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The impact of crop protection on agricultural production

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Abstract

Chemical pesticides will continue to play a role in pest management for the future. In many situations, the benefits of pesticide use are high relative to the risks or there are no practical alternatives. The number and diversity of biological sources will increase, and products that originate in chemistry laboratories will be designed for particular target sites. Innovations in pesticide delivery systems in plants promise to reduce adverse environmental impacts even further. The correct use of pesticides can deliver significant socio-economic and environmental benefits in the form of safe, healthy, affordable food; and enable sustainable farm management by improving the efficiency with which we use natural resources such as soil, water and overall land use. Genetically engineered organisms that reduce pest pressure constitute a "new generation" of pest management tools. The use of transgenic crops will probably maintain, or even increase, the need for effective resistance management programmes. However, there remains a need for new chemicals that are compatible with ecologically based pest management and applicator and worker safety. Evaluation of the effectiveness of biocontrol agents should involve consideration of long-term impacts rather than only short-term yield, as is typically done for conventional practices. But it makes sense to establish a legal framework that enables organic and pesticide-free markets to emerge and prosper so that consumers can be given an informed choice between lines of products that vary with pest management. The justifications of government intervention in the management of pest control include the need to address the externality problems associated with the human and environmental health effects of pesticides. There is underinvestment from a social perspective in private-sector research because companies will compare their expected profits from their patented products resulting from research and will not consider the benefits to consumers and users. Another reason why public research might lead to innovations that elude the private sector is the different incentives that researchers in the private and public sectors face.

Keywords

Crop protection, pesticide, biopesticide, crop losses, cost and benefit, agriculture

Introduction

Globalisation is affecting pest management on and off the farm. Reduction in trade barriers increases competitive pressures and provides extra incentives for farmers to reduce costs and increase crop yields. In a global marketplace, farmers of one country can compete with farmers from other countries where labour, land and input costs are lower only by being more "productive", with higher yields per hectare. Other forms of trade barriers create disincentives for adopting new technologies (such as the reluctance of the EU to accept genetically modified organisms). It is likely that trade will increase the spread of invasive pest species and pose risks to domestic plants and animals, as well as populations of native flora and fauna.

The goal in agriculture should be the production of high-quality food and fibre at low cost and with minimal deleterious effects on humans or the environment. To make agriculture more productive and profitable in the face of rising costs and rising standards of human and environmental health, the best combination of available technologies has to be used. These technologies should include chemical, as well as biological and recombinant, methods of pest control integrated into ecologically balanced programmes. The effort to reach the goal must be based on sound fundamen-

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tal and applied research, and decisions must be based on science. Accomplishing the goal requires expansion of the research effort in government, industry and university laboratories.

The beneficial outcome from the use of pesticides provides evidence that pesticides will continue to be a vital tool in the diverse range of technologies that can maintain and improve living standards for the people of the world. Reducing pesticide use can provide growers with direct economic benefits by decreasing the cost of inputs and increasing net returns. Some alternative methods may be more costly than conventional chemical-intensive agricultural practices, but often these comparisons fail to account for the high environmental and social costs of pesticide use. The economic and environmental impacts of agricultural policies on pesticide reduction also deserve scrutiny and policies that encourage adoption of ecologically sound farming practices need to be implemented.

The general public has a critical function in determining the future role of pesticides in agriculture. Sometimes objections to pesticides are an issue of subjective preference even when scientific evidence cannot support the objections. Investments in research by the public sector should emphasise those areas of pest management that are not now being (and historically have never been) undertaken by private industry. The justifications of government intervention in the management of pest control include the need to address the externality problems associated with the human and environmental health effects of pesticides. The public sector must act on its responsibility to provide quality education to ensure well informed decision making in both the private and public sectors.

Methods

The paper is based on the national pesticide benefit studies from the United States, where research covered fifty crops, including 5-10 crops for each state in the U.S. Several international specialist publications support the analysis (e.g. Oerke et al. 1994; Oerke and Dehne 2004, Oerke 2006, FAO, 2009; IWMI, 2007; Pimentel, 2005). The database of FAO, USDA, EUFADN and the Hungarian Research Institute for Agricultural Economics has also been used in the examination. The study focuses mainly on crop protection in the context of agricultural production, crop losses due to pests and cost-benefit analysis of crop protection measures.

Crop protection in the context of agricultural development

Improved crop management systems based upon genetically improved (high yielding) cultivars and soil cultivation techniques, enhanced soil fertility via chemical fertilisation, pest control via synthetic pesticides, and irrigation were hallmarks of the Green Revolution. The combined effect of these factors has allowed world food production to double in the past 50 years. From 1960 to the present the human population has more than doubled to reach almost 7 billion people (FAO, 2009). The doubling of grain production since the early 1960s was associated with a 6.9-fold increase in nitrogen fertilisation, a 1.7-fold increase in the amount of irrigated crop land, and a 1.1-fold increase in land in cultivation, and has resulted in a global food supply sufficient to provide adequate energy and protein for all (Tilman, 1999). The proportion of yield increase that may be attributed to genetic improvement of crops by breeders is about 0.5-0.6 providing farmers with high yielding varieties responsive to improved fertilisation (McLaren, 2000). In addition, the intensity of crop protection has increased considerably as exemplified by a 15-20 fold increase in the amount of pesticides used worldwide (Oerke, 2006). Much of the increase in yield per unit of area can be attributed to more efficient control of (biotic) stress rather than an increase in yield potential.

Human population is projected to grow by 75 million per annum, increasing by 35% to 9.1 billion by 2050 (FAO, 2009). This increased population density, coupled with changes in dietary habits in developing countries towards high quality food (e.g. more consumption of meat and milk products) and the increasing use of grains for livestock feed, is projected to cause the demand for food production to increase by 70%. The increase in production has to happen whilst the climate is changing and becoming less predictable, as greenhouse gas emissions from agriculture need to be cut, and as land and water resources are shrinking or deteriorating. The provision of additional agricultural land is limited, as it would have to happen mostly at the expense of forests and the natural habitats of wildlife, wild relatives of crops and natural enemies of crop pests. Furthermore, a higher proportion of agricultural land may be used industrially to produce biofuel or fibre instead of food. Thus, we may need to grow food on even less land, with less water, using less energy, fertiliser and pesticide than now. Given these limitations, sustainable production at elevated levels is urgently needed. Increasing productivity on existing land is by far the better choice. Globally, an average of 35% of crop yields are lost to pre-harvest pests (Figure 1). In some developing countries pre-harvest losses can reach 70%. The conservation of fertile soils, the development of high-yielding varieties and the reduction of current yield losses caused by pests, pathogens and weeds are major challenges to agricultural production.

