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REVIEW

Pesticides, environment, and food safety

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Abstract

Agrochemicals have enabled to more than duplicate food production during the last century, and the current need to increase food production to feed a rapid growing human population maintains pressure on the intensive use of pesticides and fertilizers. However, worldwide surveys have documented the contamination and impact of agrochemical residues in soils, and terrestrial and aquatic ecosystems including coastal marine systems, and their toxic effects on humans and nonhuman biota. Although persistent organic chemicals have been phased out and replaced by more biodegradable chemicals, contamination by legacy residues and recent residues still impacts on the quality of human food, water, and environment. Current and future increase in food production must go along with production of food with better quality and with less toxic contaminants. Alternative paths to the intensive use of crop protection chemicals are open, such as genetically engineered organisms, organic farming, change of dietary habits, and development of food technologies. Agro industries need to further develop advanced practices to protect public health, which requires more cautious use of agrochemicals through prior testing, careful risk assessment, and licensing, but also through education of farmers and users in general, measures for better protection of ecosystems, and good practices for sustainable development of agriculture, fisheries, and aquaculture. Enhanced scientific research for new developments in food production and food safety, as well as for environmental protection, is a necessary part of this endeavor. Furthermore, worldwide agreement on good agriculture practices, including development of genetically modified organisms (GMOs) and their release for international agriculture, may be urgent to ensure the success of safe food production.

Introduction

Pesticides and agrochemicals, in general, became an important component of worldwide agriculture systems during the last century, allowing for a noticeable increase in crop yields and food production (Alexandratos and Bruinsma 2012). Notwithstanding, the exponentially growing human population further stresses the need for enhancing food production. This need is aggravated by conflicts that paralyze food production and dislocate millions of refugees and, together with the effects of climate changes on agriculture, worsen scarcity of food in many regions and call for renewed efforts in food production (UN 2015).

At the same time, during the last decades we realized that agrochemical residues did spread in the environment, causing significant contamination of terrestrial ecosystems and poisoning human foods (Carson 1962; EEA 2013). In addition, contamination of aquatic systems by pesticide residues around the world – illustrated herein with case studies in tropical coastal ecosystems – repeatedly compromised also aquatic food resources, fisheries, and aquaculture.

Paths, alternative to the intensive use of crop protection chemicals, are open to trial and assessment. However, the selection of future paths for enhanced food production shall be made through wise and science-based decision-making processes. Scientific research for developing food production and enhancing food safety, as well as environmental protection, is thus a necessary part of this process.

This article reviews the main issues related to pesticide residues, their environmental fate, and effects and discusses pathways for enhanced food safety.

The Role of Fertilizers and Pesticides in Agriculture

Agricultural production markedly increased since the beginning of the 20th century to cope with demographic growth. In about one century, population numbers exploded from 1.5 billion in 1900 to about 6.1 billion in 2000, which corresponds to an increase in world population three times greater than during the entire history of humanity. The world has added one more billion people since 2003, and at the current growth rates, it is estimated that world population will be of about 9.4–10 billion by 2050 (UN 2015).

The increase of world population in the 20th century would not have been possible without a parallel growth in food production, and this was achieved due to fertilizers. Organic fertilizers (“guano”) were incipiently used by the end of the 19th century, but the introduction of mineral phosphate fertilizers took over in the beginning of the 20th century and continuously increased up to our days (Gilland 2015). The use of phosphates, together with development of improved crop varieties with higher yields, allowed for an unprecedented increase in agriculture productivity, the “green revolution,” and the production of cereals more than duplicated per unit surface area of agriculture land (Brown 1995; Carvalho 2006). For example, in the USA from 1950 to 1990, the cereal production grew at 2.2% per year, although it has slowed down afterward (Brown 1995 2011). The growth of human population and the world production of phosphates for use as fertilizers were significantly and positively correlated over the last century (Roser and Ortiz-Ospina 2017), with a R^2 = 0.97 for the period 1900–1988 (Hendrix 2011) (Fig. 1).

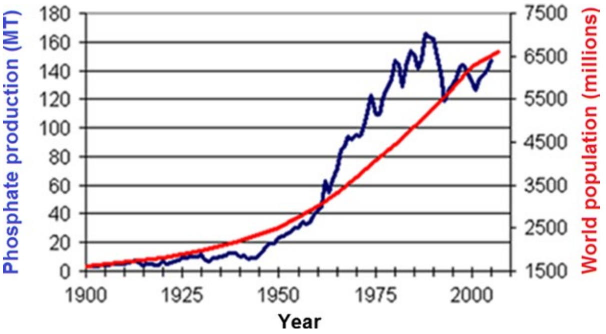

Figure 1. Increase of world population and phosphate rock production during last century (Modified from Roser and Ortiz-Ospina 2017).

