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CENTENARY REVIEW

Crop losses to pests

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SUMMARY

Productivity of crops grown for human consumption is at risk due to the incidence of pests, especially weeds, pathogens and animal pests. Crop losses due to these harmful organisms can be substantial and may be prevented, or reduced, by crop protection measures. An overview is given on different types of crop losses as well as on various methods of pest control developed during the last century.

Estimates on potential and actual losses despite the current crop protection practices are given for wheat, rice, maize, potatoes, soybeans, and cotton for the period 2001–03 on a regional basis (19 regions) as well as for the global total. 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. Overall, weeds produced the highest potential loss (34 %), with animal pests and pathogens being less important (losses of 18 and 16 %). The efficacy of crop protection was higher in cash crops than in food crops. Weed control can be managed mechanically or chemically, therefore worldwide efficacy was considerably higher than for the control of animal pests or diseases, which rely heavily on synthetic chemicals. Regional differences in efficacy are outlined. Despite a clear increase in pesticide use, crop losses have not significantly decreased during the last 40 years. However, pesticide use has enabled farmers to modify production systems and to increase crop productivity without sustaining the higher losses likely to occur from an increased susceptibility to the damaging effect of pests.

The concept of integrated pest/crop management includes a threshold concept for the application of pest control measures and reduction in the amount/frequency of pesticides applied to an economically and ecologically acceptable level. Often minor crop losses are economically acceptable; however, an increase in crop productivity without adequate crop protection does not make sense, because an increase in attainable yields is often associated with an increased vulnerability to damage inflicted by pests.

INTRODUCTION

Since the beginnings of agriculture about 10 000 years ago, growers have had to compete with harmful organisms – animal pests (insects, mites, nematodes, rodents, slugs and snails, birds), plant pathogens (viruses, bacteria, fungi, chromista) 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). The scope of the present 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

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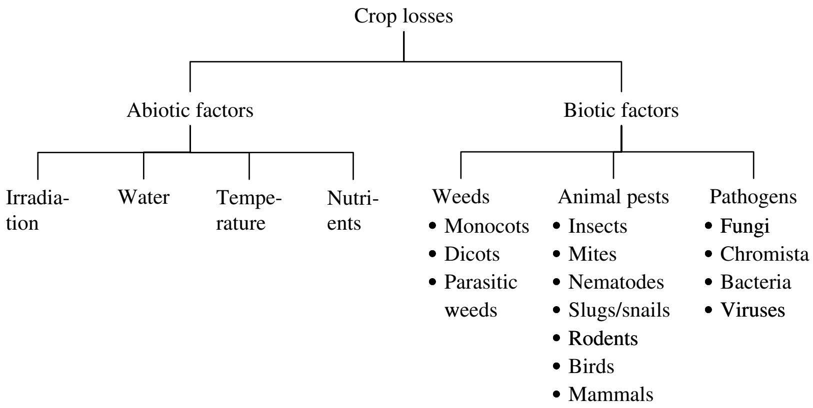

Fig. 1. Abiotic and biotic factors causing crop losses.

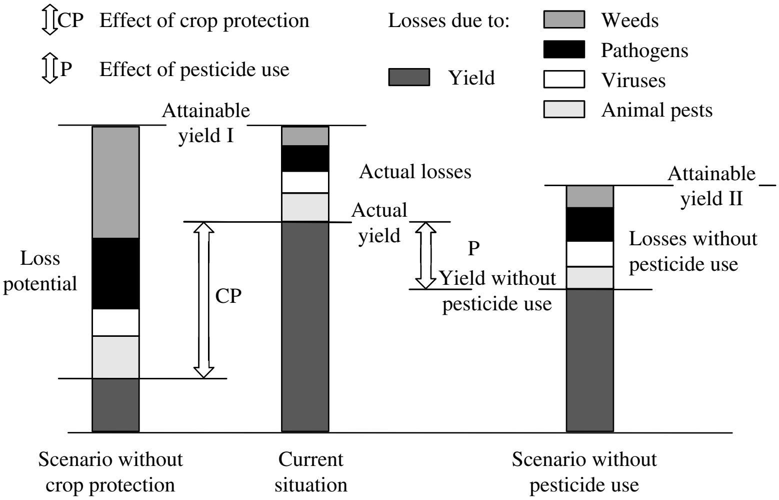

Fig. 2. Crop losses and yield levels.

minimize losses to an acceptable level. Loss data are the prerequisite for economic management of pests and for evaluating the efficacy of the present crop protection practices. Based on these data, strategies for the use of limited resources may be developed in order to optimize productivity (Nutter *et al.* 1993; Cooke 1998).

Estimates of actual losses in crop production worldwide have been published by Cramer (1967) and Oerke *et al.* (1994). Since crop production technology and especially crop protection methods are changing, loss data for major food and cash crops have been updated for the period 2001–03 (see also CABI's Crop Protection Compendium Online, http://www.cabicompendium.org/cpc/aclogin.asp?/cpc/economic.asp?).

CROP LOSS TYPOLOGY AND CROP LOSS ASSESSMENT

Crop losses may be caused by abiotic and biotic environmental factors, leading to the reduction of crop performance and resulting in a lower actual yield than the site-specific attainable yield/production of crops (Figs 1 and 2). The attainable yield is defined as the site-specific technical maximum, depending on abiotic growth conditions, which in general is well below the yield potential, a rather theoretical yield level that cannot be realized under practical growth conditions.

Pests reduce crop productivity in various ways; according to Boote *et al.* (1983) pests can be classified by their impacts, into the categories stand reducers (damping-off pathogens), photosynthetic rate reducers (fungi, bacteria, viruses), leaf senescence accelerators (pathogens), light stealers (weeds, some pathogens), assimilate sappers (nematodes, pathogens, sucking arthropods), and tissue consumers (chewing animals, necrotrophic pathogens). Weeds affect crop productivity especially due to the competition for inorganic nutrients.

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 loss rate may be expressed as the proportion of attainable yield (the preferred method of calculation) but sometimes the proportion of the actual yield is calculated. 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 (fertilization, irrigation, cultivars, etc.) in a no-loss scenario (Fig. 2). Actual losses comprise the crop losses sustained despite the crop protection practices employed. The calculation of total loss rates for loss potential and actual losses has been described earlier (Oerke *et al.* 1994). 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 fertilizer use, etc. – and often associated with a reduced attainable yield.

