Impact of Pesticide Productivity on Food Security

József Popp, Károly Pető, and János Nagy

Abstract The seven billion global population is projected to grow by 70 million per annum, increasing by 30 % to 9.2 billion in 2050. This increased population density is projected to increase demand for food production by 70 % notably due to changes in dietary habits in developing countries towards high quality food, e.g. greater consumption of meat and milk products, and to the increasing use of grains for livestock feed. The availability of additional agricultural land is limited. Furthermore, more agricultural land will be used to produce bio-based commodities such as bioenergy or fibre instead of food and feed. Thus, we need to grow food on even less land, with less water, using less energy, fertiliser and pesticide than we use today. Given these limitations, sustainable production at elevated levels is urgently needed. The reduction of current yield losses caused by pests are major challenges to agricultural production. This review presents (1) worldwide crop losses due to pests, (2) estimates of pesticide-related productivity, and costs and benefits of pesticide use, (3) approaches to reduce yield losses by chemical, as well as biological and recombinant methods of pest control, and (4) the challenges of the crop protection industry. However, as long as there is a demand for pesticide-based solutions to pest control problems and food security concerns, the externality problems associated with the human and environmental health effects of pesticides needs also to be addressed.

This chapter is an abridged version of the article Pesticide productivity and food security. A review. Agronomy for Sustainable Development: Volume 33, Issue 1 (2013), Page 243–255. DOI 10.1007/s13593-012-0105-x. Springer (Popp et al. 2013).

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E. Lichtfouse (ed.), *Sustainable Agriculture Reviews: Volume 13*,
Sustainable Agriculture Reviews 13, DOI 10.1007/978-3-319-00915-5_2,

Keywords Pest control • Pesticide use • Benefits • Externality • Crop protection industry

1 Introduction

The combined effect of the Green Revolution has allowed world food production to double in the past 50 years. From 1960 to present the human population has more than doubled to reach seven billion people. In 2050, the population is projected to increase by 30 % to about 9.2 billion (Fig. 1). Due to increasing global population and changing diets in developing countries towards meat and milk products demand for food production is projected to increase by 70 % (FAO 2009).

Globally, an average of 35 % of potential crop yield is lost to pre-harvest pests (Oerke 2005). In addition to the pre-harvest losses, food chain losses are also relatively high (IWMI 2007). Agriculture has to meet at a global level a rising demand for food, feed, fibre, bioenergy and other bio-based commodities, however, the provision of additional agricultural land is limited. Given these limitations, sustainable production and increasing productivity on existing land is by far the better choice (Fig. 2). Part of the key is also to avoid waste along the whole length of the food chain. Much of the increases in yield per unit of area can be attributed to more efficient control of (biotic) stress rather than an increase in yield potential.

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 (Popp 2011). Helping farmers lose less of their crops will be a key factor in promoting

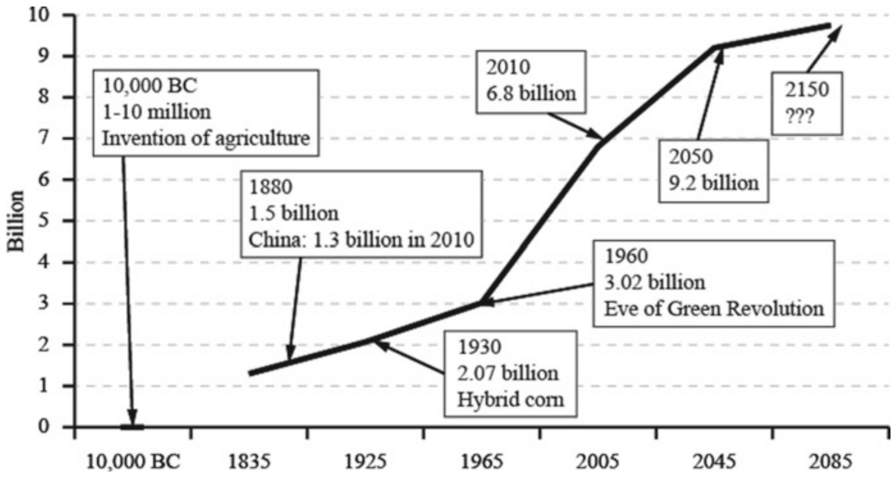

Fig. 1 World population growth. From 1960 to present the human population has more than doubled to reach seven billion people and in 2050, the population is projected to increase by 30 % to about 9.2 billion (Source: FAO 2009)