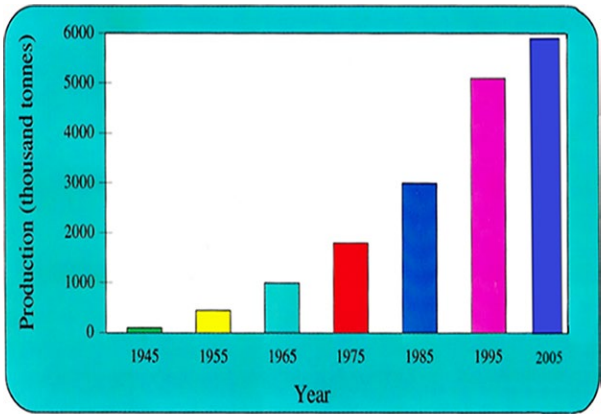

Figure 2. World production of formulated pesticides (based on FAO Statistics).

From the 1940s onwards, further increase in food production was allowed by the introduction of synthetic crop protection chemicals. Worldwide pesticide production increased at a rate of about 11% per year, from 0.2 million tons in 1950s to more than 5 million tons by 2000 (FAO 2017; Fig. 2). Pesticides, or crop protection chemicals, include several groups of compounds, namely organochlorine, organophosphate, carbamate, pyrethroids, growth regulators, neonicotinoids, and now biopesticides, which have been developed one after the other. Pesticide sales have increased for all types of pesticides, but herbicides were the group that expanded the most followed by insecticides and fungicides (Fig. 3).

The use of pesticides has not been the same across the world due to the cost of the chemicals (most of them patented), but also due to the cost of man power and the specific pests of each climatic/geographic region. Average application rates of pesticides per hectare of arable land have been computed by FAO and the highest average values, attaining 6.5–60 kg/ha, occurred in Asia and in some countries of South America (Fig. 4). While in North America and West Europe, the use of herbicides intensively applied in agriculture and in urban areas boomed in the last decades; in Asia, the use of herbicides remained low and contrasting with the use of insecticides that was very high (Fig. 4).

Early synthetic pesticides developed to control agriculture pests, such as DDT, were intensively used also for control of cattle ticks and human parasites in North America, Europe, and elsewhere (Fig. 5) and, although banned today, still are popular food preservatives of sun dry fish

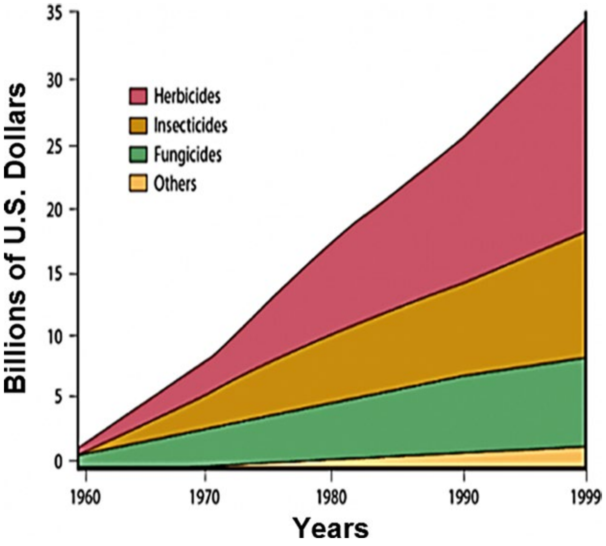

Figure 3. Estimated worldwide annual sales of pesticides (herbicides, insecticides, fungicides, and others in billion dollars; modified from Roser and Ortiz-Ospina 2017).

in South Asia and remain in use, sometimes illegally, to control malaria vectors and household pests in urban areas in the tropics (Taylor et al. 2003).

Environmental Fate and Effects of Pesticide Residues

Application of pesticides in agriculture has been made with the help of several techniques, from the manual spraying by workers on foot to truck- and airplane-based spraying techniques. At different times in different regions, some or all these techniques have been used.

Many cases of intoxication of farmers, rural workers, and their families did occur during pesticide applications and were documented in reports on poisoning and effects of synthetic chemicals on human health. It was reported that unintentional poisonings kill an estimated 355,000 people globally each year, and such poisonings are strongly associated with excessive exposure and inappropriate use of toxic chemicals (WHO 1990, 2012, Alavanja 2009; Alavanja and Bonner 2012).

Dispersion of pesticide residues in the environment and mass killings of nonhuman biota, such as bees, birds, amphibians, fish, and small mammals, were also reported (Köhler and Triebskorn 2013; Paoli et al. 2015; WHO 2017). Early reports and structured incident reporting systems certainly helped to develop regulations for pesticide applications, including dosage of chemicals and best periods of application (Hester and Harrison 2017). Over the years, a considerable research effort was developed also to understand the behavior of these chemicals in the environment, including their cycling and fate as well as their toxicity to biota.

Soon after the start of synthetic chemicals use, it was realized that the application of crop protection pesticides was causing contamination not only at local scale but also at global scale (Carson 1962; Fig. 6).

