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REVIEW

Agricultural pesticide use and food safety: California's model

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Abstract

Pesticides have been an essential part of agriculture to protect crops and livestock from pest infestations and yield reduction for many decades. Despite their usefulness, pesticides could pose potential risks to food safety and the environment as well as human health. This paper reviews the positive benefits of agricultural pesticide use as well as some potential negative impacts on the environment and food safety. In addition, using the case of California, we discuss the need for both residue monitoring and effective pest management to promote food safety. Twenty years' pesticide residue data from California's pesticide residue monitoring program were analyzed. Results showed that more than 95% of food samples were in compliance with US pesticide residue standards (tolerances). However, certain commodities from certain sources had high percentages of residues above tolerance levels. Even when residues above tolerance levels were detected, most were at levels well below 1 mg kg^{-1}, and most posed negligible acute health risk. However, a few detected residues had the potential to cause health effects. Therefore, establishing an effective food residue monitoring program is important to ensure food quality throughout the marketplace.

Keywords: food safety, food security, pesticide use, residue monitoring, environmental impacts, IPM, tolerances, maximum residue limits (MRLs)

1. Introduction

The benefits of pesticide use in agriculture are evident in every agricultural system worldwide (e.g., Popp *et al.* 2013). This is especially true in large-scale commercial agriculture such as the US state of California. At the same time, the negative impacts of pesticides on human health and the environment are well documented. Pesticide residues in food are an important pathway for human exposure. This paper reviews both the benefits and risks of pesticide use with regards to food security and food safety. We present California's program for monitoring pesticide residues in food as a case study for discussing the importance, current practices and future challenges for residue monitoring. Lastly, we discuss how good agricultural practices including integrated pest management can help protect food safety by reducing pesticide use.

Agricultural pesticide use has increased agricultural production worldwide and thereby contributed to food security (Warren 1998; Fisher *et al.* 2012). Pests such as insects, plant diseases, and weeds are an ongoing chal-

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lenge to agricultural producers. Oerke (2006) reported that globally, an average of 35% of potential crop yield is lost to pre-harvest pests. With the expected 30% increase of world population to 9.2 billion by 2050, there is a projected demand to increase food production by 70% according to the calculation by Popp *et al.* (2013). Though non-pesticidal tools have a vital role, there will be a continuing need for pesticide-based solutions to pest control and food security in the future (Webster *et al.* 1999; Fisher *et al.* 2012; Popp *et al.* 2013). Fig. 1 shows average pesticide use intensity (kg ha^{-1} yr^{-1}) on the arable and permanent cropland worldwide. High use intensity countries above 10 kg ha^{-1} yr^{-1} include Surinam, Columbia, Chile, Palestinian, Malta, Korea, Japan, and China (FAO 2015a). Fig. 2 shows that pesticide sales are increasing in Asia, Latin America, and Europe. Africa and the Middle East have far lower sales than any other region (FAO 2015b).

Attention to the impacts of pesticide use on the environment and ecosystems has grown since the book *Silent Spring* was published in 1962. Extensive published literature has well documented the impacts of pesticide use to the ecosystem and human health (Popp *et al.* 2013). Pesticides

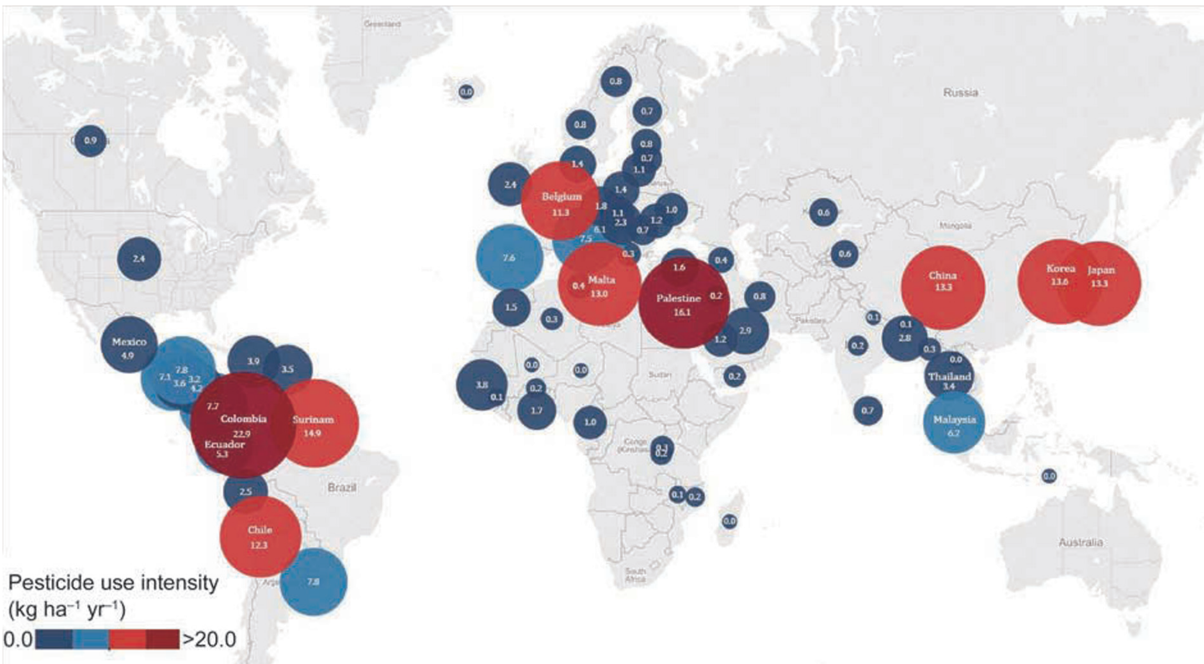

Fig. 1 Average annual pesticide use intensity (kg ha^{-1} yr^{-1}), on arable and permanent cropland from 2005 to 2009. Data are from FAO (2015a).