Fig. 2 Livestock food in the diet. Copyright: FAO/L.Rlung (FAO 2011)

food security. The beneficial outcome from 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 (National Research Council 2000).

Globally, agricultural producers apply around USD 40 billion worth of pesticides per annum. The market share of biopesticides is only 2 % of the global crop protection market (McDougall 2010). Farmers in highly developed, industrialised countries expect a four or five fold return on money spent on pesticides (Gianessi and Reigner 2005, 2006; Gianessi 2009). Can we meet world food demands if producers continue, increase or discontinue pesticide use because of reduced economic benefits? This is the greatest challenge facing scientists in history between now and the year 2050 (Popp 2011).

2 Crop Losses to Pests

An average of 35 % of potential crop yield is lost to pre-harvest pests worldwide (Oerke 2005). In addition to the pre-harvest losses transport, pre-processing, storage, processing, packaging, marketing and plate waste losses along the whole food chain account for another 35 % (Fig. 3). In addition to reduce crop losses due to pests avoiding waste along the whole length of the food chain is also key (Popp 2011). 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 chapter concentrates on pre-harvest losses, i.e. the effect of pests on

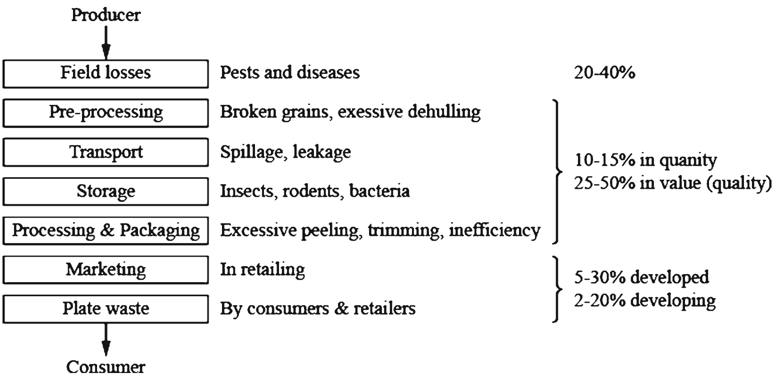

Fig. 3 Losses along the food chain. An average of 35 % of potential crop yield is lost to pre-harvest pests worldwide. In addition to the pre-harvest losses transport, pre-processing, storage, processing, packaging, marketing and plate waste losses along the whole food chain account for another 35 % (Source: IWMI 2007)

crop production in the field, and the effect of control measures applied by farmers in order to minimise losses to an acceptable level (Oerke 2005).

The assessment of crop losses 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 at seldom less than 10 % (Marlatt 1904).

Estimates of actual losses in crop production worldwide were updated for the period 1988–1990 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 70 % of crop yields could have been lost to pests (Oerke 2005).

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 1996–1998 on a regional basis for 17 regions (Oerke and Dehne 2004). Among crops the loss potential of pests worldwide varied from less than 50 % (on barley) to more than 80 % (on 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 (Oerke and Dehne 2004).

