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Safeguarding production—losses in major crops and the role of crop protection

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Abstract

It is well accepted that agricultural production must be increased considerably in the foreseeable future to meet the food and feed demands of a rising human population and increasing livestock production. Crop protection plays a key role in safeguarding crop productivity against competition from weeds, animal pests, pathogens and viruses. The loss potential of these pest groups and the actual losses—i.e. losses despite the present crop protection practices—have been estimated for wheat, rice, maize, barley, potatoes, soybeans, sugar beet and cotton for the period 1996–1998 on a regional basis for 17 regions. 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 are estimated at 26–30% for sugar beet, barley, soybean, wheat and cotton, and 35%, 39% and 40% for maize, potatoes and rice, respectively. Overall, 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 6–7% on these crops and <1–3% in other crops. The efficacy of crop protection was highest in cash crops (53–68%) and lower (43–50%) in food crops. The variation coefficient of efficacy among regions was low in cash crops (12–18%) and highest in wheat (28%). As weed control can be achieved through mechanical or chemical means, worldwide efficacy in weed control (68%) was considerably higher than the control of animal pests or diseases (39% and 32%, respectively), which relies heavily on pesticides. The intensification of crop production necessary to meet the increasing demand through enhanced productivity per unit area might be impossible without a concomitant intensification of pest control. The perspectives of integrated pest management in safeguarding crop production and preventing negative effects on the environment are discussed for developing and developed countries.

Keywords: Crop protection; Actual losses; Efficacy of control; Integrated pest management

1. Introduction

Human population is projected to grow at ca 80 million per annum, increasing by 35% to 7.7 billion by 2020, then by about 75% before levelling off at about 10 billion (United Nations, 1996; Tilman, 1999; Pinstrup-Andersen, 2000). 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; preference of wheat to sorghum) and the increasing use of grains for livestock feed, is projected to cause the demand for grain production to more than double. However, land suitable for agricultural production is limited, and most of the soils with high productivity potential are already under cultivation. In addition, the availability of water is restricted, and in some regions land resources are depleted and the cultivated area is shrinking (Nelson-Smith, 1995). Given these limitations, sustainable production at elevated levels is urgently needed. The availability and conservation of fertile soils and the development of high-yielding varieties are major challenges to agricultural production. Safeguarding crop productivity by protecting crops from damage by weeds, animal pests and pathogens is also a major requisite for providing food and feed in sufficient quantity and quality.

Improved crop management systems based upon genetically improved (high-yielding) cultivars, 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 allowed world food production to double in the past 35 years. The three annual grasses, namely maize, rice and

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wheat, occupy almost 40% of global cropland (Tilman, 1999) and are the primary sources for human nutrition worldwide. As yields of these grasses and some cash crops like soybean, cotton and sugar beet positively respond to high production levels and/or cultivation may be largely mechanised, in the last 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 productivity to the level necessary to meet the demand, these crops have to be protected 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 fertiliser applications. 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 (Cooke, 1998; Nutter et al., 1993). Assessments of crop losses despite actual crop protection strategies are required to demonstrate where action is needed and for decision making (Smith et al., 1984). Estimates of actual losses in crop production worldwide were published by Cramer (1967) and updated nearly 30 years later by Oerke et al. (1994). Since crop production technology and especially crop protection methods are changing continuously, loss data for eight major food and cash crops have been updated for the period 1996-98. Based on the loss estimates for the period 1988–1990, estimates for wheat, rice, maize, barley, potatoes, soybean, sugar beet and cotton have been revised according to the literature published since the early 1990s and are summarised below. The site-specific loss potential of pests estimated in a *no-control* scenario was compared with actual loss rates, i.e. the losses occurring despite the present mechanical and chemical crop protection practices. The percentage of the loss potential avoided was used as a parameter to quantify the efficacy of control.

2. Materials and methods

Production data for 1996–1998 on the area harvested, the yield per unit area, and the total production for the eight crops are based on FAO data (FAO, 1999). The 3-year average was used for further calculations. Crop losses due to weeds, animal pests (arthropods, nematodes, mammals, slugs and snails and birds), fungal and bacterial pathogens, and viruses were estimated from literature data. Oerke et al. (1994) was used as source of primary data on the crop loss situation as well as loss estimates by pest group. Literature searches in 1998 and 2000 were used to update the information on rice, wheat, maize, barley, potatoes, soybean and cotton. For sugar beet losses due to pests were estimated from literature data (1996–1999) and Oerke (2000).

