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The Contributions of Pesticides to Pest Management in Meeting the Global Need for Food Production by 2050

Considering the inevitability of a growing population, cost-efficient food production must increase; with effective policies, proper regulation, and safety training, pesticide use will continue to play an important role in that food production. (Photo from happykanppy/Shutterstock.)

ABSTRACT

The term *pesticide*[1] has been around for centuries, and it describes many different chemicals. The term has also—at times—been maligned and misunderstood. The authors of this publication use extensive data and provide clear examples to establish that pesticide use in agriculture has

- increased crop yield and quality,
- lessened the workload of pest management, and
- improved the prospects for long-term sustainable food production.

This paper gives a brief background about the use of pesticides and a thorough examination of why they have become popular and widely used. Considering the inevitability of a growing population, cost-efficient food production must increase. Intelligent use of pesticides has led to crop management that is more efficient, sustainable, and productive (United Nations 2012). Of course there are controversies and challenges, but with effective policies, proper regulation, and safety training, pesticide use will continue to play an important role in food production.

With a special consideration of catastrophic famines and crop management practices of the past, the authors organize the vast amount of information around several key concepts:

- *Fungicide* use and its impact both in the United States and around the world
- *Herbicide* use, weed management, and higher yields that have resulted from sound weed control practices
- *Arthropod* management involving *insecticide* use, with a consideration of the problems that have occurred

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[1] Italicized terms (except genus/species names and published material titles) are defined in the Glossary.

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and a study of the development of current and future effective practices

- *Pesticide* benefits in both the developing and developed world

Along with better pest management, pesticides have led to the development of improved agronomic practices such as no till, conservation tillage, higher plant densities, increased yields, and the efficient use of water and nutrients. When applied in safe, smart ways, pesticides lead to more sustainable agriculture.

The authors cite many statistics and specific examples. They point out that more than 800 million people in the world are food insecure today and that the amount of crop yield lost yearly to pests can run upwards of 30%. But they are optimistic about developments occurring around the globe to minimize this loss. When pesticides are effectively applied and fully integrated into a comprehensive approach, the world will be on its way to providing sustenance for the 9 billion humans on earth in 2050.

INTRODUCTION

This paper discusses the influence of pesticides in agriculture and how their use has resulted in increased crop yield and quality and lessened the drudgery of pest management, which in turn improved quality of life for farmers and their families while also improving the prospects for long-term sustainable food production. Pesticide is a term that describes many different chemicals that are used to manage pests. Pesticide groupings include insecticides, fungicides, herbicides, rodenticides, molluscicides, nematicides, plant growth regulators, and other materials that protect plants or usefully modify their physiology. Synthetic pesticides have been used for managing pests in agriculture in various forms since World War II and are the focus of this paper. Recently, pesticide use has expanded beyond agriculture to include managing undesirable insects, *pathogens*, weeds, and animals in the household and landscape, including natural and planned environments (forests, waterways, parks, recreation, etc.).

Pesticides have been used in some form for centuries, with sulfur compounds and *botanicals* being used as early as 2500–1500 BC by the Sumerians and Chinese for insect and disease control. Sulfur, copper, and organic mercury were used in the 1800s as fungicides, and *Bordeaux mix* has been used since 1885 for powdery and downy mildew control (Schumann 1991). A similar pattern occurred for insect and weed management with the early use of inorganics for management in the late 1800s to early 1900s. Since that time and beginning in the late 1930s to the present day, tremendous activity has occurred related to the development of synthetic and biological-based pesticides (Lamberth et al. 2013).

Quantifying agricultural production and the impacts of pesticides based solely on crop yields, however, presents only part of the picture. The increased yield (and value of the yield) fosters many indirect economic effects because the benefits (economic value) accrue from the production of additional crop yields moving through the economy; this revenue creates further output, jobs, and earnings for workers, strengthening local economies. These impacts—economic value added by crop protection technology, employment arising from the use of the technologies, income generated by the technologies, and contribution of crop protection to trade balances—were quantified for U.S. agriculture (CropLife America 2011). State-by-state summaries for each of the 50 states were created based on data collected from 18 field, 26 vegetable, and 38 fruit and nut crops. In this analysis (based on this subset of crops), crop protection products accounted for an additional $51.4 billion in value derived from the use in field crops, $18.9 billion in fruit and nuts, and $11.5 billion in vegetables, for a total of approximately $82 billion in added crop value. Crop protection products were critical inputs for field crops, fruits and nuts, and vegetables, but the relative importance and ranking among types of products varied. For field crops, 36% of the total value of production ($51.4 billion of the $141.3 billion) was attributed to the use of crop protection products across the United States, with herbicide use having the greatest impact.

Even though pesticide contributions to production and yield efficiencies are well documented, pesticide use has not been without societal concerns. The direct effects of pesticide use on agricultural production have been documented (with appropriate assumptions) as previously detailed. These effects include improved crop yields and quality, better shelf life, limitation of pest population expansion, and increased incomes, which lead to a multiplier effect within other commercial industries. Cooper and Dobson (2007) proposed several indirect effects of crop protection products within the community and society. Although very difficult to quantify, these items are logical extensions of the increased crop production, including improved nutrition and health, higher quality of life, food safety, food security, decreased stress, improved visual aesthetics, conservation of biodiversity, and lessened civil unrest. Many of these factors do not stand alone but rather interact in a complex matrix.

A benefit-cost ratio of approximately 4:1 is generally estimated for the private benefits and costs of chemical pesticides (Pimentel 1997). The benefits as detailed above, especially in the context of facilitating food production to feed an increasing population, are obvious. Costs of pesticide use include food safety apprehensions, environmental contamination, and human health concerns (insecticides are often highlighted among all pesticide types given their mode of action and potential impacts on other animals). Insecticides, however, have many realized and theoretical drawbacks when applied within the environment. As with other chemicals—i.e., petroleum products, paints, fire retardants, human health and cosmetic items, and others—pesticides represent a foreign agent in the environment.

Additionally, critical needs exist to develop and label only pesticides that can be used safely and as risk free as possible and to require training in application and handling for all commercial users. The goal is to minimize undo exposure and decrease negative environmental effects (Fenner et al. 2013; Köhler and Triebskorn 2013). Pesticide evaluation is now based on the concept that the benefits of its use must far outweigh any risk from that use.

An important aspect of pest management is an increasing emphasis on developing solutions that apply multiple tools of good agronomic practices in an integrated approach and do not rely solely on the use of pesticides (Whitford et al. 2004). There are groups who would ban all synthetic pesticide use, saying they are inherently unsafe and cause more problems than they solve. Most groups involved in establishing agriculture policy, however, argue that pesticides have a critical role to play in food production and, with the proper regulation and training programs, can be used safely and efficiently. A recent special issue of Science serves as an excellent resource on these issues and provides an excellent set of articles discussing the "Smarter Pest Control" (*Science* 2013); these articles discuss issues related to pesticide use as well as their impacts and the techniques employed for the discovery of new chemistries that will ensure even safer pesticides in the future.

Most pest managers, researchers, educators, and practitioners agree that pests must be managed in an integrated manner with pesticides often playing an important role in this approach (Lewis et al. 1997; Stokstad 2013). The integrated pest management (IPM) approach recognizes that not all weeds, insects, and pathogens are necessarily bad. Good pest management integrates the best agronomic practices and the best crop *germplasm* to obtain high crop yields and quality, resulting in a safe and abundant food supply.

Global challenges facing agriculture include the rapidly increasing world human population, food and nutritional insecurity in many areas, and the need to improve agriculture efficiency (Rosegrant et al. 2014). Historically, increases in food production and management of pests have involved several strategies, including increasing the area of agricultural land, enhancing yield and competitive ability of crop plants through selection and breeding, use of organic and synthetic fertilizers, use of pesticides, improved soil and water management, and, more recently, the development of genetically modified crops (GMOs) (Godfray et al. 2010). All these practices, with the sole exception of increasing agriculture land area (Smith 2013; World Bank 2008), can play a role in increased agriculture production if properly implemented. None, however, have been used without some criticism.

The two practices of most controversy have been synthetic fertilizers/pesticides and GMOs. This paper will not address the use of fertilizers or GMOs except where they influence pesticide use, but instead it will discuss how the use of pesticides has enhanced and will continue to improve human capacity to efficiently produce enough food to feed the world. Because there is little scope for expanding the current arable land area globally (Schreinemachers and Tipraqsa 2012), any real increase in the global food supply will require an intensification of agriculture on currently managed land. Shortages of input resources, labor, and water for irrigation, as well as the negative effects of climate change on crop yields, require compensatory strategies to prevent yield losses coupled with an emphasis on the design of increasingly efficient and sustainable agriculture production systems. Pesticides help address these challenges, but if not used in a diverse manner, pesticide resistance will ultimately lead to fruition of other issues. Since pesticide discovery is not keeping pace with the loss of pesticides as a result of resistance, this could have a profound impact on pesticide efficacy and ultimately our ability to feed a growing world's population, as discussed throughout the document.

By 2050, the world population is expected to grow by 30% to nine billion people (United Nations 2012). The major population growth will occur in developing countries of East and Southeast Asia (>228 million people), whereas sub-Saharan Africa's population growth will be greater than 910 million people. In the United States, population is expected to grow by 28% (88 million people) by 2050. Much of the population growth is occurring in countries that are industrializing with rapid economic growth and the development of a large middle-class population having higher incomes and an increasing demand for expanded food options. Food production by 2050 will need to increase by 70% from current levels to meet not only the need to feed more people but also an increase in food consumed per capita.

Today, more than 800 million people in the world are food insecure, and by 2050 this could reach one billion. Additionally, there are presently 130 million malnourished children (FAO 2012). The majority of malnourished people are in sub-Saharan Africa, but food insufficiencies exist throughout the world. In the developed world, the daily intake of food averages 3,500 kilocalorie (kcal), and it has been estimated that a normal adult needs a minimum of 2,900 kcal/day to work productively. Many of the poor and undernourished consume less than 2,000 kcal/day and many much less than that.

Because more than 80% of all the malnourished in the world live in rural areas where farming is the most common occupation, the problem of increasing food production is exacerbated. How do we produce enough food and how do we ensure that the food is equally distributed so that all are well nourished? An answer to this problem is to design more efficient agriculture systems that properly use available resources to ensure a sustainable and productive system for the future (Godfray et al. 2010). The important point is that the world population will increase and will place increasing societal pressure on access to an acceptable and adequate food supply for all.

Part of the increased production of food could be met through increased use of pesticides to control infestations that currently decrease crop yields. Pesticide use in 2007 was 2.4 billion kilogram (kg), with the United States using 20% of the total (Enserink et al. 2013; Hvistendahl 2013; Kupferschmidt 2013; Mascarelli 2013; Normile 2013; *Science* 2013; Stokstad 2013). Presently pesticide use is highest in "developed" countries including the United States, European countries, China, Brazil, Australia, Japan, and Canada. In these countries, almost 100% of the crop acres are treated with herbicides every year (weeds are the world's most ubiquitous pest), whereas insecticides and fungicides are used primarily on high-value crops. (China, Brazil, and the United States rank 1–3 in annual pesticide sales.) In developed countries, considerable progress has been made in minimizing crop losses due to pests through the adoption of careful pesticide use. That use in developed countries is increasing, however, and is likely to increase further as a result of invasive species, the emergence of pathogens with resistance-breaking adaptations, climate change, and the development of new chemicals for previously intractable pest problems.

Developed countries such as the United States, Brazil, Canada, and Australia play an important role in feeding the world through exports. Although organic production systems occasionally produce yields similar to production agriculture on small, intensively managed acreage (Pimentel et al. 2005), pesticides remain indispensable in maintaining high crop yields in these countries and, thus, are essential in maintaining their ability to continue to export food to the world's growing population. Another concern, however, is that developed world countries must protect currently available herbicides because there are few modes of action in the pipeline (*Science* 2013). As worldwide demand for food increases, crop prices are also likely to increase, which would make the use of additional pesticide applications economical in developed countries. Developing world countries, however, must also increase their agricultural yields if global food demands are to be met in the future; and because the introduction of new pesticides has slowed, it is important to design systems that ensure their continued effectiveness.

Another serious and increasing concern, especially in the "developing" world, is the mass movement of people from rural areas to cities, which places even more pressure on the existing and decreasing rural populations to produce enough food to feed a hungry world. Presently, pesticide use is low in developing countries such as India, Pakistan, Bangladesh, and sub-Saharan Africa. These countries have great potential to increase crop production, and increasing pesticide use can help in achieving this potential. Pesticide markets are growing rapidly in developing countries because farmers are growing more food to meet demand and lowering their cost of production.

A solution to greater food production is greater production efficiency through the use of available and newly developed sustainable technology (Godfray et al. 2010). Increased crop productivity is related to several factors, but enhancing the yield has often resulted in less competitive crop plants. Selection and breeding, which could include GMOs, must be emphasized as a primary need not only for high yields but also for increased competitive abilities against pests, followed by the efficient use of organic and synthetic fertilizers and pesticides as well as improved soil and water management. These advances all contribute to efficiency both of human labor and available inputs.