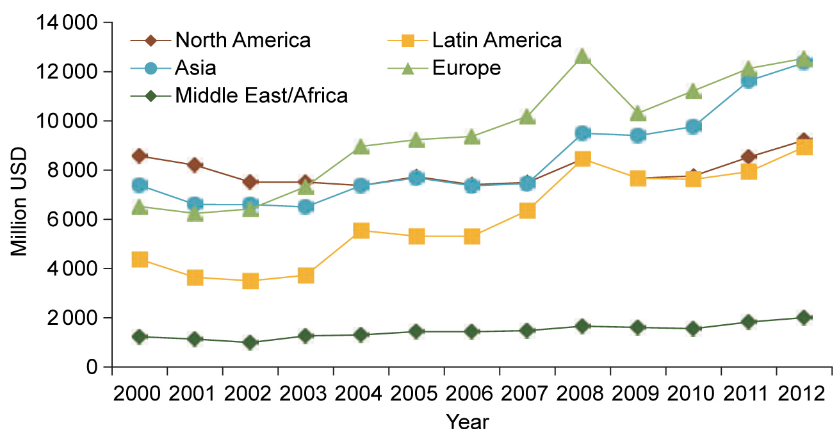

Fig. 2 Annual pesticide sales by geographic regions. Data are from FAO (2015b).

can move offsite to contaminate surface water and leach to groundwater. Damage to non-target organisms and pollution to the air and soil are all well documented (Andreu and Picó 2004). In addition, agricultural farm workers and pesticide factory workers have high risk to pesticide direct exposures (Pimentel 2005; Verger and Boobis 2013).

California is the state within the USA that has the largest population and largest agricultural productivity (US Department of Commerce 2014; ERS 2015). With more than 80 000 farms and ranches, California agriculture is a 46.4 billion USD industry that generates at least 100 billion USD in related economic activity (CDFA 2014). Therefore, California is a useful case study for how to manage pesticides' benefits and risks. California has the nation's most comprehensive pesticide regulations (CDPR 2011a, 2014a), and California agriculture uses exceed 86 million kg of pesticides annually to protect production (CDPR 2015c). Although the benefit of applying pesticides in agriculture is clear, monitoring by regulatory agencies has detected cases of pesticide contamination in California's surface water, groundwater, soil, air, and food (Zhang *et al.* 2005, 2012; CDPR 2011a; Troiano *et al*. 2013; Budd *et al.* 2015).

In recent years, pesticide residues in food have become a focus for food safety and trade. Quarantine regulations sometimes require pesticide treatment of food shipments to prevent establishment of exotic pests. Nonetheless, local consumers and international trading partners increasingly demand food that is free from unsafe pesticide residues. Therefore, many countries have initiated programs to monitor pesticide residues in food. In addition, many countries are implementing programs to reduce the use of pesticides and thereby minimize pesticide impacts. California provides a useful case study for how to monitor residues and how to minimize pesticide impacts. In particular, this paper will focus on California's program for monitoring pesticide residues in food.

2. Functions of pesticides for large-scale commercial agriculture

Pests include weeds, insects, rodents, and diseases that affect crops and livestock. Pesticides include herbicides, insecticides, rodenticides, fungicides, and other products for helping control pests.

The need for pesticide use is demonstrated by well-known cases of losses from pests for which effective pesticides were not available. For example, late blight disease (*Phytophthora infestans*) of potato caused the Irish famine of 1845–1847, resulting in the death of 1 million people. Downy mildew disease (*Plasmopara viticola*) of grapes almost caused economic ruin for the wine industry in the Mediterranean, beginning in 1865 (Robinson 2006; Simpson 2011). Pesticides were an essential part of the so called Green Revolution, which occurred between the 1940s and 1970, greatly promoted agricultural productivity and is credited with saving over a billion people from starvation (Macaray 2014). Pesticide use increases both the quantity and the quality (i.e., the diversity) of food.

Even when pesticides are used, pests have the potential to cause substantial losses. Data from 1964 to 2003 (Cramer 1967; Oerke *et al.* 1994; Oerke and Dehne 2004; Oerke 2006) showed that losses due to pre-harvest pests ranged from 24 to 34% for wheat, 30 to 38% for maize, and 25 to 38% for cotton. Pimentel (2005) reported that insect pests, plant pathogens and weeds destroyed 37% of potential crop yields in the USA despite the widespread application of pesticides. Similarly, Popp *et al.* (2013) determined that up to 40% of the world's potential crop production is lost to pests, and that losses would double if no pesticides were used.

When properly managed, pesticides have the capacity to bring dangerous pests under control. In the late 1990's, an epidemic of Pierce's disease of grapevines in southern California caused major concern of government and producers, because infected vines cannot be cured and no suitable resistant grape varieties are available currently (Gardner and Hewitt 1974; Bruening *et al.* 2014). The disease outbreak was linked to an invasive non-native insect pest, *Homalodisca vitripennis,* which is a vector of the bacterium that causes Pierce's disease. Researchers developed an effective method to manage the disease by combining insecticide applications and biological control to reduce *H. vitripennis* populations (Varela *et al.* 2001; Feil *et al.* 2003). Since then, the outbreak has been well controlled (Bruening *et al.* 2014).

In California, a study published in 1991 indicated that a 1 USD increase in pesticide use would lead to an increase of 3 to 6.5 USD of gross agricultural income (Zilberman *et al.* 1991). The large scale of agriculture in California shows that pesticide use benefits agricultural production, and the economy, and hence increases food security.

3. Agricultural pesticide use has potential to impact the ecosystem health

While the benefits of pesticide use to increase crop production and food security are clear, the unintended impact of pesticide use on the ecosystem and human health is also well documented.

Pesticides can contaminate soil, water, air, and non-crop vegetation. In addition to killing pests, pesticides can be toxic to non-target organisms including birds, fish, beneficial insects, and non-target plants if the pesticide is used in conflict with label directions. Insecticides are generally the most acutely toxic class of pesticides for animals and humans, but certain herbicides and fungicides also can pose risks to non-target organisms (Aktar *et al.* 2009)

Due in part to the adverse effects of pesticides on the environment, pesticide manufacturers have been striving to produce less toxic and less persistent pesticides while maintaining efficacy. Overall, pesticides in the market have become safer to use and less toxic to the environment and human health compared to older pesticides. For example, in California, the use of organophosphate insecticides was substantially replaced by pyrethroids and, more recently, by less acutely-toxic insecticides including biologicals based on *Bacillus thuringiensis* (Bt) and novel modes of action such as spinosad (Epstein and Bassein 2003; Zhang *et al.* 2005; IRAC 2015).

Despite overall improvements in pesticide safety, pesticides can still reach surface water through offsite movement from treated crops and soils. A study by the US Geological Survey (USGS) showed that more than 90% of water and fish samples from US streams contained one or more pesticides (Kole *et al.* 2001). Herbicides such as 2,4-D, diuron, and prometon and the insecticides chlorpyrifos and diazinon were frequently detected in major waterways in the USA (Domagalski 1998; USGS 1999) and California (Zhang *et al.* 2012; Budd *et al.* 2015).