Table 1 Estimates of actual crop losses due to pests in worldwide production of wheat, maize and cotton

		Actual loss (%)			
Period	Yield (kg/ha)	Weeds	Animal pests	Diseases	Total
Wheat					
1964/1965[a]	1,250	9.8	5.0	9.1	23.9
1988–1990[b]	2,409	12.3	9.3	12.4	34.0
1996–1998[c]	2,610	9.0	8.0	12.0	29.0
2001–2003[d]	2,691	7.7	7.9	12.6	28.2
Maize					
1964/1965[a]	2,010	13.0	12.4	9.4	34.8
1988–1990[b]	3,467	13.1	14.5	10.8	38.3
1996–1998[c]	4,190	10.0	10.0	10.0	30.0
2001–2003[d]	4,380	10.5	9.6	11.2	31.2
Cotton					
1964/1965[a]	1,029	4.5	11.0	9.1	24.6
1988–1990[b]	1,583	11.8	15.4	10.5	37.7
1996–1998[c]	1,630	7.0	12.0	10.0	29.0
2001–2003[d]	1,702	5.6	12.3	7.9	28.8

Source: Cramer (1967), Oerke et al. (1994), Oerke and Dehne (2004), and Oerke (2005) and own calculations

Worldwide estimates for losses to pests in 1996–1998 and 2001–2003 differ significantly from estimates published earlier

[a]From Cramer (1967)

[b]From Oerke et al. (1994)

[c]From Oerke and Dehne (2004)

[d]From Oerke (2005)

Since the early 1990s, production systems and especially crop protection methods have changed significantly, especially in crops like 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 have been updated most recently by Commonwealth Agricultural Bureaux International'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's Crop Protection Compendium 2005; Oerke 2005). 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.

Worldwide estimates for losses to pests in 1996–1998 and 2001–2003 differ significantly from estimates published earlier (Cramer 1967; Oerke et al. 1994). Obsolete information from old reports has been replaced by new data. Alterations in the share of regions differing in loss rates in total production worldwide are also responsible for differences (Table 1). 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 (Yudelman et al. 1998). above the global average (Yudelman et al. 1998).

3 Estimates of Pesticide-Related Productivity

The use of pesticides has increased dramatically since the early 1960s; in the same period also the yield average of wheat, rice and maize, the major sources for human nutrition, has more than doubled. Without pesticides, food production would drop and food prices would soar. Where overall crop productivity is low, crop protection is largely limited to some weed control and actual losses to pests may account for more than 50 % of the attainable production (Oerke 2005). Use patterns of pesticides vary with crop type, locality, climate, and user needs. Plant disease can be devastating for crop production, as was tragically illustrated in the Irish potato famine of 1845–1847. This disaster led to the development of the science of plant pathology (Agrios 1988). From the time when synthetic pesticides were developed after World War II, there have been major increases in agricultural productivity accompanied by an increase in efficiency, with fewer farmers on fewer farms producing more food for more people.

Ensuring the safety and quality of foods and the increase in crop loss was accompanied by a growth in the rate of pesticides use. The annual global chemical-pesticide market is about three million tonnes associated with expenditures around USD 40 billion (Popp 2011). The growing dependence on chemical pesticides has been called the "pesticide treadmill" by entomologists (Bosch 1978). A major factor in the "pesticide treadmill" involves two responses to pesticide resistance. The first is to increase the dose and frequency of use of the less effective pesticide; this typically results in higher levels of pest resistance and damage to natural enemies and the environment. The second response is to develop and commercialise a new pesticide. The treadmill concept assumes that this two-step process will continue until the pest meets a resistance-proof pesticide or until the supply of effective new pesticides is exhausted. The greater the impact of control measures on pest populations, the more extreme are their evolutionary responses. However, the moderate rates in yield increase in the major world crops during 1965–2000 did not offer a strong case for a high increase in pesticide use even taking into account the fair amount of change in the cropping systems of developing countries with an expansion of the fruits and vegetable sector (FAO 2000).

Pesticide productivity has been estimated in three general ways: with partial-budget models based on agronomic projections, with combinations of budget and market models, and with econometric models. The most widely cited studies on pesticide productivity, those of Pimentel (Pimentel et al. 1978, 1991, 1992), Cramer (1967) and Knutson et al. (1993) use partial-budget models. One of these studies (Pimentel et al. 1991) estimates that aggregate crop losses amounted to 37 % of total output in 1986, up from 33 % in 1974. In comparison, Cramer (1967) estimated crop losses of around 28 % due to all pests in all of North and Central America. Estimates of crop losses at 37 % are questionably high. Crop losses of the magnitude estimated by Pimentel et al. (1991) should be sufficient to make it profitable to use chemical pest controls at much greater rates than observed today.