At local scale, chemicals applied on crops, as for example toxaphene applied in cotton crops in Nicaragua, remained in soils year after year and were carried by surface runoff to watersheds and coastal lagoons where residues contaminated aquatic biota (Carvalho et al. 1992, 2003). DDT applied to crops was often reported also to be transported to the aquatic environment where it is rapidly metabolized to DDE and bio-accumulated in aquatic food chains being returned eventually to humans (Kale et al. 1999). Endosulfan

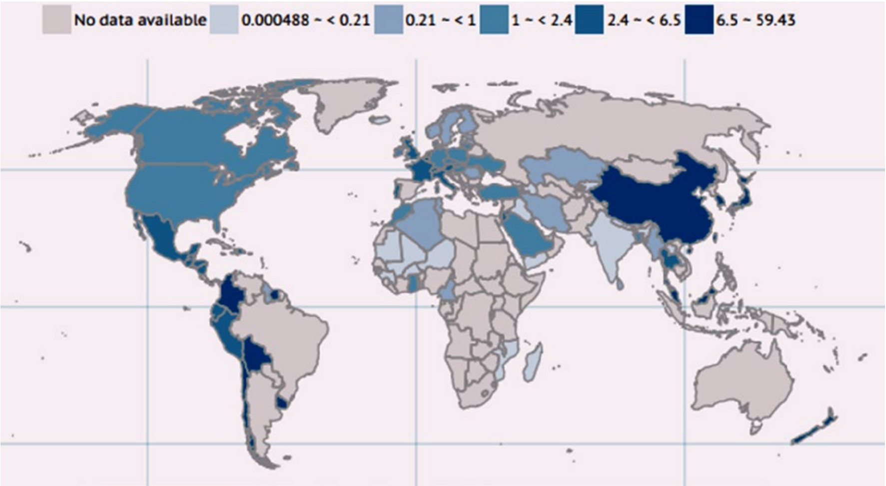

Figure 4. Use of pesticides per hectare of arable land, kg/ha, in the years 2005–2009 (FAO 2013).

Figure 5. DDT application on humans and cattle, around the 1940s (photos from Internet).

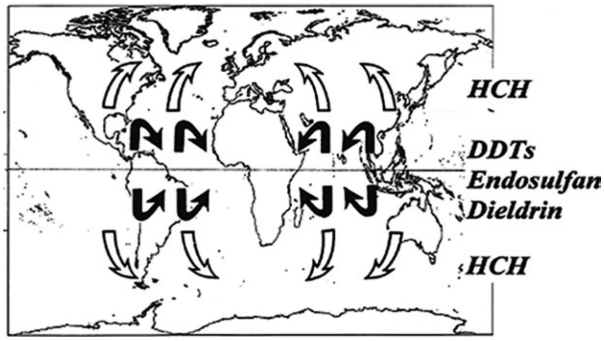

Figure 6. Volatilization and atmospheric transport of pesticides from tropical regions toward the poles.

was found to be metabolized by bacteria into endosulfan sulfate and could persist in soils and in aquatic sediments as a toxic chemical (Carvalho et al. 2002a,b). In general, these chemical compounds could undergo several chemical transformations and be transferred among environmental compartments, reaching other ecosystems outside the area of application and exerting toxic effects on nontarget species (Taylor et al. 2003).

At global scale, compounds such as hexacyclohexanes (HCH), chlordane, and toxaphene applied in fields in the south of USA were volatilized, transported by atmospheric processes, condensed in cooler climates, and deposited from the atmosphere onto the Great Lakes at Canada (Li and Jin 2013). The same did occur with HCH applied on rice fields in South Asia and transported to higher latitudes (Iwata et al. 1993; Simonich and Hites 1995). The most volatile compounds were more rapidly transported by atmospheric processes, reaching regions far away from the application areas (Fig. 6). This evaporation-condensation process was first observed with organochlorine compounds (OCs), but later was reported also for organophosphates (OPs), such as chlorpyrifos, that volatilized from application on banana plantations in the inter tropical region of Central America and reached the ice pack in the Artic (Garbarino et al. 2002). This global scale dispersion process could have been predicted based on Henri's Law, which relates the volatility (fugacity) of compounds from liquid media to the air as inversely related to water solubility, and on van ‘t Hoff equation that parameterizes the effect of temperature on volatility of compounds (Rand 1995).

The organochlorine (OC) pesticides of first generation were soon reported as environmentally persistent, remaining long time in soils and sediments and accumulating in nonhuman organisms with devastating toxic effects at population level (Köhler and Triebskorn 2013). Organochlorine residues are generally transferred also in the food chains with impact on human health (discussed further in section Human Exposures to Residues and Public Health Concerns, below). Development of resistance by pests to these OC chemicals urged to replace them by new and less persistent chemicals, such as organophosphate (OP), carbamate, and pyrethroid compounds, supposedly more specific in the fight to pests too (The Agrochemicals Handbook 1991).