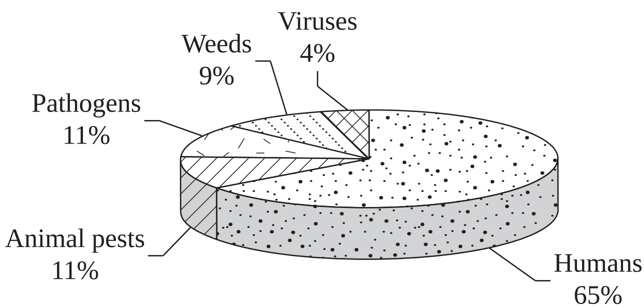

Figure 1: The world agricultural cake, 2001-03

Source: Oerke (2006)

Whilst technology will undoubtedly hold many of the keys to long term global food security, the development and testing of new varieties or techniques takes time. It may be ten years or more before people see the benefits. However, there is a lot that can be done today with existing knowledge. Part of the key is also to avoid waste along the whole length of the food chain. In addition to the pre-harvest losses (35% of crop yields) transport, pre-processing, storage, processing, packaging, marketing and plate waste losses are relatively high too (Figure 2). Insects, weeds and microbial pests cause the most problems but research, education and training can play a key role in helping the world lose less after harvest along the food chain.

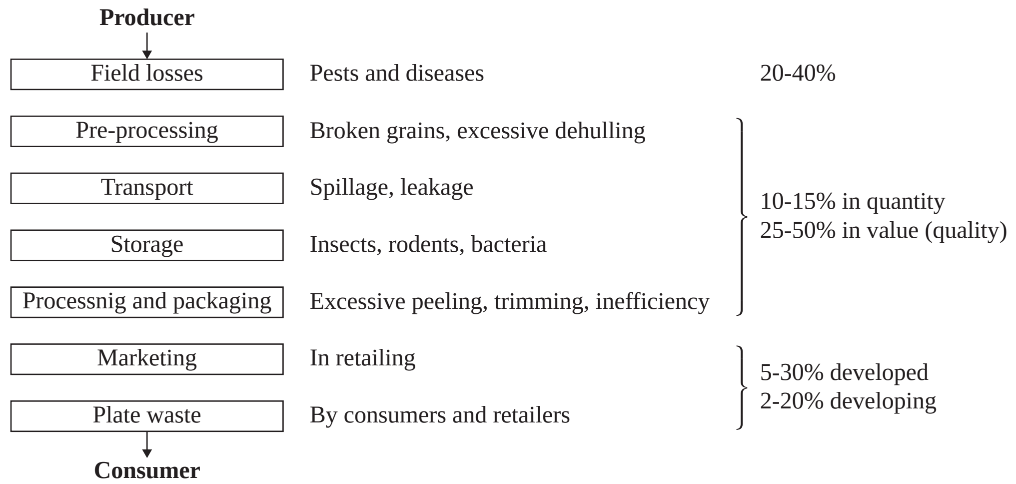

Figure 2: Losses along the food chain

Source: IWMI (2007).

Helping farmers to lose less of their crops will be a key factor in promoting food security, but even in the poorest countries those rural farmers aspire to more than self-sufficiency. They want to improve their livelihoods so as to buy higher quality, more nutritious food and to afford a better standard of living, healthcare and education. So we also need to build the knowledge and skills that will help them earn more for their crops. In an increasingly global food system, this is about quality as well as quantity. Even though tariff barriers to trade are being lowered, regulations to reduce pesticide residues and prevent the spread of plant diseases can act as major barriers to farmers who want to access the high value markets in Europe and America. More and more farmers move from growing staples into higher value horticulture and introduce techniques of integrated pest management that allow them to meet the standards for export of fruit into Europe. Food security is then only the first step towards greater economic independence for farmers.

The three annual crops, namely maize, rice and wheat, occupy almost 40% of global crop land and are the primary sources for human nutrition worldwide. As yields of these crops and some cash crops like soybean, cotton and sugar beet positively respond to high production levels and/or cultivation may be largely mechanised, in recent decades worldwide crop production has focused on a limited number of plant species. Diverse ecosystems have been replaced in many regions by simple agro-ecosystems which are more vulnerable to pest attack. In order to safeguard the high level of food and feed productivity necessary to meet the increasing human demand, these crops require protection from pests.

We are currently using around USD 40 billion worth of pesticides each year in agriculture, worldwide. What will the benefits and risks be if this level of pesticide use is continued or increased? What will they be if pesticide use is discontinued? Farmers in highly developed, industrialised countries expect a four or five fold return on money spent on pesticides. Is this still true? Can we meet world food demands if producers stop using pesticides because of reduced economic benefits? Can better integrated pest management (IPM) preserve the economic benefits of pesticide use? Although crop losses are currently greatest in less industrialised countries, can we meet the educational and training requirements to safely increase pesticide use in these areas? These are just some of the questions facing scientists and pest management experts as agriculture faces its greatest challenge in history between now and the year 2050.

Crop losses due to pests

Since the beginnings of agriculture about 10,000 years ago, growers have had to compete with harmful organisms – animal pests, plant pathogens and weeds (i.e. competitive plants), collectively called pests – for crop products grown for human use and consumption. As with abiotic causes of crop losses, especially the lack or excess of water in the growth season, extreme temperatures, high or low irradiance (factors which can be controlled only within narrow limits) and nutrient supply, biotic stressors have the potential to reduce crop production substantially. These organisms may be controlled by applying physical (cultivation, mechanical weeding etc.), biological (cultivar choice, crop rotation, antagonists, predators etc.) and chemical measures (pesticides). Crop protection has been developed for the prevention and control of crop losses due to pests in the field (pre-harvest losses) and during storage (post-harvest losses). This paper concentrates on pre-harvest losses, i.e. the effect of pests on crop production in the field, and the effect of control measures applied by farmers in order to restrict losses to an acceptable level.

Crop losses may be quantitative and/or qualitative. Quantitative losses result from reduced productivity, leading to a smaller yield per unit area. Qualitative losses from pests may result from the reduced content of valuable ingredients, reduced market quality, e.g. due to aesthetic features (pigmentation), reduced storage characteristics, or due to the contamination of the harvested product with pests, parts of pests or toxic products of the pests (e.g. mycotoxins). Crop losses may be expressed in absolute terms (kg/ha, financial loss/ha) or in relative terms (loss in %). The economic relevance of crop losses may be assessed by comparing the costs of control options with the potential income from the crop losses prevented due to pest control. Often, it is not economically justifiable to reduce high loss rates at low crop productivity, as the absolute yield gain from pest control is only low. In contrast, in high input production systems, the reduction of low loss rates may result in a net economic benefit for the farmer.

Two loss rates have to be differentiated: the potential loss and the actual loss. The potential loss from pests includes the losses without physical, biological or chemical crop protection compared with yields with a similar intensity of crop production (fertilisation, irrigation, cultivars etc.) in a no-loss scenario. Actual losses comprise the crop losses sustained despite the crop protection practices employed. The efficacy of crop protection practices may be calculated as the percentage of potential losses prevented. In contrast, the impact of pesticide use on crop productivity may be assessed only by generating a second scenario considering changes in the production system provoked by the abandonment or ban of pesticides – use of other varieties of the crop, modified crop rotation, lower fertiliser use, etc. – and often associated with a reduced attainable yield.