According to Zadoks & Schein (1979), various loss levels may be differentiated, e.g. direct and indirect losses, or primary and secondary losses, indicating that pests not only endanger crop productivity and reduce the farmer's net income, but may also affect the supply of food and feed as well as the economies of rural areas and even countries. Teng (1987) summarized the methodology of crop loss assessment.

DEVELOPMENTS IN PEST CONTROL

Pests have reduced the productivity of crops since the dawn of agriculture, and farmers have been looking for ways of protecting their crops from these organisms. At first, control of weeds and animal pests largely depended on hand or mechanical weeding and hand-picking of insect larvae, respectively. Diseases caused by microscopic organisms were hardly perceived as pest-related and control options were limited to the use of land races adapted to local growth conditions. However, the first use of insecticides and fungicides, e.g. sulphur compounds and botanicals, were recorded by the Sumerians and the Chinese 2500–1500 BC.

The evolution in fungicidal compounds has been reviewed recently by Russell (2005). Chemical disease control started more than a century ago with the use of inorganic chemicals such as copper, sulphur and organic mercury, the first generation of fungicides. Bordeaux mixture has been used for the control of powdery and downy mildew since 1885. Mercury organic seed dressings for the control of seed-borne diseases were developed early in the twentieth century followed by the development of the first dithiocarbamate fungicides and organotins in the 1930s. This second generation of fungicides included organic chemicals acting as surface protectants. Third-generation fungicides (benzimidazoles, phenylamides, azoles, morpholines, etc.) are systemic in plants, penetrate the tissue and are able to control established infections in a curative way – a prerequisite for threshold-oriented fungicide application. In 1966, the systemic fungicide ethirimol was released for the control of powdery mildew in cereals. The target specificity of systemic fungicides is often linked to the risk for the development of fungicide resistance in fungal populations as exemplified by the strobilurins – the latest major chemical class introduced into the market in the 1990s (Russell 2005). The practical use of chemical resistance inducers that enhance resistance mechanisms intrinsic to the plant and that interfere with the fungal infection process (de Waard *et al.* 1993) is restricted to some special applications.

There is a long tradition of using synthetic insecticides and acaricides to control arthropod pests. The high frequency of application of insecticides has often resulted in the emergence of insects and mites resistant to the active ingredient. The only way to prevent or to delay the emergence of resistance is to switch to compounds with other modes of action and to use integrated pest control strategies, which include the protection of beneficial organisms.

In 1942, discovery of the insecticidal activity of chlorinated hydrocarbons like DDT and lindane, the first-generation synthetic insecticides, gave rise to a new era of insect control in agriculture, horticulture, stored products, and public health. Together with organophosphorus compounds they replaced inorganic compounds and are still in use in some areas; however, the use has been restricted or banned because of their persistence and possible adverse effects (Schumann 1991).

Although declining in importance, acetylcholinesterase inhibitors (organophosphates and carbamates) and pyrethroids account for about 0·7 of the world market (Nauen & Bretschneider 2002). The first synthetic pyrethroid was introduced in 1976. Neonicotinoids, $GABA_A$-receptor ligands and insect growth regulators (e.g. benzoylureas) have been important new introductions into the insecticide market in recent times. Biological products often contain the bacterium *Bacillus thuringiensis*, which has an antagonistic activity by producing a toxic metabolite after uptake especially into Lepidoptera, Coleoptera and Diptera.

The introduction of herbicides has dramatically changed production in many crops. The first chemicals used for weed control were the inorganic copper salts in the early 1900s and sulphuric acid some time later (Hamill *et al.* 2004). The development of 2,4-D and MCPA, which were first commercialized in the 1940s, revolutionized weed control in cereals. Herbicides increasingly replaced the labour-intensive mechanic weed control and enabled machine-harvesting of crops. The first class of selective herbicides were the hormone-type herbicides with 2,4-dichlorophenoxyacetic acid introduced in 1942. Since World War II, a great number of herbicidal ingredients have been marketed and the application rate of modern selective compounds like sulphonylureas and imidazolinones is very low. Today, more than 180 selective herbicides are in use (Zimdahl 1999).

In 1972 the first *Bacillus thuringiensis* insecticide was released for the control of lepidopterous pests. To the present day, biological control of arthropod pests and plant pathogens using antagonistic organisms is largely restricted to greenhouses, which have only a very small percentage of the production area. Natural enemies include insect parasites, arthropod predators and pathogens. According to a broader understanding of biocontrol, the use of resistant varieties is a most successful example.

In 1995, the first Bt crops were approved by the United States Environmental Protection Agency (EPA). Transgenic herbicide-resistant crops, e.g. soybean, maize, oilseed rape, were introduced in the Americas in the mid-1990s and now account for a large acreage in the Americas and Asia. In 2004, transgenic soybean occupied 48·4 M ha (0·6 of global biotech area), followed by transgenic maize, Bt cotton and herbicide-resistant oilseed rape (James 2004). In 1998, the first transgenic horticultural crop, papaya resistant to Papaya ringspot virus, was released in Hawaii (Goncalves *et al.* 1998).

The aim of further developments in crop protection is Integrated Crop Management which may be defined as the economical production of high quality crop, giving priority to ecological safe methods of crop cultivation, minimizing the undesirable side effects and use of crop protection products (Dehne & Schönbeck 1994). Effective crop protection cannot rely solely on the use of chemical pesticides and as early as 1959, Stern *et al.* introduced the concepts of economic thresholds, economic levels and integrated control (Stern *et al.* 1959). Integrated Crop Management is the basis for sustainable agriculture, a production system which may be used continuously for many years, is soundly based on the potential and within the limitations of a particular region, does not unduly deplete its resources or degrade its environment, makes best use of energy and materials, ensures good and reliable yields, and benefits the local population at competitive costs (Wood 1993).

ESTIMATES OF CROP LOSSES DUE 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. The generation of experimental data is time-consuming and laborious, 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 are needed for demonstrating where future action is needed and for decision making by farmers as well as at the governmental level (Smith *et al.* 1984).

Early reports

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, Marlatt (1904) estimated pre-harvest losses caused by insect pests at being seldom less than 10%. Later, the US 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 are outdated. More recently, Oerke *et al.* (1994) published loss estimates for eight major food and cash crops. Since the early 1990s, production systems 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.