A review of the available data shows that the degree of crop production and labor inefficiencies lost each year to pests varies depending on the source of information, but upwards of 30% of yield and an additional 20 to 50% of stored harvested crops can be lost on a world basis. The International Food Policy Research Institute (IFPRI) recently estimated that the global supply of wheat could be increased by 10% simply through the increased use of fungicides, whereas increased use of insecticides and herbicides could increase world wheat production by an additional 6 to 7% and 7%, respectively (Rosegrant et al. 2014). The IFPRI estimates of increased maize production through the use of pesticides were 12% for herbicide, 9% for insecticide, and 7% for fungicide uses. The IFPRI estimates of increased rice production through pesticide use were 7% for insecticides, 8% for herbicides, and 9% for fungicides.

Sound regulation is another concern that is being aggressively implemented. Sound regulation must address the need to ensure that, as new chemicals are developed and become available, they are thoroughly evaluated for safety and efficacy (Lamberth et al. 2013). This needs to be done both by the companies producing the chemicals and by governments. Regulations must ensure that only pesticides that can be used safely are developed—that governmental agencies have strict programs so new pesticides have minimal-to-no environmental footprint, are safe to use as labeled, and have no long-term negative health effects.

Educational programs must also be implemented that require applicators and handlers to be licensed in the proper use and disposal of pesticides. Further, these programs must also ensure that reevaluation of labeled pesticides occurs in a timely fashion as new science is developed and when questions arise about product safety. Such regulations are important for all new and existing pesticides. There are valid concerns regarding older and less-safe pesticides that are often still available and used in developing countries because of their lower cost. This situation must be addressed because developing countries will play an increasingly critical role as the supplier of food to feed the growing population; it is necessary to ensure that when pesticides are used, they are used safely and the negative effects of their use are both mitigated and minimal.

This paper addresses how pesticides benefit agriculture. The following sections elaborate on the past and future importance of plant disease in crop production systems and show how insect and weed management contribute to appropriate pest management in order to deliver the high yields of quality food stuffs necessary to feed the world now and in 2050.

GENERAL OBSERVATION ABOUT PESTICIDE USE

Pesticide use (herbicides, insecticides, fungicides) grew rapidly in developed countries—particularly the United States, European countries, Japan, Australia, and Canada—following the introduction of synthetic chemical active ingredients in the 1950s and 1960s. The new fungicides and insecticides greatly increased fruit and vegetable production because of greater control in comparison to previously used inorganic products (such as lime sulfur, copper, and arsenic). The widespread use of herbicides made weed control possible following significant labor shortages for hand weeding and cultivation in both large and small acreages.

The widespread adoption of effective chemical pesticides facilitated the adoption of other yield-enhancing practices such as the planting of shorter varieties that were less competitive with weeds and the breeding of higher-yielding crop varieties with less resistance to pathogens and insects. The use of herbicides made conservation tillage possible, greatly increasing soil water storage in arid areas. Critically, higher yields enabled greater crop production with no increase in cropland. Actually, in the United States cropland area has declined since the late 1980s (USDA 2014).

In the United States, research has determined that crop losses on the order of 15% in the early 1950s fell steadily as pesticide use spread, reaching 11% in the mid-1960s, 6% in the mid-1970s, and stabilizing at about 3% from 1979 on (Chambers and Lichtenberg 1994).

HISTORY OF PLANT DISEASE CONTROL

For the purposes of this paper, the authors do not differentiate between synthetic disease-managing chemicals used in conventional production and naturally occurring or biologically produced chemicals that are acceptable for use in organic production. Both synthetic and naturally obtained pesticides are used in conventional agriculture, whereas only nonsynthetics are used in organic production. Both conventional and organic agriculture use disease-resistant cultivars that have been obtained through conventional breeding techniques. Effective disease control agents are necessary for many crops in both types of production. Fungicides are used because they provide effective control of plant diseases and dramatic increases in yield compared to nontreated plants. The discussion that follows explores the history of fungicide use and the benefits of fungicides or other pesticides—such as increases in yield, quality, and/or profitability—attributable to the disease control provided and not just to their application (Edwards-Jones 2008).

Plant diseases caused by one or more fungus, bacterium, virus, virus-like organism, or nematodes are major yield- or profit-limiting factors for crops. Depending on the crop and the agricultural, economic, and social situation in which the crop is being grown, direct losses to plant diseases may include reductions in both yield and quality, leading to decreased profitability of a crop through both direct reduction in marketable yield and increased costs of producing the crop (Main 1977). Risks of losses to plant diseases do not disappear at harvest. Many crops—especially fruit, berry, and vegetable crops—are particularly vulnerable to postharvest diseases that affect not only the grower and local community, but also various entities involved in commerce associated with wholesale and retail trade as well as consumers (Main 1977). Plant disease impacts can range from mere inconveniences to total loss of a crop in individual fields on a regional, continental, or global scale.

Historically, plant diseases have been responsible for catastrophic famines and resulting starvation such as occurred in Ireland in the 1840s (Carefoot and Sprott 1967; Large 1940) and the Bengal region of India in the 1940s. Plant diseases caused the collapse of the economy of an entire region, such as in Ceylon in the 1870s (Carefoot and Sprott 1967; Large 1940), and for the virtual elimination of the American chestnut as dominant tree species in the forests of the eastern United States and the American elm as a major landscape tree in North America (Carefoot and Sprott 1967). In addition to crop damage, some plant pathogenic fungi produce mycotoxins that can cause acute or chronic health problems in humans and other animals (Gnonlonfin et al. 2013). In some cases, such as with aflatoxin contamination of peanut or corn (Gnonlonfin et al. 2013) or deoxynivalenol contamination of small grains (Willyerd et al. 2012), mycotoxins can be problematic even when yield losses are minimal.

Necessary Disease Management

For most crops, some type of disease management is necessary if losses are to be prevented. General categories of types of plant disease management include (1) cultural practices that decrease inoculum of pathogens, interfering with inoculation processes or avoidance of the pathogens; (2) *cultivars* with resistance to one or more pathogens; (3) manipulation of the physical environment or biota of a crop system to suppress pathogen populations or disease development; and (4) chemicals that kill pathogens, prevent infection by a pathogen, slow development of disease(s), or illicit a resistance response by the plant. In many cases, no single method alone is sufficient and an integrated approach is required in which cultural, genetic, biological, and chemical approaches are combined for management of a single or multiple disease(s) in a crop (Cahoon et al. 1999). Diseases caused by pathogens new to an area or crop can be especially damaging. Adapted cultivars may not be available with resistance to a new pathogen, and knowledge of practices that work to manage the disease may not exist. Therefore, exclusion of pathogens and vectors from an area can be critical for production of many crops. Preventing introduction of pathogens into noninfested areas may involve sanitation practices including disinfesting equipment to prevent movement of pathogens on soil or crop residues, using pathogen-free seed or propagative plant parts, or regional or international quarantines.

Fry (1977) stated that chemicals for plant disease management become essential only after other available methods of management prove to be inadequate; however, given the explosive rate at which many pathogens reproduce and the genetic variability among pathogen populations, inadequacy of nonchemical methods is commonplace. Other methods may not be available, and all methods have limitations. Cultural methods such as crop rotation or tillage may be key components of the disease management approach by decreasing the initial inoculums. They often do not completely eradicate pathogen populations, however, and instead only delay or suppress epidemics. Cultural methods alone may not be sufficient to prevent losses in situations where the initial inoculum is excessively high, often the result of unfavorable weather/environmental conditions.

Also, a practice that suppresses or controls one disease may have the inadvertent effect of worsening epidemics of others. Conservation tillage in corn may decrease some stalk rot disease's severity (Cahoon et al. 1999), but it may also increase the inoculum of *Cercospora zeae-maydis* (gray leaf spot) and other pathogens that survive on corn debris (Paul and Munkvold 2004). Similarly, in the southeastern United States, planting peanuts in April decreases the risk of damage by early and late leaf spot, caused by *Cercospora arachidicola* and *Cercosporidium personatum*, respectively, compared to planting in mid-May or later, but earlier planting increases the risk of damage from tomato spotted wilt (wilt tospovirus) and stem rot (*Sclerotium rolfsii*) (Kemerait et al. 2012). Cultural practices for disease management must be implemented in advance of epidemic development and provide few options once the epidemic is in progress. In such cases, other methods are required to respond to epidemics developing later in the season.

Cultivars resistant to plant diseases are typically easy to use, inexpensive, and safe to both the grower and the environment. The availability of adapted resistant cultivars, however, requires a breeding program, usually within the general area in which the crop is grown, and this may not be feasible in developing countries or in developed countries where production levels are high. Cultivar development through breeding often takes a long time, especially if cultivars are needed with resistance to a new pathogen or a new strain of a pathogen. Available resistance may not be complete, high enough, or stable, so other control measures are needed, especially in environments conducive to disease development. Pathogens may overcome available resistance genes, especially when resistance is imparted by a single gene. Multiple pathogen and pest resistance is often required but difficult to obtain and often not available for all important pathogens within a cultivar. As with cultural practices, resistant cultivars do not provide within-season responses to disease epidemics.

Exclusion of Pathogens

Exclusion of pathogens from areas in which they are not established is the best way to prevent problems. Increased global commerce and movement of agricultural products or stock between countries and continents, however, has complicated the use of exclusion of pathogens (Savary et al. 2011). Increased frequency and intensity of tropical storms may likewise increase opportunities of long-distance transport of new pathogens or vectors into a new area (Savary et al. 2011). The intentional introduction of a pathogen into a new area represents a potential threat as well. The introduction of new pathogens or new strains of endemic pathogens requires a rapid response, often by destroying infested crops or through treatment to prevent damage and subsequent spread and survival.

During the past century, many fungicides and other chemicals for plant disease management, such as bactericides and nematicides, have been developed that provide options for disease management when other available options are not adequate. This was essential, since crop losses to plant pathogens were commonplace in the United States in the 1800s and early 1900s. In the 1840s, 20 to 90% of the potatoes in northeastern states rotted because of late blight; in the 1850s, it was reported that 50 to 75% of the peaches in Georgia were typically destroyed by brown rot; and in the 1890s, most asparagus fields in Atlantic states were entirely destroyed by rust (Smith 1905; White 1852). Fungi and oomycetes, which were previously considered fungi, are the most prevalent plant pathogens, so fungicides will be the focus of most of this discussion.

Protective Inorganic Fungicides

Until the mid-1930s, chemicals available for control of plant diseases caused by fungi and bacteria were limited primarily to inorganic materials such as sulfur (which was also used as an insecticide), copper, and mercury (McCallan 1967; Schumann and D'Arcy 2012). Spraying fungicides to kill plant fungal pathogens began in earnest in the 1800s in France. The first fungicide, sulfur, was found to completely inhibit powdery mildew, which had lowered French wine production by 75% in the 1850s.

The Bordeaux mix of copper sulfate

and lime was developed in 1885 after Pierre-Marie-Alexis Millardet discovered that treated grape vines had less downy mildew than nearby untreated vines (Large 1940). The downy mildew fungus lowered French wine grape production by 50% in years prior to the regular use of the Bordeaux mix (Schumann 1991). Testing of the Bordeaux mix and sulfur in the United States demonstrated their effectiveness for disease management, which led to widespread adoption resulting in significant declines in crop losses. Twenty years of tests with the Bordeaux mix at the University of Vermont (1890–1910) resulted in an average potato yield increase of 64% as a result of late blight control (Jones, Giddings, and Lutman 1912). The Bordeaux mix decreased cranberry rots by 50%; sulfur applications to Georgia peaches decreased brown rot losses to 13%.

Widespread production of fruit and vegetable crops in diverse areas and in many countries became dependent on the regular use of fungicides. In the early 1900s, powdery mildew was considered capable of destroying the entire grape crop in California if sulfur sprays were not used (Bioletti 1907). Most U.S. acres of fruit and vegetable crops were routinely treated with a fungicide (sulfur, lime sulfur, copper, or Bordeaux mix) for control of one or more plant diseases beginning in the early 1900s. By the 1920s, spraying of lime sulfur for scab became a universal practice in U.S. apple orchards, and it was impossible to grow apples for the fresh market without fungicide sprays. In Germany, late blight of potatoes occurred in numerous regions from the 1840s until 1900 with production losses of 29 to 77% (Kolbe 1982). The first spray trials with the Bordeaux mix for control of late blight occurred in 1886. Long-term trials in Germany (40 years) have shown an average yield loss of 20% in fields not sprayed with fungicides (Kolbe 1982). In severe late blight years, losses in unsprayed potatoes were as high as 63%. The late blight fungus arrived in Ireland in 1845 and destroyed 40% of the potato crop. In 1846, the fungus destroyed 100% of the crop and more than 1.5 million people died and a comparable number moved to America. Today, the fungus is still present in Ireland and it would be extremely difficult to grow potatoes without fungicides (Cooke 1992). Unsprayed potatoes were completely destroyed in the Czech Republic in 2011 (Hansen et al. 2011), which was an ideal year for the late blight organism.

Copper sulfate is active against many fungi, bacteria, and oomycetes, but it can be *phytotoxic*. The lime decreases the phytotoxic effects of the copper sulfate (Schumann and D’Arcy 2012), however, and this mixture is still commonly used. Inorganic fungicides require frequent application at high rates (often more than 10 kg of the active ingredient of pesticide applied per hectare) (McCallan 1967) and typically are preventive and do not provide consistent control (McCallan 1967); many, like copper sulfate, are phytotoxic (McCallan 1967). After 1910, organic mercury compounds were used as seed treatments for protection from seed rot pathogens and for seedlings from damping off pathogens (McCallan 1967). Although effective, they represented a major environmental risk of mercury persistence and bioaccumulation in food chains.