Crop losses to weeds, animal pests, pathogens and viruses continue to reduce available production of food and cash crops worldwide. Absolute losses and loss rates vary among crops due to differences in their reaction to the competition of weeds and the susceptibility to attack of the other pest groups. The overall loss potential is especially high in crops grown under high productivity conditions as well as in the tropics and sub-tropics where climatic conditions favour the damaging function of pests. Actual crop protection depends on the importance of pest groups or its perception by farmers and on the availability of crop protection methods. As the availability of control measures greatly varies among regions, actual losses despite pest control measures differ to a higher extent than the site-specific loss potentials. Actual loss rates show higher coefficients of variation than absolute losses.

The economically acceptable rate of crop losses is well above zero in most field crops. Some crop losses may not be avoidable for technological reasons (or availability of technology in developing countries); others are not or will not be available furthermore because of ecological hazards (soil disinfectants). In many cases, however, higher pesticide use in order to produce extra yield from preventing crop losses is economically not justified because other environmental factors than pests, especially water availability, are yield-limiting. Therefore, a drastic reduction of crop losses is highly desirable for many regions from the point of view of feeding the human population; however, pest control and the use of pesticides in particular are mainly applied according to the economic benefits of the farmer. The increased use of pesticides since 1960 has not resulted in a significant decrease of crop losses; however, in many regions they have enabled farmers to increase crop productivity considerably without losing an economically non-acceptable proportion of the crop to pests.

Although crop protection aims to avoid or prevent crop losses or to reduce them to an economically acceptable level, the availability of quantitative data on the effect of weeds, animal pests and pathogens is very limited. An assessment of the full range of agricultural pests and of the composition and deployment of chemical pesticides to control pests in various environments would be an impossible task because of the large volume of data and the number of analyses required to generate a credible evaluation. The generation of experimental data is time-consuming and labour-intensive, losses vary from growth season to growth season due to variation in pest incidence and severity, and estimates of loss data for various crops are fraught with problems. The assessment of crop losses despite actual crop protection strategies is important for demonstrating where future action is needed and for decision making by farmers as well as at the governmental level.

According to German authorities in 1929, animal pests and fungal pathogens each caused a 10% loss of cereal yield. In potato, pathogens and animal pests reduced production by 25 and 5%, respectively; while in sugar beet, production was reduced by 5 and 10% due to pathogens and animal pests respectively (Morstatt, 1929). In the USA, in the early 1900s pre-harvest losses caused by insect pests were estimated to be seldom less than 10% (Marlatt, 1904). Later, the United States Department of Agriculture (USDA) published data on pre-harvest losses in 1927, 1931, 1939, 1954 and 1965 (Cramer, 1967). This book gives the most comprehensive overview on crop losses throughout the world; however, due to significant changes in area harvested, production systems, intensity of production, incidence of pests, control options, product prices the loss data became outdated.

Estimates of actual losses in crop production worldwide were updated nearly 30 years later for the period 1988-90 on a regional basis for 17 regions by Oerke *et al*. (1994). Increased agricultural pesticide use nearly doubled food crop harvests from 42% of the theoretical worldwide yield in 1965 to 70% of the theoretical yield by 1990. Unfortunately, 30% of the theoretical yield was still being lost because the use of effective pest management methods was not applied uniformly around the world and it still is not. Without pesticides, natural enemies, host plant resistance and other nonchemical controls, 70% of crops could have been lost to pests. Since 1965 worldwide production of most crops has increased considerably. Simultaneously, crop losses in wheat, potatoes, barley and rice increased by 4 to 10 per cent, in maize, soybean, cotton and coffee losses remained unchanged or slightly decreased. These estimates should be taken only as a rough guide to the scope of the problem (Figure 3).

Since crop production technology and especially crop protection methods are changing continuously, loss data for eight major food and cash crops – wheat, rice, maize, barley, potatoes, soybeans, sugar beet and cotton – have been updated for the period 1996-98 on a regional basis for 17 regions (Oerke and Dehne, 2004). Among crops the loss potential of pests worldwide varied from less than 50% (in barley) to more than 80% (in sugar beet and cotton). Actual losses were estimated at 26-30% for sugar beet, barley, soybean, wheat and cotton, and 35%, 39% and 40% for maize, potatoes and rice, respectively. The percentage of losses prevented ranged from 34-35% in Central Africa and the European part of the Commonwealth of Independent States (CIS) to 70% in Northwest Europe. In East Asia, North America and South Europe efficacy was calculated to reach 55-60% (Figure 3).

Since the early 1990s, production systems and especially crop protection methods have changed significantly, especially in crops such as maize, soybean and cotton, in which the advent of transgenic varieties has modified the strategies for pest control in some major production regions. Loss data for major food and cash crops were last updated by CABI's Crop Protection Compendium for six food and cash crops – wheat, rice, maize, potatoes, soybeans, and cotton – for the period 2001-2003 on a regional basis (CABI, 2005, Oerke, 2006). Nineteen regions were specified according to the intensity of crop production and the production conditions. Among crops, the total global potential loss due to pests varied from about 50% in wheat to more than 80% in cotton production. The responses are estimated as losses of 26-29% for soybean, wheat and cotton, and 31, 37 and 40% for maize, rice and potatoes respectively (Figure 3).

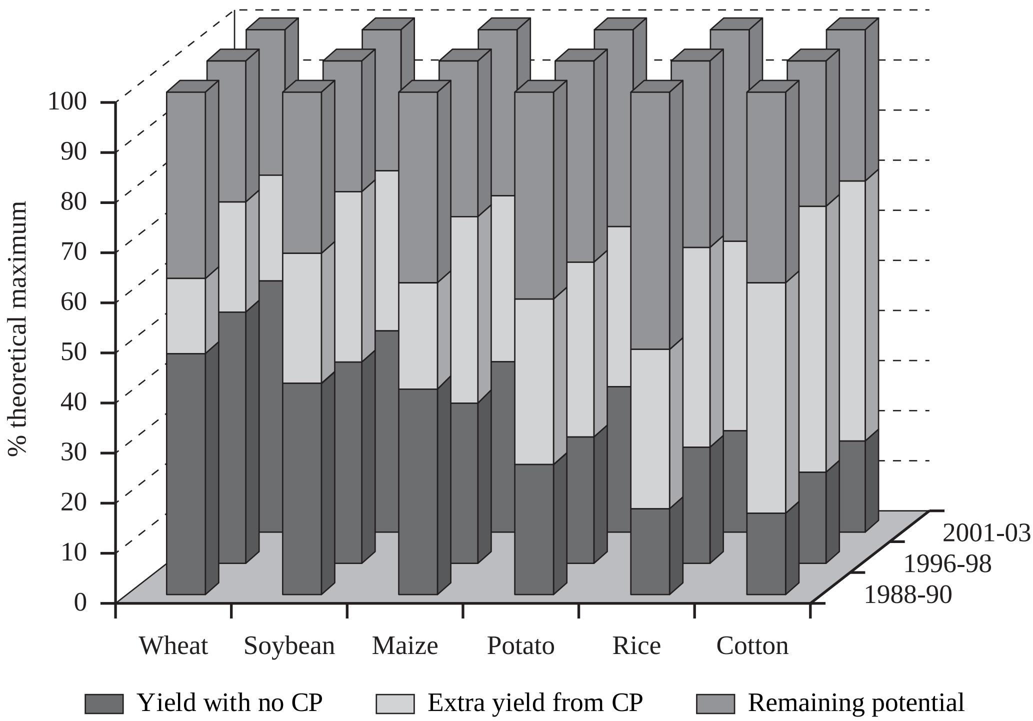

Figure 3: Development of crop losses from 1996-98 to 2001-03

Source: Oerke et *al*. (1994), Oerke and Dehne (2004), Oerke (2006) and own calculations