Other studies have attempted to estimate pesticide related effects of large reductions in pesticide use by combining partial-budget models with models of output markets (Zilberman et al. 1991; Ball et al. 1997). These studies use the same approach as partial-budget models in estimating yield and cost effects of changes in pesticide use. The productivity of pesticides – and thus the effects of reducing pesticide use – depends in large measure on substitution possibilities within the agricultural economy (Zilberman et al. 1991). In general, pesticide productivity will tend to be low in situations where substitution possibilities are large. Real prices of energy and durable equipment have fallen relative to agricultural chemical prices (Ball et al. 1997). On the other hand the prices of hired and self-employed labour have risen steadily, both in real terms and relative to agricultural chemical prices, and this suggests that labour-intensive pest-control methods have become less attractive relative to pesticide use. Zilberman et al. (1991) estimated that every dollar increase in pesticide expenditure raises gross agricultural output by USD 3–6. Most of that benefit is passed on to consumers in the form of lower prices for food.

Econometric models capture all forms of substitution in production, including short-term and long-term substitutes for pesticides on individual farms and at the regional and national levels. Headley (1968) estimated such a model by using state-level cross-sectional data in the US for the year 1963. He used crop sales to measure output and expenditures on fertilisers, labour, land and buildings, machinery, pesticides and other inputs as measures of input use and found that an additional dollar spent on pesticides increased the value of output by about USD 4 showing a high level of productivity for that period. The Headley model generates estimates of the marginal productivity associated with pesticides, that is, the additional amount (value) of output obtained by using an additional unit of pesticides. Multiplying the marginal productivity of pesticides by the quantity of pesticides used thus understates the total value added by pesticides (Pimentel et al. 1992). Carrasco-Tauber and Moffitt (1992) applied this approach to state-level cross-sectional data on sales and input expenditures in the U.S. like those used by Headley (1968). Their use of sales as a dependent variable generated an implicit estimate of aggregate US crop losses in 1987 of 7.3 % at average pesticide use, far less than estimates of other studies (Pimentel et al. 1991; Oerke et al. 1994). Chambers and Lichtenberg (1994) developed a dual form of this model based on the assumptions of profit maximisation and separability between normal and damage-control inputs. Implicit crop losses in 1987 estimated from those models ranged from 9 % to 11 %, only about one quarter to one third of the size estimated by others (Pimentel et al. 1991; Oerke et al. 1994). Estimated crop losses with zero pesticide use ranged from 17 to 20 %.

4 Costs and Benefits of Pesticide Use

The economic analyses of pesticide benefits is hindered by the lack of pesticide use data and economic models for minor crops and non-agricultural pesticides. Cost-benefit analysis is increasingly used to assess resource management and environmental policies. The most commonly recognised economic incentives are based on the "polluter pays" principle, including the use of licensing fees, user fees or taxes. The experience of those countries (Denmark, Sweden and Norway) that have introduced these taxes is that they appear to have played some role in reducing pesticide use. However, their price elasticity estimates are low and this suggests comparatively little effect in terms of quantity reductions, unless they are set at very high rates relative to price. There is some suggestion that revenue recycling may have been more effective, with revenues redirected to research and information. Using revenues to further research or encourage changes in farming practice would appear to make more sense (Pearce and Koundouri 2003).