Pesticide contamination of groundwater is another common problem worldwide (Bubb 2001; Aktar *et al.* 2009). According to the USGS (1999), at least 143 different pesticides and 21 transformation products have been found in groundwater. In the San Joaquin Valley of California, herbicides including simazine, diuron, bromacil, dibromochloropropane, and others were found in groundwater at concentrations of concern for ecosystem and human health (Troiano *et al.* 2013). These pesticides were commonly used in grapes and deciduous orchards such as citrus (Zhang *et al.* 1997; Domagalski 1998).

In addition to the impact of pesticides on the environment, there is also evidence that some pesticides pose a potential risk to human health (Igbedioh 1991; Koureas *et al.* 2012; Thongprakaisang *et al.* 2013). Worldwide, deaths and chronic disease due to pesticide exposure exceed 1 million annually (Environnews Forum 1999). In California, the Pesticide Illness Surveillance Program (PISP) documented 237 cases of illnesses or injuries related to agricultural pesticide use during 2012 (CDPR 2015b).

Another clear path by which pesticide use impacts human health is through dietary exposure. Therefore, many countries have established programs for monitoring pesticide residues in food to protect food safety and public health. California also has established an extensive food residue monitoring program.

4. Sampling and monitoring pesticide residues in food

4.1. Why monitor pesticide residues?

Residue monitoring provides society with four main benefits. First, the monitoring results enable regulatory agencies to confiscate and prevent sale of shipments of food containing unacceptable pesticide residues (CDPR 2014a; FDA 2015) to protect public health.

Second, the monitoring results allow the identification of commodity sources having higher incidence of unacceptable pesticide residues. Though slower than confiscation, ultimately this offers a more effective opportunity to address the cause of the unacceptable residues. Corrective actions can include training farmers in pest management, outreach to vendors, and/or punitive fines for repeat violators (CDPR 2014a; AMS 2015; FDA 2015).

Third, the monitoring can provide quantitative estimates of residue levels of specific pesticides in the food supply. Such data help researchers and regulators assess the dietary safety of current and future pesticides (USEPA 2012; CDPR 2014a; AMS 2015; FDA 2015).

Fourth, the monitoring can identify certain produce sources having a high rate of compliance and safety. Increasingly, consumers and trade partners demand objective data to document that residue levels are in compliance with safety standards. For example, distributors of California produce appreciate the availability of data showing that California-grown produce had a 97.8% compliance rate in 2013 (CDPR 2014a).

4.2. Scientific standards for residues: Establishment and enforcement

The US Environmental Protection Agency (USEPA) sets the maximum amount of each pesticide residue allowed for the foods sold within the US. Although many nations use the term maximum residue limit (MRL), the maximum residue values set by USEPA are called "tolerances". USEPA tolerances are legally binding throughout the US, and are applied both to food grown within the US and to food imported into the US (USEPA 2012). Tolerances for the same pesticide may differ depending on the commodity, thus there are thousands of individual tolerances in effect (Gandhi and Snedeker 1999; USEPA 2012; GAO 2014).

For setting each tolerance, the *US Food Quality Protection Act* requires USEPA to ensure that the pesticide can be used with "reasonable certainty of no harm" (Schierow and Esworthy 2012; USEPA 2012). To ensure this, USEPA considers: (1) the toxicity of the pesticide and its breakdown products; (2) how much of the pesticide is used in agriculture; (3) what proportion of the pesticide remains in the food after harvest; and (4) the amount of each commodity consumed in the US diet (USEPA 2012; GAO 2014; FDA 2015).

In response to new data about pesticide toxicity, USEPA may modify or revoke tolerances. In other words, tolerance values change over time. Therefore, when evaluating whether a particular pesticide residue is in compliance with tolerances, it is essential to use the tolerance value that was in effect on the date when the residue was sampled. Websites provide the most up-to-date sources for current tolerance values. Official tolerances are published in the US Federal Register, title 40, part 180 which can be accessed online at http://www.ecfr.gov. In addition, a private company maintains a website (http://www.globalmrl.com/) that provides convenient utilities for searching for tolerances. Both websites are updated frequently for providing up-to-date tolerance levels.

Within the US, food in violation of USEPA tolerances is subject to seizure by the government (USEPA 2012). There are two distinct situations when food is in violation:

1) USEPA already has established a tolerance for the pesticide on the specific commodity where it was detected, but the amount of residue is higher than the established tolerance (USEPA 2012).

Or 2) USEPA has not established any tolerance for the pesticide on the specific commodity where it was detected. By law, residue of a pesticide for which USEPA has not set a tolerance, or an exemption from a tolerance, is considered unsafe and therefore prohibited in foods (GAO 2014).

To enforce USEPA's tolerances, several federal-government agencies monitor residues in food nationwide. All federal monitoring programs sample both food produced within the US and imported from other countries. The federal Food and Drug Administration (FDA) monitors most raw and processed foods, including targeted sampling for regulatory enforcement (FDA 2015). In addition, the Food Safety and Inspection Service (FSIS) of the US Department of Agriculture (USDA) monitors and enforces residues in meat, milk, and processed egg products (FSIS 2014, 2015). Another branch of the USDA, the Agricultural Marketing Service (AMS), administers the Pesticide Data Program (PDP) that samples and analyzes certain highly-consumed commodities, particularly foods commonly consumed by infants and children (AMS 2015).

Federal monitoring is an essential safeguard. However, given the size and complexity of the US food system, federal monitoring alone is not sufficient. For example, in fiscal year 2012 FDA tested residues on less than one-tenth of 1% of food shipments imported into the US (GAO 2014). To provide additional protection, the enforcement agencies of certain individual states conduct independent programs to monitor residues in food. In particular, California conducts one of the most extensive state monitoring programs (CDPR 2014b).

4.3. Procedures for sampling and monitoring: California's approach

Sample collection The California Pesticide Residue Monitoring Program is administered by the California Department of Pesticide Regulation (CDPR). A schematic of the program is shown in Fig. 3. Sampling focuses on raw fruits and vegetables, and includes both US and imported produce. Sampling does not include processed foods or foods derived from animals (CDPR 2014a). CDPR samples at multiple points within the food-marketing system, including wholesale and retail outlets, distribution centers of supermarket chains, and direct sales by farmers at farmers' markets (CDPR 2011c, 2014a).