Research on all these chemicals, in particular using carbon-14 (^{14}C)-labeled compounds, shed light on the degradation rates in soils and in aquatic environments, and in accumulation by nontarget biota (e.g. Carvalho et al. 1992, 1997). Organochlorine compounds, such as DDT, HCH, heptachlor, toxaphene, and lindane, are in general, much more persistent and their residues may remain in soils and sediments over days, weeks, and even years (Fig. 7; Carvalho et al. 2002a,b, 2003). In the aquatic environment, OPs were expected to degrade rapidly, but experimental research has shown that they persist days/weeks and are accumulated by crustacean and fish (Carvalho et al. 1992). Moreover, once released into the aquatic systems, these compounds are bio-accumulated in a few minutes and undergo also partitioning between water and particulate matter/sediment, with partitioning coefficients

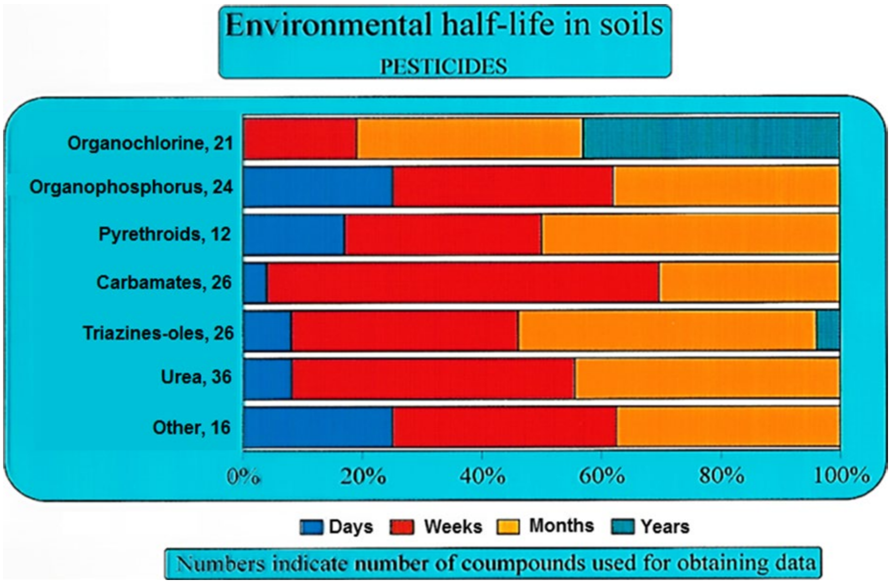

Figure 7. Environmental persistence (half-lives) of pesticides in soils by chemicals group. Numbers indicate number of compounds for which data are available (modified from Carvalho et al. 1997).

(K_p) that are positively correlated with the octanol-water partitioning coefficients (k_{ow}) of the compounds. Experimental studies in mesocosmos have shown that compounds, such as endosulfan, could persist long time as well and were accumulated up to the point to represent a toxicological risk to aquatic biota (Carvalho et al. 1999, 2002a,b; Nhan et al. 2002). Taking into account chemical properties and persistence in the environment, chemicals applied in agriculture fields may be transported and reach other ecosystems (Fig. 8). As predicted from results of experimental studies using ^{14}C-labeled compounds, the endosulfan applied in coffee and leguminous plantations and at the time seen as a nonpersistent compound, through field investigations was consistently found in aquatic systems near agriculture regions in central and North America countries (Carvalho et al. 2002b, 2009a,b). Later, it was verified that endosulfan residues are widespread in the environment and it is considered nowadays a "global pollutant" (Weber et al. 2010).

Compounds of different chemical groups have different toxic mechanisms and act on pest organisms in different ways. Organochlorine compounds (insecticides, e.g., aldrin, DDT, HCH, heptachlor, chlordane, endosulfan) are in general very effective contact insecticides, and they are structurally related to steroid hormones and act on the respective hormone receptor (Tebourbi et al. 2011). Organophosphates (mostly insecticides, e.g., parathion, malathion, chlorpyrifos, diazinon, dichlorvos) and carbamates (mostly herbicides and fungicides, e.g., aldicarb, carbofuran, ethienocarb, fenobucarb, methomyl) act as acetylcholinesterase (AchE) inhibitors causing disruption of nervous impulse transmission at synaptic level. Pyrethroids (insecticides, e.g., cypermethrin, deltamethrin, esfenvalerate, fenvalerate) act on the voltage gated-sodium channels in cell membranes disrupting the Na^+ ion flux. The neonicotinoids (insecticides, e.g., acetamiprid, clothianidin, dinotefuran, imidacloprid) act as agonists at the nicotinic acetylcholine receptors (nAChRs), are neurotoxic, and act on the insect's nervous system, resulting in paralysis and death (Tomizawa and Casida 2005).

The mechanism for toxic action is not restricted to target pests, and toxicity is exerted also on nontarget similar organisms causing damage to biodiversity and ecosystems health. OCs impacted heavily the top predators in terrestrial food chains, as birds of prey, and accumulate in adipose tissues of animals and humans, being transferred to newborns with the milk fat, and act as endocrine disruptor (EEA 2013). Organophosphates were reported as highly toxic to arthropods in general, which includes insects but also shrimp, crabs and other crustacean, and also to vertebrates. Pyrethroids have also impact on insects and vertebrates. Many other compounds used, as herbicides have shown effects also on central nervous system and excretory system of mammals (Casida 2009; Singh et al. 2016).