Nevertheless, the "polluter pays" principle (i.e. adding the environmental and public health costs to the price paid by consumers) can be an effective approach to internalise the social costs of pesticide use. The fees and taxes generated can be used to promote improved (sustainable) pest management. In order to set the right level of levies and taxes, it may be necessary to calculate the negative impacts of pesticides. Various attempts have been made to determine the costs that relate to public health (risks to farm workers and consumers, and drift risk), and damage to beneficial species, and to the environment (Pimentel et al. 1992; Pimentel and Greiner 1997; Pimentel 2005). However, pesticides can result in a range of benefits including wider social outcomes with benefits being manifested in increased income and reduced risk, plus the ability to hire labour and provide employment opportunities. Other outcomes were the evolution of more complex community facilities, such as schools and shops, and improved health (Bennett et al. 2010).

The costs of pesticides and non-chemical 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. However, there is wide variation among Member States fluctuating between 11 % in France and Ireland and 4 % in Slovenia (Popp 2011). Pesticides account for 5–6 % of total farm input in monetary terms in the USA (USDA 2010).

Overall, farmers have sound economic reasons for using pesticides on crop land. The global chemical-pesticide market is about three million tonnes associated with expenditures around USD 40 billion in a year. As a result of the increasing use of GM herbicide tolerant and insect resistant crop seed and sales of agrochemicals used in non-crop situations (gardening, household use, golf courses, etc) the value of the overall crop protection sector is estimated to reach about USD 55 billion. The increasing sale of GM seeds has had a direct impact on the market for conventional agrochemical products (McDougall 2010). In spite of the yearly investments of nearly USD 40 billion worldwide, pests cause an estimated 35 %

Table 2 Value of herbicides, insecticides and fungicides in U.S. crop production

USD billion	Herbicides 2005	Insecticides 2008	Fungicides 2002	Total 2002–2008
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, 2006), Gianessi (2009) and own calculations
In the US. pesticide use saves around USD 60 billion on crops that otherwise would be lost to pest destruction indicating a net return of USD 6.5 for every dollar that growers spent on pesticides and their application

actual loss (Oerke 2005). The value of this crop loss is estimated to be USD 2,000 billion per year, yet there is still about USD 5 return per dollar invested in pesticide control (Pimentel 2009).

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 (Gianessi and Reigner 2005, 2006; Gianessi 2009). This pesticide use saves around USD 60 billion on crops that otherwise would be lost to pest destruction. It indicates a net return of USD 6.5 for every dollar that growers spent on pesticides and their application. However, the USD 60 billion saved does not take into account the external costs associated with the application of pesticides in crops (Table 2).

Obviously, when pesticides are not used correctly, then the socio-economic and environmental benefits may not be realised and the economic damage resulting from widespread pesticide use should also be highlighted. The environmental and public health costs of pesticides necessitate the consideration of other trade-offs involving environmental quality and public health when assessing the net returns of pesticide usage. Pimentel (2005) found that pesticides indirectly cost the U.S. USD 9.6 billion a year including losses from increased pest resistance; loss of natural pollinators (including bees and butterflies) and pest predators; crop, fish and bird losses; groundwater contamination; and harm to pets, livestock and public health. Should the past assessments of environmental and social impact be narrow and should they be broadened to USD 20 billion per year the previous estimate of USD 60 billion worth of production benefits to the U.S. from pesticide use would be lower (USD 40 billion) if net effects are considered. However, the net benefit still shows a high profitability of pesticides indicating a net return of USD 3 for every dollar spent on pesticides (Popp 2011).

Genetically engineered organisms that reduce pest pressure constitute a "new generation" of pest-management tools. Biotechnology has delivered economic and environmental gains through a combination of their inherent technical advances and the role of the technology in the facilitation and evolution of more cost effective and environmentally friendly farming practices.

5 Biopesticides and Integrated Pest Management

Biopesticides offer important social benefits, as compared with conventional pesticides. Yet in an agricultural industry that is still dominated by pesticides, biological control has found its place in the form of augmentative releases, particularly for the management of pests that are difficult to control with insecticides. There has been a strong tendency to consider biopesticides as “chemical clones” rather than as biological control agents, and therefore the chemical pesticide model has been followed. On the other hand, regulation of biopesticides is needed because being “natural” does not mean it is safe. However, the challenge of new and more stringent chemical pesticide regulations, combined with increasing demand for agriculture products with positive environmental and safety profiles, is boosting interest in biopesticides. It takes an average of 3–6 years and USD 15–20 million to develop and register a biopesticide compared with 10 years and USD 200 million for synthetic pesticides (REBECA 2007). Many of the major pesticide manufacturers are jumping into the biopesticide industry (Fig. 4).