The main goal of the program is to prevent public exposure to illegal pesticide residues (CDPR 2011c, 2014). Therefore, sampling is not statistically representative of the overall food supply. Instead, sampling intentionally over-represents commodities that are often consumed by infants

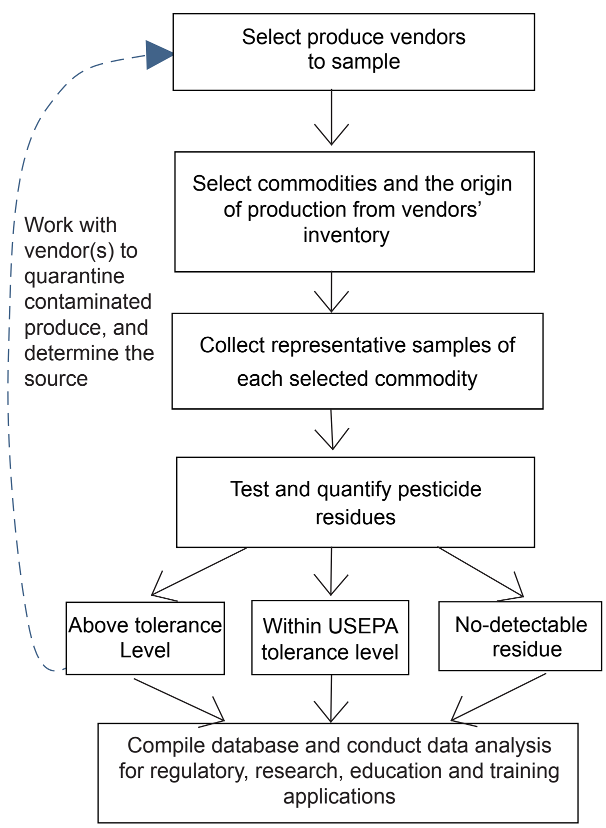

Fig. 3 Schematic of California's pesticide residue monitoring process.

or children, commodity sources with a history of residue violations, and vendors with large volumes of production or imports (CDPR 2011c, 2014). Further, CDPR is committed to ensuring that people of all races, cultures, and incomes are adequately protected (CalEPA 2004). Therefore, CDPR staff ensures that sampling includes commodities and sampling sites that reflect differences in food-consumption patterns among cultural, ethnic, and socioeconomic groups (CDPR 2011c, 2014).

In 2013, the most recent year for which statistics are available, the program collected 3483 samples of more than 155 different fruits and vegetables. Of the 3 483 samples collected, 65.9% were grown within the US, 33.4% were imported, and 0.7% were of undetermined origin (CDPR 2014a).

Laboratory analysis California's produce samples are analyzed by the state's official laboratories: the Center for Analytical Chemistry (CFAC) of the California Department of Food and Agriculture. California began analyzing produce for pesticide residues in 1926. During the 1980's and 1990's, CFAC laboratories developed multi-residue analytical methods (called screens) capable of detecting more than 200 pesticide active ingredients and breakdown products (Mills *et al.* 1963; Lee *et al.* 1991; CDPR 2011c). Multi-residue screens greatly increase efficiency because they do not require a separate analysis for each pesticide (Tao *et al.* 2009; Dorweiler 2013; AMS 2015; FDA 2015).

Currently, CFAC laboratories use a modified QuEChERS method for extracting and purifying residues prior to analysis (Anastassiades *et al.* 2003). Since 2009, the CFAC laboratories have increasingly been using the analytical techniques of gas chromatography/mass spectrometry (GC/MS) and liquid chromatography/mass spectrometry (LC/MS) which together can detect more than 300 pesticide compounds, including newer chemical classes of pesticides difficult to detect by other methods (Fig. 4; CDPR 2014a; AMS 2015). CFAC laboratories are accredited by the International Organization for Standardization (ISO) to the ISO 17025 standard for testing laboratories (Western Farm Press 2005; ISO 2005).

Response to illegal residues When a residue above the tolerance is detected, CDPR immediately contacts the produce vendor and quarantines any remaining produce from the shipment that contains the residue. Based on vendor records, CDPR determines the source of the contaminated produce, and then contacts the distributors and wholesalers who distributed it. CDPR conducts additional sampling and imposes additional quarantines as needed (CDPR 2014a).

Quarantined produce must be destroyed or, in some cases, reconditioned at the expense of the produce owner. Reconditioning involves treating produce in an effort to eliminate illegal residues, for example by washing or heating the raw produce (Bajwa and Sandhu 2014). Before releasing the produce from quarantine, CDPR verifies that the reconditioning removed the illegal residues (CDPR 2014a).

After analyzing the results from monitoring, CDPR conducts outreach to agricultural trade organizations and grower groups, helping to educate their constituents about preventing illegal pesticide residues. For example, analysis of California's monitoring data showed that in 2006–2007, more than 50% of shipments to California of snow peas produced in Guatemala carried illegal residues of pesticides, particularly the insecticide methamidophos (CDPR 2008). CDPR communicated these results to representatives of the Guatemalan snowpea industry, perhaps contributing to the decision by the Guatemalan government to phase out the use of methamidophos (Ministry of Agriculture, Cattle and Food 2008). In subsequent years, detections of methamidophos in Guatemalan snow peas dropped to zero (CDPR 2011c, 2013, 2014a). Another example of outreach is that, in 2014, CDPR representatives travelled to Mexico to explain US tolerances and pesticide regulations to growers and exporters based in Mexico.

CDPR has authority to impose penalties against any individual or company that packs, ships, or sells produce with illegal pesticide residues. Since 2010, CDPR has imposed high penalties against California-based importers with histories of recurring pesticide residue violations, mostly on produce imported from Mexico and China. News releases that specify the names of the companies being penalized increase the deterrent effect of such penalties (CDPR 2010, 2011b, 2015a).

CDPR also coordinates enforcement response with state and federal agencies. For example, in 2013 CDPR monitoring discovered multiple shipments of cactus pads imported from Mexico that were contaminated with the organophosphate insecticide monocrotophos, at levels that had the potential to cause health effects. In addition to tracing and quarantining many shipments, CDPR worked with the California Department of Public Health to issue an alert to consumers, and requested the US Food and Drug Administration to increase inspections of cactus shipments at the US-Mexico border (CDPH 2014; CDPR 2014b).