Comparing crop production and actual losses to pests for 1988-90 and 2001-03 to data from 1965, when Cramer (1967) estimated crop losses for more than 60 crops using a similar methodology, the differences between regions and crops, respectively, are evident. Worldwide, production of food and cash crops increased considerably, the actual losses of the six food and cash crops have decreased considerably in relative terms during the last 40 years (Table 1).

Table 1

Estimates of actual and potential crop losses due to pests of six food and cash crops

Crop	Actual loss rate (%)			Potential loss rate (%)		
	1988-90[1)]	1996-98[2)]	2001-03[3)]	1988-90[1)]	1996-98[2)]	2001-03[3)]
Cotton	38	29	29	84	82	82
Rice	51	39	37	82	77	77
Potato	41	39	40	73	71	75
Maize	38	33	31	59	66	68
Soybean	32	28	26	59	60	60
Wheat	34	29	28	52	50	50

1) From Oerke *et al*. (1994)
2) From Oerke and Dehne (2004)
3) From Oerke (2006)
Source: Oerke et al. (1994), Oerke and Dehne (2004), Oerke (2006) and own calculations.

It was estimated that for the period 1988-90 42% of the production of the eight major food and cash crops of the world – wheat, rice, maize, barley, potatoes, soybeans, cotton and coffee – were lost to pests, with 15% attributable to insects and 13.5% each to weed and pathogens, despite the application of an estimated 2.5 million tonnes of pesticides in a year at a cost of USD 26 billion, plus the benefits of various nonchemical controls. An additional 10% of the potential value was lost postharvest. Potential losses worldwide were estimated to be as high as 70%. Weeds produced the highest potential loss (30%), with animal pests and pathogens being less important (losses of 23 and 17%). The efficacy of crop protection was higher in cash crops than in food crops. Worldwide, disease control reduced the potential losses by 23%. The yield limiting potentials of animal pests and weeds were reduced more efficiently by 31 and 55%, respectively. Due to the small share of Western Europe in worldwide production of 8%, the efficacy of actual crop protection worldwide was only 40%. However, regional variation was higher than the differences among crops. In total, the loss potential of about 70% was reduced to actual losses of 42% (Figure 4).

For the period 1996-98 weeds had the highest loss potential (32%) with animal pests and pathogens being less important (18% and 15%, respectively). Although viruses cause serious problems in potatoes and sugar beets in some areas, worldwide losses due to viruses averaged 3%. In terms of the efficacy of actual pest control measures by pest group, weed control, which can be done manually, mechanically or chemically achieved an overall efficacy of 71%. The control of animal pests and diseases caused by fungi and bacteria was considerably lower at 42% and 34%, respectively, with virus control reaching an efficacy of only 13%. The efficacy of actual crop protection worldwide was 52%. In total, the loss potential of about 67% was reduced to actual losses of about 32% (Figure 4).

In many crops, weeds are the most important pest group, and as these may be controlled manually, by mechanical weeding or by the use of synthetic herbicides, weed control is more effective than the reduction of crop losses from diseases or animal pests. For the period 2001-2003 weeds produced the highest potential loss (34%), with animal pests and pathogens being less important (losses of 18 and 16%). The efficacy of control of pathogens and animal pests only reached 32 and 39%, respectively, compared to 74% for weed control. The control of soil-borne pathogens and nematodes, in particular, often causes problems. In most regions, the potential loss due to viruses is relatively low (4% on average) and virus control reduced the potential losses by

5% since the efficacy of the control of viruses was largely restricted to the use of insecticides for the control of the virus vectors. However, there are big differences in the efficacy of pest control. In Northwest Europe, from 2001 to 2003, efficacy was as high as 71%, in North America 63%, in South Asia 42%, in West Africa 43% and in East Africa 32%. The efficacy of actual crop protection worldwide was around 52%. In total, the loss potential of about 72% was reduced to actual losses of about 35% (Figure 4).

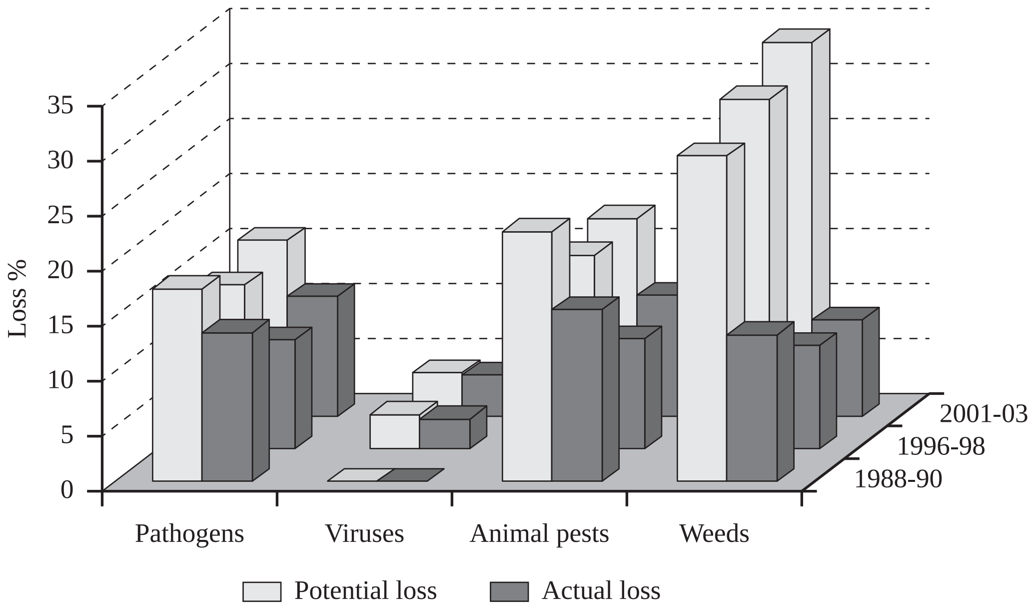

Figure 4: Development of efficacy of actual crop protection practices from 1996-98 to 2001-03

Source: Oerke et al. (1994), Oerke and Dehne (2004), Oerke (2006) and own calculations.

