platform on

Box 5.4-1 **IPBES reporting categories for nature's contributions to people (NCP) which are most susceptible to being impacted by the use of pesticides** Díaz *et al.* (2018); Nienstedt *et al.* (2012).

Reporting category	How pesticides can affect nature's contributions to people (NCP)	Likelihood of adverse impact
2. Pollination and dispersal of seeds and other propagules	Pesticides can directly or indirectly reduce pollinator populations, leading to reduced pollination, which in turn can result in lower crop quality and yield as well as loss of diversity in natural vegetation.	Moderate to high (Chapter 4.3.3)
8. Formation, protection and decontamination of soils and sediments	Pesticides can affect soil organisms and plants which contribute to the formation of soils, the supply of organic matter and nutrient cycling. This in turn can affect soil fertility, leading to changes in the production of agricultural commodities, in forests, and in the diversity and production of natural vegetation.	Low to moderate (Chapter 4.3.2 and 4.3.4)
10. Regulation of detrimental organisms and biological processes	The main objective of using a pesticide is to reduce detrimental organisms, but pesticides can also adversely affect the natural capacity to regulate pests and diseases. Moreover, pesticide use can lead to the development of pest and disease resistance.	Moderate to high (Chapter 4.3.3 and 4.3.3)
12. Food and feed	Increased food production is the principal objective of agricultural pesticide use. However, effects on, for example, resistance, soils, pollinators and the natural enemies of pests can reduce food and feed production. Pesticide use in fish farming can increase production, but pollution may also reduce the sustainability of aquaculture as well as adversely affect aquatic ecosystems.	Low to high (Chapter 4.3.3 and 4.3.5)
18. Maintenance of options	Pesticides may affect biodiversity, which can in turn reduce the capacity of (agro-)ecosystems to keep options open to support good quality of life in the future, e.g. to adapt to change, new pests and diseases and the development of antibiotic resistance, or to produce new medicines or materials.	Low to high (Chapter 4.3.4, 4.3.5 and 4.3.6)

Note: Many other NCP or ecosystem services can also potentially be affected, but pesticides are likely to be less important compared to other stressors.

Biodiversity and Ecosystem Services [IPBES] 2019).

The 18 reporting categories which have been recommended for IPBES assessments partly overlap with the ecosystem services of the MA. Five of these categories are most likely to be directly affected by the use of pesticides: pollination, soil formation, regulation of detrimental organisms, production of food and feed, and maintenance of options (Box 5.4-1).

Ecosystem services are increasingly being considered in the risk assessment and management, as well as impact monitoring, of chemicals in general and pesticides in particular (US EPA 2016; European Food Safety Authority Scientific Committee 2016; Devos *et al.* 2019). Nevertheless, significant challenges still need to be addressed with regard to the use of ecosystem services-based risk assessments in regulatory decision-making (Munns *et al.* 2017).

5.4.2 The impact of pesticides on ecosystem services or nature's contributions to people

Pesticides are mentioned several times in *The Global Assessment Report on Biodiversity and Ecosystem Services* (IPBES 2019) as drivers of change affecting ecosystem services. However, specific cases are not provided. Evidence that pesticides are affecting ecosystem services from other sources is summarized below.