Dithiocarbamate and quinone fungicides developed in the mid-1930s are more effective for many diseases than the inorganic fungicides and require less active ingredient (McCallan 1967; Morton and Staub 2008). In addition, they are less likely to accumulate because they are degraded by sunlight and microorganisms (Schumann and D’Arcy 2012). Like the inorganic fungicides, most are only protective and must be applied before infection occurs.

Synthetic Chemical Fungicides

Research with synthetic chemical fungicides began in the 1940s and demonstrated that crop yields were higher as a result of improved disease control efficacy and/or decreased damage to the crop. Growers of apples, potatoes, and, by the late 1950s, most other crops rapidly switched from older fungicides to new synthetic fungicides.

Researchers determined that apple trees sprayed with ferbam yielded 41% more than trees sprayed with the standard lime sulfur treatment. Much of the yield increase was attributed to decreased damage to trees from ferbam in comparison to the lime sulfur sprays. When growers switched to synthetic fungicides in the late 1940s and early 1950s, U.S. apple yields increased dramatically because of decreased phytotoxicity. Experiments with zineb and nabam resulted in potato yields that were 23 to 35% higher than with the Bordeaux mix. When U.S. growers switched to the synthetic fungicides in the late 1940s and early 1950s, potato yields increased dramatically. For some diseases, the synthetic chemicals offered the first effective controls. For apples, there were no effective spray materials for black rot prior to the introduction of ferbam and 25 to 50% fruit losses were commonplace in the Southeast. Ferbam decreased the incidence of black rot to 1% (Brown and Britton 1986; Muncie and Morofsky 1947; Palmiter 1949).

In a 1950 report to Congress, the American Phytopathological Society reported that many fruit and vegetable crops could not be produced in reliable volume without chemical protection from diseases (APS 1950).

Fungicides are regularly tested for control efficacy and impacts on crop yield. For more than 40 years, the annual incidence of scab in untreated apple trees has been 98 to 100% in experiments at Michigan State University (Jones 1995). Some recent test results include the following: (1) garlic yields doubled with control of rust; (2) watermelon yields increased 61% with gummy stem blight control; (3) fungicides decreased the incidence of citrus scab from 44% to 0.4%; (4) fungicides decreased purple spot losses in asparagus by 99%; (5) fungicides decreased the defoliation of cherry trees due to leaf spot from 80% to 0.3%; and (6) control of blast with fungicides increased rice yields by 45%. Additionally, fungicide treatments for *Phytophthora* control increased the yield of sweet peppers by 28,000 kg/hectare (ha).

Until the mid-1960s, fungicides were only occasionally used on wheat in Europe. During the 1960s, however, there was a growing body of evidence that diseases of wheat were causing more losses than had previously been acknowledged (Lawrence and Appel 1997). Since the 1990s, more than 95% of wheat acres in the UK, France, Germany, Denmark, Belgium, and the Netherlands have been treated with fungicides (Jørgensen et al. 2008). Average responses to treatment usually range between 0.5 tonnes/ha and 2.5 tonnes/ha.

During the 1960s and '70s, several new fungicide chemistries, such as phthalonitriles, carboxanilides, and benzamidazoles, and the sterol inhibitors, morpholine, anilide, strobilurin, and carboxamide fungicides, were developed (McCallan 1967; Morton and Staub 2008). The triazole fungicides in the sterol-inhibiting class and the strobilurin fungicides are the largest group of agricultural fungicides in terms of number of fungicides and frequency of use (Morton and Staub 2008). Many of the fungicides developed since the late 1960s can be absorbed into the plant, are not phytotoxic, and have at least some systemic activity that increases their longevity and allows protection of plant parts not directly sprayed (Schumann and D'Arcy 2012). Many modern fungicides also have some degree of curative effect, being able to eliminate some of the infection that occurred before the fungicide was applied. Most recent fungicides have more specific modes of action than earlier-developed materials, resulting in lowered toxicity to nontarget organisms (Schumann and D'Arcy 2012).

Specific modes of action, however, also represent greater risks for pathogens to develop resistance (Schumann and D'Arcy 2012). The specific mode of action fungicides and some newer plant protection chemicals, such as acibenzolar-S-methyl that works by stimulating the host plant's defense mechanisms against a broad range of pathogens including fungi, oomycetes, bacteria, and viruses (Morton and Staub 2008), represent an important component of modern plant disease control. These chemicals not only have provided excellent pathogen management that results in improved crop yields and quality of fresh and stored food stuffs, but they are more environmentally friendly and have low-to-no toxicity to nontarget organisms, making them attractive for use in all parts of the world.

FUNGICIDE USE IMPACT ON CROP YIELD INCREASES IN THE DEVELOPED AND DEVELOPING WORLD

Gianessi and Reigner (2006) reviewed the benefits of fungicide use in the United States, with examples across a range of crops and diseases. This report showed an average yield increase in 50 crops attributable to fungicides, including field crops, vegetable crops, and tree fruits, that ranged from 16% to 100%. They estimated that use of effective fungicides increased farm income in the United States by almost $13 billion per year.

There are many examples of the economic benefits of disease control achieved with fungicide use over time in the United States as summarized by Gianessi and Reigner (2006) and more from other countries. Following are some recent specific examples.

The critical role of fungicides in managing Asian soybean rust (*Phakopsora pachyrhizi* Syd. & P. Syd.) in Brazilian soybean is demonstrated in the meta-analytical summary by Scherm et al. (2009) of more than 71 experiments during the 2003–2004 and 2006–2007 cropping seasons. Across trials with different fungicides and application regimes, there was an average of a 58.7% reduction in disease and a 43.9% increase in yield in response to fungicide treatments (Scherm et al. 2009).

The predominant peanut cultivars currently grown in the southeastern United States have great yield potential and high levels of field resistance to tomato spotted wilt virus, but most have little resistance to early leaf spot (*Cercospora archidicola*), late leaf spot (*Cercosporidium personatum*), or stem rot/white mold (*Sclerotium rolfsii*) (Kemerait et al. 2012). Studies across four peanut fungicide trials in Tifton, Georgia, in 2012 resulted in peanut yields without fungicide averaging 1,906 kg/ha, whereas peanuts treated with standard fungicides for leaf spot and standard fungicides for leaf spot and stem rot had 190% and 212% increases in yield, respectively (A. Culbreath, unpublished data). Use of fungicides for control of those diseases was a critical factor in record yields in 2012 despite environmental conditions being very conducive for disease development.

Fungicides can help with prevention of mycotoxin contamination. Fusarium head blight caused by *Fusarium graminearum* Schwabe (FHB) of wheat not only decreases yields, but the pathogen produces deoxynivalenol (DON), which contaminates kernels and represents health risks to humans and animals through consumption (Willyerd et al. 2012). In studies conducted from 2007 to 2010 from 37 trials in 12 states, Willyerd and colleagues (2012) showed the application of mixtures of tebuconazole and prothioconazole fungicides at anthesis to a moderately resistant cultivar resulted in 75% control of FHB and 71% reduction in DON concentration compared to the nontreated susceptible cultivar and better control for both variables compared to moderately resistant cultivars with no fungicide application or to susceptible cultivars with fungicide applications. This also serves as a good example of the efficacy of integrating multiple disease control factors when no single management tool is adequate.

Resistant cultivars for control of wheat stem rust (*Puccinia graminis* f. sp. tritici Erikss. & Henning) have been successfully grown in many regions of the world. Rust resistance in wheat, however, is dependent on a single gene and this is prone to breakdown by new virulent races of the pathogen. Efforts to provide resistant cultivars for the predominant races of the rust pathogen in an area and to predict which races will likely be prevalent in the next growing season have been described by Schumann and D'Arcy (2012) as "The Never-Ending Battle." Development of new virulent races of the pathogen may require new management tools to prevent losses to this disease until new resistant cultivars can be developed, especially with the emergence of the virulent race "Ug99" in wheat-growing areas of eastern Africa (Wanyera et al. 2009). Wanyera and colleagues (2009) reported that several fungicides were effective for control of this race of stem rust. They reported losses in yield of 32 to 57% in the nontreated plots compared to better fungicide treatments (Wanyera et al. 2009). In situations such as those presented with emergence of new races of the wheat rust pathogen that overcome single-gene resistance or introduction of a new pathogen (such as with Asian soybean rust to the western hemisphere), fungicides, at least for the short term, may be the only viable option for managing a potentially devastating disease.

Management of plant diseases is often interrelated with management of weeds, insects, and other pests. Weeds or other noncrop plants may serve as alternate hosts of rust pathogens, with destruction of those plants decreasing initial inoculum or pathogen genetic variability (Schumann and D'Arcy 2012). Parasitic plants such as dodder (*Cuscuta* spp.) or witchweed (*Striga* spp.) that cause problems in agronomic crops (Schumann and D'Arcy 2012) could be considered both weeds and pathogens. Therefore, with those pests weed control is disease control. Insects and other invertebrates may vector plant pathogens as well as cause direct damage themselves. Insect damage may also predispose plants to infection by pathogens or mycotoxin contamination (Gnonlonfin et al. 2013). Therefore, control of plant disease may depend at least in part on control of other pests by appropriate methods.

Rice blast epidemics caused a major food crisis in South Korea in the 1970s. Estimates indicate yield losses of 10 to 50% (Mew et al. 2004). Since the 1970s, Korean rice farmers have regularly used fungicides for blast control. Currently, rice blast is estimated to decrease South Korea's rice production by only 0.02% (Chang 1994).

Farmers in South Korea harvest approximately 900 million pounds of apples annually. Because of frequent rains during the growing season, the disease problem is very serious and most apple growers spray fungicides 14 to 16 times (Uhm et al. 2008). If fungicides were not used, more than 90% of the fruit may be rotten (Uhm et al. 2008).

Apple scab is the dominant reason that European apple growers spray fungicides 15 to 22 times per season. Without these sprays, approximately 80% of apple production would be lost in the European Union (Holb, Heijne, and Jeger 2003).

HISTORY OF WEED CONTROL

Hand Weeding and Tillage

For thousands of years, farmers used alternative nonchemical methods for weed control. The two primary nonchemical methods used historically were hand weeding and cultivation/tillage. These two practices are still the major alternatives to herbicide usage. In the early years of crop production, human labor was used to remove weeds from fields. In the 1800s, farmers were advised that a scrupulously weeded field produced twice as much corn as a similar one given minimal effort (Hudson 1994). A well-hoed corn crop required four hoeings during the growing season and, hoeing by hand, a farmer might have to spend 12 days/ha (6 days/acre) chopping out the weeds (Fussel 1992). As late as 1850, 65% of the U.S. population lived on farms and removing weeds was one of the main farm tasks representing a large proportion of the labor necessary to produce a crop (Cates 1917). Chemical weed control substituted for 49 hours (h) of labor per ha on 405,000 cotton ha in Mississippi (Holstun et al. 1960). Growers were estimated to have saved $10 million per year.

In Germany in the early 1960s, heavy manufacturing industry needed an increasing number of workers and rural people left the countryside. Without herbicides to replace the departing workers, it is not likely that widespread crop production would have been practiced any longer in that country (Koch 1992). In Japan, herbicide adoption decreased the amount of time required for weeding by 97% (Takeshita and Noritake 2001).

Prior to the 1960s, the Korean economy was one of the poorest in the world. In the 1960s, the Korean government embarked on a policy of industrialization and the economy began to take off. Rising living standards and employment opportunities in urban areas drew farmers away from rural areas. More than 12 million people migrated from rural to urban areas from 1957 to 1982. In Korea, manual weeding had been the prevalent control for centuries. As labor shortages appeared, herbicide use was recommended, and by 1971, 27% of the rice ha were treated (Wang 1971). By 1977, 65% of the total rice area was treated with herbicides, and since the 1980s, 100% of Korea's rice ha have been treated with herbicides (Kim 1981).

The first experimental crop of wheat was sown in 1843 at the Broadbalk field at the Rothamsted Research Center in the UK. Until the First World War, the experiment was hand weeded. Lack of labor during World War I and after made hand weeding impossible. The 40% decline in yield between 1900 and 1925 was almost certainly due to increasing competition from weeds (Moss et al. 2004).

Use of the short-handled hoe was the primary weed control method for most vegetable crops in California from the early 1900s through the 1960s. Weeding of celery took 111 h/ha, carrot took 69 h/ha, and strawberry took 69 h/ha (Lange and Brendler 1965; Adams 1938). Numerous complaints were received from farm workers, however, who stated that they suffered permanent back damage as a result of using the short-handled hoe for extended periods of time. The California Industrial Safety Board issued a regulation that permanently banned the use of the short-handled hoe in 1975. Most growers switched to the use of herbicides, which proved to be more economical than the use of workers wielding hoes. The cost of herbicides plus application was $25/ha in comparison to hand-weeding costs of $247/ha for spinach, $198/ha for celery, $309/ha for onion, and $988/ha for strawberry (Ashton 1960). The use of herbicides is credited with decreasing the use of labor in California onion fields by 297 h/ha, which was equivalent to two million h per year (Nylund, Nelson, and Dinkel 1958).