Due to the increased use of pesticides the absolute value of crop losses and the overall proportion of crop losses appear to have decreased in the past 40 years (Table 1). Worldwide estimates for losses to pests in 1996-98 and 2001-03 differ significantly from estimates published earlier (Cramer, 1967; Oerke *et al*., 1994). Obsolete information from old reports has been replaced by new data. Despite a broader database the lack of systematically collected data is still evident. Alterations in the share of regions differing in loss rates in total production worldwide are also responsible for differences. Moreover, the intensity and efficacy of crop protection has increased since the late 1980s especially in Asia and Latin America where the use of pesticides increased above the global average.

Irrespective of the availability of control measures, the control of pests having a low potential loss is not economically justifiable. Therefore, the efficacy of pest control often increases with the loss potential. These figures indicate that in the regions with the highest need for additional food there is still a great deal of room for increasing productivity simply by reducing the current yield losses through improved crop and postharvest protection. Crop losses from biotic stresses are likely to increase from future attempts to intensify agricultural production. These will include the use of varieties with higher yield potential, large-scale cropping with genetically uniform plants, reduced crop rotation and expansion of crops into marginal land. In addition, because of climate change many weeds, pests and diseases will reproduce faster and spread more widely causing significant yield losses over what is experienced today.

However, new scientific knowledge and modern technologies provide considerable opportunities, even for developing countries, to further reduce current yield losses and minimise the future effects of climate change on plant health. Continuously finding new cost-effective and environmentally sound solutions to improve control of pest and disease problems is critical to improving the health and livelihoods of the poor. The need for a more holistic and modernised IPM approach in low-income countries is now more important than ever before.

The efficacy of pest control strategies has changed in many regions. The use of pesticides has increased dramatically since the early 1960s; in the same period also the yield average productivity in the production of wheat, rice and maize, the major sources for human nutrition, has more than doubled. The intensity of pest control has increased sometimes dramatically, e.g. in Asia and Latin America, where the use of pesticides increased well above the global average (McDougall, 2010). There are new compounds available that are highly effective against pests which were formerly less controllable. Importantly, better training of farmers and advisors by governmental and non-governmental organisations has contributed to an improvement in pest control in recent decades. In large parts of Asia and Latin America great advances have been made in the education of farmers, whereas the situation is still poor in Sub-Saharan Africa and has worsened in the countries of the former Soviet Union because of the lack of resources.

The EC Directive 2009/128/EC on the sustainable use of pesticides establishes a framework to achieve a sustainable use of pesticides by reducing the risks and impacts of pesticide use on human health and the environment and promoting the use of IPM and alternative approaches or techniques such as non-chemical alternatives to pesticides. Each Member State government needs to prepare an action plan which covers measures such as compulsory testing of application equipment, certification of operators, distributors and advisors, banning aerial spraying, protecting the aquatic environment, public spaces and conservation areas and minimising risk to human health and the environment. Member States should ensure that the appropriate decision support systems are in place to support plant protection (i.e. decision support systems and advisory services) as users must not simply record that they have used a pesticide, but also why they have used it on that particular occasion. Member States should set up a system for training of advisors and distributors if this does not currently exist, and all Member States should implement the Directive by 14 December 2011 by means of national laws. National governments can define the appropriate record keeping and reporting systems.

In conclusion, the global situation on pest problems and the relative effectiveness of the methods used to control them strongly suggests that unilateral control strategies such as chemical pesticides are unlikely to provide sustainable solutions to pest problems. Such observations also provide a warning to those who put much hope on single biotechnology approaches. Therefore, the global situation with pests and the methods used to control them underlines the need to develop and implement IPM on the broadest possible level.

Cost and benefit of pesticides

The costs of pesticides and nonchemical pest-control methods alike are low relative to crop prices and total production costs. Pesticides account for about 7-8% of total farm production costs in the EU (Figure 5). However, there is wide variation among member states fluctuating between 11% in France and Ireland and 4% in Slovenia (EUFADN, 2010). Pesticide use was relatively low in the new Member States prior to EU-accession. Pesticides account for 5-6% of total farm input in the USA (USDA, 2010).

Figure 5: Share of crop protection cost in total input (EU)

Source: EUFADN Database (2010) and own calculations.

EU farmers spend on average 90-100 euro per hectare of field crops on pesticides but there is wide variation among Member States (Figure 6). In 2008 farmers in the Netherlands spent 329 and in Estonia only 25 euro a hectare. Crop protection cost per hectare has increased in the new Member States following EU accession.

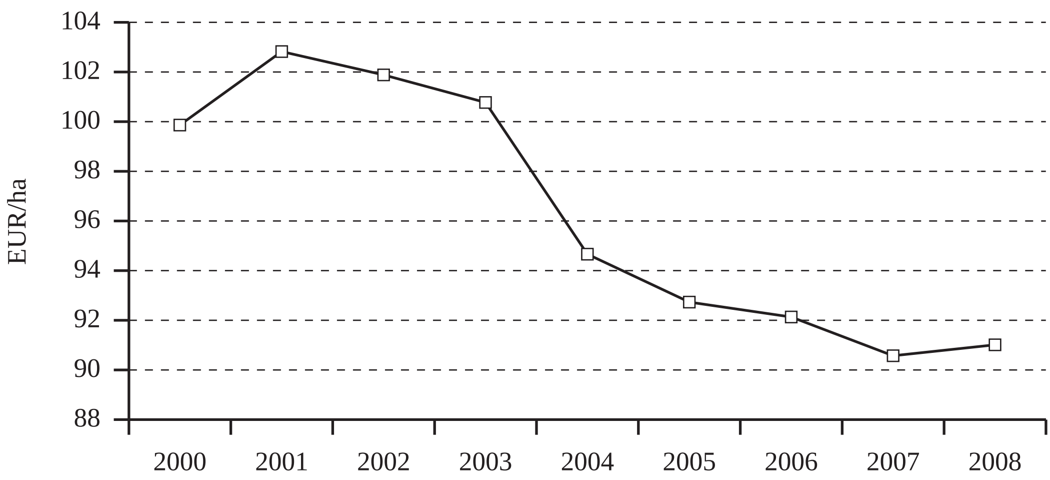

Figure 6: Crop protection cost in the EU

Source: EUFADN Database (2010) and own calculations.

