Food, Agriculture,
and the Environment
Discussion Paper 25

Pest Management and Food Production

Looking to the Future

Montague Yudelman

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David Nygaard

INTERNATIONAL
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Contents

Foreword	v
1. Introduction	1
2. Estimates of Crop Losses from Pests	3
3. Chemical Pesticides: Past and Future Growth and Their Impact on Reducing Losses	9
4. Negative Aspects of Pesticide Use, and New Technologies and Future Trends	15
5. Nonchemical Technological Approaches	23
6. Integrated Pest Management	34
7. Conclusion	40
References	45
Appendix 1: Recommendations of a Workshop Held at IFPRI in 1995	50
Appendix 2: Workshop Participants and Papers Presented	52

Tables

1. Crop loss due to rice pests in various countries 6
2. Actual production and estimated losses for eight crops during 1988–90, by pest and region 7
3. Actual global production of eight major crops and estimated losses, 1988–90 8
4. Regional pesticide market shares, 1992 10
5. World pesticide consumption, 1983–98 10

Boxes

1. Pests 4
2. Pesticides 9
3. Biological Control: Cassava in Africa 25
4. The Case of Biopesticides in India 29
5. Cuba's Technological Change: From Conventional to Alternative Agriculture 30
6. Defining IPM 35
7. IPM in Indonesia 37

Foreword

With continued population growth and income increases, global demand for food is expected to increase substantially during coming decades. Meeting increased food needs will call not only for increasing food production but also for minimizing losses to pests before, during, and after harvest. Tremendous improvements have been made in increasing productivity, but when a significant proportion of the food produced is damaged by pests before it can reach the consumer, it behooves us to pay closer attention to the role of pest management in assuring global food security.

In their comprehensive paper, Montague Yudelman, Annu Ratta, and David Nygaard examine the key issues with regard to pest management and food production over the coming decades. They draw attention to the lack of adequate information on the magnitude and impact of pest losses; without such information, policymakers are handicapped when devising strategies for meeting food needs. The authors address both chemical and nonchemical approaches to pest management, highlighting the importance of biotechnology. There is growing public sentiment against biotechnology but little appreciation as yet of its contributions to alleviating hunger by, among other things, controlling pest losses. The authors also address the important subject of the roles of different actors in pest management, most notably the private sector.

A world without pests is unrealistic and probably undesirable. However, a world with severely reduced losses of food production to pests is achievable by 2020. This paper shows us how.

Per Pinstrup-Andersen
Director General, IFPRI

1. Introduction

The supply of food—especially grains—in the developing countries will have to rise by around 70 percent by 2020 if the 6.5 billion people who are expected to be living in Africa, Asia, and Latin America by then are to be food secure (Yudelman 1998b).[1] Nearly all of this in)crease in food supply is expected to come from the developing countries themselves. Increasing food production by as much as 70 percent by 2020 will be a formidable task. Nonetheless, it can be done, provided governments adopt appropriate policies and allocate increased resources for agricultural development, including additional resources from multilateral and bilateral donors. Meeting the projected goal will require a sustained rise in yields of the major grains and legumes grown by hundreds of millions of small-scale producers in Africa, Latin America, and Asia (Yudelman 1994 and 1998b).

Attaining substantial increases in average yield per acre will be more difficult than in the recent past. Prospects for expanding low-cost irrigation, one of the driving forces facilitating yield increases, are becoming more limited as are the prospects for converting marginal lands into productive arable land. More significantly, the highly productive yield-increasing technologies introduced over the past three decades are already being used on much of the land under production (especially in Asia). There are indications that these technologies may be reaching a point of diminishing returns. While there has been rapid progress in developing some new technologies, such as genetically engineered, yield-increasing transgenic plants, there is some question whether the new technologies can be a major factor for increasing food production in the developing countries by 2020 (Ruttan 1991). Consequently, future strategies will have to focus on raising productivity by using available resources more efficiently than in the past. There could hardly be a less efficient use of these resources than to invest time, money, and effort in producing food only to have it totally, or partially, destroyed by pests. Depending on the levels of losses and costs involved, pest management would seem to be an important strategic component for promoting the more efficient use of resources and thereby increasing available supplies of food in developing countries.