Due to reports on contamination of the environment and toxic effects on biota, considerable efforts have been made to design new chemicals, improve pesticide formulations, application devices, and chemical delivery mechanisms such as the use of degradable nanoparticles as a vehicle to pesticides in an attempt to reduce exposure of biota and environmental contamination (De et al. 2014).

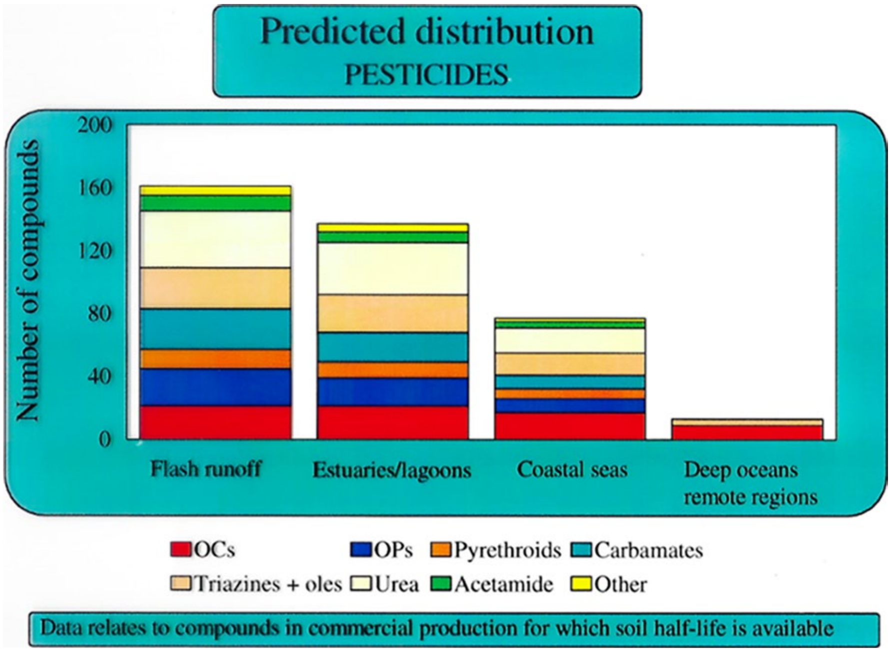

Figure 8. Potential for transport and dispersion of pesticides in the environment with ecosystems that they may reach. Data relate to compounds in commercial production for which soil half-life is available (modified from Carvalho et al. 1997).

Nevertheless, this has not resolved the collateral effects of pesticides and recurrent episodes with new chemicals, including neonicotinoids, have been reported (Bouwman et al. 2013; Hallmann et al. 2014; Park et al. 2015).

Residues in Soils and in Aquatic Environments

Persistent and bio-accumulative chemical compounds, such as DDT, HCH, toxaphene, aldrin, and dieldrin, were banned by the Stockholm Convention, approved in 2002, and have been replaced by environmentally friendly and less bio-accumulative chemicals. This has been the trend over the last decades, and it was driven by the toxicity of chemical residues present in food to humans as well as to chemicals' persistence in the environment and toxicity to nonhuman biota. However, from the massive application of OCs in the past, they are still present in soils, in sediments, and in the biosphere and are toxic. For example, toxaphene in cotton fields is not used anymore in Nicaragua but many years after cessation of applications, the deposit in agriculture soils was still a source of contaminants transported by surface runoff to aquatic environment and a threat to shrimp farming in coastal lagoons (Carvalho et al. 2002a,b, 2003).

Indeed, the ban of persistent OC compounds in agriculture abated application of OC pesticides in many regions but was not the end of concerns about toxic effects of these compounds. Today, we still find these OC compounds in environmental compartments as a legacy of past applications. Soils are the main reservoir of persistent OCs, and soil erosion, surface runoff, and river discharges carry and cycle significant amounts of persistent OCs in the environment. For example, results from the annual surveys of USA pollution trends reported pesticide residues in coastal sediments and biota (mussels and oysters) originated in river catchments. Many years after the ban of these compounds (e.g. DDT, chlordane), they were still present in the coastal environment where they degraded very slowly, as reflected by decreasing concentrations in biota over the years (Fig. 9). Similarly slow decrease of residue concentrations was also recorded in coastal environments of Mediterranean Sea in Europe (Villeneuve et al. 1999).