Global sales of biopesticides are estimated to total around USD 1 billion, still small compared to the USD 40 billion in the worldwide pesticide market. It is pegged at around 2 % of the global crop protection market (Popp 2011). While biopesticides may be safer than conventional pesticides, the industry is composed mostly of small to medium sized enterprises and it is difficult for one company to fully and comprehensively fund research and development, field development and provide the marketing services required to make a successful biopesticide company. Another challenge is the lack of innovative biopesticide products coming to the marketplace and their registration (Farm Chemical Internationals 2010).

Fig. 4 Landscape in Hungary (Copyright: Popp 2012)

During the past two decades, IPM (Integrated Pest Management) programmes have reduced pest control costs and pesticide applications in fruit, vegetable and field crops. For farmers, very often the main benefit of IPM is the avoidance of uneconomical pesticide use. However, a large part of the benefits are reduction of externalities and therefore occur to other groups. This poses considerable measurement and valuation problems. Although the IPM programmes did reduce pesticide use, most of the programmes still relied heavily on pesticides. The institutional environment for IPM at the global level has become more complex. For the pesticide market, liberalisation without effective regulations and adequate market-based incentives may lower the costs of supplying pesticides, but at the same time can increase the tendency for ineffective, inefficient and non-sustainable crop protection. For a system-wide programme on IPM to make a significant contribution, the policy and institutional environment of global crop protection cannot be ignored (Settle and Garba 2011).

The European Commission 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. Other provisions include compulsory testing of application equipment, training and certification of all professional users, distributors and advisors; a ban (subject to derogations) on aerial spraying; special measures to protect the aquatic environment, public spaces and conservation areas; minimizing the risks to human health and the environment through handling, storage and disposal (Official Journal of the European Union 2009).

6 Challenges of the Global Pesticide Market

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. Liberalisation of input markets, often labelled as successful market reform, can lead to inefficient pesticide use and high external costs (FAO 2009). 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 important to point out that it is not only the big multinationals that are important players in pesticide policy but also the many new companies in developing countries who produce generics. A trend in agrichemical industry is the movement of many chemical pesticides off patent. As these chemicals become generic pesticides, manufacturers lose their monopolies on them. Overall, generic companies make up about 30 % of total sales (McDougall 2010). Rising sales of generic pesticides, especially in countries in Africa and Latin America but also in some Asian countries, is often facilitated by weak regulatory control and the lack of an IPM oriented national policy framework countries (FAO 2009).

Around 30 % of pesticides marketed in developing countries with an estimated market value of USD 900 million annually do not meet internationally accepted quality standards. They are posing a serious threat to human health and the environment. Such pesticides often contribute to the accumulation of obsolete pesticide stocks in developing countries (FAO 2009). Another negative economic consequence of a higher use of pesticides in developing countries is the loss of export opportunities for developing countries especially with horticultural crops as the developed countries are tightening maximum residue levels (FAO/WHO 2010).

Sustainable, IPM based on biological control is urgently needed, opening increasing possibilities for biopesticides. Their beneficial features include that they are often very specific, they are "inherently less toxic than conventional pesticides" compatible with other control agents, leave little or no residue, are relatively inexpensive to develop, and support the action of natural enemies in ecologically-based IPM.

As a result of the various merger and acquisition that have taken place, the agrochemical sector is relatively highly consolidated. An increasing number of merger and acquisition transactions have been targeted at strengthening the respective product portfolios of the purchasing company through the acquisition of a particular agrochemical product or product range. While product acquisitions have always been a feature of the agrochemical industry, the overall level of this type of merger and acquisition activity has increased significantly in the last 10 years (Mc Dougall 2010).