The average cost of pesticides for all treated crop hectare in the U.S. was around USD 270 for the period 2002-2008 (Gianessi and Reigner, 2005, Gianessi and Reigner, 2006, Gianessi, 2009). Another rough calculation, with lots of assumptions and guesswork, is to divide recent USDA survey estimates of farm pesticide expenditures by crop land acres harvested. But the expenditure surveys summarise pesticide costs for all uses on the farm including livestock, pasture land, idled cropland and cropland planted but not harvested. In 2009 annual expenditures for all pesticides were about USD 11.5 billion and crop acres harvested was about 340 million which implies about USD 34 an acre. It is known that much of the small grains (wheat, barley, oats etc.) acreage is not treated with any pesticides. Even at 300 million acres, that implies about USD 38 an acre or USD 95 a hectare. Pesticides account for about 5-6% of total farm production costs in the USA (USDA, 2010). Using other assumptions one can derive different ratios. However, there is wide variation in pesticide cost among commodities. For example, fruit and vegetable as well as cotton and rice production costs are much higher (USD 170-290/ha) than those of wheat, barley, soybean and maize production (USD 25-70/ha). Application costs are included in estimated pesticide costs. The increasing reliance on GMO seeds (e.g. herbicide resistant seed and seed with Bt traits for insect control) have shifted some of the costs from pesticides to seed especially for soybeans, corn and cotton.

There are many kinds of benefits that may be attributed to pesticides. The most obvious and easiest to calculate are economic benefits derived from the protection of commodity yield and quality, and the reduction of other costly inputs such as labour and fuel. These benefits can accrue to a variety of different recipients, such as farmers and other users of pesticides, the marketplace, consumers and society. Other kinds of benefits include the maintenance of aesthetic quality, the protection of human health from disease-carrying organisms, the suppression of nuisance-causing pests and the protection of other organisms, including endangered species, from pests.

When reliable commodity loss data are available, monetary benefits are relatively easy to calculate from current market statistics and economic theory. In this sort of analysis, benefits are equated with the potential value of the commodity that is lost because the pesticide is not used. This approach to analysing benefits is realistic only if no other methods of reducing commodity losses are available. While this is rarely the case for any pesticide, the analysis commonly employed in pesticide risk/benefits analyses does not consider other methods of reducing crop or other losses. Non-monetary benefits are more difficult to calculate. Policy makers have long wrestled with how to put USD-based values on such things as aesthetic quality, the survival of certain endangered species, and peace of mind. In practice, such non-market benefits are rarely considered by policy makers to be as important as benefits that can be measured in the marketplace and hence they are generally simply ignored.

Furthermore, the practice of using yield data from plants grown with and without a pesticide to determine the economic impact of banning that pesticide is certainly not realistic. Farmers and other resource managers will not simply stand by and do nothing if a specific pesticide is eliminated as an option. They are necessarily resourceful and will make adjustments to maximise their economic gain. Possible adjustments include adopting IPM, altering cropping practices, shifting to resistant varieties or alternative crops, or utilising new markets, such as those for organic produce. All of these possibilities should be incorporated into various reasonable alternatives that can be objectively evaluated for both economic and non-market benefits.

Loss data, including the importance of pests, key pests and their control and use of pesticides, are a prerequisite to the economic management of pests and for evaluating the efficacy of present crop protection practices. Based on these data, strategies for the use of limited resources may be developed in order to optimise productivity. Assessments of crop losses despite actual crop protection strategies are required to demonstrate where action is needed and for decision making. Overall, farmers have sound economic reasons for using pesticides on crop land. Despite of the yearly investments of nearly USD 40 billion worldwide pests cause an estimated 35% actual loss (Oerke, 2006). The value of this crop loss is estimated to be USD 2000 billion per year, yet there is still about USD 5 return per dollar invested in pesticide control (Pimentel, 2009).

Detailed pesticide benefit analyses have been made mainly in the United States. In the late 1990s, growers in the USA could expect a USD 4 return for each dollar they spent on agricultural pesticides (Fernandez-Cornejo *et al.*, 1998). However, when all the indirect costs for pesticides were considered, there was only a USD 2 return to society at large for each dollar that growers spent on pesticides (Pimentel and Greiner, 1997). Later, the national pesticide benefit studies from the second half of the 2000s documented a huge net return of costs that growers spend on herbicides, insecticides, fungicides and their application. Research covered fifty crops, including 5-10 crops for each state in the U.S.

U.S. farmers have sprayed herbicides on close to 90% of the nation's crop land acreage for the past thirty years. The value of the use of herbicides in 2005 is estimated to have been USD 16 billion in increased crop yields and USD 10 billion in reduced weed control costs totalling a herbicide non-use net income impact of USD 26 billion. Increased fuel and labour costs have made the costs of alternatives to herbicides higher. The aggregate cost of cultivation and hand weeding as replacements for herbicides increased to USD 16.8 billion, resulting in a net increase in weed control costs without herbicides to USD 10 billion in 2005. The value of the crops, which means the loss in production without herbicides, were worth USD 16 billion. Cost estimate consists of three components: cost of the product, cost of application, and premiums for use of herbicide tolerant soybean, corn, canola, rice and cotton seeds. Nationally, it is estimated that growers spent USD 4.4 billion on herbicide products in 2005. The total costs of herbicide application are estimated at USD 1.9 billion and the total premium for planting herbicide tolerant seed is estimated at USD 0.8 billion, which represents a total cost of USD 7.1 billion (Gianessi and Reigner, 2006). It gives a net return of USD 3.7 for every dollar that growers spend on herbicides and their application (Table 2).

Table 2

Value of herbicides, insecticides and fungicides in U.S. crop production

USD billion	Herbicides 2005	Insectisides 2008	Fungicides 2002	Total 2002-08
Cost to growers	7.1	1.2	0.9	9.2
Non-use cost increase	9.7	-	-	9.7
Yield benefit	16.3	22.9	12.8	52.0
Net benefit	26.0	21.7	12.0	59.7
Return ratio: benefit/cost (USD)	3.7	18.1	13.3	6.5

Source: Gianessi and Reigner (2005), Gianessi and Reigner (2006), Gianessi (2009) and own calculations.

Most fruit and vegetable crops have been sprayed with insecticides for over 100 years. The key insect pests that led to the initial use of insecticides remain as annual threats. In addition, new invasive crop-feeding insects arrive regularly. Insecticides are the chief means of controlling 90% of the major insect pests attacking crops in the U.S. Farmers sprayed insecticides at a cost of USD 1.2 billion in 2008 (Gianessi, 2009). Growers gained USD 22.9 billion in increased production value from the control of crop-feeding insects with insecticides. For every dollar spent on insecticides, farmers gain about USD 18 in increased production value (Table 3).

The fungicide benefit study identified net return rates of USD 13.3 for every dollar spent on fungicides and their application. Growers gained USD 12.8 billion in increased production value from the control of plant diseases with fungicides in 2002 spending USD 880 million on fungicides and their application (Table 3). If left untreated, yields of most fruit and vegetable crops would decline by 50% to 95% (Gianessi and Reigner, 2005).

According to the national pesticide benefit studies in the United States, USD 9.2 billion are spent on pesticides and their application for crop use every year. This pesticide use saves around USD 60 billion on crops that otherwise would be lost to pests. It indicates a net return of USD 6.5 for every dollar that growers spent on pesticides and their application (Table 3). However, the USD 60 billion saved does not take into account any of the negative effects that result from pesticide use because most benefits of pesticides are based only on direct crop returns.