Table 1. *Estimated loss potential of weeds, animal pests (arthropods, nematodes, rodents, birds, slugs and snails), pathogens (fungi, bacteria) and viruses, and actual losses due to pest groups in six major crops worldwide, in 2001–03*

Crop	Attainable production [M t]	Crop losses [%]^{1} due to									
		Weeds		Animal pests		Pathogens		Viruses		Total	
		Potential	Actual	Potential	Actual	Potential	Actual	Potential	Actual	Potential	Actual
Wheat	785·0	23·0 (18–29)	7·7 (3–13)	8·7 (7–10)	7·9 (5–10)	15·6 (12–20)	10·2 (5–14)	2·5 (2–3)	2·4 (2–4)	49·8 (44–54)	28·2 (14–40)
Rice	933·1	37·1 (34–47)	10·2 (6–16)	24·7 (13–26)	15·1 (7–18)	13·5 (10–15)	10·8 (7–16)	1·7 (1–2)	1·4 (1–3)	77·0 (64–80)	37·4 (22–51)
Maize	890·8	40·3 (37–44)	10·5 (5–19)	15·9 (12–19)	9·6 (6–19)	9·4 (8–13)	8·5 (4–14)	2·9 (2–6)	2·7 (2–6)	68·5 (58–75)	31·2 (18–58)
Potatoes	517·7	30·2 (29–33)	8·3 (4–14)	15·3 (14–20)	10·9 (7–13)	21·2 (20–23)	14·5 (7–24)	8·1 (7–10)	6·6 (5–9)	74·9 (73–80)	40·3 (24–59)
Soybeans	244·8	37·0 (35–40)	7·5 (5–16)	10·7 (4–16)	8·8 (3–16)	11·0 (7–16)	8·9 (3–16)	1·4 (0–2)	1·2 (0–2)	60·0 (49–69)	26·3 (11–49)
Cotton	78·5^{2}	35·9 (35–39)	8·6 (3–13)	36·8 (35–41)	12·3 (5–22)	8·5 (7–10)	7·2 (5–13)	0·8 (0–2)	0·7 (0–2)	82·0 (76–85)	28·8 (12–48)

[1] Figures in parentheses indicate variation among 19 regions.
[2] Seedcotton.

Potential and actual losses in major food and cash crops in 2001–03

Estimates on crop losses to pathogens (fungi, chromista, bacteria), viruses, animal pests, and weeds have been updated for six food and cash crops on a regional basis (for details see CABI Crop Protection Compendium, http://www.cabicompendium.org/cpc/aclogin.asp?/cpc/economic.asp?). Nineteen regions were specified according to the intensity of crop production and the production conditions: North Africa, West Africa, East Africa, Southern Africa; North America, Central America, Northern part of South America, Southern part of South America; Near East, South Asia, Southeast Asia, East Asia, Asian states of the CIS; Northwest Europe, Southern Europe, Northeast Europe, Southeast Europe, European part of the CIS; Oceania.

Wheat

Wheat is grown on all continents and is the most important cereal crop in the Northern hemisphere as well as in Australia and New Zealand. Major wheat producing countries are the PR China, India, the USA, France and Russia. In 2001–03, almost 564×10^{6} t of wheat were grown on $209{\cdot}4 \times 10^{6}$ ha (annual data from FAO 2005). With a worldwide average of 2690 kg/ha the yield per unit of area varied from less than 500 kg/ha to almost 8500 kg/ha in Ireland.

Weeds are the most important pest group in wheat production worldwide (Table 1). The incidence and impact of pathogens, especially *Blumeria graminis*, *Septoria* spp., and rust fungi, increase with the intensity of crop productivity (i.e. with attainable yield). In regions with low productivity, and without seed dressing, smuts and bunts are of greater importance. Soil-borne pathogens, e.g. *Tapesia* spp., *Gaeumannomyces graminis* and *Cochliobolus sativus*, are favoured by a high proportion of cereals in the crop rotation, with take-all and common root rot limiting productivity in some areas of North America and Australia. Arthropods, nematodes, rodents, birds or snails cause significant losses in some regions, whereas losses due to viruses are of minor importance worldwide. Estimates of the loss potential of

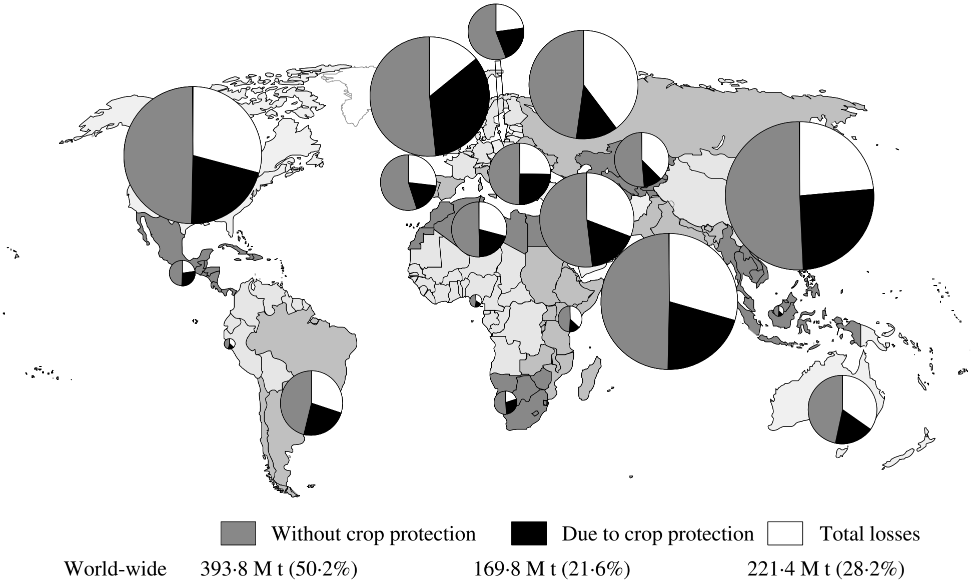

Fig. 3. Estimated contribution of actual crop protection (mechanical, biological, chemical) in safeguarding wheat production, by region, in 2001–03 (size of pies corresponds to attainable production).

pathogens, viruses, animal pests and weeds in wheat totalled 16, 3, 9, and 23 %, respectively (Table 1). In Western Europe, the loss potential of pathogens was as high as that of weeds under intensive production conditions, demonstrating the increasing importance of diseases with increases in productivity. Crop protection practices reduced the overall potential losses of 50 % to actual losses of about 29 %, comprised of 10 % to pathogens, 2 % to viruses, 8 % to animal pests and 8 % to weeds. Total actual losses varied considerably, with 14 % in Northwest Europe and 35 % or even more in Central Africa, Southeast Asia, CIS and Oceania (Fig. 3).