From a vast study carried out in tropical coastal ecosystems worldwide, it was concluded that pesticide residues were everywhere and were concentrated by marine fauna (Taylor et al. 2003). Other case studies showed similar conclusions, such as in the Manila Bay, Philippines, Mekong River Delta in Vietnam, coastal lagoons of NW Mexico, Laguna de Terminus, Caribbean Sea, Mexico, Todos-os-Santos Bay in Salvador, Brazil, coastal areas of Florida in USA, and North Sea and Baltic Sea in Europe (Carvalho et al. 1997, 1999, 2008, 2009a,b,c). In all these coastal areas, the residues of a large collection of crop protection chemicals, such as DDTs, HCHs, lindane, aldrin, toxaphene, and endosulfan, were determined (Carvalho et al. 2002a,b, 2003; Kimbrough et al. 2008;

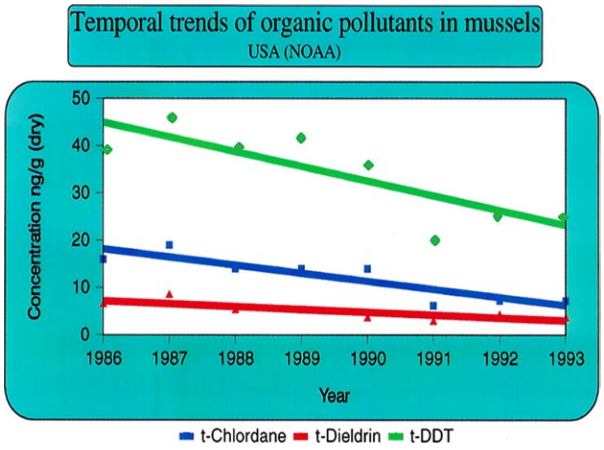

Figure 9. Temporal trends of organochlorine pesticides in coastal mussels. Average concentrations based on data from USA-NOAA Status and Trends Reports. Environmental half-lives in mussels are from 6 to 12 years depending on compound.

Moreno-Gonzalez and Leon 2017). More modern pesticides and other chemicals used in industry, such as PCBs, tributyltin, and pharmaceutical drugs, have been detected also in river waters and coastal areas and often originate in urban wastewater discharges (Barceló and Petrovic 2008).

Pesticide residues carried to the sea are also a threat to large marine ecosystems such as coral reefs. Agrochemical residues are currently monitored in sea water by the Great Barrier coral reef, Australia, where recent studies demonstrated the widespread contamination by pesticides, particularly herbicides which may impinge on symbiotic algae and destroy the coral reef (Lewis et al. 2009; Smith et al. 2012). Similarly, residues of persistent organic contaminants were found in biota in the deep sea, by many still seen as a remote and pristine environment (Jamieson et al. 2017).

Contamination of aquatic bodies by residues from periodic application of pesticides in crops was, thus, found in many environments, and this called for preventive measures. Not much was done at global scale, but near golf greens, where the use of herbicides and fertilizers is intensive, contamination of watercourses and groundwater by residues was of concern, and improved area management was advised and locally introduced through using constructed wetlands (Klaine et al. 1988).

Persistent OCs are not anymore used in Europe also, but HCH, DDT, and lindane still are present in rivers in Europe and are bioaccumulative (McKnight et al. 2015; Rasmussen et al. 2015). Organochlorine compounds residues are almost always present in environmental samples although in decreasing concentrations with the years, as reported, for example, in Denmark. There, the presence of OC residues in river waters is from leaching of legacy applications persisting in soils, but their potential for toxic effects on aquatic fauna remains current (Rasmussen et al. 2015).

More recently, introduced and more degradable pesticides, such as chlorpyrifos, parathion, isoproturon, and mecroprop, are often detected also in river waters (Barceló and Petrovic 2008; Moreno-Gonzalez and Leon 2017). Residues of these new chemicals show the opposite concentration trend in surface waters, with concentrations often increasing over the years, such as for glyphosate (McKnight et al. 2015; Portier et al. 2016). This is very worrisome because this widespread presence of chemical residues compromises natural resources such as water for human consumption including groundwater and water for aquaculture activities.

Water Quality and Biodiversity in Freshwater and Coastal Ecosystems

The monitoring of water quality has been subject to stricter control with the EU Water Directive Framework (Directive 2000/60/EC of the European Parliament and of the Council) that required each contaminant concentration to be below 1 pg/L. Water quality for aquaculture is, however, more difficult to ensure because aquaculture itself makes use of chemicals. For example, salmon production, which in EU provided about 1/3 of fish for human consumption, uses antifouling agents, antibiotics, and chemicals for protection against lice, the main parasite of farmed salmon (SEP 2015). Residues from these chemicals, plus natural toxins from harmful algal blooms, dioxins, and PCBs, put the quality of coastal waters and the aquaculture production under pressure of contamination (SEP 2015). Although there has been a decrease of farmed salmon contamination by organic chemicals over the years, still the consumption of fish is a matter of concern and advice on intake limitation has been given to consumers (Nøstbakken et al. 2015; Ruzzina et al. 2015).

Discharges of industrial waste water and urban sewage into water lines and coastal zones have been a common procedure in most countries. The adoption of urban sewage treatment and their success has always been introduced, or attained late. One may recall the impact of pesticide residues on corals, fisheries, and shrimp aquaculture to understand that contamination has been always followed by ecological disasters and public health impacts, before regulations and mitigation measures were adopted. Increasing awareness of contamination multiplied the monitoring efforts that are continuously developing now. For example, the EU project Ocean of Tomorrow included a several initiatives to control chemical residues in sea food and development of a real-time monitoring system to respond to these challenges (e.g. Research Project Sea-on-a-Chip; http://www.sea-on-a-chip.eu). Removal of emerging contaminants from industrial waters and treatment of urban waters are also progressing (Barceló and Petrovic 2008).