Such assessments do not include the external costs associated with the application of pesticides in crops. The external costs of pesticides include: productivity loss (crops, animals), pollution costs (water, soil, air), environmental costs (biodiversity, wildlife), human health costs (acute, chronic), information costs (regulation, monitoring), dependency (resistance, loss of beneficals), and equity issues (failure of the polluter pays principle). Assessments of the external costs of chemical pesticides from several countries around the world show that many of these assessments are incomplete in the sense that not all of the important externalities have been included. For example in Germany over 50% of the estimated external costs arise from ground water contamination. In the U.S. the biggest monetary value for externalities was attributed to bird losses. Too few studies have been carried out in this area. Case studies on external costs of pesticides should be added, previous studies should be repeated, and meta-analysis of external costs should be carried out. Similarly, meta-analysis of the economics of using benefit and cost analysis should be carried out for comparison.

A well-documented analysis on environmental and economic costs of pesticide use found that pesticides indirectly cost the U.S. USD 8.1 billion a year (Table 3). This includes losses from increased pest resistance; loss of natural pollinators (including bees and butterflies) and pest predators; crop, fish and bird losses; groundwater contamination; harm to pets, livestock and public health (Pimentel *et al*., 1992). Who pays this cost? Of this USD 8.1 billion a year in indirect costs of pesticide use, users of pesticides in agriculture paid directly for only approximately USD 3 billion, which included problems arising from pesticide resistance, destruction of natural enemies and crop losses. Society eventually paid the remaining USD 5.1 billion in environmental public health costs (including through taxes, insurance costs, etc.).

These costs increased since 1992, when this study was made, and these are just U.S. figures; the worldwide costs are much higher. An obvious need for an updated and comprehensive study prompted another investigation of the complex of environmental costs resulting from pesticide usage (Pimentel, 2005). The second study estimates that the total indirect cost of pesticide use was around USD 9 billion in 2005. The major economic and environmental losses due to the application of pesticides in the U.S. were: public health, USD 1.1 billion a year; pesticide resistance in pests, USD 1.5 billion; crop losses caused by pesticides, USD 1.4 billion; bird losses due to pesticides, USD 2.2 billion; and groundwater contamination, USD 2.0 billion. Users of pesticides pay directly only about USD 3.4 billion, which includes problems arising from pesticide resistance, destruction of natural enemies and crop losses, and society pays the remaining USD 6.2 billion in environmental and public health costs. These are the costs of only the damage that can be estimated monetarily, and the cost figures result from economic valuations of essentially non-economic things like a human life, human health and pet's health (Table 4).

From a strictly cost/benefit approach, pesticide use is beneficial. However, the nature of the environmental and public health costs of pesticides has other trade-offs involving environmental quality and public health. Pesticides provide about USD 60 billion per year in saved U.S. crops, the environmental and social costs of pesticides to the nation total approximately USD 10 billion. But the estimated full environmental, public health and social costs might double the USD 10 billion figure to USD 20 billion per year, in addition to the USD 9.2 billion spent on application of these pesticides. Including the estimated full indirect environmental, public health and social costs associated with pesticides and the direct costs of pesticides to farmers the net benefit still accounts for USD 31 billion each year, showing a high profitability of pesticides. Each dollar invested in pesticide control returns at least USD 3 in protected crops (Table 3 and Table 4).

Table 3

Total estimated environmental and social costs from pesticide in the USA

USD mln/year

Impact	Cost, 1992	Cost, 2005
Public health impacts	787	1,140
Domestic animals deaths and contaminations	30	30
Loss of natural enemies	520	520
Cost of pesticide resistance	1,400	1,500
Honeybee and pollination losses	320	334
Crop losses	942	1,391
Fishery losses	24	100
Bird losses	2,100	2,160
Groundwater contamination	1,800	2,000
Government regulations to prevent damage	200	470
Total	**8,123**	**9,645**

Source: Pimentel et al. (1992), Pimentel (2005)

Biopesticide

Global sales of biopesticides are estimated to total around USD 1 billion annually, still small compared to the USD 38-40 billion in the worldwide pesticide market. Biopesticides are used most widely on specialty crops. Orchard crops hold the largest share of biopesticides use at 55%. Biopesticides are also used on non-food crops such as forage crops, as well field crops such as corn and soybeans. This class of products also has important applications outside of production agriculture in the areas of public health and forestry (Farm Chemical International, 2010). Some companies value the global biopesticide market at USD 700-900 million, while others say it is hard to quantify because of different definitions for what is considered a biopesticide. There is no up-to-date data on the market worldwide. It is always pegged at around 2% of the global crop protection market but the segment's market share is growing faster than conventional chemicals. Increasing demand for chemical-free crops and more organic farming has led to increased usage of biopesticides in North America and Western Europe (ICIS CBA, 2009).

Key factors in this growth include a larger overall investment in biopesticide R&D, a more established application of the IPM concept and increased area under organic production. Products not requiring registration and products which already have been registered have priority in the R&D of these companies. Big agricultural chemical companies will invest heavily in this area. The industry is very dynamic right now compared to a few years ago, looking for technology that complements what they already have or complements a segment that they are focused on. Several companies would bring more biological plant protection products into the European market if conditions for registration were more favourable; others prefer to focus on other geographical regions where the climate for this business is more favourable (North America, Asia).

Alliances of biopesticide companies with major agricultural chemical companies (Bayer and BASF) seem to be increasing. Other companies, such as US-based FMC, Japan's Arysta LifeScience, Switzerland's Syngenta, Israel's Makhteshim and US-based Monsanto, have their own development efforts in biopesticides through collaborations with smaller firms. Marrone Bio Innovations (MBI) has an exclusive licence with US-based chemical giant DuPont which provides them access to more than 20 proprietary natural product discoveries from DuPont's marine microorganism screen. DuPont's compounds and mixtures that are too complex for chemical synthesis often make good candidates for biopesticides. DuPont itself launched a new insect repellent active ingredient from the catmint plant *Nepeta cataria* in 2010. Another major agrochemical firm offering its own green pesticide, reduced-risk pesticides products is Dow AgroSciences. This product could very closely be considered to be a biopesticide but it has been registered under conventional pesticides.

Reduced-risk or green pesticides is a growing sector and companies are striving to discover new products for that market segment. While biopesticides may be safer than conventional pesticides, the industry is plagued by the lack of critical mass to effectively develop and market its products, as well as compete with multinational synthetic pesticide producers. The industry is composed mostly of small and medium sized enterprises and it is difficult for one company to fully and properly fund research and development, field development and provide the marketing services required to make a successful biopesticide company. Companies need to be clear in their objectives and allocate resources appropriately. Another problem is the lack of product stewardship. The industry is trying to become much better stewards of the technology so that people who use biopesticide products will be more confident and credible. The perception is changing but it is a slow process. Another challenge is the lack of innovative blockbuster products to the marketplace and the registration.