4.4. Results of California monitoring

Results of each sample collected since 1986 may be downloaded, free of charge, from the CDPR website (http://www.cdpr.ca.gov/docs/enforce/residue/rsmonmnu.htm). During 2009–2013, California monitoring detected pesticide residues in 40% of samples of fresh fruits and vegetables. Of the detected residues, 8% were above tolerance levels and 92% were in compliance with US requirements. Of the

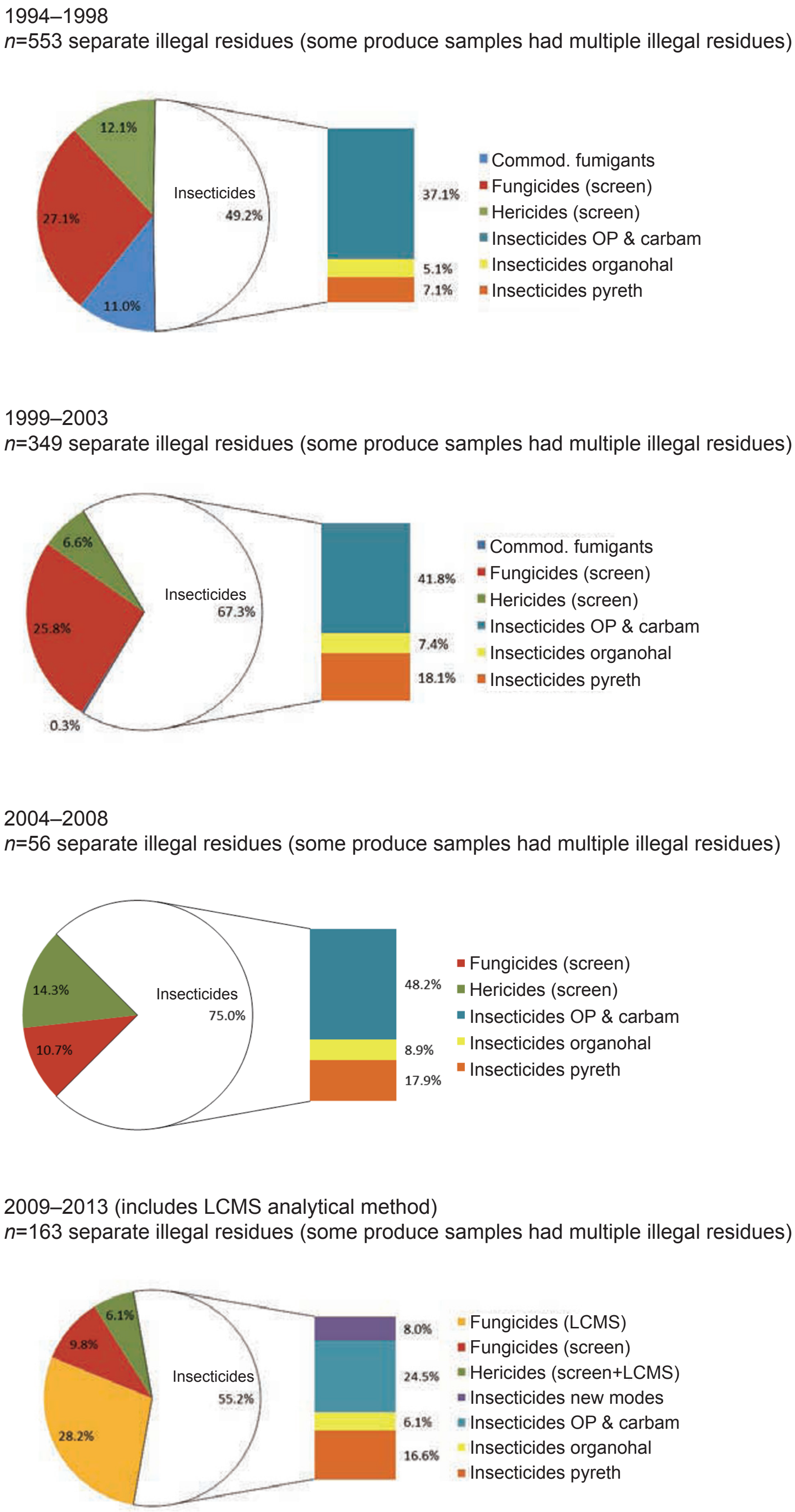

Fig. 4 Chemical classes of illegal pesticide residues detected on US-origin produce, 1994–2013. Source of data: California Pesticide Residue Monitoring Program, California Department of Pesticide Regulation (http://www.cdpr.ca.gov/docs/enforce/residue/rsmonmnu.htm). The same as below.

residues above tolerance, 70% were from imported produce while 30% were from US produce.

During this period, a total of 94 pesticides were detected at levels above tolerance in food. Of these, 37 pesticides were detected at levels above tolerance on imported produce but never detected on US produce. Conversely, 25 pesticides were detected at levels above tolerance in US produce but never detected on imported produce.

Most pesticide residues detected are at concentrations substantially below 1 mg of pesticide kg^{-1} food (mg kg^{-1}). The maximum residues of some pesticides detected above tolerance levels during 2009 through 2013 are shown in Table 1. Only one fungicide was detected above tolerance level on US produce, while 7 fungicides were detected above tolerance levels on imported produce. There were 7 insecticides detected above tolerance levels on US produce while 11 insecticides were found to be above tolerance level for the imported produce.

As shown in Fig. 5, monitoring consistently has shown that 95% or more of raw produce samples are in compliance with USEPA tolerances. Of the samples that are in compliance, more than half have no pesticide residues detected, and the remainder have detectable pesticide residues that comply with (do not exceed) tolerances (CDPR 2014a). Fruits and vegetables produced within California have an even better safety record: in 2013, California-grown produce had a 97.8% compliance rate (CDPR 2014a). Even when residues above tolerance levels were detected, most were at levels well below 1 mg kg^{-1}, and most posed negligible acute health risk (CDPR 2014b). However, a few detected residues had the potential to pose health risks to people (e.g., CDPR 2014b). Most residues of potential concern to human health have been older insecticides (especially aldicarb, methamidophos, and monocrotophos) on produce from certain Latin American and Asian countries. These overall results are comparable to those of nationwide monitoring by the federal Food and Drug Administration, USA (FDA 2015).

Although overall results provide a useful perspective, it is also important to evaluate the results for individual pesticides, individual commodities, and individual vendors. Understanding the sources and chemical classes of illegal pesticide residues helps researchers and regulators determine what actions (if any) are needed to reduce future violations (Fig. 3).

Residues vary by crop and country of origin The rate of compliance with USEPA tolerances varies by crop and by the country where the crop was grown. Table 2 shows violation rates for produce samples from selected countries. Table 3 summarizes the country-commodity combinations found to have the highest violation rates in California sampling.