Two loss rates have been differentiated: the *loss potential* of pests includes the losses without physical, biological or chemical crop protection using similar intensity of crop production (fertilisation, irrigation, cultivars, etc.); it characterises the risk that pests exert on crop production in a *no-control* scenario. The *actual losses* comprise the crop losses occurring despite the crop protection practices. The calculation of total loss rates for potential and actual losses has been described earlier (Oerke et al., 1994). The efficacy of the crop protection practices was calculated as a percentage of potential losses prevented.

Crop losses caused by pests were calculated for all crops on a regional basis. Seventeen regions were specified according to the intensity of crop production and the production conditions. As far as possible they correspond with the continents: North America, Central America, South America and Oceania; for Africa: North Africa, Central Africa (=sub-Saharan Africa) and Southern Africa; for Asia: the Near East, South Asia, Southeast Asia, East Asia and the Asian states of the CIS; and for Europe: Northwest, Southern, Northeast, Southeast, and the European part of the CIS.

3. Loss potential and actual losses due to pathogens, viruses, animal pests and weeds

3.1. 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. The major wheat-producing countries are the PR China, India, USA, France and Russia. In 1996–1998, 596 million t of wheat were grown on 227.9 million hectares. With a worldwide average of 2.61 t/ha, yield varied between 0.37 t/ha in Rwanda and Venezuela, respectively, and 8.2 t/ha in Belgium and Ireland. In 1998 the international wheat trade amounted to 106 million tons (=18% of worldwide production) with the USA, Canada, France, Argentina and Australia being the major exporters.

In wheat production weeds are the most important pests worldwide. The incidence and impact of pathogens—especially *Blumeria graminis*, *Septoria* spp. and rust fungi—increase with the intensity of crop productivity (=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*, attack a high portion of cereals in 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 fungal and bacterial pathogens, viruses, animal pests and weeds in wheat totalled 16%, 3%, 9%, and 23%, respectively. In West Europe the loss potential of pathogenic microorganisms was as high as that of weeds under intensive production conditions, demonstrating the increasing importance of diseases with increased productivity. Crop protection practices reduce the overall loss potential of 50% to actual losses of about 29%: 10% to pathogens, 2% to viruses, 8% to animal pests and 9% to weeds. Total actual losses varied considerably, from 14% in Northwest Europe to 35% and above in Central Africa, Southeast Asia, CIS and Oceania.

3.2. Rice

Rice production is largely concentrated to Asia, where it is considered to be the major source of food. *Oryza sativa* is grown under different growth conditions with widely differing yield levels, with irrigated and non-irrigated lowland rice and dryland rice being the most important. In West Africa *O. glaberrima* is also grown. In 1996–1998 521 million tons of rice were produced on 135.9 million hectares giving an average yield of 3.76 t/ha compared to 3.56 t/ha in 1988–1990. Yield levels varied between 0.72 t/ha in Congo and Sudan, respectively, and 7.8–8.3 t/ha in Australia and Egypt. Rice is mainly grown for subsistence or local markets, and only about 4% of global production reach the international market.

In rice production, weeds, animal pests as well as fungal and bacterial pathogens—especially *Magnaporthe grisea*, *Thanatephorus cucumeris* and *C. miyabeanus*—are regularly of economic importance with estimates for the worldwide loss potentials of 35%, 24% and 16%, respectively. Regional differences in the various pests 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 loss potential 2.3%) and caused actual losses of less than 2%. The total loss potential of pests accounted for 65–80% of attainable yields. The variation for total actual loss rates—ranging from 23% in Oceania, to 52% in Central Africa—was considerably higher, indicating significant differences in the efficacy of crop protection practices. Weed control, whether mechanical or chemical, was effective in all regions, whereas the control of animal pests and diseases, with its heavy reliance on synthetic pesticides, showed great variation.

Actual crop protection safeguarded about 38% (= 362 million tons) 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 and the CIS. Nevertheless, actual losses remained high, at almost 40% of the potential production.

3.3. Maize

In East Asia, Latin America and parts of Africa maize is the staple food for human consumption. Maize production is highest in the Americas—USA is by far the greatest producer and exporter. In 1996–1998, worldwide maize production reached 589 million tons produced on 140.5 million hectares. The yield per unit area averaged 4.19 t/ha and varied from 0.3–0.5 t/ha in some African countries and 9.4–9.8 t/ha in Italy and New Zealand. As maize is used worldwide for feed, international trade of maize reached 72 million tons (= 12% of production) in 1998.