The total cost of agrochemical research and development expenditure in 2007 for 14 leading companies was 6.7 % of their agrochemical sales. Over the next 5 years it is expected that herbicides will lead market growth while the insecticides sector is likely to suffer further generic pressure and the fungicide sector is expected to grow relatively modestly with increases generated from a further expansion of the seed treatment sector. The GM crop sector is also expected to continue to move increasingly toward multiple trait stacked gene varieties, in both established and developing markets (McDougall 2010).

Industrial leaders expect that advances in genomics will lead researchers to the precise location and sequence of genes that contain valuable input and output traits. A shift in research and development resources from input to output traits probably would have a large impact on the future of plant protection. Will the cycle of innovation on the input side continue? Because of the high investment required for development of chemical pesticides and transgenic crops, will large agrichemical and life-science firms focus primarily on crops with large markets? Whether companies will develop pesticides and input traits for minor use crops remains an open question. These are the main questions research and development of plant protection is facing at present.

7 Conclusion

The main reasons why world food supply is tightening are population growth, accelerated urbanization and motorization, changes in diets and climate change. Furthermore, agricultural land is used to produce more bioenergy and other bio-based commodities. To meet the increasing world food demand the necessary production growth will to a large extent have to be met by a rise in the productivity of the land already being farmed today. However, this will be difficult to accomplish as global agricultural productivity growth has been in decline since the Green Revolution. In addition to the reduction of waste along the whole food chain priority has to be given to effective crop protection measures to cut further crop losses to pests.

Cost-benefit analyses are important tools for informing policy decisions regarding use of chemical pesticides. The impacts of pesticides on the economy, environment and public health are measured in monetary terms. However, there are many uncertainties in measuring the full array of benefits and costs of pesticide use. Making wise tradeoffs to achieve a fair balance between the risks that a community bears and the benefits that it receives is one of the most difficult challenges for policy-makers.

Chemical pesticides will continue to play a role in pest management because environmental compatibility of products is increasing and competitive alternatives are not universally available. Pesticides provide economic benefits to producers and by extension to consumers. One of the major benefits of pesticides is protection of crop quality and yield. Pesticides can prevent large crop losses, thus raising agricultural output and farm income. The benefits of pesticide use are high relative to risks. Non-target effects of exposure of humans and the environment to pesticide residues are a continuing concern. Side effects of pesticides can be reduced by improving application technologies. Innovations in pesticide-delivery systems in plants promise to reduce adverse environmental impacts even further but are not expected to eliminate them. The correct use of pesticides can deliver significant socio-economic and environmental benefits.

Genetically engineered organisms that reduce pest pressure constitute a "new generation" of pest-management tools. This change in production system has made additional positive economic contributions to farmers and delivered important environmental benefits. But genetically engineered crops that express a control chemical can exert strong selection for resistance in pests. Thus, the use of transgenic crops will even increase the need for effective resistance-management programmes.

Many biocontrol agents are not considered acceptable by farmers because they are evaluated for their immediate impact on pests. 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. The global sale of biopesticides is very small compared to the pesticide market. However, the market share of biopesticides is growing faster than that of conventional chemicals. Finding continuously 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.

Total investment in pest management and the rate of new discoveries should be increased to address biological, biochemical and chemical research that can be applied to ecologically based pest management. There is underinvestment from a social perspective in private-sector research because companies will aim to maximise only what is called suppliers' surplus. Transmission of knowledge in the past was the responsibility mostly of the public sector, but it has become more privatised. 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 by emphasising systems-based interdisciplinary research.

Acknowledgements This chapter was made with the support of the Hungarian Development Agency for the research project TECH_09-A3-2009-0227. We gratefully acknowledge Dr. Andrew Fieldsend for his accurate comments and his careful English language reviewing.

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http://www.springer.com/978-3-319-00915-5

Sustainable Agriculture Reviews
Volume 13
Lichtfouse, E. (Ed.)
2014, V, 315 p.,
ISBN: 978-3-319-00915-5