Rice

Rice production is largely concentrated in Asia, where it is considered to be the major food source. *Oryza sativa* is grown under different growth conditions with widely differing yield levels, with irrigated and non-irrigated lowland rice and dryland rice being most important. In West Africa *Oryza glaberrima* is also grown. In 2001–03, 583×10^6 t rice were produced on $149{\cdot}6 \times 10^6$ ha giving an average yield of 3900 kg/ha (annual data from FAO 2005). Yield levels varied from less than 800 kg/ha in some Sub-Saharan countries to 9280 kg/ha in Egypt.

In rice production, weeds, animal pests and pathogens, especially *Magnaporthe grisea* and *Thanatephorus cucumeris* and *Cochliobolus miyabeanus*, are regularly of economic importance. The estimates for the potential losses averaged 37, 25 and 13 %, respectively, worldwide (Table 1). Regional differences resulted from the cropping intensity (diseases, weeds), climatic conditions (especially insects) and cropping systems (weeds). Viruses transmitted by insect vectors, although devastating in some fields, were of minor importance (average potential losses 2 %) and caused actual losses less than 1·5 %. The total potential losses from pests accounted for 65–80 % of attainable yields. The variation for total actual losses (22 % in Oceania, up to 51 % in West Africa) was considerably higher, indicating significant differences in the efficacy of crop protection practices. Mechanical or chemical weed control was effective in all regions, whereas the control of animal pests and diseases by relying heavily on synthetic pesticides showed great variation. Actual crop protection prevented almost 40 % ($= 369 \times 10^6$ t) of attainable rice production from being lost to pests. The percentage varied between more than 50 % in North Africa and South Europe and less than 30 % in Sub-Saharan Africa. Nevertheless, actual losses higher than 37 % of the attainable production remained very high.

Maize

Maize production is highest in the Americas – the USA are by far the greatest producer and exporter – and in East Asia; in Latin America and parts of Africa maize is the staple food for human consumption. In 2001–03, worldwide maize production reached 612×10^6 t on $139{\cdot}8 \times 10^6$ ha (annual data from FAO 2005). The yield per unit of area averaged 4·38 t/ha and varied from less than 500 kg/ha in some African countries to more than 10 000 kg/ha in New Zealand and some countries in the Near East.

Worldwide maize production is endangered by the competition from weeds, which are the most important pest group (Table 1). The potential loss due to weeds was estimated to be higher than the sum of the potential losses due to animal pests (16%), pathogens (9%) and viruses (3%). Despite variation in the weed species, the regional differences in the potential losses were smaller than for animal pests (12–19%) and pathogens (8–13%). For these pest groups, climatic conditions and geographical distribution of pests (downy mildews, corn borers, etc.) restrict the importance to some hot spots. Actual losses to weeds worldwide averaged 10% (range from 5% in West Europe up to 19% in West Africa), indicating low competitiveness of young maize seedlings as well as control problems in maize rotations where some species have become key pests. Actual losses to animal pests and pathogens showed greater variation than the loss potentials, averaging 10 and 8%, respectively. Losses are effectively reduced under intensive production conditions in great parts of the Northern hemisphere; in Central Africa and Southeast Asia, where attainable yields are low, crop protection is largely restricted to weed control. In 2001–03, more than 50% of actual maize production was only available due to manual, mechanical and chemical crop protection. Worldwide, about 332×10^6 t maize (=37% of attainable production) were protected from being lost to pests. The percentage varied from 21 to 38%, being higher in South Europe and the USA, the most important maize producer and exporter. Nevertheless, despite crop protection practices, almost one third of attainable production was lost to pests.

Potatoes

Potato production has been expanded in recent times and *Solanum tuberosum* is now one of the five most important food crops. Potatoes produce more starch per hectare than any other crop, for proteins they are number two next to soybeans. In 2001–03, potatoes were grown on $19{\cdot}1 \times 10^6$ ha producing $309{\cdot}0 \times 10^6$ t (annual data from FAO 2005). The yield per unit of area varied from less than 3000 kg/ha in some African countries and 50 000 kg/ha in Germany and New Zealand, with a worldwide average of 16 150 kg/ha.

As vegetative propagation predominates in potato production, all pest groups are of high economic importance (Table 1). The estimates for actual losses due to pathogens, viruses, animal pests and weeds worldwide totalled 14, 7, 11 and 8%, respectively. Without crop protection almost 75% of attainable potato production would be lost to pests. Major pathogens (*Phytophthora infestans*, *Alternaria solani*, *Thanatephorus cucumeris*), viruses (potato leafroll luteovirus, potato potyvirus Y, etc.) and animal pests (potato cyst nematodes, Colorado beetle, *Phthorimaea operculella*, etc.) are widely distributed, resulting in low variation of total loss rates among regions. Actual total losses are estimated to vary from 24% in Northwest Europe to more than 50% in Central Africa, indicating marked differences in crop protection intensity. Manual, mechanical and chemical control practices protected about 34% of attainable potato production from being lost to pests (Table 1). The share reached only 20% in Central Africa where pest control is largely restricted to the control of weeds, which are favoured by environmental conditions, but amounted to almost 50% in North America and West Europe where intensive crop protection allows high productivity. However, because the control of potato late blight, some nematodes and viruses is problematic due to the biology of pests, actual losses despite crop protection practices were still high at about 40% of attainable production.

Soybeans

Soybean is an annual member of the leguminosae providing about half the global demand for vegetable oils and proteins. Originating in East Asia breeding has provided site-adapted cultivars for different growth conditions. The most important producers are the USA with almost half of worldwide production, Brazil, the PR China and Argentina. In 2001–03, $180{\cdot}4 \times 10^6$ t soybeans were produced on $79{\cdot}7 \times 10^6$ ha (annual data from FAO 2005). The yield per unit of area averaged 1973 kg/ha and varied between 0·2–0·4 t/ha in Georgia and Tanzania and more than 3500 kg/ha in Switzerland. In the USA, by far the most important producer, yields averaged 2421 kg/ha.