Worldwide maize production is hampered by competition from weeds which are the most important pest group for this crop. At 37%, the loss potential of weeds was estimated to be higher than the sum of the loss potentials of animal pests (15%), fungal and bacterial pathogens (11%) and viruses (3%). Despite variation in the weed species, regional differences in the loss potential of weeds were smaller than for animal pests (12–19%) and pathogens (8–14%). Climatic conditions and the geographical distribution of the latter pest groups (e.g. downy mildews, corn borers, etc.) restrict their importance to some hot spots. Actual losses to weeds worldwide averaged 10% (range from 5% in West Europe up to 17% in Central Africa) indicating low competitiveness of young maize seedlings as well as control problems in maize rotations where some weed species have become key pests. Actual losses to animal pests and pathogenic microorganisms showed greater variation than did loss potentials, both averaging 10%. 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 1996–1998, about 50% of maize production was only available thanks to manual, mechanical, and chemical crop protection. Worldwide, about 290 million tons of maize (= 33% of attainable production) were protected from being lost to pests. The percentage varied from 21–38% and more 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.

3.4. Barley

Barley is grown mostly in the Northern Hemisphere, especially in dry areas and those with short cropping periods. In 1996–1998 barley was grown on 64.1 billion hectares, resulting in a production of 149.7 billion tons. With yields varying between 0.3–0.4 t/ha in Lesotho and Gaza Strip, respectively, and almost 6.7 t/ha in Belgium, the worldwide barley yield averaged 2.34 t/ha. For the past 10 years, the area harvested and the yield per unit of area were stagnating. Barley is hardly grown for human consumption anymore; production for feed and for malting is predominant. The international trade of barley amounted to 19 million tons (=13% of production) in 1998.

The total loss potential of pests in barley production worldwide was estimated to account for less than 50% of the attainable yield. Weeds had the highest share (23%) in this loss rate, followed by fungal pathogens—especially *Pyrenophora teres*, *Rhynchosporium secalis*, *Puccinia hordei, B. graminis* f.sp. *hordei* and *C. sativus*—(15%), animal pests (7%) and viruses (3%). Variation among regions was very similar to that for wheat. Losses in barley due to fungal pathogens and animal pests were estimated at lower levels than in wheat as barley is often grown at lower fertiliser levels, restricting its susceptibility to many pests. Worldwide, actual losses to pathogenic microorganisms, viruses, animal pests and weeds totalled 9, 3, 6 and 8%, respectively. Variation among regions was greater for actual loss rates than for loss potentials, e.g. for fungal pathogens actual losses varied between 5% in Northwest Europe and 15% in Southeast Asia versus 12–18% for the loss potential.

The proportion of barley production saved by pest control practices was estimated as 21% of attainable production worldwide; in 1996–1998 about 73% of attainable barley production was harvested. The contribution of crop protection differed considerably among regions, as under extensive production conditions crop protection is restricted to weed control resulting in an addition of 10–20% of the attainable yield to the primitive yield of about 50%. Only in intensive production in Northwest Europe crop protection did safeguard about 30% of the high yield potential because, in addition to weeds, pathogens are regularly controlled effectively. The crop losses despite actual crop protection practices were estimated to amount to 27% of attainable production.

3.5. Potatoes

Potato production has been expanded in recent times and *Solanum tuberosum* belongs to the five most important food crops. Potatoes produce more starch per hectare than any other crop and are second to soybeans in protein content. In 1996–1998, potatoes were grown on 18.1 million hectares producing 292.8 million tons. The yield per unit area varied between 2 and 3 t/ha in some African countries and 43.8 t/ha in Switzerland, with a worldwide average of 16.2 t/ha. International trade amounted to 25.9 million (=5% of production), largely accounting for seed potatoes.

As vegetative propagation predominates in potato production, all pest groups are of high economic importance. The loss estimates for pathogens, viruses, animal pests and weeds in 1996–1998 totalled 22%, 8%, 18% and 23%, respectively, worldwide. Without crop protection about 71% of attainable potato production would be lost to pests. Major pathogens (*Phytophthora infestans*, *Alternaria solani*, *T. 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. Overall, weed control results in a reduction of losses to 8% (range 5–14%), disease control to 13% (7–19%) and control of animal pests and viruses to 7% (5–10%) and 10% (7–15%), respectively.

In 1996–1998, manual, mechanical and chemical control practices protected about 32% of attainable potato production from being lost to pests. 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, as the control of potato late blight, some nematodes and viruses is problematic because of the biology of these pests, actual losses in spite of crop protection practices were still high at almost 39% of attainable potato production.