Hand weeding is a widespread practice among organic growers who farm without herbicides. In the Netherlands, h/ha for manual intrarow weeding on organic farms are 177 for onions, 152 for carrots, 9 for potatoes, and 12 for cereals (Van Der Weide et al. 2008). In Europe, hand weeding onions may reach 500 to 1,000 h/ha in particularly weedy situations (Melander 1998; Rasmussen et al. 2011). In 2004 the California legislature banned "unnecessary" hand weeding, citing concerns about field workers' health and safety; this ruling did not apply to the state's organic growers (State of California 2004). Hand weeding is used extensively on organic farms in California: lettuce (123.5 h/ha [50 h/acre]), celery (123.5 h/ha [50 h/acre]), carrots (185.25 h/ha [75 h/acre]), onions (177.84 h/ha [72 h/acre]), and cotton (29.64 h/ha [12 h/acre]) (Bolgenholm 2004; Klonsky 1994; Klonsky et al. 1995). Organic growers sometimes experience complete crop failure due to their inability to hire labor for hand weeding (Wheat 2012).

Hand weeding labor is expensive and is usually not readily available or commonly used in agronomic crops in Europe, the United States, and many other countries (Riemens et al. 2007). With the increase of herbicide-resistant weeds in the United States, however, especially in the Midsouth and Southeast, hand removal is a necessity (Riar et al. 2013). In Japan, perfect hand weeding of the nation's rice fields would require the work of 1.89 million people every day for 60 days, which is totally impractical today (Takeshita and Noritake 2001).

Benefits of Herbicides

The benefits of herbicides are best understood by comparing their practicality, cost, effectiveness, and reliability to hand weeding (terrible workload in repetitive activities and lost human capital) and cultivation (degrades soil quality and promotes soil erosion).

Experimentally, it has been shown that if enough hand weeding or cultivation is done at the right time, crop yields can be equivalent to those attained when using herbicides (Lanini and Strange 1994). In the entire world (in both developed and developing countries), however, there is a serious shortage of workers (and capital for labor costs) for farm work, and hand weeding alone is not often a practical or affordable option in much of the world. The reliability of cultivation can be compromised by weather when fields are too wet for tractors and the weeds continue to grow, causing yield loss.

Tillage has been a major tool in weed management since the invention of the plow. In the early 1900s, plows were pulled by horses or tractors through fields to kill weeds (Wimer 1946). The land was kept bare of vegetative cover after harvesting. Tillage required 10 or more trips over the field (Triplett 1976). Tillage in the United States moved more than 226,796,185,000 tonnes (250 billion tons) of soil each year. Experiments in the late 1800s and early 1900s showed that the only benefit of cultivation was weed control (Cates and Cox 1912). Thus, in the early 1900s, the realization was made that if a practical alternative method of weed control could be devised, cultivation could be dramatically decreased; however, it was not until the development of herbicides that an effective alternative method was available.

Research in the late 1940s with the first herbicide (2,4-D) available for corn growers indicated that a *preemergence* application could eliminate one to three cultivations, whereas a *postemergence* application could eliminate one or more in-season cultivations (Slife et al. 1950). By the 1960s, the invention of new machines to plant through mulch combined with the widespread availability of chemical herbicides to control weeds allowed commercial adoption of conservation tillage (Montgomery 2008). As more effective herbicides were developed, farmers continued to decrease tillage before planting and, in some cases, completely eliminated postemergence cultivation (Triplett 1976).

Approximately 36% of U.S. cropland (35.64 million h [88 million acres]) planted to eight major crops had no tillage operations in 2009, which represents a sixfold increase since 1990 (Horowitz, Ebel, and Ueda 2010). Herbicides are so crucial to conservation tillage that the National Academy of Sciences has concluded widespread adoption of conservation tillage would likely not have taken place without them, which is especially true in the case of glyphosate resistant crops (NRC 2000).

Organic growers make extensive use of tillage for controlling weeds. In Iowa, organic corn and soybean fields require four to five weed-removal trips during the season with rotary hoes and cultivators (Chase, Delate, and Johanns 2011). In France, cereal crops grown without herbicides require six tillage trips (Deytieux et al. 2012). Tillage is extensive on organic farms in California: cotton, onions, lettuce, and grapes (Klonsky 1994; Klonsky et al. 1995; Tourte et al. 2009; Vasquez et al. 2008). In Michigan, organic soybean farmers use up to ten tillage operations to control weeds (Mutch 2008). The experiences of organic growers are also a useful perspective because they cannot use synthetic herbicides. The problem of weed control without herbicides is regularly cited as the biggest problem facing organic growers and is the single biggest factor constraining expansion of organic production (Rasmussen and Ascard 1995).

Tillage equipment, such as rotary hoes, is most effective when weeds are very small, with effectiveness declining as weeds develop (Melander et al. 2013). Research shows that tillage for weed control is often unreliable because of frequent rainfall making the soil too wet to weed mechanically (Eyre et al. 2011). The consequence is that weeds become too large to control with any type of cultivation. Researchers at the University of Wisconsin determined that in 34 of every 100 experiments, there was a weed control problem with tillage resulting in decreased weed control and an average yield loss of 26% (Posner, Baldock, and Hedtcke 2008).

The USDA estimated that the average annual national loss due to weeds in soybean in the 1950s was 17%. One major reason for the loss was lack of timely weed removal with rotary hoes (USDA–ARS 1965). Weeds must be removed from crop fields to prevent crop loss due to competition for light, space, nutrients, and moisture; they can also contaminate and lower the quality of vegetables, both for fresh and processing markets, but this is especially critical in fresh leafy vegetables. Herbicides are chemical products that are used to decrease weed populations in crop fields. Herbicides are a relatively new technology, first adopted on a widespread scale in the United States, European countries, and Japan in the 1950s/60s followed by widespread adoption in many other countries—e.g., Australia, Canada, and Brazil. Rapid adoption of herbicides is occurring in many developing countries, such as India and China.

The primary benefits that farmers receive when they use herbicides are less expensive weed control, better weed control, and more reliable weed control, which generally leads to higher crop yields and lower costs of production in comparison to alternative methods of weed control.

Another perspective on the benefits of herbicides can be gained by examining studies that estimate what would happen without herbicides. These studies invariably estimate that crop yields would fall throughout the world because the amount and timing of hand weeding and cultivation would be inadequate to provide weed control equivalent to herbicides.

The historical record is clear that herbicide adoption has led to greater crop yields by substituting for less effective former practices. In addition, there were several crops where weed control was not previously practiced for which herbicides offered effective weed control for the first time and yields grew as a result. Herbicides made it possible for crop production to continue in countries where wages increased for off-farm work and millions of workers left agriculture. Herbicides facilitated the adoption of other agronomic practices—fertilization and planting short-stature cultivars—that led to higher crop yields.

Synthetic Herbicides

The dawn of the synthetic herbicide age began after World War II with the introduction of the synthetic auxinic herbicides. From that time until the present, there has been a great expansion in the number of and types of herbicides that are available for use in agriculture. Today there are herbicides that are applied preemergent to the weeds (soil active), herbicides that are applied after weeds emerge (foliar active/postemergent), and herbicides that have activity both in the soil and foliar applied.

The herbicides available are in many different chemical families and at present comprise approximately 63 different families, but worldwide there are approximately 220 specific herbicides (HRAC 2014). Herbicides are available that are *broadspectrum* and kill broadleaf, grasses and sedges, broadleaf specific, grass specific, and types that are systemic and move throughout the plant after application or are nonsystemic in nature so they kill only the plant tissue they contact. Herbicides are also available that are selective within a crop, or nonselective herbicides can be used within a crop where selectivity is achieved through physical placement of the product or specific application techniques. In addition, there are now crops that have been genetically engineered to be resistant to an applied herbicide; the largest example of this is the crops engineered for resistance to glyphosate. In this case, the herbicide, which is broadspectrum and has limited selectivity, can be applied over an emerged resistant crop such as corn or cotton and cause no damage (Monaco, Weller, and Ashton 2002).

In 1949, herbicides were used on 9.31 million ha (23 million acres) of cropland in the United States; in 1952, on 12.14 million ha (30 million acres); in 1959, on 21.45 million ha (53 million acres); in 1962, on 28.73 million ha (71 million acres); in 1965, on 48.56 million ha (120 million acres); and by 1975, on more than 80.94 million ha (200 million acres). In the United States, more than 90% of the hectares of vegetable and field crops (89.03 million ha [220 million acres]) have been treated with herbicides since the mid-1970s (Osteen and Fernandez-Cornejo 2013). In recent years, herbicide use has increased in many orchard crops because of the trend to dwarf trees.

Typically, a field will receive two to three herbicide applications: a burndown treatment before planting, a preemergence treatment at planting, and a postemergence treatment during the season. Residual herbicides stay active in the soil and kill weeds as they germinate and start to grow or shortly after they emerge for an extended period of time (two to three months), providing effective control of many individual emerged weed species. Herbicides possess selective properties for controlling weeds in many crops and under many soil and climate conditions.

The pattern of herbicide use in Europe is similar to that used in the United States, with more than 90% of most field, vegetable, and tree crops being treated every year in all countries. A recent survey of maize growers in 11 European regions showed that herbicides were used on more than 90% of the acres with one to two applications per year (Meissle et al. 2010). Recent UK surveys show that 97% of field crop acreage, 92% of vegetable acreage, 70% of orchard acreage, and 77% of soft fruit acreage are treated with herbicides (FERA 2014).

The adoption of herbicides was spurred by a desire to decrease weed control costs because labor became scarce and more expensive in the years following World War II. A mass exodus of farm labor occurred in the late 1940s and early 1950s when workers moved from rural areas to cities. Several southern states experienced a net loss of 200,000 to 300,000 farm workers within a decade (Mayo 1965). The farm population in the United States in 1940 was 30 million; by 1985, it had dropped to less than 3 million.

Recently, herbicides have been promoted for their beneficial impact on the environment and on the sustainability of crop production. By substituting for cultivation, herbicide use leads to lower fuel use, less carbon emissions, less soil erosion, less water use, and fewer injuries from hoeing and other farm equipment (Harman et al. 1998).

Smallholder farmers in sub-Saharan Africa have a low level of herbicide adoption (~5%) (Mavudzi et al. 2001; Overfield et al. 2001). Herbicides are being promoted to these farmers as a means to significantly raise crop yields and lower costs of production because labor for hand weeding has become scarce and expensive.

Impact of Herbicides and Weeds on Crop Yields

Despite cultivation and hand weeding in the early 1900s, the annual crop loss to weeds was enormous (Cates 1917). In a 1932 Illinois study, it was estimated that 10% of the cropland had 50% or greater crop loss due to weeds in a “normal year” (Case and Mosher 1932). Substantial acreages of otherwise productive wheat land were almost entirely out of production because of infestations of field bindweed. Within a year or two of the use of 2,4-D, these acreages were released for wheat production (Freed 1980).

In river bottoms, where soil was often too wet for timely cultivation, corn crops were often lost because weeds took over. In some areas, farmers stopped growing corn because of weed problems (Raleigh and Berggren 1964). One report from 1947 states that 25,401 additional tonnes (one million bushels) of corn were produced from 7,200 ha (18,000 acres) of bottomlands in Kentucky as a result of 2,4-D spraying (Hanson 1947). More than 20,000 ha (50,000 acres) of corn were sprayed in Nebraska in 1947 with a yield increase of 11 to 49% (Hanson 1947).

For most crops, historical data indicate an increase in yields due to herbicide use. Numerous experiments were conducted that compared yields using herbicides with yields using standard practices. Cucumber yield increased by 24%, dry bean by 38%, sorghum by 34%, peach by 167%, potato by 29%, and rice by 160% (Burnside and Wicks 1964; Comes, Timmons, and Weldon 1962; Daniell and Hardcastle 1972; Glaze 1975; Mueller and Oelke 1965; Nelson and Giles 1989). A four-year study showed that wheat yields increased by 255 kg/ha when 2,4-D was used (Alley 1981). An analysis of 1961–1975 data from the University of Minnesota and the University of Illinois indicated that corn yielded 15% more with herbicides whereas soybean yielded 19% more with herbicides (Dexter 1982).

In the UK, the application of MCPA (2-methyl-4-chlorophenoxyacetic acid) to cereals is credited with raising yields approximately 20% (Lever 1991). Herbicides have been credited with being the main factor in the doubling of wheat yields in Canada (Freyman et al. 1981). In Australia, research demonstrated that using herbicides instead of tillage resulted in 27 millimeters of extra water in the soil profile and an increase in grain yields of 15–25% (Wylie 2008).

Aggregate changes in national crop yields from the 1950s to the 1970s were influenced by several factors, including adoption of herbicides, increased fertilization and irrigation, new plant hybrids, and the introduction of synthetic fungicides and insecticides. For corn and soybean, researchers have statistically determined the contribution of herbicides to improved yields. Herbicides accounted for 20% of the increase in corn yields from 1964 through 1979 and 62% of the yield increase in soybean from 1965 through 1979 (Schroder, Headley, and Finley 1981, 1984).

Although statistical studies have not been conducted, a similar close relationship between increased crop yields and increased herbicide use has been observed for other crops. The use of herbicides is cited as a primary factor in the doubling of peanut yields (Grichar and Colburn 1993). Better weed control with herbicides is credited as an important factor in increased rice yield (Smith, Flinchum, and Seaman 1977).