In soybean production, weeds are the predominant pest group. Almost 37% of attainable production is endangered by weed competition worldwide compared to 11, 1, and 11% by pathogens, viruses and animal pests, respectively (Table 1). Regional variation of loss rates for weeds was low (35–40%), whereas variations in loss rates for pathogens and animal pests were estimated to be high (7–16% and 4–20%) because of the regionally restricted distribution of some key pests (*Mycosphaerella uspenskajae*, *Phakopsora* spp., *Pyrenochaeta glycines*, nematodes). As soybean rust has been invasive in South America since 2001 and was also confirmed for the USA in November 2004, the impact of this destructive pathogen has dramatically increased in global soybean production within a short period of

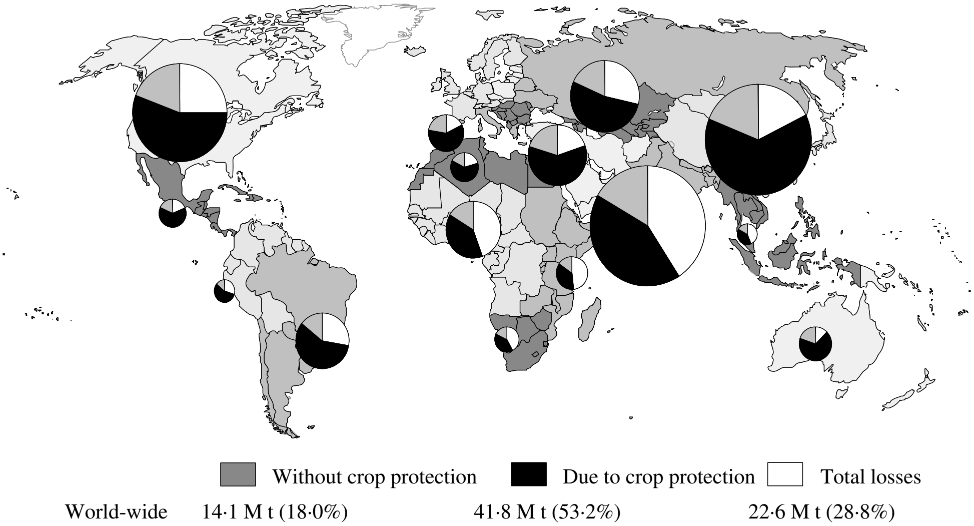

Fig. 4. Estimated contribution of actual crop protection (mechanical, biological, chemical) in safeguarding cotton production, by region, in 2001–03 (size of pies corresponds to attainable production).

time. Actual losses to these pest groups worldwide were estimated to be only slightly lower than the potential losses because crop protection in soybean concentrates on weed control. Mechanical and chemical control reduced the potential losses due to weeds by more than 70 % to a worldwide average of 8 %, varying from 5 % in South Europe to 16 % in West Africa in response to the intensity of control practices. Control practices protected almost 34 % of attainable soybean production from destruction by pests. Therefore, production without pest control was increased from 40 % to almost 74 % of the attainable production worldwide. Regionally the contribution of pest control to production varied between 25 % under low productivity farming conditions in Central Africa to 43 % in South Europe where cropping area, however, is small. In North America, by far the greatest soybean producer, the share was 35 % of attainable production. Despite the actual control measures pests reduced worldwide soybean production by 26 %.

Cotton

Cotton, *Gossypium* spp., is the most important fibre crop in the world and is grown in almost all tropical and subtropical countries. The most important producers worldwide are the PR China, the USA, India, Pakistan and Uzbekistan. For many developing countries cotton is an essential cash crop. In 2001–03, $55{\cdot}9 \times 10^6$ t seedcotton were produced on $32{\cdot}8 \times 10^6$ ha (annual data from FAO 2005). The yield per unit of area averaged 1702 kg/ha varying by factor 10, from less than 500 kg/ha in some African countries to 4317 kg/ha in Israel. In the PR China, the greatest cotton producer, yields averaged 3436 kg/ha.

Cotton production is especially threatened by insect attacks (Homoptera, Lepidoptera, Thysanoptera, Coleoptera) and by weed competition during the early stages of development. Pathogens may be harmful in some areas and years, but are considered to be only of minor importance; only recently have viruses reached pest status in South Asia and some states of the USA. The estimates of the potential losses of animal pests and weeds averaged worldwide 37 and 36 %, respectively (Table 1). Pathogens and viruses added about 9 % to a total potential loss of almost 82 %. The variation among regions was small, indicating that successful cotton production without crop protection is not feasible. Actual global losses to pathogens, viruses, animal pests and weeds showed greater regional variability and totalled 7, 1, 12 and 9 %, respectively. The proportion of cotton production receiving pest control practices was calculated at 0·53 (and was equivalent to 42×10^6 t), increasing production from 18 to 71 % of the worldwide potential. The proportional contribution of crop protection in cotton production varied from 0·37 in West Africa to 0·65 in Australia where the intensity of cotton production is very high (Fig. 4). Despite the actual measures about 29 % of attainable production is lost to pests.

EFFICACY OF CROP PROTECTION

The use of pesticides has increased dramatically since the early 1960s; in the same period also the

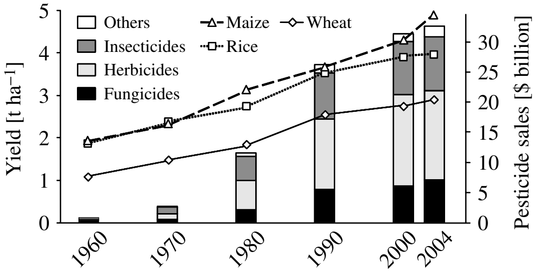

Fig. 5. Development of the worldwide average yield per unit of area for wheat, rice and maize and pesticide sales in the period 1960–2004.

yield average productivity in the production of wheat, rice and maize, the major sources for human nutrition, has been increased by a factor >2 (Fig. 5). This overall trend, however, masks significant regional differences in the efficacy of current pest control strategies. Depending on growth conditions, crop and intensity of production the loss potential of pests varies largely among regions (Fig. 6). In tropical and subtropical areas, high temperatures and high rainfall often favour the development of pests. In combination with the production of susceptible crops, often grown with two harvests per year or without crop rotation, this results in a high potential loss due to pests. Under moderate climatic conditions, e.g. in Northwest Europe and North America, the potential loss is markedly lower and as pesticides are commonly available and training of farmers is widespread, losses are reduced effectively to an acceptable level. 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 0·50 of the attainable production.