The importance of controlling contamination of aquatic systems goes beyond the immediate need for water with quality for human consumption. Toxic residues in aquatic systems may eliminate aquatic species, reduce biodiversity, and compromise the functioning of ecosystems. A large research effort has been made in aquatic toxicology to understand bioaccumulation mechanisms and define toxicity levels to species selected as representative (plants, crustacean, fish) and elaborate guidelines for pollution control within tolerated limits (Rand 1995). However, toxic substances even in very low concentrations always bioconcentrate and may act on sensitive species or larval stages of biota impairing the ecosystem healthy functioning and compromising their services (Chagnon et al. 2015; Gilbert 2016). Dramatic examples are the reduction of pollinating insects, elevated concentrations of PCBs, and pesticides in farmed salmon, and the dying of the Great Barrier Coral Reef which may compromise entire ecosystems (Smith et al. 2012; Nøstbakken et al. 2015; Park et al. 2015). Eventually, instead refining toxicity testing and determination of LD_{50}, we should move the efforts to develop processes to remove contaminants from soils and effluents and prevent them to attain aquatic systems and bioaccumulate in food chains.

Human Exposures to Residues and Public Health Concerns

Worldwide, about 25 million agricultural workers experience unintentional pesticide poisonings each year, and it is estimated that approximately 1.8 billion people engage in agriculture and most use pesticides to protect food and commercial products that they produce. A few more are occupationally exposed during the use pesticides in sanitary campaigns and for lawn and garden applications (Alavanja 2009).

To reduce further exposure of population from widespread environmental contamination by these chemicals, it is not surprising that residues from both legacy applications and current agricultural, industrial, and household applications need to be controlled tightly in the environment and in the foods (EFSA 2016).

Currently, pesticide residues in North America and in EU are thoroughly monitored. In general, market foods are compliant with maximum permissible concentrations (MPC) and percentages of samples with detected residues exceeding MPCs fortunately are in small number. For example in the EU, among more than 83,000 food samples from 28 Member States analyzed in 2014, 97% of samples analyzed were within legal limits; of these, 53.6% were free of quantifiable residues, and 43.4% contained residues that were within permitted concentrations (EFSA, 2016). Notwithstanding, in plant products, 154 different substances were found in measurable concentrations including recent and old crop protection chemicals and, although the food authority EFSA assessed the risk to consumers as low, recommendations were deemed necessary to further improve food safety and abate consumers exposure through diet (EFSA 2016).

Exposure to pesticides and synthetic chemicals were related to cancer, obesity, endocrine disruption, and other diseases in humans (Gorell et al. 1998; Bassil et al. 2007; George and Shukla 2011; Mrema et al. 2013; Araújo et al. 2016; WHO 2017). Phasing out persistent chemicals, as agreed in the Stockholm convention, contributed to reduce human exposure to toxic chemicals. Indeed, over the last decades, studies carried out in several countries have shown a consistent decrease of DDTs in human adipose tissues and milk (EEA 2013). Notwithstanding, exposure to chemical residues via water and food ingestion remains for the members of the public (i.e. without occupational exposure), a subject of concern and a burden to public health. Recent reviews of exposure and health impact of pesticides on human health have underlined the burden on human health and re-evaluated the current toxicity of legacy pesticide residues (Mrema et al. 2013). The WHO and IARC, among other organizations, keep under close scrutiny and revision the advisories on toxicity of new and old chemicals. Many agrochemicals were related to prostate cancer and other types of cancer and are increasingly regulated (Singh et al. 2016; ECA 2017).

At present, there is a widespread concern about effects of herbicides on human health, such as glyphosate that is of common use in agriculture and in cities to control weeds, and is a main carcinogenic agent (Araújo et al. 2016; Benbrook 2016). Glyphosate is the most widely applied pesticide worldwide, and in the USA, in 2014 farmers applied glyphosate at a rate of about 1 kg/ha in croplands (Benbrook 2016). The EU set the daily chronic reference dose for glyphosate to 0.5 mg/kg body weight per day, while the US EPA has set glyphosate daily chronic reference dose at 1.75 mg/kg body weight per day. However, recent compilation of toxicological data on glyphosate supports the need for reducing further the daily chronic reference dose to 0.1 mg/kg body weight per day (Antoniou et al. 2012).

In general, the maximum tolerated limits of residues in foods have been decreasing over the years, although exposure has not decreased sufficiently still due to legacy compounds in the environment and new chemicals introduced. Furthermore, it was recognized that most of the work done in the toxicity field has been reactive to problems and with marginal efficiency in anticipating and preventing the collateral toxic effects (EEA 2013).