The historical record clearly indicates that significant improvements in yield occurred for several crops only after the introduction of effective herbicides. Since the introduction of an effective herbicide in the 1980s, blueberry production in Maine has more than tripled (Yarborough and Ismail 1985; Yarborough et al. 1986). In the early 1970s, the introduction of three major herbicides (dichlobenil, norflurazon, and glyphosate) is credited as the most important factor in the doubling of cranberry yields from 1960 through 1978, whereas the registration of another herbicide (glyphosate) is credited with a 50% increase in cranberry yields in the 1980s (Dana 1989; Eck 1990). Sugarcane yields in Louisiana increased significantly following the introduction of herbicides in the 1950s.

Alternative Weed Control Methods

Much research into alternative methods of weed control has been conducted during the past 20 years. A major conclusion of this research is that the levels of weed control achieved by alternative practices are inferior to the degree and consistency of control expected from herbicides (Lutman 2013). A recent review of nonchemical methods for control of grass weeds in the UK determined the average percentage reduction achieved: plowing (67%), delayed drilling (37%), higher seed rates (30%), competitive cultivars (27%), spring cropping (80%), and fallowing (70%) (Moss 2010). On herbicide labels in the UK, weeds are given a rating of “susceptible” (95% for grass weeds), “moderately susceptible” (75–80%), “moderately resistant” (60–75%), and “resistant” (<60%) (Moss 2010). If nonchemical practices were assessed on the same basis as herbicides, grass weeds would be described as “resistant” to most of the nonchemical practices (Lutman 2013).

Not only is control lower and more variable, but the management complexity for adopting nonchemical practices is much greater than for the relatively simple application of herbicides (Lutman 2013). Costs of nonchemical control practices, either direct financial costs or costs in terms of management time, are also often higher than for herbicide applications (Lutman 2013).

University of Missouri rural sociologists studied the reasons why farmers stopped cultivating between corn rows. Cultivation of large crop acreages requires continuous weeks of effort. Farmers criticized cultivation as too time consuming, intrusive into other needed work, and inefficient. It also can lead to soil compaction and increases in erosion and is one job they are not eager to resume (Rikoon, Vickers, and Constance 1993).

Agronomy Practices Possible Because of Herbicides

The use of herbicides to control weeds has facilitated the adoption of several important agronomic practices and has major impacts on all phases of crop production.

Until the 1950s, delayed seeding was the most effective way of controlling weeds in spring-sown crops. Early sowing, as is common today, was impossible because weeds would outcompete the crop. Spring cultivation after weed emergence removed weeds before crop planting but delayed planting by approximately three weeks. Earlier planting, as now practiced, reflects the availability of hybrid seed with more cold tolerance and decreased need for spring tillage made possible by the use of herbicides (USDA–ERS 1963; Warren 1998). In the U.S. Midwest, corn planting occurs two weeks earlier today than it did in the late 1970s (Kucharik 2006), and in the midsouthern part of the United States, the 50% corn-planted date has moved earlier by about a month (from early May to early April) during the past 30 years (Kucharik 2006). Without herbicides, corn planting dates would have to be delayed to allow for the mechanical destruction of the first germinating population of weeds. This would eliminate the use of high-yielding, full-season hybrids in Midwest corn production with a resulting shift to shorter-season, lower-yielding cultivars. Delaying planting where cultivation occurs after weed emergence allows early-germinating weeds to be controlled with preplant tillage; however, delaying corn planting in Iowa from May 1 to May 20 results in an average yield loss of 8%.

Traditionally, corn was planted with sufficient row spacing to permit cultivation on all four sides of individual plants (Pike, McGlamery, and Knake 1991). Today, closer row spacing is used in many crops because of the decreased need for cultivation. The introduction of hybrid cultivars with higher yields when planted at higher plant densities has resulted in a narrowed spacing between both plants and rows. Although cultivating can do a good job of weed control in row middles, it cannot be used within the row itself; effective herbicides control weeds within and between the rows (Warren 1998). The average corn seeding rate increased from 30,000 plants per hectare in the 1930s to 38,000 in the 1950s and 46,000 in the 1970s, and it is often at 80,000 plants per hectare today (Cardwell 1982; Duvick 2005); row spacing decreased from 102 centimeters (cm) in the 1950s to 90 cm in the late 1970s.

Similar trends have been observed with sorghum among the High Plains farmers in Texas where decreased row spacing from 100 cm to 25 cm (40 inches to 10 inches) resulted in yield increases of 1,088 kg/ha (986 pounds/acre) on irrigated land (Irving 1967), again because of herbicides and effective weed control. Closer row spacing and higher plant populations per hectare are also common practices for peanut, soybean, and vegetable crops where, after herbicides introduction, crop yields increased in snap beans (45%), sweet corn (50%), carrots (22–33%), and broccoli (65%) (Mack 1969).

Closer plant spacings also improve efficiency of nutrient uptake and use. Experiments demonstrated that effective weed control was essential for uptake of nitrogen fertilizers (Vengris, Colby, and Drake 1955). Corn grown with weeds took up only 58% as much nitrogen as corn grown alone without weeds. Readily available (fertilizer) nitrogen often is absorbed faster by young weeds than by young crops. In rice fields infested with barnyardgrass in the vegetative stage, the traditional practice was to delay the application of nitrogen until the weed was at the heading stage because the weed would have used most of the nitrogen (Ennis et al. 1963). This delay was undesirable for the optimum time of nitrogen needs for the rice plant. With herbicides to remove barnyardgrass, the nitrogen is applied in a timely fashion for optimum yields (Ennis et al. 1963).

Since approximately 1900, researchers at state and federal experiment stations have worked to develop crop production systems better suited to the Great Plains. One of the practices that evolved for dryland crop production was the use of summer fallow, wherein no crop is grown during a season when a crop might normally be grown. Since most wheat is grown on soils capable of storing considerable amounts of water, fallowed soil can supply water to the crop in a subsequent season during prolonged periods without rainfall (Smika 1983). In rainfed, dryland farming areas of the central Great Plains, the substitution of herbicides for tillage resulted in preserving enough soil moisture to make possible the sustained annual production of crops without the need for a fallow year to store soil water. Fallow acreage in the United States has declined significantly in recent decades mostly because of improved herbicides (Derksen et al. 2002). Data indicate there can be as much or more stored water in no-tilled managed soils in the spring after wheat harvest as when fallow is continued until fall wheat planting (Peterson and Westfall 2004), and this finding has resulted in an expansion of summer corn and sorghum acreage in the Great Plains.

Other examples include herbicides for short-statured wheat with higher yields, more seed, and less straw (Gressel 1999). Herbicides led to rapid adoption of mechanical harvesting in the UK (a major labor-saving technology) because previously, weeds often clogged harvesting machines and mechanical harvesters were not widely used (Lever 1991). Herbicides also allowed changes in rotation schemes to be possible. During the 18th, 19th, and early part of the 20th centuries, cereals were usually grown in the UK and Europe as part of a rotation with a row crop such as turnips. Two seasons' consecutive cereal cropping tended to build up a mixed-weed flora, which was then "cleaned up" by frequent interrow cultivations in the root crop (Lever 1991). Herbicides decreased this need and allowed farmers to grow better-income crops in their rotations. Maintaining a particular rotation solely for weed suppression is difficult to justify when economic and market forces also influence the cropping sequence. With herbicides, growers can now choose the most profitable crops.

Herbicide Use Has Resulted in Higher Yields in Developed Countries

As discussed, herbicide use has expanded greatly in the developed world since the late 1940s, and the examples provided show how herbicides have influenced advances in good agronomic practices. The adoption of herbicides in developed countries was spurred by a desire to decrease weed control costs because labor for hand weeding became scarce and more expensive in the years following World War II. This has been demonstrated in several countries, including Germany, Japan, Korea, and the United States, because farm workers left for industry jobs, farmers had labor shortages, and herbicides helped to efficiently manage weeds (Kim 1981; Koch

1992; Takeshita and Noritake 2001; Wang 1971).

Data since the early 1960s indicate that an increase in yields in the United States has been due to herbicide use and has been shown in rice, dry bean, sorghum, and potato (Burnside and Wicks 1964; Comes, Timmons, and Weldon 1962; Mueller and Oelke 1965; Nelson and Giles 1989), wheat (Alley 1981), and corn (Dexter 1982). Similar results have been obtained in the UK for cereals (Lever 1991), in Australian grains (Wylie 2008), and in Canadian wheat production (Freyman et al. 1981). Improved weed control has resulted not only in less weed competition, but also in better seedbed moisture because fewer cultivations are needed (Nalewaja 1975).

The primary cause of the expansion of production and economic viability of soybean and maize production in Argentina was the widespread adoption of herbicides (particularly glyphosate) for weed control. This widespread adoption of glyphosate in Argentina was in large part due to the almost total adoption of glyphosate-resistant soybean (Penna and Lema 2003). The increased use of glyphosate facilitated the rapid adoption of no-till crop production, reversing decades of destructive farming practices and leading to higher crop yields, economic viability, and expansion of planted acres.

Research has demonstrated that the productivity of crops has been consistently higher under no till, with yields of maize, soybean, and wheat cultivated under no till being 17% higher than under conventional tillage (Ribeiro et al. 2007).

In Brazil, migration from rural to urban areas was fuelled by better wages in the cities, a consequence of the growing industrialization that was taking place. The rural population of Brazil decreased from 64% of the total population in 1950 to 32% in 1980 and 16% in 2010 (Cerri et al. 2010). As a result, there were fewer workers in rural areas to do the work of weeding by hand or with tractors. A significant number of smallholder farmers in Brazil practice no till. Surveys show that the decreased need for labor has been a major incentive for the adoption of no till by smallholders (Ribeiro et al. 2007). The substitution of herbicides for hand weeding, plowing, and harrowing decreased the need for labor in maize by 38%.

In the past in China, farmers weeded by hand. Approximately 1 billion person-days of labor would be required to hand weed China's rice fields adequately (Askew 1991). Since the late 1970s, however, rapid expansion of industries has caused an outflow of the farming population as well as a corresponding increase in wages, making herbicide use more attractive to farmers (Zhang 2003). From 1978 to 1990, with encouragement and promotion from the research and extension sectors, an increasing number of Chinese farmers began to adopt herbicides to control weeds (Zhang et al. 2007). The herbicide application areas of crop fields have steadily increased from less than 1 million ha in the early 1970s to more than 70 million ha in 2005 (Zhang 2003).

In 1973 in China, it was estimated that rice crop losses due to weeds were 40%, even though the crop was hand weeded several times. In 1988, with increased adoption of herbicides, the loss of rice to weeds was estimated to be 6 to 8% (Moody 1991). A 2010 survey of a rice production zone of the Yunnan Plateau indicated that the current yield loss of rice to uncontrolled weeds above the canopy was 2.8%, whereas below the canopy uncontrolled weeds resulted in a 1.5% yield loss (considered separately) (Dong et al. 2010). The researchers noted that the weed loss estimates were considerably lower than earlier estimates and cited the adoption of herbicides as a cause.

In Russia in the 1960s, research demonstrated that herbicide use led to a 50% increase in cereal yield on state farms (Chenkin 1975). Herbicide use in Russia rose from 25 million ha in 1968 to 47 million ha in 1973 (Keiserukhshy and Kashirsky 1975). The dissolution of the Soviet Union in 1991 led to privatization of the collective farms. Government support of agriculture collapsed, and many farms were without the financial resources to buy herbicides. The decreased use of herbicides was a major factor resulting in lower wheat production in Russia in the 1990s. The annual loss of Russian cereal production as a result of weed infestation during 1996–2000 was estimated to be 9.5 million tonnes (10.5 million tons) (Zakharenko 2004). Losses in the 1990s would have been greater had farmers been unable to use herbicides altogether. Estimates by the Russian Academy of Agricultural Sciences for 1990–1999 were that the additional yield on the 15 million ha treated with herbicides was 5.4 million tonnes (6 million tons) per year (Zakharenko 2000). Measures aimed at suppressing weeds were identified as the foremost priority for improving cereal production in Russia (Zakharenko 2004). In recent years, the Russian government has introduced policies to increase the availability and use of herbicides in crop production. The herbicide market in Russia in 2010 was valued 2.8 times higher than in 2003 (McDougall 2013).

HISTORY OF INSECT MANAGEMENT

Insects are the most successful organisms on earth, with upward of 2 million species; 900,000 insect species are presently described and tens of thousands of new species are named each year. In fact, insects represent approximately 80% of all the world's species. Insects reside in the larger classification of animals called arthropods, which also includes organisms such as mites, spiders, scorpions, millipedes, lobsters, and shrimp, as well as some extinct members. Besides being very diverse, insects are also very common. It is estimated that there are some 10 quintillion (10,000,000,000,000,000,000) individual insects alive at any time, which averages to more than 200 million insects for each human on the planet and 300 pounds of insects for every pound weight of humans.

Although most common and diverse in tropical ecosystems, insects and related arthropods are also common in temperate ecosystems, as shown by studies from North Carolina detailing soil to a depth of 5 inches with approximately 124 million animals per acre, of which 90 million were mites, 28 million were springtails (close relatives of insects), and 4.5 million were other insects. A similar study in Pennsylvania yielded numbers two- to threefold higher than the North Carolina study for numbers of mites, springtails, and insects (Sabrosky 1953). In terrestrial systems, van den Bosch and Stern (1969) estimated that approximately 1,000 species of arthropods were associated with alfalfa in California's Central Valley, whereas Pimentel and Wheeler (1973) collected 591 arthropod species from alfalfa in upstate New York. Only a few of these insect species feed on the alfalfa and were classified as pests; several of these are beneficial through their activities as predators and parasitoids, and the majority have neither a positive nor negative effect on alfalfa. Overall, only a small percentage of arthropod species (less than 1%) are considered pests, but those are extremely problematic for humankind.