3.6. Soybeans

Soybean is an annual member of the leguminosae that is native to East Asia. The crop satisfies about half the global demand for vegetable oils and proteins. Soybean breeding has provided site-adapted cultivars for different growth conditions. The most important producers are the USA with almost 50% of worldwide production, Brazil, the PR China and Argentina. In 1996–1998, 144.3 million tons of soybeans were produced on 66.7 million hectares. The yield per unit area averaged 2.16 t/ha (1988–1990 1.83 t/ha) and varied between 0.2 and 0.4 t/ha in Georgia and Tanzania and 3.6 t/ha in Italy. In the USA, by far the most important producer, yields averaged 2.59 t/ha. Grown for feed and industrial raw material about 26% of soybean production is traded internationally: in 1998 the trading volume reached 37.2 million tons.

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 fungal and bacterial pathogens, viruses and animal pests, respectively. Regional variation of loss rates for weeds was low in 1996–1998 (34–39%), whereas loss rates due to microbial 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). Actual losses to these pest groups worldwide were estimated to be only slightly lower than the loss potentials as crop protection in soybean concentrates on weed control. Mechanical and chemical control reduced the loss potential by more than 70% to a worldwide average of 10%, varying from 5% in South Europe to 16% in Central Africa depending on the intensity of control practices.

In 1996–1998, pest control practices protected almost 32% of attainable soybean production from destruction by pests. Therefore, production was increased from 41% without pest control to 72% of the worldwide production potential. 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 is, however, small. In North America, the greatest soybean producer, the share was 34% of attainable production. Despite actual control measures pests reduced worldwide soybean production by almost 28%. One explanation for this high loss rate is the large-scale production of soybeans in the Americas where the land area available allows production without high expenditures on pest control.

3.7. Sugar beet

Sugar beet, the most important sugar-producing crop after sugar cane, is grown preferentially in the Northern Hemisphere under moderate to semi-arid conditions. Sugar beet accounts for 35% of global raw sugar production. The most important producers are France, the USA and Germany, each of them producing more than 25 million tons annually. In 1996–1998 the total production was 261 million tons, produced on 7.2 million hectares. The yield per unit area varied between 5.8 t/ha in Ecuador and almost 70 t/ha in France, averaging 36.3 t/ha worldwide.

As the development of seedlings is rather slow and long, sugar beet often suffers losses from weed competition which is estimated to be by far the most important pest group in sugar beet production. Irrespective of the growing region, the loss potential of weeds accounted for about 50% of attainable yields. Loss potentials of fungal pathogens (especially *Cercospora beticola*), viruses and animal pests also showed only low variability among regions totalling worldwide 14%, 7%, and 12%, respectively. Without any crop protection measures sugar beet yields would be reduced by an average of more than 80% in all growing areas. Actual losses in sugar beet, however, are estimated to be lower than for most of the other crops investigated because weed competition may be eliminated mechanically as well as chemically. Actual losses to weeds varied from 3% in South Europe to about 10% in the CIS, totalling 6% worldwide. Losses to fungal pathogens, viruses, and animal pests were very similar, levelling at 8%, 6%, and 6%, respectively. Viral diseases (beet yellows, beet necrotic yellow vein, etc.) and the cyst nematode *Heterodera schachtii* continue to play an important role in sugar beet production because control of these pests is still difficult in many regions.

Actual crop protection practices, especially weed control, safeguard more than 56% of attainable sugar beet production (= 199 million tons) from destruction. Production without any crop protection would produce only 17% of the worldwide potential. In 1996–1998, the share of attainable production saved by crop protection measures varied from 44% in the CIS to 62–65% in Northwest Europe and Chile. In 1996–1998, the losses despite crop protection accounted for 26% of attainable production, with 8% to fungal pathogens having the highest proportion.

3.8. Cotton

Cotton, *Gossypium* spp., is the most important fibre crop globally and is grown in almost all tropical and subtropical countries. The most important producers worldwide are PR China, USA, India, Pakistan and Uzbekistan. For many developing countries cotton is an essential cash crop. In 1996–1998, 55 million tons of seed cotton were produced on 33.7 million hectares. The yield per unit area averaged 1.63 t/ha, varying by a factor of 10, from less than 0.5 t/ha in some African countries to 5.1 t/ha in Israel. In the PR China, the greatest cotton producer, yields averaged 2.82 t/ha. The international trade reached 5.5 million tons of cotton lint, corresponding to about 28% of global production.

Cotton production is threatened especially by attack from insects (Homoptera, Lepidoptera, Thysanoptera, Coleoptera) and by weed competition during early stages of development. Fungal and bacterial pathogens may be harmful in some areas and years, but are considered to be only of minor importance; only recently viruses have reached pest status in South Asia and some states of the USA. The estimates of the loss potentials of animal pests and weeds worldwide averaged 37% and 34% respectively. Microorganisms and viruses added about 11% to a total loss potential of almost 82%. The variation among regions was small, indicating that successful cotton production without crop protection is hardly feasible. Actual losses to pathogens, viruses, animal pests and weeds showed greater regional variability and totalled 9%, 1%, 12% and 7%, respectively, worldwide.