Violation rates in Tables 2 and 3 are comparable to those

Table 1 Maximum pesticide residues in food samples that exceeded USEPA tolerances, 2009–2013[1)]

Pesticide name	Maximum illegal residue from imported produce (mg kg^{-1})	Maximum illegal residue from US produce (mg kg^{-1})
Fungicides		
Captan	4.8	
Carbendazim	4.8	
Chlorothalonil	3.6	
Iprodione	2.8	
Propamocarb Hydrochloride	10.3	
Tebuconazole	11.2	
Triadimefon	3.2	
Fludioxonil		2.1
Insecticides		
Acephate	2.8	7.2
Bifenthrin		7.9
Chlorpyrifos	1.7	1.3
Difenoconazole		1.2
Diflubenzuron	1.3	
Dimethoate	1.8	
Dinotefuran	11.6	
Endosulfan	3.6	
Flonicamid	1.7	
Fludioxonil		2.1
Methamidophos	1.3	1.1
Methomyl	9.8	1.6
Monocrotophos	2.4	
Permethrin	6.8	2.2

[1)] To determine the relative toxicity of a particular residue, the value of the residue must be compared to a measure of acute toxicity for that pesticide (e.g., NPIC 2015). Data source: Annual residue data of the California Pesticide Residue Monitoring Program, California Department of Pesticide Regulation (http://www.cdpr.ca.gov/docs/enforce/residue/rsmonmnu.htm). The same as below.

Table 2 Samples of fruits and vegetables produced in selected countries, and rates of violation of USEPA tolerances for pesticide residues, 2009–2013[1)]

Country of origin (from produce labeling and vendor records)	Total shipments sampled	Samples in violation of USEPA tolerances	Violation rate (%)
United States	10000	142	1.4
Latin America			
Chile	546	10	1.8
Ecuador	182	2	1.1
Guatemala	232	20	8.6
Mexico	3576	231	6.5
Asia			
China	687	53	7.7
Thailand	55	8	14.5

[1)] Countries with fewer than 50 samples have been excluded.

Table 3 The 10 commodity/country-of-origin combinations with the highest percentage of illegal pesticide residues, 2013[1)]

Commodity and origin (also among highest violation rates in 2012)	Total samples in 2013	Samples in violation of USEPA tolerances	Violation rate in 2013 (%)
Cactus pads and cactus fruit/Mexico	35	13	37.1
Cilantro/US[2)]	33	11	33.3
Snow peas/Guatemala	32	8	25.0
Summer squash/Mexico	33	8	24.2
Limes/Mexico	60	11	18.3
Papaya/Mexico	41	7	17.1
Tomatillo/Mexico	100	17	17.0
Chili peppers/Mexico	41	4	9.8
Ginger/China	51	4	7.8
Spinach/US	123	5	4.1

[1)] Commodities with small sample sizes have been excluded. Source of data: California Pesticide Residue Monitoring Program (CDPR 2013, 2014a).
[2)] Of the 2013 samples of US cilantro, 12.1% (4 of the 33 samples) were illegal due to very low levels of dichloro diphenyl dichloroethylene (DDE), a breakdown product of the insecticide dichloro diphenyl trichloroethane (DDT). DDT has not been used in the US since 1972, yet low levels of DDT and its breakdown products still can be found in soil previously treated with the insecticide. In addition, 21.2% (7 of the 33 samples) were illegal due to low-level residues of other pesticides not approved for use on cilantro (CDPR 2014a; Thomas *et al.* 2008).

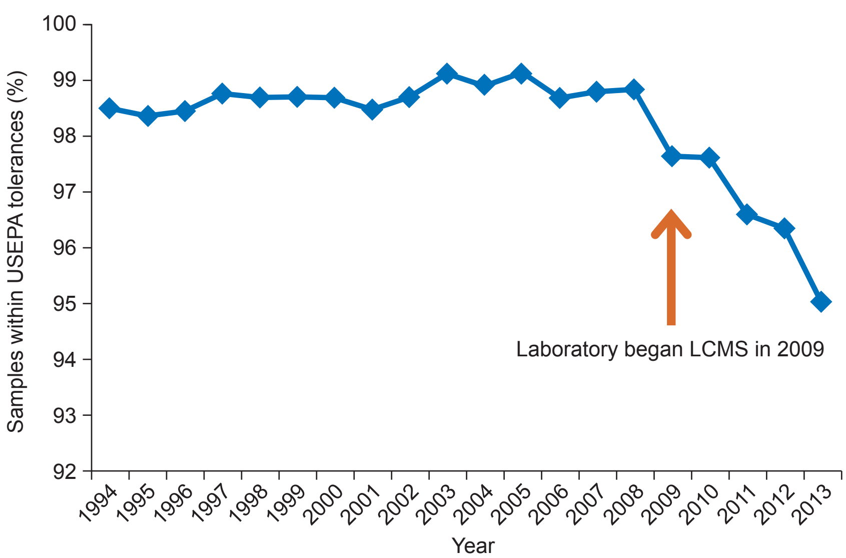

Fig. 5 Percent of produce samples for which laboratory analysis showed compliance with USEPA tolerances for pesticide residues, 1994–2013. LCMS, liquid chromatography/mass spectrometry.

detected in nationwide monitoring by FDA, which like CDPR, emphasizes sampling of commodities and places of origin with a past history of violations, and to a lesser extent emphasizes larger-sized shipments (FDA 2015).

Residue monitoring conducted outside of the United States measures compliance rates with locally-applicable maximum residue limits (MRLs) and/or international Codex Alimentarius standards (Handford *et al.* 2015), rather than compliance with USEPA tolerances. This makes it difficult to compare California results directly to those from other countries. Nonetheless, monitoring programs in Asia and elsewhere likewise have determined that residue levels vary by country of origin and by commodity (Kannan *et al.* 1997; Akiyama *et al.* 2002; Poulsen and Andersen 2003; GAIN 2012; Syed *et al.* 2014).

Historic residues reflect changes in pesticide use and analytical methods Fig. 4 shows the distribution of illegal residues among chemical classes of pesticides, and how that distribution has changed during the past 20 years. To reduce variability, only results from produce grown in the US were included (about 67% of all samples collected during those years). Historic results reflect changes in US agricultural pesticide use. Between 1994 and 2007, use of organophosphate insecticides (OP's) decreased about 60% nationwide (Grube *et al.* 2011). During those same years, illegal residues of OP's decreased and illegal residues of pyrethroid insecticides increased (Fig. 4), as many growers substituted less acutely-toxic pyrethroids for some organophosphate or carbamate insecticides (Epstein and Bassein 2003; Zhang *et al*. 2005). In contrast, other changes in pesticide use are not apparent from residue monitoring data. Despite cancellation of most agricultural uses of organohalogen insecticides, illegal residues of organohalogens, particularly dichloro diphenyl trichloroethane (DDT) and dichloro diphenyl dichloroethylene (DDE), continued to be detected through 2013 (Fig. 4), presumably because of these chemicals' decades-long persistence in soil (Thomas *et al.* 2008).