Arthropods have a variety of detrimental effects on ecosystems and human existence. Insects vector disease organisms to humans, other animals, and plants, with one mosquito-vectored parasite, malaria, causing an estimated 627,000 deaths of mostly African children in 2012. Other insect-pathogen systems are similarly devastating, and insect-vectored human diseases have had major impacts on societies, impacted the outcomes of wars, etc. Besides the immeasurable impacts of the loss of human life, these diseases have resulted in significant other economic consequences in agriculture systems. Arthropods inflict damage to natural systems such as forests and rangelands. This results in damage to ecosystems, potential impacts to endangered species and species diversity, and compromises to aesthetic value, including recreational uses. More quantifiable results of arthropod damage to forests and rangeland include loss of productivity, increased wildfire incidence, greater potential movement of soil into waterways, damage to infrastructure, etc. The topic of this paper, however, is the impact of pests, arthropods in this case, on agricultural production and specifically in meeting the global need for food production by 2050. Insects and mites clearly play a key role in competing with humans for food resources, and this is especially critical with the increasing human population and the need for plentiful, healthy diets in developing countries.

Insects possess several properties that facilitate them competing very effectively with humans in every aspect of our lives, including food, fiber and forage production, animal/livestock production, maintaining our possessions and structures, protecting our recreation and natural areas, infrastructures, human health, etc. The attributes of insects and mites that make them so successful include their (1) small size, which helps them to fill several niches, including hard-to-reach locations; (2) rapid reproduction and population buildup, allowing them to quickly adapt and respond to new conditions; (3) high mobility, which allows them to move to and occupy new areas; (4) ability to reside in different niches between the immature and adult stages, i.e., decreasing intraspecific competition between the lifestages, including drastically different ones for some species such as aquatic for immatures and terrestrial for adults or soil for immatures and aboveground for adults of the same species; (5) high degree of speciation; (6) numerous feeding guilds, including on roots, leaves, stems (including within stems), buds, flowers, and fruit; and (7) ability to evolve and rapidly adapt to selection pressures, including those created by various management/control tactics.

Insect pests have competed with humans for resources, including food, throughout history. No less than 13 types of insects (ants, bees, beetles, various caterpillars, fleas, flies, gnats, grasshoppers, hornets, locusts, lice, moths, and maggots) are mentioned in the Bible. Locusts occupy a predominant position as the eighth of the ten plagues in the Bible—"locusts cover the land and eat the remaining vegetation not destroyed by the hail" (the seventh plague). The desert locust and migratory locust still today are major pests and threats to agricultural production in Africa, the Middle East, and Asia. The livelihood of at least one-tenth of the world's human population is affected by this voracious insect, as it has been for centuries.

The history of arthropod pest control in agricultural systems includes three distinct phases: (1) the era of traditional approaches (ancient to 1938); (2) the era of pesticides (1938 to 1975); and (3) the era of integrated insect management (1976 to present) (Metcalf 1980).

Era of Traditional Approaches (Ancient to 1938)

Cultural and mechanical practices (crop rotation, flooding, field sanitation, hand collection) were commonly used during this period. Botanical insecticides derived from neem, chrysanthemum, and tobacco were also used. Several synthetic inorganic insecticides containing arsenic, mercury, tin, and copper were used in the early 1900s. The origins of host plant resistance and biological control were recorded, with key examples of management of grape phylloxera by grafting European grapevine scions to resistant North American rootstocks and use of the vedalia beetle imported from Australia to control the cottony cushion scale in California, respectively (DeBach 1964). Substantial crop losses resulted from insects during this period, however, and this was just "accepted" because more effective control measures were not available.

Era of Insecticides (1938 to 1975)

Insecticides and *acaricides* are a subset of pesticides and specifically are targeted to control insects and mites, respectively (for the purposes of this document, insecticides and acaricides are referred to collectively as insecticides). The era of insecticides began with the discovery of the insecticidal properties of DDT by Paul Muller in 1939, for which he was awarded the Nobel Prize in 1948. The discovery of DDT was followed by the development of several other related insecticides, as well as by insecticides in the organophosphate and carbamate classes of chemistry in the 1950s. Because of their efficacy, convenience, flexibility, and economics, these insecticides played a major role in increasing crop production. With increased and widespread use of these insecticides, however, problems started to appear and to intensify. Insecticide use can have undesirable effects within agroecosystems, including contamination of the environment (air, soil, forage, and water), negative impacts on animal populations (birds, fish, insect predators, and parasitoids), insecticide residues within the fat tissues of most humans, and unfavorable responses by the arthropods themselves.

The development of resistance to insecticides by pest insects and mites is a major problem. Through natural selection and basic evolutionary principles, insects and mites can adapt to the toxic effects of the insecticides. Insecticide resistance has occurred in more than 550 species of insects and mites to various insecticide classes of chemistry and modes of action (Georghiou 1990). Defined as a "heritable change in the sensitivity of a pest population that is reflected in the repeated failure of a product to achieve the expected level of control when used according to the label recommendation for that pest species," resistance can arise from changes in the insect's metabolic, target-site, penetration (cuticular barrier), or behavioral characteristics (Insecticide Resistance Action Committee 2013).

Insecticide resistance is not a new phenomenon but rather was first reported for house flies (*Musca domestica*) and DDT in the mid-1950s. Pest resurgence and development of secondary pests are additional potential drawbacks of insecticides and stem from the effects on population dynamics of nontarget organisms in agroecosystems. When a management tactic such as an insecticide is applied to a crop with a damaging pest population, reductions in populations of nontarget arthropods can also occur in the system. Some of these insects and mites may be acting as predators and parasitoids of the target pest insect or of other insects in the system. As the efficacy of the insecticide application dissipates,

- the population of the target pest increases unchecked to even higher levels than before the insecticide application because the natural biological checks on the population have been decreased (pest resurgence), or
- the population of another insect species within the system increases to damaging levels because the predators and parasitoids that were keeping it in check have been negatively affected by the insecticide application (secondary pest).

Although a highly effective and useful tool, it was obvious that insecticide use had to be managed better and it could not be a stand-alone device on a long-term basis. As part of an integrated system, however, insecticides could play a critical role.

Era of Integrated Insect Management (1976 to Present)

Integrated pest management can be traced back to 1946 when the first supervised control entomologist was hired in California to monitor and make control decisions in alfalfa (Hagen, van den Bosch, and Dahlsten 1971). The origins and concepts of IPM, however, are generally attributed to Stern et al. (1959). Integrated pest management is a systems approach that integrates a range of management tactics for the economic control of pests, emphasizing sustainability of pest controls as well as maintaining the utility of insecticides as a viable tool. Specifically, IPM is an ecosystem-based strategy that focuses on long-term prevention of pests or their damage through a combination of techniques such as biological control, habitat manipulation, modification of cultural practices, use of resistant varieties, and selective use of insecticides.

Insecticides are used only after monitoring indicates they are needed according to established guidelines, and treatments are made with the goal of removing only the target organism. Pest control materials are selected and applied in a manner that minimizes risks to human health, beneficial and nontarget organisms, and the environment (UC IPM Online 2013). Using insecticides within the context of an IPM system will insure sustainability of these tools for future generations. Insecticides are a powerful and useful device for facilitating food production and protecting the food supply that is badly needed to address the dietary needs of an expanding world population. The potential drawbacks of insecticide use within the environment and to biological systems, however, dictate that insecticides be used judiciously. Overreliance on and excessive use of insecticides, such as during the Era of Pesticides (Insecticides) (1938 to 1975), was shown to be not sustainable.

Insect pests even today are estimated to destroy up to 30% of agricultural production in spite of the use of the most advanced management tactics; also, postharvest losses from insects are an additional detriment to the food supply. The use of IPM tactics in terms of rigor, intensity, etc., is a continuum, but IPM is practiced at some level in the majority of agricultural production in the United States and worldwide. Regulatory controls are often the initial management tactic of an IPM program. Quarantines, border inspections, import/export rules, etc., help to decrease pest movement among jurisdictions. While still effective, the expansion of global trade and international travel has strained the system and led to severe challenges with invasive pests in many areas, particularly parts of the United States. These invasive pests often infest an area, and populations reproduce unchecked because the natural constraints are absent.

Control Measures

Cultural control measures are an important aspect of IPM programs and one practiced in most agricultural systems. Using well-adapted crop varieties, optimal production practices, appropriate planting dates, crop rotation, etc., help to produce a vigorous, healthy plant; these practices can aid in mitigating injury from insect pests and decrease the overall crop losses. These same practices are important for optimizing crop yields so minimal efforts are required to also positively impact IPM. More IPM-specific cultural practices, such as trap crops, *intercropping*, destruction of alternative hosts, tillage, etc., are often used in developed countries.

The push-pull cropping system, which takes advantage of repellent "push" plants and trap "pull" plants, has been developed and successfully used for subsistence farming in Africa and delivery of the *semiochemicals* for lepidopterous pests attacking maize and other cereals (Hassanali et al. 2008). Mechanical and physical controls have niche fits for IPM such as row covers and other physical barriers in high-value crops.

Biological control is another component of IPM. Naturally occurring populations of insect natural enemies attack and decrease population densities of pest insects. Predatory insects prey on pests, and insect parasitoids infest and kill hosts. *Epizootics* of insect-infecting microorganisms occur, which can decrease pest populations under specific conditions. These organisms provide important, free control of pest insects in many systems. Biological control can take on a more planned and strategic approach with deliberate releases of insectary-reared organisms, but the naturally occurring populations of beneficial organisms are a part of all IPM systems.

Finally, host plant resistance is an important component of IPM management tools in some host plant–pest scenarios. These resistant cultivars require a significant research effort to develop, but the trade-off in terms of effectiveness, cost/benefit ratio, favorable environmental aspects, and ease of use and acceptance by growers can justify the effort. The use of resistant cultivars for IPM of insect pests, however, does not fit all systems because the pest and crop must be amenable to the development of this type of tactic.

Biological, cultural, plant-based, mechanical, and regulatory controls are integral tactics within IPM for management of key insect and mite pests. These options help to moderate pest population levels but, in many cases, the remaining pest level exceeds the economic threshold and must be managed. Pest population levels are decreased by these nonchemical tactics, but remedial methods such as insecticides are needed to prevent crop losses because pest populations escape the limitations placed upon them. In this case, insecticides are critical management tools to be used when pest populations reach threshold levels as defined by the IPM concept. Integrating these nonchemical tactics with insecticides is one of the key elements of IPM.

Changes in Pesticides

The types of insecticides used in IPM have changed significantly during the last 50 years. Insecticides with environmental concerns (organochlorines) and those with high acute toxicity to mammals, including humans, have been largely replaced in developed countries with decreased risk, biorational, biological, and other environmentally and user-friendly materials. Insect growth regulators, pheromones (semiochemical), and other novel chemistry products that take advantage of weak points in the pest biology (i.e., target specific lifestages, orders, or biological pathways) are becoming increasingly common, and in essence they provide a surgical level of management (Gilbert and Gill 2010). These advancements have enabled optimal control of insect pests while minimizing nontarget effects and environmental consequences.

The development of plant pesticides (e.g., plants that have been genetically engineered to contain the delta-endotoxin genes from *Bacillus thuringiensis*) has revolutionized IPM initially in maize and cotton in developed countries during the last 20 years. The development of this approach is expanding to additional crops and to developing countries. The rapid evolutionary capacity of insects and strong selection pressures presented by some of the newer pest management techniques—e.g., GM crops—make resistance a continued threat for controlling plant pests. Insects as well have the capacity to overcome other IPM tactics such as cultural and biological controls, so the development of robust management tools is an ongoing process.

Numerous studies have quantified the effects of changes in pesticide policy and product availability within the United States. A study by Knutson and others described the possible effects on U.S. society of a hypothetical ban of herbicides, insecticides, and fungicides (Knutson 1999). Under the conditions of 1999, without the availability of organophosphate and carbamate insecticides (two chemical classes of insecticides each with several members) on 13 commodities, U.S. production would drop by 1% (wheat) to 38% (apples) and food prices would increase by 1% (six of the thirteen commodities) to 23% (cotton). With lower production and higher prices, U.S. agricultural producers would be less competitive in global markets for major grains, cotton, and peanuts. The U.S. exports of corn, wheat, and soybeans would drop 27%, with a commensurate loss of approximately 132,000 jobs.

This analysis published in 1999 found that loss of these two classes of insecticides in the United States would significantly decrease year-ending supplies of corn, wheat, and soybeans, trigger price instability, slow U.S. food aid programs to poor countries, and increase worldwide hunger. More recently, insecticide use on 50 U.S. crops (commodities with the highest U.S. acreage, totaling ~109.35 million ha [270 million acres] annually) was quantified as well as the impacts of this usage (Gianessi 2009). For 42 of the 50 crops, more than 50% of the acreage was annually treated with insecticides, and more than 90% of the acreage was insecticide treated for 23 of these 50 crops. These insecticides were applied to prevent crop loss from insects, which was the primary criterion used. If left untreated, 31 and 7 of the 50 surveyed crops would suffer nationwide production losses of greater than 40% and greater than 70%, respectively. This study found that by mitigating the damaging effects of crop insect pests, U.S. farmers produced an additional 144 billion pounds of food, feed, and fiber and accumulated an additional $22.9 billion in farm income.