The share of cotton production protected by actual pest control practices was calculated at 52% (=41 million tons) in 1996–1998 increasing production from 18–70% of the worldwide potential. The contribution of crop protection in cotton production varied from 37% in Central Africa to 65% in Australia where the intensity of cotton production is very high. Despite the actual measures about 30% is lost to pests, especially animal pests (12%) and pathogens (9%).

4. Efficacy of crop protection practices

The efficacy of actual crop protection practices was calculated as the percentage of the loss potential prevented by mechanical, biological and chemical pest control measures directed against the occurring pests. Among crops the share of the loss potential prevented showed considerable variation and was positively correlated to the loss potential of pests ($r^2 = 0.58, p \leqslant 0.05$). Worldwide the efficacy was low in wheat, potatoes and barley (43–46%), moderate in rice, maize and soybeans (50–53%), and high in cotton and sugar beet (64–68%).

Regional variation in the efficacy of actual crop protection practices was low in sugar beet and cotton (variation coefficient 12% and 18%, respectively), and high in potatoes and wheat (26% and 28%, respectively). The percentage of losses prevented ranged from 34–35% in Central Africa and the European part of the CIS to 70% in Northwest Europe. In East Asia, North America and South Europe efficacy was calculated to reach 55–60% (Fig. 1). 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 68%. The control of animal pests and diseases caused by fungi and bacteria was considerably lower at 39% and 32%, respectively, with virus control reaching an efficacy of only 13%. In total, the loss potential of about 50% was reduced to actual losses of about 34% (Table 1). The use of synthetic pesticides per unit of arable land reflects the differences in crop protection intensity among regions. With expenditures—averaged for all compounds and crops—above $90 ha^{-1} and the intensive use of fungicides, intensity of pest control was highest in West Europe (Fig. 2). In North America where herbicides are by large the most important pesticides, and in the Far East where weeding rather relies on manpower, and insecticides hold the highest percentage, pesticide use was above the worldwide average; in East Europe, West and South Asia as well as in Africa the average pesticide use per area of arable land was well below $10 ha^{-1}.

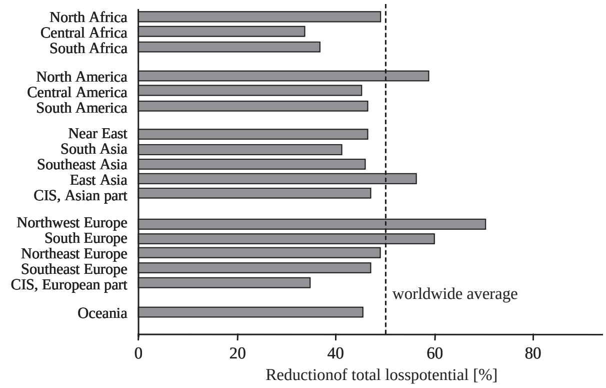

Fig. 1. Regional differences in the overall efficacy of actual crop protection practices in wheat, rice, maize, barley, potatoes, soybean, sugar beet and cotton (calculations based on loss estimates for 1996–1998).

Table 1
Overall summary of the loss potential and the actual losses due to fungal and bacterial pathogens, viruses, animal pests and weeds as well as the efficacy of the actually applied pest control measures in wheat, rice, maize, barley, potatoes, soybean, sugar beet and cotton, in 1996–1998

	Pest group				
	Fungi and bacteria	Viruses	Animal pests	Weeds	Total
Loss potential (%)[a]	14.9	3.1	17.6	31.8	67.4
Actual losses (%)[a]	9.9	2.7	10.1	9.4	32.0
Efficacy (%)[b]	33.8	12.9	42.4	70.6	52.5

[a] As percentage of attainable yields.
[b] As percentage of loss potential prevented.

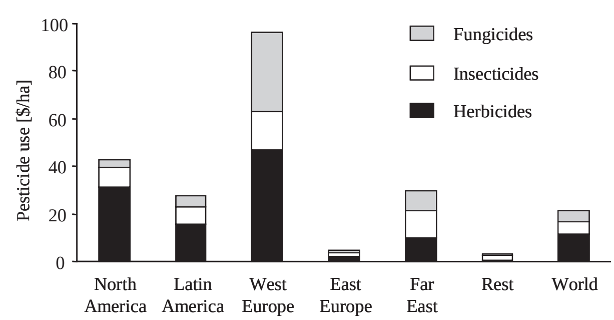

Fig. 2. Regional differences in the expenditures on chemical crop protection products per unit of area of arable land in 1998 (calculated from various sources).