This paper is intended to highlight some of the issues involved in improving pest management in developing countries, which are mostly in the tropics (where ecological conditions differ from those in the temperate zones). The focus here is on preharvest losses. Unfortunately, there is not much reliable information available on many aspects of the costs and benefits of reducing plant losses. The shortage of information includes basic data about the extent and value of crop losses due to pests in all their forms. There is also a shortage of reliable scientific and economic information on the impact of the use of modern pesticides, not only on reducing crop losses, but also on human health and the environment. This is all the more regrettable as one of the central issues regarding pest management is the future role of chemical pesticides in such strategies as integrated pest management (IPM), which attempts to reduce crop losses with a minimum of

[1]This paper is based on information gathered by the authors during some of their field assignments, as well as on secondary research and discussions at a workshop called “Pest Management, Food Security, and the Environment: The Future to 2020,” held at IFPRI from May 10 to 11, 1995. Experts from agricultural, research, environmental, and industrial groups attended the workshop (see Appendixes 1 and 2 for a list of workshop recommendations and participants).

harmful side effects. There is also limited information about another major issue in the future of pest management—the role of biotechnology in crop management in the tropics. The latter limitation stems, in part, from the fact that the development of this technology is in the private sector, which has its proprietary interests. Also, the path of development has been so rapid that available data have soon become outdated.

The paper begins with a look at some estimates of the magnitude and nature of crop losses to pests in recent decades. Thereafter, the paper considers strategies and approaches that have been used to manage pests, starting with chemical pesticides—their rapid increase in use, their effectiveness, the negative side effects from their use, the circumstances that encourage their use, and the paradox of increased use of pesticides and ever greater losses from pests. This is followed by a discussion of "nonchemical" strategies, including plant breeding and the use of biological control agents and biopesticides, and the constraints on their use despite their many desirable characteristics. The potential gains from the use of genetically engineered crops are also discussed. The next section considers IPM as a strategy for reducing pest losses. This strategy combines the nonchemical and chemical inputs in order to sustain yields while minimizing possible harmful side effects from the use of chemicals. The conclusion considers the four important issues that will confront policymakers in the years ahead: the need to improve knowledge about pest losses, the need to limit and regulate the use of chemical pesticides, the importance and difficulty of promoting integrated pest management, and the importance of exploiting the great potential of biotechnology in developing countries. The chapter ends with a final comment on the importance of encouraging the private sector to sustain its very substantial investment in research and development to produce effective and socially acceptable inputs for agricultural development in general and developing countries in particular.

2. *Estimates of Crop Losses from Pests*

The Nature of the Data

A wide array of pests constrains agricultural production, especially crop production. These pests include animals, pathogens, weeds, and insects (see Box 1). Their distribution and frequency of appearance depend on a complex set of ecological, agroclimatic, and socioeconomic conditions. Changes in patterns of crop production also influence the size and frequency of appearance of pest populations. Crop losses to pests have always been part of the natural ecology and a by-product of the diversity of nature. Historically, there have been major infestations—such as the destruction of the Irish potato crop by blight in the 1840s—but massive losses from pests and plagues have been exceptions more than the general rule. Pest-induced losses have ebbed back and forth as part of a "natural order of things." Prior to World War II, most agriculture in developing countries was based on traditional systems of production that yielded a small surplus but held down the ratio of pest losses to production through natural checks and balances and farm management practices. These practices included multiple cropping, crop rotations, and shifting cultivation that permitted natural predators to limit the losses from pest infestations. However, in the years following World War II, increased trade and commerce led to the spread of pests of all kinds into ecologies without natural enemies. Crop losses increased. Also, growing human population, increasing pressure on the land, and expanding market opportunities led farmers in developing countries to intensify their production. Output was raised by using high-yielding varieties of grains, along with fertilizers and regular supplies of water. Yields of the major grains, especially wheat, rice, and maize, rose rapidly. In order to increase their returns, many farmers shifted to monoculture and continuous cultivation. Losses from pests rose, but with high yields it became economical for farmers to use purchased inputs, including chemical pesticides, to reduce these losses.

Relatively reliable data on crop losses exist for North America, Europe, and Japan, but not for developing countries. Few governments in developing countries have systematic research and monitoring programs to generate a sound basis for assessing losses. Much of the data that are available are based on a limited number of site-specific tests. Many of these tests have been conducted or supported by pesticide manufacturers and are intended to compare crop losses over one season with and without the application of particular pesticides. The tests have provided useful but limited information on specific pesticides and losses. Other fragmentary data have come from field tests by some governmental and nongovernmental organizations, agricultural colleges, and the like, as well as by researchers working under the aegis of the Consultative Group on International Agricultural Research (CGIAR). An added difficulty in estimating overall crop losses in developing countries is that there have been, as yet, only limited efforts to develop acceptable methods (and models) for extrapolating regional, national, or even international assessments of crop losses from scanty data.