In summary, for every dollar spent on insecticides, U.S. growers gained $19 in increased production value. Therefore, as small business entrepreneurs, U.S. agricultural producers used insecticides to protect their investments. The use is not haphazard but rather a calculated response to pest populations and the risk of crop loss.

Minnesota garnered the greatest value from all crop products ($4.6 billion; 6% from insecticides compared with 19% attributable to herbicides), whereas Florida and Georgia gained the most on a percentage basis (more than 50%) from the use of insecticides (Georgia gained the most from insecticide usage at ~$890 million). The value of fruit-nut and vegetable crops was more responsive to the use of fungicides and insecticides than field crops; this likely corresponds with the higher quality standards of these crops given their end use of the consumer food supply. California garnered the greatest value from the use of insecticides on fruit-nut and vegetable crops at ~$5.6 billion and $2.8 billion, respectively.

Numerous studies have developed empirical data on crop losses from arthropods. Losses from insects are notoriously spatially and temporally heterogeneous. Populations vary annually as well as from field to field (even within a field, populations can range from severe to noneconomic). Cotton entomologists in the United States have quantified cotton losses from insects and mites by state since 1979. These data arise from observations, research plots, discussions with growers, etc. (Mississippi State University 2013). For instance, in 2000, arthropod pests decreased overall cotton yield by 9.26%, and total cost of management and loss to insects to the 2000 crop was $289.78 per ha ($117.32 per acre). In 2013, cotton losses to arthropod pests decreased overall yields by 2.68%. Total cost of management and loss to insects to the 2013 crop was $223.58 per ha ($90.52 per acre).

Internationally, insecticides have been shown to have a role in preventing crop losses to stalk borers in maize in Africa because the average national crop loss of 13.5% could be prevented by the use of the granular insecticides (De Groote et al. 2011; Gianessi and Williams 2012). Desert locust outbreaks with widespread insecticide spraying in Israel and Madagascar were estimated by the United Nations to have prevented a loss of ~25% of Madagascar's rice crop, which would have been destroyed without treatment (FAO–ECLO 2013; Gianessi 2013a), brown planthoppers in Japanese rice (Gianessi 2013b; Holt et al. 1996; Kiritani 1979), and cocoa beans for chocolate in West Africa (Dormon, van Huis, and Leeuwis 2007; Gianessi and Williams 2011). When used as part of an IPM program combining early planting, close spacing cowpea, and three insecticide applications, a 51% yield gain was obtained by African farmers over the traditional practice of five to six insecticide applications. The three-spray treatment also provided the highest net returns for growers, with a return of 3:1. While cultural practices alone increased yields, the combination with insecticides produced the highest cowpea yields (Gianessi 2013c; Karungi et al. 2000; Nabirye et al. 2003).

Pesticide Concerns

Some of the human and environmental concerns of insecticide use include potential contamination of water, soil, and atmospheric resources; food safety; applicator and agricultural worker safety; effects on nontarget organisms; and others. The battery of scientific testing required before insecticides can be registered with regulatory agencies, the safeguards in place and enforced by regulatory agencies, the checks and balances imposed by the various watchdog groups as well as the general public at large regarding pesticide use, and the social responsibility and desire for agricultural and societal sustainability from manufacturers of crop protection products have mitigated these unwanted effects. For example, regarding food safety, in testing during 2011 in Californi by the California Department of Pesticide Regulation, 97.9% of fresh produce samples (1,009 samples) from California of more than 160 kinds of produce were found to be below U.S. Environmental Protection Agency (EPA) pesticide tolerances (CDFA 2011). In fact, 60.8% had no residues and 35.8% had residues that were within the legal tolerance levels established by the U.S. EPA. These samples were tested for all major pesticide types.

Regarding human exposure from pesticide use, since 1971 California agencies have annually investigated cases of potential health effects of pesticide exposure (California EPA 2010). In 2010, agricultural use of pesticides and pesticide exposure were definitely implicated in 21 cases of human exposure, which represents 0.00088% of the 2.4 million applications (California EPA 2010). The costs of insecticide use (in the context of the benefit:cost relationship) are tangible, and considerable research efforts have been aimed at decreasing those costs. Compared with the benefits and importance of insecticide use for increasing food production in light of an increasing demand and human population, however, these costs are on a downward trend as new reduced-risk insecticides and genetically modified plant approaches are developed.

PESTICIDE BENEFITS IN THE DEVELOPING/DEVELOPED WORLD

Lower Crop Yields in Developing Countries Are Due in Large Part to Uncontrolled Pests

Cassava

Cassava is a major staple food for more than 200 million people in sub-Saharan Africa, but cassava yields in Africa are low, averaging 8.17 to 9.07 tonnes/ha (9–10 tons/ha), which is 50% lower than yields on experimental farms (Fermont et al. 2009). Weed infestation is a major constraint in cassava production in Africa because few herbicides are available and the requirement for four hoeings per crop cycle results in poor weed control and yield reductions ranging between 40% and total loss (Bamidele et al. 2004).

Rice

A recent rice study estimated that between 109 and 181 million tonnes (120 and 200 million tons) of grain yield are lost yearly to pests (insects/diseases/weeds) in rice fields in tropical Asia (Willocquet et al. 2004). The mean regionwide yield loss was estimated at 37.2% (Savary et al. 2000), and weeds were the main constraint with diseases causing 15% yield reductions (Ziegler and Savary 2010). A recent report from Africa estimates that 2.09 million tonnes (2.3 million tons) of rice are lost annually because of weed infestations (15% of total production) (Rodenburg and Demont 2009), and in India, annual losses of rice yield because of weeds were estimated at 13 million tonnes (15 million tons) (Ghosh et al. 2004). The gap in rice yields in farmers' fields due to poor weed control in Bangladesh was 43 to 51% (Rashid et al. 2012), being as high as 0.9 tonne/ha (1 ton/ha), with 30% of the farmers losing in excess of 500 kg/ha from uncontrolled weeds (Ahmed et al. 2001). Insects cause a 4 to 14% decrease in rice yield in Bangladesh every year (Mondal 2010), and in Burkina Faso at the irrigated rice scheme of Vallee du Kou, stem borers cause yield losses of up to 40% during the dry cropping season (Sama et al. 2013).

Wheat

Participants in the International Symposium on Increasing Wheat Yield Potential in 2006, from 19 developing countries, were surveyed to identify the main constraints to wheat production in their countries (Kosina et al. 2007). These countries account for 47% of the global wheat area and 89% of the wheat grown in developing countries. Estimated yield loss caused by weeds varied between 8.5 and 23.9%, depending on the region, and overall could cause up to 21.8 million tonnes (24 million tons) in losses annually. Yield loss caused by diseases varied between 14 and 27%, depending on the region, and overall annual losses of up to 20 million tonnes (22 million tons) could occur, with the most serious diseases being the leaf and stripe rusts, FHB, *Septoria* blotch, powdery mildew, spot blotch, and eyespot. Estimated yield loss caused by insect pests varied between 12.2 and 22% and were estimated to result in 18.1 million tonnes (20 million tons) of yield loss annually, with aphids, sunn pest (which includes members of the "shield bug" [*Scutelleridae*] and "stink bug" [*Pentatomidae*] families), Hessian fly, and weevils being the most common insects.

Higher-yielding varieties of wheat responsive to intensive irrigation and fertilizer application in India and Pakistan have excellent yield potential; however, there is a wide gap between potential yield of wheat and yield obtained in farmers' fields (Singh and Varshney 2010), with weed infestation being the main cause of low wheat yields by 25 to 30% (Anjum and Bajwa 2010; Banga, Yadav, and Malik 2003).

Maize

In Asia, maize is largely a rainy season crop, but under these conditions a variety of grass and broadleaf weeds invade maize fields before the crop germinates. Traditionally, manual hand weeding was the predominant method of weed control used by maize farmers (Shad, Chatha, and Nawaz 1993). If this weeding is performed with enough frequency and at the right time, maize yields equivalent to yields with herbicides can be obtained (Prasad, Singh, and Upadhyay 2008). Because of shortage of labor and frequent monsoon rains during the early growth period of maize, however, hand weeding is often delayed or neglected altogether (Prasad, Singh, and Upadhyay 2008), resulting in severe weeds causing low maize yields (Hussain et al. 2010). In the Philippines, actual losses due to weeds in maize fields have been reported at 15 to 30% (Paller, Ramirez, and Malenab 2001), whereas in Pakistan, maize yield losses due to weeds have been estimated at 14% (Sohail et al. 1993).

The Asian corn borer and stem borers are a principal limiting factor in maize production in Southeast Asia, and a major reason for the low productivity in India, Pakistan, and the Philippines is damage by insects—notably stem borers (Ganguli, Chaudhary, and Ganguli 1997). In India, stem borers cause yield losses of 7.5% on 80 to 100% of the maize (Joshi et al. 2005); in Pakistan, yield losses total 18% (Sohail et al. 1993); and in the Philippines, maize yield losses average 16% (Gonzales 2005). A similar scenario exists in the sub-Saharan Africa countries of Mozambique, Zimbabwe, and Ethiopia, where yield losses are often more than 50% in farmers' fields (Chinwada, Omwega, and Overholt 2001; Cugala and Omwega 2001; Getu et al. 2002). Several insecticides are registered for stem borer control in African countries (Chinwada, Omwega, and Overholt 2001), and, because of their effectiveness and relative ease of application, the use of granular formulations is recommended for small-scale farmers. Research in Kenya in 135 farm fields compared typical farmer practice with the application of a granular insecticide into the maize whorl (De Groote et al. 2011). The resulting estimate was that an average national crop loss of 13.5% was occurring because of stem borers—a loss that could be prevented through the use of the granular insecticide (De Groote et al. 2011).

Grey leaf spot is one of the principal constraints to maize production in sub-Saharan Africa and was first observed causing economic losses in maize fields in South Africa during the 1990–1991 growing season. The pathogen has been reported as being widespread in Ethiopia, Kenya, Malawi, Mozambique, and Zimbabwe, and to a lesser extent in the Congo, Nigeria, Tanzania, and Zambia. A plausible explanation for the sudden appearance of grey leaf spot in Africa is that infested maize residue accompanying maize imports from the United States was the original source of the fungus (Ward et al. 1999). Yield losses due to grey leaf spot have been observed in Malawi (29–69%) (Mpeketula, Saka, and Msuku 2003), in western Ethiopia (22–75%) for both improved and local varieties (Tilahun et al. 2001), in Kenya (45%) and Zimbabwe (35%) (Simons 2003), in Tanzania (15–40%) (Lyimo 2006), and in South Africa (30–40%) (Ward and Nowell 1998).

Hand weeding is the predominant weed control practice on smallholder maize farms in Africa, and studies have documented that season-long weed competition causes maize yield losses of 50 to 90% (Chikoye, Udensi, and Lum 2005). Average yields obtained by smallholder farms are considerably less than yields demonstrated in African research plots using best management practices, typically 0.9 to 1.8 tonnes/ha (1–2 tons/ha) compared to 7.3 tonnes/ha (8 tons/ha) in research plots. On experimental farms, it has been determined that maximum yields are achieved if maize fields are kept weed free for the first 56 days after planting (Akobundu 1987), and one week's delay in first weeding may decrease maize yields by one-third (Orr, Mwale, and Saiti 2002). On most farms, weeding usually competes with other farm activities and is postponed to a later date; survey data suggest that in Malawi, one-third of the area planted to maize by smallholders is either left unweeded or weeded after the critical first six weeks (Orr, Mwale, and Saiti 2002). Shortages of labor early in the season result in delayed weeding, and subsequent maize yield losses of 15 to 90% due to weed competition are common (Kibata et al.

2002). In Nigeria, maize farmers' weeding practice (one weeding) resulted in 42% yield loss in comparison to fields weeded three times (Chikoye, Schulz, and Ekeleme 2004).

Pesticide Research in Developing Countries Shows Great Potential to Increase Yields

Cowpea

Research using pesticides for pest management under various cropping situations in Africa has shown the potential of pesticide application in decreasing pest pressure, resulting in higher crop yields. Cowpea, a major source of plant proteins in the diet of rural populations in sub-Saharan Africa, has many insect pests, but research has shown farmers can improve yield tenfold if insecticides are used (Kamara et al. 2010). The International Institute of Tropical Agriculture's *Farmers Guide to Cowpea Production in West Africa* states that "generally, 2–3 sprays with insecticides are required for a good crop of cowpea" (Dugje et al. 2009).

Groundnut

Groundnut yield in Africa is low compared to Asia, Latin America, and the United States because farmers in Africa do not apply fungicides. Farmers usually attribute leaf defoliation to maturing of the crop and yield loss from foliar disease is not recognized, but research has shown that application of fungicides could be used to successfully control leaf spot and improve groundnut yields up to 80% in western and southern Africa (Naab et al. 2005).