5. Discussion

5.1. Development of crop production and crop losses

The doubling of grain production and tripling of livestock production since the early 1960s have resulted in a global food supply sufficient to provide adequate energy and protein for all (Pinstrup-Andersen, 2000). It was associated with a 6.9-fold increase in nitrogen fertilisation, a 1.7-fold increase in the amount of irrigated cropland, and a 1.1-fold increase in land under cultivation (Tilman, 1999), the use of high yielding varieties and a 15–20-fold increase in the amount of pesticides applied. Between 50% and 60% of the rate of yield increases can be attributed to genetic improvement (McLaren, 2000). In 40 years, US maize yield has improved by a factor of 2.13 and UK wheat by 1.86. For cereals, however, yield plateaued in the mid-1980s and may be on a downward trend in the late 1990s. Much of the observed yield increase can be attributed to greater control of—biotic—stress rather than an increase in yield potential (Cassman, 1999).

Progress in improving food security has been uneven, and many developing countries have failed to participate in such progress. The persistence of food insecurity reflects regional differences rather than a lack of overall capacity. The world already produces sufficient food, and in some regions overproduction has become a problem. But many people are undernourished because they are poor in terms of agricultural resources, education, technology, etc. and thus are unable to produce their own food (Alexandratos, 1999). In the 1990s, there has been a slowdown in the growth of agricultural production. World cereal outputs stagnated and fluctuated widely and—in per person terms—fell from the peak of 342 kg achieved in the mid-1980s to 323 kg in 1996–1998. However, worldwide indicators are of limited value, and the variables must be observed at a more disaggregated level for correct interpretation. Absolute population increase will be highest in Asia, but the relative increase will be greatest in sub-Saharan Africa, where the population is expected to increase by 80% by 2020 (Pinstrup-Andersen, 2000).

The continuation of recent cereal yield trends should be sufficient to cope with most of the demographically driven expansion of cereal demand that will occur until 2025. Because of the increasing divergence between the expansion of regional demand and the potential for supply, world food trade is projected to expand considerably (Dyson, 1999). By 2030 the net cereals exports of the major exporters—North America, Western Europe, Australia and Argentina—would need to approximately double from the mid-1990s level of 160 million tons. The required growth rate of production of 1.1% p.a. is below the 2.0% p.a. achieved in the preceding 35 years (Alexandratos, 1999).

Increases in cultivated area will contribute less than 20% of the increase in global cereal production until 2020 (Pinstrup-Andersen, 2000). Because at present the rate of increase in yield potential is much less than the expected increase in grain demand (Cassman, 1999), the average farm yields have to narrow the gap between the actual available yield and the site-specific yield potential. In high-production systems in which average farm yields are presently above 70% of attainable yield—e.g. rice production in Japan, Korea, parts of the USA and China, and wheat production in some areas of Northwest Europe—further yield increases will be difficult to achieve without an increase in the genetic yield potential of crop varieties and hybrids (Cassman, 1999).

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 kg/ha, Oerke, 2000). Actual loss rates alone, however, are not suitable for an assessment whether actual control practices in a region are sub-optimal, because control practices have to be cost-effective. In the tropics and subtropics the yield potential of adapted crops is often low due to low-input farming systems, whereas the loss potential of pests is high due to climatic conditions promoting the development of pests, the growth of susceptible crop species, and the sometimes continuous cropping of the same species in order to meet the demand for food.

Worldwide estimates for losses to pests for 1996–1998 differ significantly from those published earlier (Oerke et al., 1994). Estimates for rice (40% versus 51%) have been corrected downwards according to new publications (e.g. Savary et al., 2000) and the response to the former publication. 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 from 1993–1998 by 5.4%

annually, well above the global average of 4.4% (Yudelman et al., 1998). The development of new compounds that are highly effective against formerly less controllable pests, the use of genetically modified crops especially in North America and Asia—where China is the country with the highest growth in land cropped with GMOs—(McLaren, 2000), and better training of farmers by governmental and non-governmental organisations, all have contributed to an improvement in pest control in the past 10 years. In large parts of Asia and Latin America farmers' education has made great advances, whereas the situation is still unfavourable in sub-Saharan Africa and has become worse after the breakdown of communism in the countries of the former Soviet Union because of the lack of resources.