Historic results also reflect improvements in detection capability of the CFAC analytical laboratory. The most dramatic change has been increased detection of certain fungicides during the most recent five years (Fig. 4), corresponding to the phase-in of liquid chromatography/mass spectrometry (LCMS) methodology by the CFAC laboratory beginning in 2009 (CDPR 2011c, 2014a). Some of these fungicides were being used as far back as 1990, whereas others are more recent (Epstein and Bassein 2003), but none could be detected by routine multi-residue screens because of their specific chemical properties (FRAC 2015). Similarly, during 2009–2013 LCMS enabled detection of neonicotinoid insecticides such as clothianidin and dinotefuran; and insecticides in even newer chemical classes such as flonicamid, indoxacarb, pyridaben, and spirodiclofen (IRAC 2015). Future development of new chemical classes of pesticides will require analytical laboratories to continually improve their detection capabilities.

5. Future challenges for residue monitoring: Ensuring fairness for growers, vendors, and consumers

Future residue-monitoring programs will need to overcome several challenges in order to create an agricultural system that is fair for all participants: growers, vendors, and consumers.

5.1. Keeping pace with changing pesticide chemistries

Laboratories must continuously upgrade their analytical methods to keep pace with new pesticide chemistries (FDA 2015; FRAC 2015; IRAC 2015). At the same time, laboratories need to maintain the capability to analyze older, more acutely-toxic pesticides, because these are still used for agricultural production in some developing countries (Kannan *et al.* 1997; Ecobichon 2001; Dinham 2003; Syed *et al.* 2014). Further, even after they have ceased to be used for crop production, persistent pesticides such as organohalogen insecticides may continue to be taken up by plants (Thomas *et al.* 2008) or livestock (Clark 1978; Mukherjee and Gopal 1993). The need to detect both old and new pesticides will continue to challenge laboratories in the future.

5.2. "Chasing a smaller zero" — enforcing very low residues fairly

In addition to detecting a wider range of active ingredients, analytical laboratories have greatly increased their power to detect low concentrations of pesticides. GCMS and LCMS methodologies can detect many pesticides at concentrations as low as a few parts per billion (AMS 2015; FDA 2015), and ongoing improvements are pushing the detection limit even lower. DeVries (2006) refers to this as "chasing a smaller zero": as laboratories improve, food must be more and more pure in order to be classified as having "zero" contaminants.

For most pesticides, the power to detect ever-lower concentrations may have little public health benefit (DeVries 2006). The reason is, toxicologists consider that most pesticides are toxic at higher concentrations, but toxicologists have not observed adverse effects below a certain threshold concentration (USEPA 2012). An important exception is pesticides with chemical structures that inadvertently mimic human hormones, a health risk called "endocrine disruption". Endocrine-disrupting pesticides actually can be more hazardous to developing fetuses at certain lower concentrations than at higher concentrations (Vandenberg *et al.* 2012). An additional exception is potential synergistic effects when residues of several different pesticides all are present on a single food item. Low-dose exposure to chemical mixtures might result in health impacts such as cancer that the individual chemicals do not trigger alone (Goodson *et al.* 2015).

Though regulators must consider low-dose toxicity, increasingly stringent requirements for purity can be impossible for agricultural producers to achieve, and thus unfair. Producers who comply with all pesticide regulations sometimes unknowingly have their crops contaminated with very low, but still illegal, levels of pesticides not approved for use on their crops. Inadvertent contamination can occur *via* drift from neighbors' applications of pesticides approved for the crops the neighbors are growing, or from wind-blown soil particles containing environmentally-persistent pesticides such as organohalogen insecticides (Thomas *et al.* 2008; DPR 2014a) or persistent herbicides (Curran 2001).

A partial solution is for regulatory agencies to establish a default MRL, thereby allowing very low residues of no public-health concern for most pesticides provided that the agency has not already established a higher MRL for a particular pesticide. For example, Japan and the European Union both have established a default MRL of 0.01 mg kg^{-1} for all pesticides for which no higher MRL is in effect (Ministry of Health, Labour and Welfare 2006; European Commission 2008). We consider this a safe and fair approach for pesticides that are not endocrine disruptors, and that therefore are more toxic at higher concentrations, provided that the default MRL would apply only to individual residues (not mixtures). We encourage additional regulatory agencies to consider adopting default MRLs for individual residues of most pesticides that are not endocrine disruptors. Even with default MRLs, the need to protect agricultural producers from unattainable requirements for "zero" contaminants while still protecting public health will continue to challenge regulators in the future.

5.3. International harmonization of MRLs

MRLs for a particular pesticide on a particular commodity sometimes differ from country to country. This lack of harmonization of regulatory standards impedes international trade, because agricultural producers who conform to pesticide regulations of the country in which they produce nonetheless can face penalties for illegal residues when exporting their produce (Racke 2007; Dorweiler 2013; Handford *et al.* 2015). A partial solution is for individual countries to default to the MRLs of the international Codex Alimentarius (Racke 2007; Ellis 2008; Handford *et al.* 2015). However, new pesticides can be in use for years before the Codex adds a corresponding MRL. This lag can create a need for individual countries to establish their own MRLs for new pesticides. In addition, differences in pest pressure, agricultural production methods, and food consumption patterns can require country-specific MRLs in some cases (Dorweiler 2013; FDA 2015). Nonetheless, we encourage all regulators to work towards harmonization of MRLs, including defaulting to Codex MRLs except when there is a compelling reason not to.

5.4. Country-of-origin labeling

When buying food, consumers often prefer to know the country from which food products originated. Indeed, some consumer advocates consider that consumers have a right to know the country of origin, in order to select food that consumers consider is the healthiest for their families. However, labeling food to identify the country of origin can also be seen as violating the rights of food exporters. In May 2015, the appeals body of the World Trade Organization (WTO) determined that US country-of-origin labeling requirements for beef and pork (AMS 2009) created an unfair advantage for US livestock producers, and violated the WTO Rules of Origin Agreement (WTO 2015).