In many crops, weeds are the most important pest group, and as these unwanted plants 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 (Fig. 7). The efficacy of control of pathogens and animal pests only reaches 32 and 39 %, respectively, compared to almost 75 % 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 and the control of viruses is largely restricted to the use of insecticides for the control of the virus vectors. 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.

PRODUCTIVITY AND CROP LOSSES

Crop productivity may be increased in many regions by high-yielding varieties, improved water and soil management, fertilization and other cultivation techniques. An increased site-specific yield potential of crops, however, is often associated with higher vulnerability to pest attack, especially fungal pathogens favoured by high plant density and nutrient-rich plant tissue. Not only do absolute losses rise but loss rates also often increase significantly, as exemplified for wheat in Fig. 8 (Oerke *et al.* 1994; Oerke 2000). The potential loss from wheat diseases increased from less than 10 % (= <400 kg/ha) up to more than 20 %, equivalent to 2500 kg/ha with an attainable yield of 12 t/ha. For weeds, the trend of potential losses was similar, but very high wheat yields can only be obtained in production systems with excellent soil management, thus reducing the potential loss from weeds. Modern high-yielding varieties are also reported to show low tolerance to the competition from pests and to respond with high yield losses. In Australia, breeders improved the yield potential of wheat between 1860 and 1994 by 16·6 kg/ha annually; however, in the presence of weeds newer cultivars showed significantly higher yield losses due to suppression of wheat growth (Coleman & Gill 2003).

The increased threat of higher crop losses to pests has to be counteracted by improved crop protection whatever method it will be: biologically, mechanically, chemically, training of farmers and advisors in Integrated Crop Management. The monetary benefit of pest control increases with the attainable yield level. In order to guarantee sustainable production at higher levels its dependence on external sources may increase. An intensification of crop production without an adequate protection from damage caused by pests is not economically justifiable and is in fact economically harmful, because the crop has to be grown on a larger area which otherwise could be handed over to nature.

Worldwide estimates for losses to pests in 2001–03 differ significantly from estimates published earlier (Table 2; Cramer 1967; Oerke *et al.* 1994). Besides differences in data sources and methodology resulting in differing estimates, various changes in agricultural production may have contributed to these differences. Firstly, alterations in the share of regions in total production worldwide and differing in loss rates to pests affect total loss rates. Secondly, changes in cultivation techniques have resulted in higher pest incidence and susceptibility of plants to damage from pests. The use of varieties with high yield potential and high susceptibility to diseases and increased, sometimes unbalanced, fertilization has increased and extended susceptibility. Large-scale cropping of genetically uniform plants, multiple cropping, reduced crop rotation and/or reduced tillage cultivation have

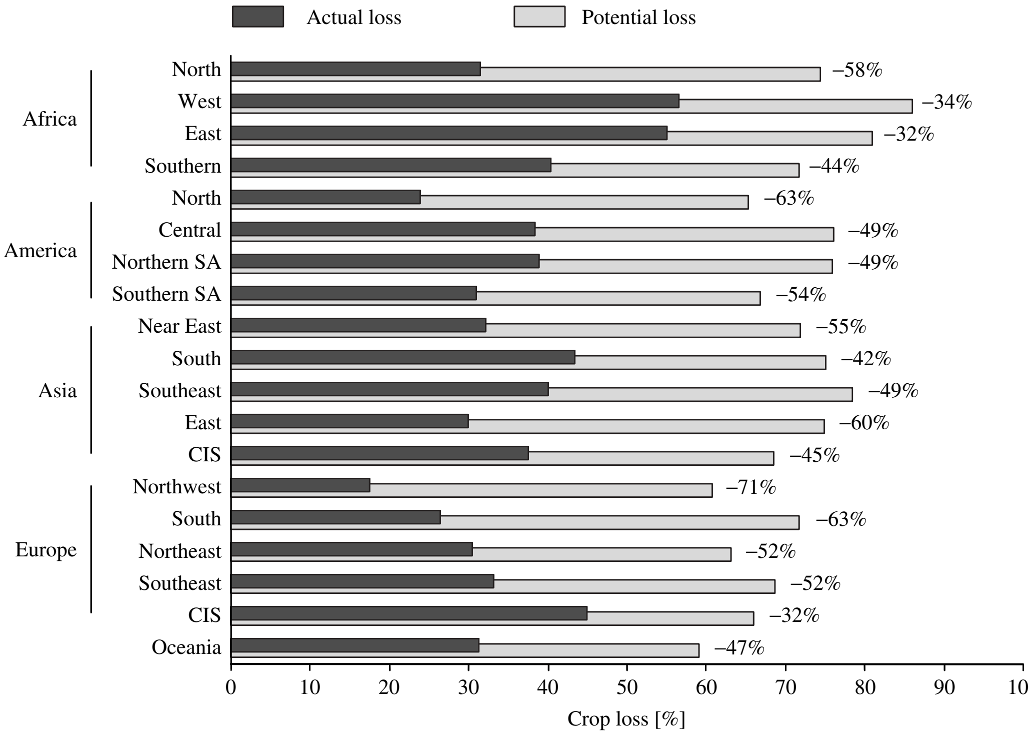

Fig. 6. Regional differences in the efficacy of actual crop protection practices in 2001–03. Figures indicate reduction of total pest losses as calculated from regional loss potentials and actual loss rates (data based on estimates of monetary production losses in barley, cottonseed, maize, oilseed rape, potatoes, rice, soybean, cotton, sugar beet, tomatoes and wheat, by region).

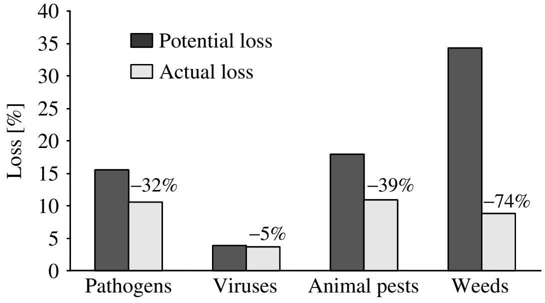

Fig. 7. Average efficacy of pest control practices worldwide in reducing loss potential of pathogens, viruses, animal pests, and weeds, respectively (reduction rates calculated from estimates of monetary production losses in barley, cottonseed, maize, oilseed rape, potatoes, rice, soybean, cotton, sugar beet, tomatoes and wheat, in 2001–03).