Pulse Crops

Approximately 30% of the potential production of pulse crops (beans, peas) in India is lost annually to insects, diseases, and weeds (Dhar and Ahmad 2004). Research has demonstrated that these losses can be significantly decreased by fungicides, insecticides, and herbicides. Insecticides decreased pod borer populations by 90%, whereas fungicides decreased the incidence of ascochyta blight by 60% (Ameta, Sharma, and Jain 2010; Maheshwari et al. 2012). It is often almost impossible to remove weeds by hand or mechanical means in Indian pulse crops. Research has shown that bean yield doubled with herbicide use in comparison to traditional farmer practice (Sekhon et al. 2004).

Maize

Downy mildew diseases have been a major limiting factor in the production of maize in Asia throughout this century, and they cause yield losses of 20 to 90% in Indonesia, the Philippines, and India (Mikoshiba 1983; Putnam 2007). Research has shown that systemic fungicides applied as seed treatments and/or foliar sprays provide excellent control of downy mildew on maize in Asia. Yield increases of 8 to 10% are possible through seed treatment alone. Seed treatment combined with one foliar spray to control downy mildew increased maize yield by 34% (Lal, Saxena, and Upadhyay 1980).

Fungicides have been found to provide excellent control of grey leaf spot in Africa. Few hybrids have sufficient resistance to prevent yield losses due to grey leaf spot. Research in South Africa has demonstrated that even the most resistant hybrids respond to fungicide treatment. Yield losses of up to 50% have occurred in unsprayed hybrids with moderate resistance as opposed to 65% yield reductions in unsprayed susceptible varieties (Ward et al. 1999). In seasons less conducive to grey spot disease development, yield losses in unsprayed susceptible and moderately resistant varieties were 38 and 20%, respectively (Ward et al. 1999). In tests in Zambia, grain yield differences in sprayed and unsprayed treatments ranged from 27 to 54%, depending on the susceptibility of the genotype (Verma 2001).

The spraying of chemical herbicides to remove weeds from maize fields is an alternative to hand weeding African fields. Maize yields doubled in Nigeria when atrazine was used (Benson 1982). In Zimbabwe, herbicides resulted in yield increases of up to 50% in maize (Chivinge 1990), and in Kenya, herbicides resulted in 33% higher yields than the farmer practice of hand weeding (Muthamia et al. 2002).

The parasitic *Striga* species is considered the greatest biological constraint on the cultivation of cereal crops (sorghum, millet, and maize) in sub-Saharan Africa. Two species of *Striga* infest 22 to 40 million ha of farmland (Woomer 2006). The most deleterious effects occur on maize, where approximately 2.5 million ha suffer grain losses of 30 to 80% (Woomer 2006). Up to 40% of total farmland in some areas has been abandoned for maize and sorghum because of *Striga* infestation (Mutengwa et al. 1999).

During the past few years, a promising technology has been developed by the International Maize and Wheat Improvement Center in collaboration with the Weizmann Institute of Science and the chemical company BASF. A natural mutant of maize provides the maize with resistance to imidazoline (IR) herbicides. Seed coating of the IR-maize varieties with imazapyr, a systemic herbicide from that group, provides the plant with protection from *Striga* (De Groote et al. 2008). *Striga* seeds, stimulated to germinate by maize roots, attach and are killed by imazapyr in the maize seedling before any damage is inflicted. Research has demonstrated that seed coating with imazapyr gives season-long *Striga* control, resulting in a three- to fourfold increase in maize yield when *Striga* density is high (Kanampiu et al. 2003).

Pesticide Use in Developing Countries Has a Very Favorable Cost/Benefit Ratio

As more Asian economies have been industrializing, millions of people are migrating from rural to urban areas, creating shortages of workers for hand weeding and increasing the cost of hand weeding when labor is available. Farmers have been left with little choice but to decrease labor and production costs, particularly for the most labor-intensive tasks, such as weeding. In the Philippines, the proportion of rice farmers using herbicides increased from 14% in 1966 to 61% in 1974 (De Datta and Barker 1977). Today, 96 to 98% of Philippine rice farmers use herbicides (Marsh et al. 2009). A recent study in the Philippines determined that, with increased labor cost, herbicide application in rice fields is superior to manual weed control even at the lowest weed density by $US25 to 54/ha (Beltran, Pannell, and Doole 2012). At the highest weed density and highest labor cost, herbicide application is approximately 80% (approximately $US200/ha) more profitable.

In recent years, with rapid urbanization occurring in many African countries, shortages of workers for hand weeding have increased. Research has shown that herbicides are about one-third the cost of hired labor for hand weeding (Maina et al. 2003). Research in Zambia suggests that the benefits of herbicide use are quite high. Applying herbicides increases gross margin for maize between $70 and $72 per ha for an increase in gross margins of roughly one-third (Burke et al. 2011).

The use of herbicides in Africa, India, and Bangladesh would significantly decrease the hours of labor required for hand weeding and lessen the cost of weeding. In Africa, farmers save at least $US388/ha worth of time to be used on other off- or on-farm activities (Muoni, Rusinamhodzi, and Thierfelder 2013). The cost-benefit ratio for insecticide use on brinjal in India ranges from a minimum of 1:5 to a maximum of 1:20 (Abrol and Singh 2003). Economic analysis of rice production in Bangladesh revealed that net income from herbicide application was 116% higher than hand weeding three times (Rashid et al. 2012).

Pesticide Use in Developing Countries Will Promote Use of Other Sustainable Practices

The adoption of herbicides in African maize fields is likely to lead to increased production not only because of improved weed control but also by facilitating the adoption of fertilizer use and expansion of planted acres. Despite being promoted for 40 years, fertilizer use in sub-Saharan Africa remains low, with only 5% of smallholders adopting their use (Dar and Twomlow 2007). The benefits of fertilizer depend on weed control. The application of fertilizers causes more weeds to grow, which, in turn, increases the need for more hand weeding. By controlling the weed problem with herbicides, maize farmers will be more likely to use fertilizers for an even greater maize yield increase. African farmers often plant only 50% of their available fields to crops, leaving the remaining area fallow, because they make a determination that not enough labor would be available to weed the additional fields (Bishop-Sambrook 2003). By greatly decreasing the amount of labor required for weeding, the adoption of herbicides can lead to a greater area planted to crops, including maize.

In South Asia, rice has traditionally been grown by manually transplanting seedlings into flooded soil. Flooding benefits rice by controlling the first flush of weeds and providing the rice seedlings a head start on subsequent weed flushes. Weeds that emerge during the season are typically controlled by hand weeding.

Water and labor resource scarcity threaten the sustainability of rice production in Asia. Rice consumes approximately 50% of total irrigation water used. Agriculture's share of water is declining because of competition with domestic household and industrial use. In Asia, the share of water used for agriculture declined from 98 to 80% in the last century and is likely to drop to 72% by 2020 (Kumar and Ladha 2011). Rapid economic growth has increased the demand for labor in nonagricultural sectors, resulting in decreased labor availability for agriculture. Many people prefer nonagricultural employment to agriculture work such as transplanting and weeding rice by hand. Because of increasing labor scarcity, labor wages have increased, making the traditional rice production system uneconomical in many Asian countries.

Rice can be planted by sowing seeds in dry soil instead of transplanting rice seedlings into flooded soils. The dry planting system requires 35 to 57% less water and 67% less labor than transplanting seedlings into flooded fields (Farooq et al. 2011; Mazid et al. 2006). Weeds are more problematic in the dry system, however, because they are not controlled by flooding (Kumar and Ladha 2011). A variety of herbicides has been screened and found effective for burndown, pre-emergence, and postemergence weed control in dry-seeded systems (Kumar and Ladha 2011). Direct seeding of rice has largely replaced transplanting in the Philippines, Vietnam, Malaysia, and Thailand. Virtually all rice farmers who practice direct seeding adopt chemical herbicides because they decrease weed control time in dry-seeded crops by 500 h/ha in comparison to hand-weeded transplanted rice (Ho 1996; Mazid et al. 2006).

CONCLUSIONS

The basis of pesticide use in agriculture and its impacts on increased food production due to improved pest management have been discussed in this paper. The evidence is strong that pesticides have played a major role in easier and more efficient management of pests and allowed fewer farmers to produce higher amounts of food. Pesticides have helped not only to better manage pests but in the development of improved agronomic practices. These practices, such as no tillage and reduced tillage agriculture, have helped conserve valuable soil resources, improved genetic materials that allow higher plant densities, and increased yields. They also allow more efficient use of nutrients and water inputs, produce higher quality crops that maintain quality during storage, improve nutrient availability, and are more acceptable to the consuming public. These outcomes are all largely due to more efficient management of pests before, during, and after the crop production cycle.

An important aspect of synthetic pesticides is that in the last 30 years, many new pesticides have been introduced into agriculture that are designed by new technologies, are safer to use, have a lower environmental footprint, are designed to be more pest-type specific, are applied at extremely low rates of grams or ounces per hectare instead of kilograms, and, with improved technologies, are applied more precisely through site-specific agriculture. Examples include the sulfonylurea herbicides, the piperidinylthiazole fungicides, and the mectin insecticides and acaricides (Lamberth et al. 2013). New approaches will also include not only synthetically derived pesticides but, as Lamberth and colleagues (2013) state, “those from natural products, competitor inspired chemistry, compound acquisition from universities, combinational chemistry libraries, intermediates from projects in other indicators, and compound collections from pharmaceutical and animal health companies.” The sources of new pesticides have many opportunities but also many challenges, including cost of development, fit in the market, efficacy and length of activity, safety to the environment, and nontarget organisms. For those interested in a more detailed description of the technologies and chemistries that are involved in pesticide development, the reader is referred to the article by Lamberth and colleagues (2013).

For example, many new mechanism-of-action herbicides have been developed since the early 1980s that are species specific (only for grasses or only for broadleaf weeds), are more specifically applied, or are most active on existing emerged weeds. They also have much lower environmental footprints and low toxicology to nontarget organisms. The only new mechanism-of-action class of herbicides, however, was released in the early 1990s. This was largely because of the development of crops resistant to glyphosate herbicide, which resulted in a tremendous increase in no till agriculture. This, in turn, saved some labor input into soil tillage for site preparation and in-season weed cultivation but resulted in less soil erosion, soil compaction, and the need to apply the herbicide only when emerged weeds were present. This herbicide class also dominated the herbicide market to the detriment of other less broadspectrum herbicides. This glyphosate resistant technology has had benefits well beyond just weed control in terms of the environment. As with any effective technology, however, the problem of weeds developing resistance to glyphosate has resulted in long-term peril to this technology if the agriculture sector does not start practicing weed management approaches that include a variety of tools used in an integrated manner, thus eliminating dependence on one tool. The opposite view is that these problems have now created opportunities for new herbicide development and increasing market share for effective and safe compounds.

The trends related to insecticide and fungicide development have not mirrored the situation with herbicides. There have been more than a dozen new chemical classes with novel modes of action of insecticides brought to the market since 1995, and are these classed as low- or reduced-risk chemicals. Fungicides reflect a similar pattern. The challenges for development, testing labeling, and fit in the market, however, along with issues related to human and nontarget organism safety and low environmental effects holds true for all classes of pesticides. There are many new technologies available for pesticide development, and there will be new pesticides developed. The overall grand challenge is how these pesticides fit into food production programs throughout the world, if they are affordable for all farmers, and whether or not they will help address the overall need for feeding a world population of 9 billion people by 2015.

This paper has described how pesticides have allowed great increases in agriculture production; have alleviated the need for high percentages of people to be, by necessity, involved in agriculture production; and have resulted in yield increases that stagger the imagination. These efforts will require a coordinated approach to pesticide development that includes chemical companies, academics, and government and citizen groups and must result in solutions that are acceptable to society.

The authors agree with the point made by the National Academy of Sciences (NRC 1993):

> Pesticides are used widely in agriculture in the United States. When effectively applied, pesticides can kill or control pests, including weeds, insects, fungi, bacteria, and rodents. Chemical pest control has contributed to dramatic increases in yields for most major fruit and vegetable crops. Its use has led to substantial improvements over the past 40 years in the quantity and variety of the U.S. diet and thus in the health of the public.

The authors, however, would change “when effectively applied” to “when integrated into a comprehensive approach to agriculture that uses all tools available to meet the needs for food production to feed the 9 billion humans on the earth in 2050 . . .”

GLOSSARY

Acaricide. A pesticide that kills mites and ticks.

Arthropod. An invertebrate animal having a segmented body and jointed appendages.

Bordeaux mix. An effective fungicide and bactericide composed of copper sulfate, lime, and water.

Botanicals. Of or relating to plants or the study of plant life.

Broadspectrum. Effective against a wide range of organisms.

Cultivar. An organism originating and persistent under cultivation.

Epizootic. An outbreak of disease affecting many animals of one kind at the same time.

Fungicide. An agent that destroys fungi or inhibits their growth.

Germplasm. The hereditary material of germ cells.

Herbicide. An agent used to destroy or inhibit plant growth.

Insecticide. An agent that destroys insects.

Intercropping. Growing two or more crops in proximity at the same time.

Mycotoxin. A poisonous substance produced by a fungus.

Pathogen. A specific causative agent of disease.

Pesticide. A chemical used to kill animals or insects that damage plants or crops.

Phytotoxic. Poisonous to plants.

Postemergence. After seed has sprouted.

Preemergence. Prior to plant appearing above ground level.

Semiochemical. Genetic term for a chemical substance or mixture that carries a message for purpose of communication.

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