The need to balance consumers' right to know, versus producers' right to free trade, will continue to challenge regulators in the future. We consider that, at least for fresh fruits and vegetables, differences among countries in rates of illegal residues provide an objective justification for country-of-origin labeling (Tables 2 and 3; Kannan *et al.* 1997; Akiyama *et al.* 2002; Poulsen and Andersen 2003; Syed *et al.* 2014). However, we acknowledge that such labeling may unfairly stigmatize individual producers who comply with pesticide regulations. Even for California's current worst case, namely cactus pads from Mexico, the majority of Mexican cactus pads are in compliance with USEPA tolerances (Table 3). Thus, to ensure fairness for both consumers and producers, country-of-origin labeling needs to be combined with systems for tracing food back to the specific farm or ranch that produced it.

5.5. Traceability of food

The ability to trace food back to individual producers helps regulators and vendors determine which producers are, and are not, involved with cases of illegal residues. Traceability thus helps prevent unfair stigmatization of producers who conform to pesticide regulations but happen to be located in geographic areas with high rates of illegal residues. In the US, the 2011 *Food Safety Modernization Act* established the requirement for an information system to enable regulators to trace domestic and imported produce back to its source (Mejia *et al.* 2010). Similarly, the *European Union's General Food Law* requires the capability to track food through all stages of production, processing and distribution (European Commission 2007). We encourage other regulators and food distributors to consider adopting similar systems.

5.6. Paying for monitoring and enforcement

Sampling, laboratory analysis, and enforcement all require human and financial resources. Paying for these services will continue to challenge regulators in the future. Costs of the California Pesticide Residue Monitoring Program are covered primarily by an assessment on the initial sale into California of each pesticide active ingredient (CDPR 2011a). Regardless of the mechanism used, funding for monitoring and enforcement should be viewed as an investment rather than merely an expense. Investing in residue monitoring may give returns by increasing sales for agricultural produce from producers able to demonstrate compliance with regulatory requirements. Further, investing in residue monitoring gives returns by reducing potential health risks for both consumers and producers (Mejia *et al.* 2010; Tago *et al.* 2014).

5.7. Asking a better question: How to reduce illegal residues?

Monitoring pesticide residues is important, but by itself is not sufficient to ensure food safety. Rather than asking only how to measure pesticide residues, regulators also need to ask, how can we reduce the incidence of illegal residues? Food safety can be achieved through careful adherence to the pesticide labels regarding safe and effective use, and adoption of integrated pest management (IPM) to reduce the use of pesticides, especially the use of pesticides most hazardous to human health. Maintaining Good Agricultural Practice (GAP) is also essential in this equation.

6. Pesticide management to reduce potential exposure

Instead of asking which pesticide will control a pest outbreak, pest management should start with the question ''Why is the pest a pest?'' (Lewis *et al.* 1997). Long term resolution of pest problems can be achieved only by restructuring and managing agricultural systems to "build-in" preventive strengths, with therapeutic tactics such as pesticides serving strictly as backups to natural regulators of pest populations (Lewis *et al.* 1997). Therefore, in recent years, GAP, IPM, and reducing the use of pesticides have been common themes worldwide.

GAP is "practice that address environmental, economic and social sustainability for on-farm processes, and result in safe and quality food" (FAOCOAG 2003). Adoption and monitoring of GAP has three potential benefits. First, it helps improve the safety and quality of food. Second, it reduces the risk of non-compliance with national and international standards regarding maximum levels of contaminants (including pesticides, veterinary drugs, and mycotoxins) in food. Third, GAP contributes to meeting national and international environment and social development objectives. However, implementing GAP also presents challenges. For example, implementation of GAP may increase farmers' costs for record keeping. In addition, different buyers of food may require different standards for data collection and farm operations.

One kind GAP is IPM, which is an effective environmentally sensitive approach to pest management that relies on a combination of common-sense practices. IPM programs use current, comprehensive information on the life cycles of pests and their interaction with the environment. This information, in combination with available pest control methods, is used to manage pest damage by the most economical means, and with the least possible hazard to people, property, and the environment (Kogan 1998; Soejitno 1999; Baker *et al.* 2002). When pesticides must be used, growers apply at the right time and place, limiting applications to spot treatments whenever possible. Based on reports from Epstein and Zhang (2014), the IPM approach does not always reduce pesticide use but can direct it to the areas with the greatest pest problems. When one can reduce the amount of pesticide used per unit area, the risk of pesticide residues in harvested food could be minimized. Hence, food safety can be better achieved *via* applying IPM as one of the GAP.

Another possible strategy for protecting food safety is organic agriculture. Organic agriculture emphasizes soil health, nutrient cycling, and whole-farm ecosystem management. Organic regulations strictly limit use of synthetic pesticides, sewage sludge, and genetically-modified organisms (IFOAM 2005). Organic agriculture greatly reduces pesticide residues on food (Baker *et al.* 2002), a key aspect of food safety. However, another aspect of food safety, microbial contamination, may be more difficult to manage in organic agriculture (Rodrigues *et al.* 2014). Further, organic yields average 10–18% lower than conventional agriculture, though organic agriculture is significantly more profitable than conventional given current price premiums for organic produce (Crowder and Reganold 2015).

According to Klonsky and Richter's (2011) report, California dominates the nation in organic production of agricultural commodities. California leads the US in the number of organic farms, the amount of land in organic production, and the value of organic sales. The state accounts for 36% of the country's organic sales. Due to market demand, it is expected that organic production will increase steadily with approximate annual sales of 2.2 billion USD in the US according to USDA, Economic Research Service using data from Nutrition Business Journal (http://www.ers.usda.gov/topics/natural-resources-environment/organic-agriculture/organic-market-overview.aspx).

7. Conclusion

Pesticide use is an essential tool for agriculture worldwide. However, pesticides pose unintended risks to the environment and human health. To protect human health, pesticide contamination should be monitored in soils, air, water and food.

For monitoring residues within food, California's program provides an effective model. In this model, sampling emphasizes foods often consumed by children, and commodities with a history of illegal residues. Results are analyzed to identify major sources of illegal residues. A combination of education and penalties is used to address the causes of illegal residues. Further, data are continually analyzed to improve future sampling.

Overall, California's monitoring has shown that most food had safe levels of pesticide residues (95% of samples are within USEPA tolerances). Nonetheless, certain commodities from certain countries had higher risk, and a few illegal residues were at levels that had the potential to cause health effects. Most residues of potential concern to human health have been older insecticides (especially aldicarb, methamidophos, and monocrotophos) on produce from certain Latin American and Asian countries.

Future monitoring will face challenges including the need for analytical laboratories to keep pace with changing pesticide chemistries, and how to respond to detections of very low but illegal residues. For food safety, monitoring is not enough; we also need to reduce the source of pesticide residues. GAP, IPM, and organic production offer promising opportunities to reduce pesticide use, minimize pesticide exposure, and protect food safety.

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