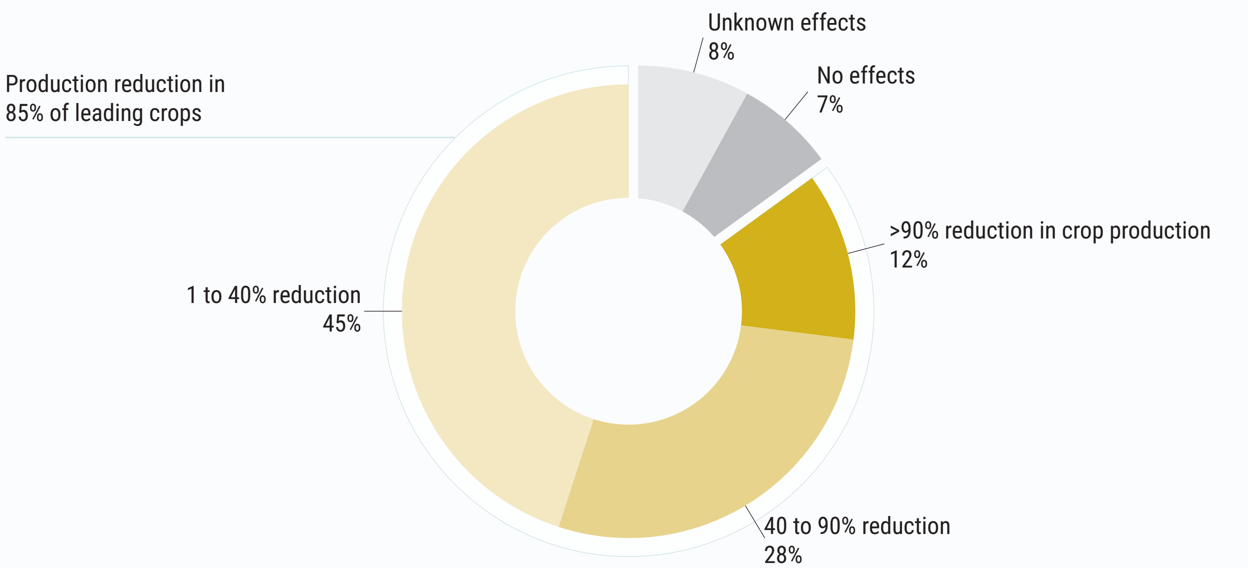
Pollination services

Biotic pollination is an ecosystem function that is fundamental to plant reproduction, agricultural production and the maintenance of terrestrial biodiversity. As part of IPBES, a specific assessment report on pollinators, pollination and food production was elaborated (Potts, Imperatriz-Fonseca and Ngo 2016). It outlines many ways in which pesticides can affect pollinators, as well as evidence of cases where this has occurred in real pesticide use situations (Chapter 4.3.3).

The link between the presence of pollinators and pollination services is generally very clear. The absence or reduction of pollination will result in a reduction in fruit set, crop yield and quality for many crops (Figure 5.4-1).

The most recent estimate of the global annual market value of additional crop production

Figure 5.4-1 Percentage dependence on animal-mediated pollination of leading global crops that are directly consumed by humans and traded on the global market. Potts, Imperatriz-Fonseca and Ngo (2016).



Note: Only crops that produce fruits or seeds for direct human use as food (107 crops) are included.

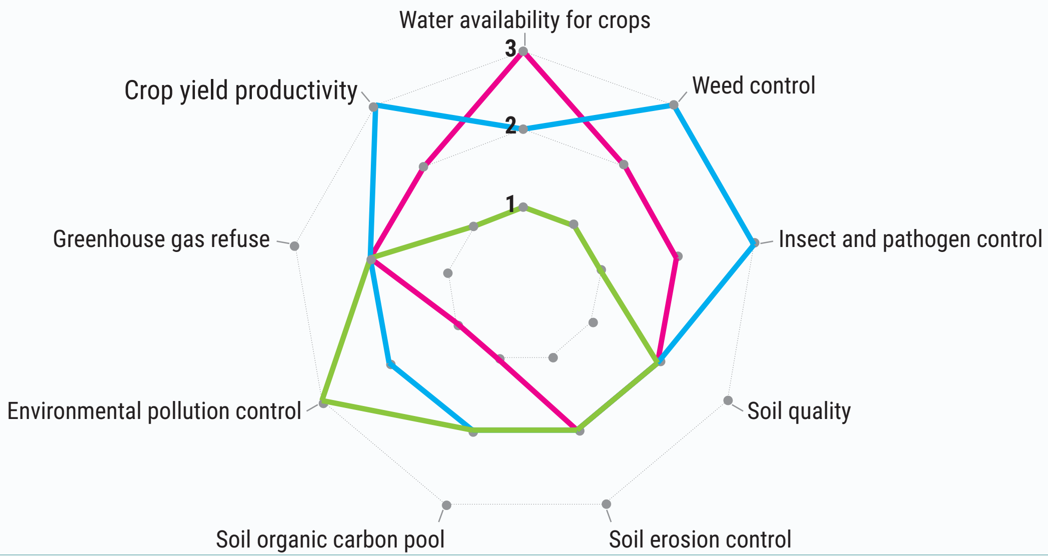
directly linked with pollination services ranges from USD 235-577 billion (in 2015 US dollars). In addition, in the absence of animal pollination, changes in global crop supplies could increase prices for consumers and reduce profits for producers, resulting in a potential annual net loss of economic benefits of USD 160-191 billion globally to crop consumers and producers, and a further USD 207-497 billion to producers and consumers in other, non-crop markets (e.g., non-crop agriculture, forestry and food processing). Nevertheless, current economic indicators fail to capture the full range of benefits provided by pollinators and the full costs of supporting managed pollinators (Gallai *et al.* 2016).

There is little argument that high levels of pesticide use in a pollinator dependent crop will result in a reduction in pollination (Potts, Imperatriz-Fonseca and Ngo 2016; Potts *et al.* 2016). This is the main reason why instructions such as to avoid spraying while crops are flowering may be put on a pesticide label. An example often cited is from Sichuan, China, where apples and pears are hand-pollinated because continuous insecticide applications were one of the main causes of the virtual extinction of bees in the area (Partap and Ya 2012).

Another issue is whether sublethal effects of pesticide exposure affect the provision of pollination. In the IPBES review, Kovács-Hostyánszki *et al.* (2016) suggest that there are indications that sublethal effects of pesticide exposure can impair the ability of bees to provide pollination, which could have wider implications for sustained production of pollinator-dependent crops and the reproduction of many wild plants. However, there is currently no evidence of such impacts on pollination under field conditions.