In sugar beet and cotton, which are grown as cash crops, 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 situation applies not only to developed countries, but is especially true for developing countries where food crops generally lack the inputs accorded cash crops such as cotton. 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 pest enemies, pest resistance and secondary pests. However, although pests can develop resistance to pesticides, insensitivity to pesticides hardly contributes to this relationship. On the contrary, changes in cultivation techniques have resulted in higher pest incidence and susceptibility of plants to damage from pests: use of varieties with high yield potential and high susceptibility to diseases; increased, sometimes unbalanced fertilisation increasing and extending susceptibility; large-scale cropping of genetically uniform plants; multiple cropping, reduced crop rotation and/or reduced tillage cultivation increasing the inoculum of pests in the upper soil layer; 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; and the spread and import of pests by human activities into regions without the natural restrictions (climate, enemies, etc.) of the region of origin.

Figures on overall pesticide expenditures per area of arable land may reflect the intensity of crop protection, however, regional figures mask differences within regions and among crops. Pesticide use in West Europe is high because of intensive production in greenhouses, the growth of fruits and vegetables requiring repeated use of pesticides, and the high quality standards of consumers for food and ornamentals. In other regions, ornamentals associated with high pesticide use are hardly grown and the intensity of pesticide use in cash crops like cotton and groundnut is often similar in developing and developed countries, respectively.

5.2. *Perspectives and challenges for integrated pest management*

Global crop production is presently sufficient to feed the human population; however, hunger and malnourishment prevail in some regions because of the uneven distribution of crop productivity and because food demand has both demographic and economic dimensions. The problem of food allocation can be alleviated to some extent by an intensification of crop productivity where the demand is high. Where opportunities are limited because of physical constraints like water availability, temperature, etc. the problem has to be managed globally by improving the supply of food from external sources, whereby, however, the dependence of such regions on these sources is also increasing.

In many regions crop productivity may be increased by high-yielding varieties, improved water and soil management and other cultivation techniques. Increased site-specific yield potentials are often associated with higher vulnerability of crops to pest attack, especially fungal pathogens. Not only do absolute losses soar but loss rates also often rise significantly (Oerke et al., 1994; Oerke, 2000). The increased threat of higher crop losses to pests has to be counteracted by improved crop protection by whatever method, e.g. biologically, mechanically, chemically, or training of farmers and advisors in integrated pest management (IPM). 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 pests damage is economically not justified and ecologically harmful because the amount of production necessary has to be produced on a larger area which otherwise could be handed over to nature.

The rate of economically acceptable crop losses in most field crops is well above zero and the overall losses in the US crop production have been estimated at 37% (Yudelman et al., 1998). Some crop losses cannot be avoided for technological reasons (or availability of technology in developing countries), others are not or will not be available because of ecological hazards (e.g. soil disinfectants). In many cases, however, higher pesticide use in order to produce extra yield is economically not justified because environmental factors other than pests, especially the availability of water, are yield-limiting. Therefore, although a drastic reduction of crop losses is highly desirable for many regions from the point of view of feeding the human population, pest control and the use of pesticides in particular are applied according to the economic benefits to the farmer. The concept of economical sound use of pesticides should, on the other hand, result in lower pesticide use when crop prices are falling, as exemplified for cereals in Western Europe.

Integrated pest management includes various techniques suitable to maintain pest infestations below economically acceptable levels rather than attempting to eradicate all pests. According to US Department of Agriculture (USDA, 1993) 'IPM is a management approach that encourages natural control of pest populations by anticipating pest problems and preventing pests from reaching economically damaging levels. All appropriate techniques are used such as enhancing natural enemies, plant pest-resistant crops, adapting cultural management, and using pesticides judiciously'. Programs have been developed to reduce the dependency of production on synthetic pesticides, to minimise the effect on the environment and to maintain the efficacy of crop protection products in order to enable sustainable crop production at higher intensities.

IPM programs have been established in various crops around the world and have proven their suitability in developed and developing countries (Fernandez-Cornejo, 1998; Cuyno et al., 2001). IPM is successfully practised in perennial and annual crops in temperate and tropical conditions for the control of all pest groups, especially insect pests and fungal pathogens (Way and van Emden, 2000; Berg, 2001; MacHardy, 2000; Verreet et al., 2000). Expanding the acceptance and use of IPM onto a larger percentage of production area would enhance sustainability and productivity of the world food system.

Especially in developing countries where food supply often suffers from poor crop production technology and crop losses are high-despite of low yield potentials—due to inadequate pest control, the necessary intensification of food production can be realised only by the responsible implementation of IPM into cropping systems reducing the probability of catastrophic pest losses and minimising environmental degradation. It requires (a) development of IPM models also for the key pests in crops grown for domestic consumption, e.g. cassava, millets, leguminosae; (b) teaching and training of farmers—e.g. in Farmer Field Schools—and distributors of pesticides and the build-up of extension services by GOs and NGOs; (c) availability of ecologically sound compounds (in developing countries often obsolete compounds hazardous to man and environment and products with expired registration are used) effective against pests specific to the tropics and subtropics, and formulations suitable for application by farmers under sometimes extreme environmental conditions (heat, relative humidity) and/or with poor equipment.