Current Trends in Chemicals Control

The data base CAS Registry (www.cas.org) provided by the American Chemical Society includes more than 129 million unique organic and inorganic chemical substances and more than 67 million nucleotide sequences (by April 2017). More than 4000 new substances are added each day. The number of chemicals increased exponentially over the years with an average annual growth rate of about 15% in the last decades (Binetti et al. 2008). In this universe of chemicals, a small fraction is pesticides. In the data base of the US Pesticide Action Network (PAN), 6,400 pesticide active ingredients and their transformation products, as well as adjuvants and solvents used in pesticide products, were listed (www.pesticideinfo.org/). In the EU pesticide database, there are 1359 entries, not all approved for use, and about 700 registered chemicals are in use as pesticides (Eurostat, 2017). However, toxicological information about these chemicals is very poor for most of them.

In the USA, an EPA report of 1998 indicated that no information on toxicity was available for 43% of high production volume chemicals and a full set of toxicity data was available for 7% of them only (USEPA, 1998). A similar situation occurred also in the EU, and a study carried out in Denmark for 100,000 substances listed in the European Inventory of Existing Commercial Chemical Substances (EINECS) concluded that for 90% of them few toxicological data were available (Niemelä 1992).

The EU adopted in 2007 the new policy to control industrial chemicals called REACH (Registration, Evaluation, and Assessment of CHemicals), intended to create a central database on chemicals and entrusting the industry with the responsibility to evaluate and manage the risks of chemicals. In spite of large progress made in improving the knowledge about toxicity and environmental impact of chemicals, control of risks is far from being grasped and controlled (EUROSTAT 2012; EEA 2013). In a recent report, it was appreciated that, in the decade 2004–2013 in the EU, the production of environmentally harmful chemicals averaged about 150 million tons per year, representing about 40% of the total production of industrial chemicals (EUROSTAT, 2014). It was registered also a shift in production from more harmful to less harmful chemicals (based on aquatic toxicity and persistence), but still far from the objectives of sustainable development (EUROSTAT 2014).

EU objectives for 2020 foresee further action to implement REACH and achieve improvements in human life quality and environmental management regarding chemicals (7th EU Environment Action Plan). However, as pointed out before, experiments on hazards and risks cannot follow the same increasing trends for chemicals produced, because this would require very large amounts of expertise and very large amounts of human and laboratory resources to carry out complex tests (Binetti et al. 2008). Thus, timely risk assessment may be delayed.

Can we do better?

The need for producing more food to feed the growing human population is likely to increase (UN, 2015). To meet this goal, several options are open. One option might be to continue the path of intensive use of agrochemicals, including pesticides, with subsidiary research to produce more selective pesticides and improved application techniques. Other alternative options have been proposed and include the use of genetically modified organisms for better yield crops and crops resistant to pests, organic farming, development of new cultivars and recuperation of old cultivars, increased use of bio-pesticides and pheromone traps to control pests, and change of dietary habits of human populations.

The current pathway of applying synthetic crop protection chemicals has been walked through on a circular approach consisting of identification of a pest, development of a chemical, observation of collateral effects and rise of new problems, development of new chemicals, etc. We could consider this as an approach based on the trial and error method. There has been results temporarily achieved, certainly, but they always have come with an associated cost. Today, food and environment contamination with toxic chemicals impinging on public health over several human generations is considered unaffordable. We need to learn the lessons from the past and, desirably, this circle of trial and error should come to an end.

Probably, agriculture and intensive food production may not dispense the use of current agrochemicals in the next few years. Several measures could be introduced to better mitigate their collateral effects in the meantime. For example, introduction of precision application of agrochemicals (as well as precision irrigation) could reduce the amount of chemicals (and water) applied over the fields. Some other simple measures could be also immediately applied everywhere, such as: a) recovery and treatment of contaminated agriculture runoff with installation of wetland stripes suitable to clean up runoff and water drainage; b) reinforce education of farmers and the public in general about chemical hazards; and c) thorough toxicity testing and proper registration of chemicals and formulations. These measures may help to gain some extra time.

Meanwhile, we should look beyond the present time for sustainable solutions. There is a consensus that intensified research on better food production and production of food with better quality is needed. Furthermore, it is recognized that productive soil is a finite resource (as water) and, in order to ensure continued production of food, the agriculture must go side by side with soil and ecosystems preservation, restoration, and agronomic research on better yield cultivars. Therefore, it is urgent to achieve a generalized agreement on pesticide application and adoption of good agriculture practices, with consideration to Integrated Pest Management (IPM) techniques.

Consumers and the public in general have rejected already the environmental and health costs of hazardous chemicals, and awareness of chemical residues in foods created the demand for clean foods. More food and safer food is, therefore, required, but the human population and natural ecosystems may not survive longer to poor planning and poor agriculture practices. A systematic application of the precautionary principle in the introduction and application of all chemicals, including pesticides, is needed (EEA 2013). This requires thorough risk assessment of chemicals toxicity to environment and humans.

Emerging alternative paths in food production, such as development of GMO varieties and their release for international agriculture without application of the precautionary principle and satisfactory risk assessment, must be avoided. This issue deserves urgent international discussion. An agreement should be reached based on science and on ethical principles for ensuring food security and food safety. Moreover, alternative paths for food production should not repeat the mistakes of pesticide applications and must succeed in ensuring food safety and food security.

Conflict of Interest

None declared.

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