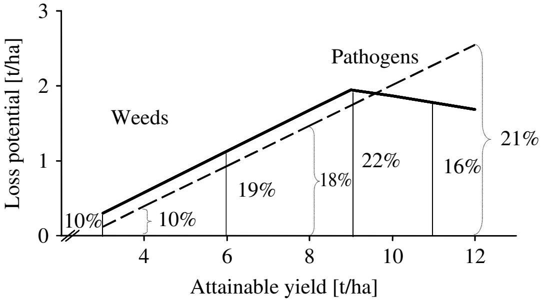

Fig. 8. Relationship between the intensity of production (=attainable yield) and the loss potential of weeds and fungal diseases in wheat production (summary of 477 field trials on weed competition and 206 fungicide trials in Germany, 1985–90).

increased the inoculum of pests in the upper soil layer. Thirdly, expansion of crops into less suitable regions with higher incidence of other pests, where plants are less adapted and high-yielding varieties replace well-adapted local varieties. Fourthly, the import and spread of pests by human activities into regions without the natural restrictions (climate, enemies, etc.) of the region of origin. Lastly, increases in the demand for higher quality food have led to an increase in the crop not suitable for consumption (Yudelman *et al.* 1998).

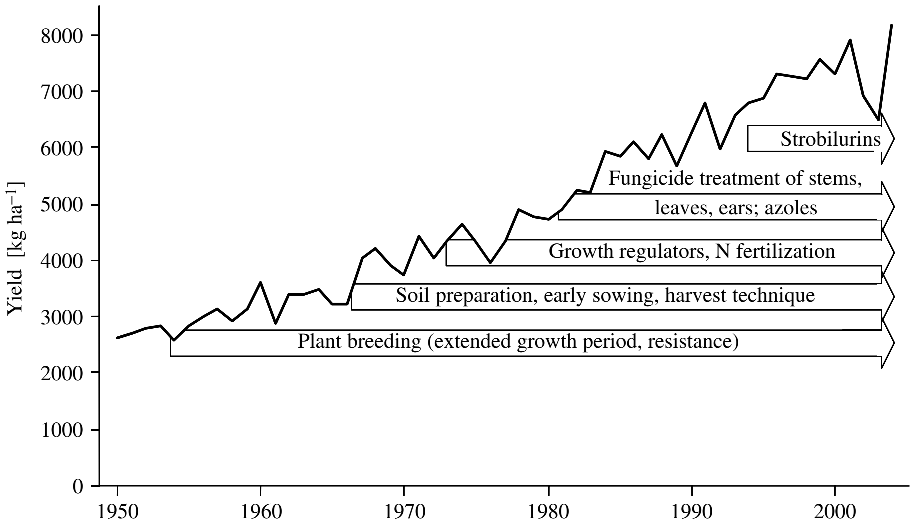

Fig. 9. Development of wheat yield in Germany resulting from various improvements in crop production (modified from Reschke 2000).

Table 2. *Estimates of actual crop losses due to weeds, animal pests, and diseases in worldwide production of wheat, maize and cotton for the years 1964/65, 1988–90 and 2001–03*

Period	Yield (kg/ha)	Actual loss [%] Weeds	Animal pests	Diseases	Total
Wheat					
1964/65[1]	1250	9·8	5·0	9·1	23·9
1988–90[2]	2409	12·3	9·3	12·4	34·0
2001–03	2691	7·7	7·9	12·6	28·2
Maize					
1964/65[1]	2010	13·0	12·4	9·4	34·8
1988–90[2]	3467	13·1	14·5	10·8	38·3
2001–03	4380	10·5	9·6	11·2	31·2
Cotton					
1964/65[1]	1029	4·5	11·0	9·1	24·6
1988–90[2]	1583	11·8	15·4	10·5	37·7
2001–03	1702	8·6	12·3	7·9	28·8

[1] From Cramer (1967).
[2] From Oerke *et al.* (1994).

Besides these trends, which often increase the potential loss of crops, the efficacy of pest control strategies has changed in many regions. The intensity of pest control has increased sometimes dramatically, e.g. in Asia and Latin America, where the use of pesticides increased from 1993 to 1998 by 5·4% annually, well above the global average of 4·4% (Yudelman *et al.* 1998). The use of genetically modified crops, especially in the Americas and Asia, where China is the country with the highest growth in land cropped with transgenic crops (McLaren 2000). 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 organizations has contributed to an improvement in pest control in the last 15 years. 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.

CONCLUSIONS

Because of global population growth in a world of limits, sustainable crop production at elevated levels is urgently needed. The active control of crops and their genetics, of soil fertility via chemical fertilization and irrigation, and of pests via synthetic pesticides are hallmarks of the Green Revolution. The combined effect of these factors has allowed world food production to double in the past 40 years. Diverse ecosystems have been replaced in many regions by simple agro-ecosystems vulnerable to pest attack. In order to safeguard the high level of productivity necessary to meet the human demand, these crops require protection from pests. The yield of cultivated plants is threatened by competition and destruction from pests, especially when grown in large-scale monocultures or with heavy fertilizer applications.

From 1960 to 2003, the human population has doubled to reach $6{\cdot}3 \times 10^9$ (FAO 2005). The doubling of grain production since the early 1960s was associated with a 6·9-fold increase in nitrogen fertilization, a 1·7-fold increase in the amount of irrigated cropland, 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; Pinstrup-Andersen 2000). The proportion of yield increase that may be attributed to genetic improvement of crops by breeders is about 0·5–0·6 (McLaren 2000), providing farmers with high yielding varieties responsive to improved fertilization. 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 (Fig. 5). 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 (Cassman 1999). The joint effects of plant breeding, optimum sowing time, soil cultivation techniques, fertilizer application, coordinated use of plant growth regulators, and the use of fungicides with broad-spectrum activity against the most important diseases has resulted in a remarkable increase in wheat yield in Germany, demonstrating that sustainable production at a high level of productivity relies on external input (Fig. 9).

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.