Pesticides may be used in order to complete the methods for pest control; preventive strategies like crop rotation, cultivation techniques and the use of adopted cultivars should have priority. Host-plant resistance is often more effective than pesticides use and may reduce pesticides as exemplified for rice production in PR China by Widawsky et al. (1998). Also the use of genetically engineered crops has been reported to decrease pesticide use significantly in both, developed and developing countries (Huang et al., 2003; Qaim and Zilberman, 2003) thereby producing positive health and environmental impacts. Health hazards—especially in developing countries—result from the use of pesticides by farmers who are not aware of their exposure or lack proper knowledge and training. Average toxicity and environmental impact of pesticides often decrease with the adoption of IPM, especially for the use of insecticides (Fernandez-Cornejo, 1998). Evaluations of farmers using IPM programs have generally found an insignificant effect on yield, a small increase in profit, and a reduction in environmental risk associated with lower use rates or improved timing of application (Brethour and Weersink, 2003). For several IPM systems a win–win outcome has been reported as the productivity of farmers increases and negative effects on the environment are reduced (i.e. Antle et al., 1998; Heger et al., 2002).

In many developed countries, e.g. Sweden, the Netherlands, Canada, as well as in intensive rice production in Southeast Asian countries like Indonesia, governments have implemented national and international pesticide regulation programs; in addition to strict regulation of pesticide re-registration the introduction of IPM systems has contributed to a significant reduction of the pesticide use per unit of area without affecting crop productivity nor increasing the probability of crop losses. In Germany, the average amount of pesticides applied per unit of arable land decreased from $3.65\,\mathrm{kg\,ha^{-1}}$ in 1987 to $1.64\,\mathrm{kg\,ha^{-1}}$ in 2001 (Schmidt, 2003). Analysis of variables like the amount of active ingredient applied or money spent on pesticides may be used only as a first approximation, because the dosage of active ingredients is not closely related to environmental activity, and environmental friendly, innovative compounds are often more expensive than obsolete, hazardous ones. The environmental benefits from IPM systems are largely due to the reduction in the level of high and moderate-risk pesticides (Brethour and Weersink, 2001).

In some developed countries as well as in cash crops like cotton the use of IPM strategies should be expanded in order to reduce pesticide use to a minimum level safeguarding production and simultaneously preventing hazards to the environment. In some cases farmers may be forced to use IPM programs in order to meet the requirements for the export of cash crops like groundnut and cotton to developed countries with high quality standards and low tolerances for pesticide residues.

Some pest problems are still unsolved or control has become even more difficult because of environmental concerns; this applies especially to nematodes and soil-borne fungal pathogens and viruses in areas where crop rotation is not suitable for economic or ecological reasons. The sustainability of these production systems is at risk and needs innovative solutions.

Because the best land has already been cultivated, the amount of land dedicated to agriculture may have to increase disproportionately to the gain in global food production. Furthermore, as the availability of water for irrigation is limited—and is actually declining in some areas (Kishore and Shewmaker, 1999)—the efficiency of irrigation has to be improved in order to increase the productivity per unit of land (Dyson, 1999). It is only in that way that the detrimental effects of increasing food production on sustainability of agro-ecosystems as well as on non-agricultural ecosystems can be limited.

Pesticides have been classified as irreplaceable at present in Denmark (Jorgensen et al., 1999) as well as by the US National Research Council (Anonymous, 2000). The availability and diversity of food for all people—at least for the poor—would be endangered if crops were to be produced without the chemical control option. In some cases, the reliance of crop production on chemical control may be reduced. However pesticide-free production would be a disaster in other crops, especially fruits and vegetables (Knutson et al., 1997) because (a) genetic resistance is often overcome by animal pests and pathogens, (b) the efficacy and reliability of biocontrol agents is limited, and (c) today manual weed control cannot be expected from farmers in most regions, the use of synthetic pesticides is often unavoidable and its significance is projected to increase, especially in developing countries. However, an increase in the efficacy of pest control does not depend on an increase in the amount of pesticides used, but primarily on the targeted application of suitable products when needed—based on the knowledge of the farmers and advisors. For that purpose, environmentally sound pesticides of high activity and specificity have to be used in IPM systems in order to have available a diversity of tools for maximising flexibility, precision and stability of pest management in agriculture.

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