Efficacy testing is an issue in registration since efficacy testing could be 50% of registration costs for biologicals, but just 10% for chemicals. Chemicals can use quite small treatment plots, but biologicals need larger plots to achieve statistical significance because individual replicates are more variable. Efficacy trials also do not always work the first time, e.g. in one set of trials the pest was not present two times out of three. Biopesticides have an accelerated registration path in the US and could get to market in three or four years, versus eight to ten years for a synthetic pesticide, whereas in Europe, the times are six to eight years and eight to ten years respectively. Mutual recognition between the USA and the EU is another key issue in future development of the biopesticide area. The EU is supposed to have an internal market, which should help to overcome the problem of small market size.

While biopesticides are typically seen as an alternative to synthetic chemicals, some experts see biopesticides as complementary to conventional pesticides already on the market. Biopesticides can enhance and synergise synthetic chemical active ingredients and also fill unmet market needs. It is increasingly difficult to discover new chemical pesticides that meet all of today's environmental and safety requirements, so biopesticides can fill the market need for new active ingredients. Perhaps the single most important factor in the growth of the biopesticide market is advancements in biopesticide technology. Extensive and systematic research has resulted in enhancements to formulation, the ability to manufacture biopesticides through mass production, increased storage and shelf life capabilities, and improved application methods. Biopesticides can be added in a spray programme to reduce the amount of synthetics to their lowest label rate. Positioning biopesticide products as part of a low-chemical spray programme or in a tank mix alongside synthetics is an excellent way to reduce chemical load and manage resistance without sacrificing the efficacy conventional growers demand.

Conclusions

Chemical pesticides will continue to play a role in pest management for the foreseeable future, in part because the environmental compatibility of products is increasing – particularly with the growing proportion of reduced-risk pesticides being registered, and in part because competitive alternatives are not universally available. In many situations, the benefits of pesticide use are high relative to risks or there are no practical alternatives. Scientific advances and regulatory pressures have driven and continue to drive some of the more hazardous products from the marketplace. This trend has been promoted by regulatory changes that restricted use of older chemicals and by technological changes that lead to competitive alternative products. The novel chemical products that will dominate in the near future will most likely have a very different genesis from traditional synthetic organic insecticides; the number and diversity of biological sources will increase, and products that originate in chemistry laboratories will be designed with particular target sites or modes of action in mind. Innovations in pesticide delivery systems in plants promise to reduce adverse environmental impacts even further but will not eliminate them.

The correct use of pesticides can deliver significant socio-economic and environmental benefits in the form of safe, healthy, affordable food; contribute to secure farm incomes; and enable sustainable farm management by improving the efficiency with which we use natural resources such as soil, water and overall land use. Indeed, growing more from the same amount of land can help to protect biodiversity by ensuring that there is no further encroachment on wild spaces. Obviously, when pesticides are not used correctly, then the socio-economic and environmental benefits may not be realised and can in fact become a cost to society.

The new products share many of the problems that have been presented by traditional synthetic organic insecticides. For example, there is no evidence that any of the new chemical and biotechnology products are completely free of the classic problems of resistance acquisition, non-target effects and residue exposure. Genetically engineered organisms that reduce pest pressure constitute a “new generation” of pest-management tools but genetically engineered crops that express a control chemical can exert strong selection for resistance in pests. Thus, the use of transgenic crops will probably maintain, or even increase, the need for effective resistance-management programmes. Because pests will continue to evolve in response to pest controls, research needs to support development of pest-management tools that reduce selection pressure, delay selection for resistance and thus increase the life of chemical and other products. There remains a need for new chemicals that are compatible with ecologically based pest management and applicator and worker safety.

The best way forward for pest control is to maintain a diversity of tools for maximising flexibility, precision and stability of pest management. No single pest-management strategy will work reliably in all managed or natural ecosystems. However, chemical pesticides should not automatically be given the highest priority. Pesticides should be evaluated in conjunction with all other alternative management practices not only with respect to efficacy, cost and ease of implementation but also with respect to long-term sustainability, environmental impact and health. The most promising opportunity for increasing benefits and reducing risks is to invest in developing a diverse toolbox of pest management strategies that include safe products and practices that integrate chemical approaches into an overall, ecologically based framework to optimise sustainable production, environmental quality and human health.

Many biocontrol agents are not considered acceptable by farmers because they are evaluated for their immediate impact on pests (that is, they are expected to perform like pesticides). Evaluation of the effectiveness of biocontrol agents should involve consideration of long-term impacts rather than only short-term yield, as is typically done for conventional practices. Some biocontrol pathogens used against weeds might cause as little as a 10% reduction in fecundity, which might not be a visible result but has a major long-term effect causing population decline. Low-efficacy biocontrol agents alone might not be acceptable for pest management but, in combination with other low-efficacy measures, they could be preferable because they avoid the selection for resistance for that is associated with high-efficacy measures.

The general public has a critical function in determining the future role of pesticides in agriculture. Sometimes objections to pesticides are an issue of subjective preference even when scientific evidence cannot support the objections. In this case, banning a pesticide is not appropriate. It makes much more sense to establish a legal framework that enables organic and pesticide-free markets to emerge and prosper so that consumers can be given an informed choice between lines of products that vary with pest management. Consumer interest in food and other goods perceived as safe and healthy fuels the rapid growth of the organic-food market; at the same time, consumer use of pesticides in the home and on the lawn continues to grow.

The justifications of government intervention in the management of pest control include the need to address the externality problems associated with the human and environmental health effects of pesticides. Public goods are products and services to which people have free access for which they do not need to compete (free air is a pure public good, as is national defence). However, few incentives exist for efficient and environmentally sound pest control strategies. Introduction of incentives that would reduce the reliance on riskier pest control strategies and encourage the use of environmentally friendly strategies is likely to lead to increased efficiency in pesticide use. Such incentives as taxes and fees for the use of various categories of chemicals have been recommended, but because of user objections they might not always be politically feasible. Users might prefer subsidies to reduce pesticide loads but this policy may strain the public budget. Establishing regional pesticide targets and implementing them through tradable permits is a better solution that will achieve the same outcome.

There is underinvestment from a social perspective in private-sector research because companies will aim to maximise only what is called suppliers' surplus (difference between suppliers' income and their production costs) rather than the social surplus. Companies will compare their expected profits from their patented products resulting from research and will not consider the benefits to consumers and users. Publicly supported research, through the process of technology transfer, has become a source of economic growth in several countries. Another reason why public research might lead to innovations that elude the private sector is the different incentives that researchers in the private and public sectors face. For the most part, private sector researchers emphasise projects that improve existing product lines. The advancement of public researchers is affected by their publications in refereed journals, where novelty and originality have a premium. A further argument for public support of research is that much of the funding is allocated to institutions of higher education and used to train future scientists for the private sector. Availability of trained scientists will be a key to future innovation in pest management technologies. The public sector should also conduct research in areas that are pursued by the private sector to have the information and background for regulatory purposes. There is a need to educate legislators and the general public about ecologically based pest management in research and in practice.

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