In conclusion, there is considerable evidence of acute adverse effects of pesticides on pollinators (Chapter 4.3.3). There is also a direct and strong link between pollinator abundance and diversity on the one hand and pollination as an ecosystem service on the other (Dainese *et al.* 2019). Whether

Figure 5.4-2 Spider chart of pest management's impact on soil functions and ecosystem services. Stavi, Bel and Zaady (2016).



Impact scale:	1	Low	2	Medium	3	High
Pest management system		Chemical		Integrated		Organic

Note: Impacts are separately presented for the three levels of intensity of pest management: chemical, integrated and organic. The major soil functions and ecosystem services are graded for each of the pest management intensities according to the scale of the following: 1 for low score for positive agro-environmental ranking, 2 for moderate score, and 3 for high score.

sublethal exposure of pollinators to pesticides leads to a reduction in pollination services has not been clearly shown so far.

Soil functions

Stavi, Bel and Zaady (2016) reviewed the impact of different cropping systems on soil functions and ecosystem services. The studies they evaluated were categorized, among others, according to three pest management approaches: chemical pest management, integrated pest management, and organic pest management. From an agro-environmental point of view, chemical pest management scored well on water availability for crops, but had a medium or low positive impact on all other soil functions and ecosystem services (Figure 5.4-2). Pest management in organic cropping systems had a highly positive impact on environmental pollution control, but a low impact on water availability for crops as well as on weed, insect and pathogen control. Integrated pest management scored best on weed, pest and disease control, as well as on crop yield productivity; it had the best average ranking overall for all soil functions and services.

However, our understanding of how pesticides affect soil functions and its implications for ecosystem services provided by soils is still very limited (Dornbush and von Haden 2017).

Natural regulation of pests and diseases

As indicated above, the Millennium Assessment considered natural pest regulation to be an ecosystem service that had undeniably been adversely affected by pesticide use (MA 2005). Pesticides kill or otherwise adversely affect the natural enemies of pests, which in turn may reduce biological control of pests and diseases.

Recent studies have confirmed that this ecosystem service continues to be compromised by the use of pesticides under current use conditions (Chapter 4.3.3).

No reviews of the economic impact of a reduction in biocontrol potential, or the costs of pest resurgence and secondary pest development resulting from pesticide use, were available. Nevertheless, Losey and Vaughan (2006) estimated the value of natural control attributable to insects of native agricultural pests in the United States at USD 4.5 billion. Roubos, Rodriguez-Saona and Isaacs (2014) noted that this type of information is not available for most cropping systems, but the limited data compiled more recently show that this earlier estimate may be much too low. Wyckhuys *et al*. (2020), who assessed the economic value of biological control across 23 countries in Asia and the Pacific, estimated that classical biological control, through introductions of natural enemies of pests, ensured annual accruing farm benefits of USD 14.6 to 19.5 billion per year in critical food, feed and fibre crops in these countries.

Production of food and feed

The principal objective of agricultural pesticide use is the maintenance or increase of food production. In many cases, pesticides have contributed to a reduction of crop losses and agricultural production growth (Chapters 2.7.1 and 2.7.3). However, pesticide use can also have adverse effects on the extent and sustainability of agricultural production, for example through the development of pest resistance and effects on soil processes, pollinators and natural pest control (Chapters 4.3.3 and 4.3.4). Pesticide use can also adversely affect other forms of food production such as fisheries and aquaculture (Chapter 4.3.5), while pesticide residues may influence the quality of food and feed (Chapter 4.4.6).

The use of pesticides will therefore have both a positive and negative impact on the production of food and feed as an ecosystem service.

As indicated above, relatively few comprehensive cost-benefit assessments of pesticide use are in the public domain. When only the direct costs of pesticides to the farmer are considered, the production benefits of using pesticides often – but not always – outweigh their costs. On the other hand, if indirect cost (externalities) are included, costs greatly increase and may surpass benefits (Chapter 5.3.3).

Maintenance of options

Pesticides may affect biodiversity, which in turn can reduce the capacity of (agro-)ecosystems to adapt to change, new pests and diseases, and the development of antibiotic resistance, or to produce new medicines or materials.

In major biodiversity status reports pesticides are often listed as a key driver of biodiversity loss in agricultural and natural ecosystems, but the number of studies able to directly link pesticide use with adverse effects on biodiversity parameters (such as species richness) are relatively rare. Moreover, the large majority of studies have been conducted in North America and Europe with an almost complete absence of data from other parts of the world (Chapter 4.3.6). Nevertheless, whenever large-scale studies or reviews have been available, most of them have shown adverse effects of pesticide use on biodiversity (Chapter 4.3.6).

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