In cash crops such as soybean and cotton, the efficacy of actual crop protection as measured by the portion of loss potential prevented is considerably higher than in crops grown for food. This applies not only to developed countries, but is especially true for developing countries where food production often lacks the support the production of cotton or other cash crops is receiving. Despite the increased use of pesticides the absolute value of crop losses and the overall proportion of crop losses appear to have increased in the past 40 years. In some regions, inappropriate and excessive pesticide use, especially insecticides, have led to increased pest outbreaks and losses in some crops (rice, cotton) because of the inadvertent destruction of natural enemies of pests, pest resistance and secondary pests. However, although pests can develop resistance to pesticides, insensitivity to pesticides hardly contributes to this relationship.

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 human population; however, pest control and the use of pesticides in particular are applied according to the economic benefits of the farmer.

The increased use of pesticides since 1960 obviously 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. The concept of the threshold-based application of pest control measures is associated with the acceptance of crop losses and may be used successfully for an economically and ecologically sound crop production.

REFERENCES

BOOTE, K. J., JONES, J. W., MISHOE, J. W. & BERGER, R. D. (1983). Coupling pests to crop growth simulators to predict yield reductions. *Phytopathology* **73**, 1581–1587.

CASSMAN, K. G. (1999). Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture. *PNAS* **96**, 5952–5959.

COLEMAN, R. & GILL, G. (2003). Trends in yielding ability and weed competitiveness of Australian wheat cultivars. In *Solutions for a better environment*. Proceedings of the 11th Australian Agronomy Conference, Geelong, 2–6 February 2003 (Eds M. Unkovich & G. O'Leary), pp. 1–4. Horsham, Australia: Australian Society of Agronomy.

COOKE, B. M. (1998). Disease assessment and yield loss. In *The Epidemiology of Plant Diseases* (Ed. D. G. Jones), pp. 42–72. Dordrecht, the Netherlands: Kluwer Publishers.

CRAMER, H. H. (1967). Plant protection and world crop production. *Bayer Pflanzenschutz-Nachrichten* **20**, 1–524.

Dehne, H.-W. & Schönbeck, F. (1994). Crop protection – past and present. In *Crop Production and Crop Protection – Estimated Losses in Major Food and Cash Crops* (Eds E.-C. Oerke, H.-W. Dehne, F. Schönbeck & A. Weber), pp. 45–71. Amsterdam: Elsevier Science.

De Waard, M. A., Georgopoulos, S. G., Hollomon, D. W., Ishii, H., Leroux, P., Ragsdale, N. N. & Schwinn, F. J. (1993). Chemical control of plant diseases: problems and prospects. *Annual Review of Phytopathology* **31**, 403–421.

FAO (2005). FAOSTAT – Agriculture. Available online at http://faostat.fao.org/faostat/collections?subset=agriculture.

Goncalves, D., Ferreira, S., Manshardt, R., Fitch, M. & Slightom, J. (1998). Transgenic virus resistant papaya: New hope for control of Papaya ringspot virus in Hawaii. *Online. APSnet feature*, American Phytopathological Society.

Hamill, A. S., Holt, J. S. & Mallory-Smith, C. A. (2004). Contributions of weed science to weed control and management. *Weed Technology* **18**, 1563–1565.

James, C. (2004). *Global Status of Commercialized Biotech/GM Crops: 2004*. ISAAA Publications, International Service for the Acquisition of Agri-biotech Applications.

Marlatt, C. L. (1904). The annual loss occasioned by destructive insects in the United States. *US Dep. Agric. Yearbook*, 461–474.

McLaren, J. S. (2000). The importance of genomics to the future of crop production. *Pest Management Science* **56**, 573–579.

Morstatt, H. (1929). Die jährlichen Ernteverluste durch Pflanzenkrankheiten und Schädlinge und ihre statistische Ermittlung. *Ber. über Landw.* **9**, 433–477.

Nauen, R. & Bretschneider, T. (2002). New modes of action of insecticides. *Pesticide Outlook* **13**, 241–245.

Nutter, F. W., Jr, Teng, P. S. & Royer, M. H. (1993). Terms and concepts for yield, crop loss, and disease thresholds. *Plant Disease* **77**, 211–215.

Pinstrup-Andersen, P. (2000). The future world food situation and the role of plant diseases. Available online at: http: www.scisoc.org/feature/FoodSecurity/Top.html.

Oerke, E.-C. (2000). *Infection, damage, loss – an assessment of crop losses to pests and their avoidance* (in German). -Habilitation thesis, University of Bonn, 313 pp.

Oerke, E.-C., Dehne, H.-W., Schönbeck, F. & Weber, A. (1994). *Crop Production and Crop Protection – Estimated Losses in Major Food and Cash Crops*. Amsterdam: Elsevier Science.

Reschke, M. (2000). Chemischer Pflanzenschutz als Produktionsfaktor in der modernen Pflanzzenproduktion an der Schwelle zum 3. Jahrtausend. *Mitt. Biol. Bundesanst. Land- und Forstwirtsch.* **371**, 52–67.

Russell, P. E. (2005). A century of fungicide evolution. *Journal of Agricultural Science, Cambridge* **143**, 11–25.

Schumann, G. L. (1991). *Plant Diseases: Their Biology and Social Impact*. St. Paul, USA: APS Press.

Smith, I. M., Chiarappa, L. & van der Graaff, N. A. (1984). World crop losses: an overview. In *Plant Diseases: Infection, Damage and Loss* (Eds R. K. S. Wood & G. J. Jellis), pp. 213–223. Oxford: Blackwell Scientific Publications.

Stern, V. M., Smith, R. F., van den Bosch, R. & Hagen, K. S. (1959). The integrated control concept. *Hilgardia* **29**, 81–101.

Teng, P. S. (1987). *Crop Loss Assessment and Pest Management*. St. Paul, USA: APS Press.

Tilman, D. (1999). Global environmental impacts of agricultural expansion: The need for sustainable and efficient practices. *PNAS* **96**, 5995–6000.

Wood, R. K. S. (1993). Sustainable agriculture: The role of plant pathology. *Abstracts, 6th International Congress of Plant Pathology*, July 28–August 6, 1993, Montreal, Canada, National Research Council Canada, Ottawa, 1.

Yudelman, M., Ratta, A. & Nygaard, D. (1998). *Pest Management and Food Production: Looking to the Future*. Food, Agriculture, and the Environment Discussion Paper 25. Washington, DC: International Food Policy Research Institute.

Zadoks, J. C. & Schein, R. D. (1979). *Epidemiology and Plant Disease Management*. Oxford: Oxford University Press.

Zimdahl, R. L. (1999). *Fundamentals of Weed Science*. London: Academic Press.