Agroecological circumstances also make it difficult to estimate pest-related damage in agriculture. One such difficulty stems from natural factors: pest infestations often coincide with changes in climatic conditions such as early or late rains, drought, or increases in humidity, which in themselves can reduce output. In these circumstances, attributing losses to pests *per se* can be misleading. Determining the extent of losses from pests among small

Box 1 Pests

Pests are usually defined as any insect, rodent, nematode, fungus, or weed, or any other form of terrestrial, aquatic plant, or animal life, or virus, bacteria, or other microorganism that harms or kills crops. Pests can reduce the value of crops before and after harvests.

Pests can be classified as

1. *Vertebrates:* all animals, including birds. Generally, animals have inflicted less damage than other categories of pests, though they can be devastating in some circumstances. Rodents cause heavy losses in rice- and sugar-growing areas in Southeast Asia, while "kwela-kwela" birds take a heavy toll on sorghum and millet grown in East Africa.
2. *Insects:* there are possibly as many as 5 million species of insects, of which there are some 70,000 known species. Insects include *Aculiata* (ants, bees, wasps), *Phasmidia* (leaf insects and stick insects), and *Trichoplira* (caddis flies). Insects flourish in all climates—locusts and midges are active in semi-arid areas, while the brown plant hopper has devastated rice harvests in the moist tropics.
3. *Weeds* are a universal problem and include any wild plant, especially those competing with crops for soil nutrients and space. In general, the ecology of weeds is one of the more obscure aspects of pest management as weeds tend to be site-specific and are difficult to deal with.
4. *Pathogens* include any agent capable of causing diseases among crops. Pathogens include viruses, bacteria, fungi, and helminths. Pathogens flourish in the tropics, so the incidence of diseases in basic food crops, such as maize, is much higher in Africa than in other regions (the maize streak virus, which has been a major problem, now appears to be under control). By and large, pathogens have been the most difficult of pests to control, especially in the tropics. Plant breeding of resistant and well-adapted varieties has contributed significantly to the reduction of potential losses from pathogens in both the developed and developing countries.

Two "man-made" activities have changed the incidence and importance of pathogens, animal pests, and weeds. These are

1. the expansion of worldwide trade in food and plant products, which has increased the impact of pests and diseases; and
2. changes in cultural techniques, particularly the intensification of cropping, reduction in crop rotations, and increase in monoculture, all of which have increased the activity of pests.

farmers in developing countries also poses special problems. The lack of any farm records, the absence of well-defined acreage planted to different crops, and the practice of shifting cultivation all contribute to the difficulties. Additional challenges arise in estimating losses when there are periodic or migrating pest outbreaks, such as locust invasions in parts of Africa, that may destroy a crop in one year but only cause marginal losses in other years. (In these circumstances, "average" annual losses may have little meaning.) Where data have been assembled, they are often presented as the percentages of attainable output lost to pests. This expression of crop loss raises the question of what constitutes attainable output and what is the extent to which pests or other man-made factors, such as poor farm management, contribute to the departure from the attainable norm. Ascribing all shortages to pests may well exaggerate the estimates of pest-induced losses.

The use of percentages adds to the complications in weighing the significance of losses from pests, because traditional low-yield crop varieties usually suffer lower pest losses in percentage terms than do modern high-yield varieties. Thus, when pest losses are compared in percentage terms, high-yield varieties will seem worse off than traditional low-yield varieties, but this may be misleading. Native varieties of upland rice in the Philippines suffer pest losses as low as 2 percent, and the high-yielding varieties in the area have pest losses up to 24 percent according to the International Rice Research Institute (IRRI). But because the yield of the native variety is only about 200 kilograms per hectare, the ouput per hectare of high-yielding varieties is still higher than the native varieties (Way 1990).

The difficulties of deriving a reliable estimate of pest-induced annual crop losses can be illustrated by examining some of the published estimates of losses for one crop—rice. Rice is grown primarily in developing countries and is the most important crop grown and consumed in Asia. More pesticides are used on rice than on any other food crop in developing countries. The extent of pest-induced rice losses can have a major bearing on the food security of more than 2 billion people. Yet, estimates of annual losses of rice vary so widely by year and by country that it is difficult to get a sense of the magnitude of the losses of this important crop.

IRRI, the major repository for information on rice production in the tropics, has sponsored field research on pest losses and improving pest management. One of its publications (Rola and Pingali 1993) includes information on a number of studies by different researchers on losses in rice from pests, primarily insects (Table 1). These estimates of crop losses varied widely by location and year. Estimated annual losses ranged from 6 percent a year in Bangladesh to 44 percent a year in the Philippines. Crop losses from one pest—stemborers—ranged from 3 percent in India to 95 percent in neighboring Bangladesh. In contrast, estimates of crop losses due to other major insect pests—leaf and plant hoppers— ranged from 1 percent in India to 80 percent in Bangladesh. Estimates of losses have also varied widely over time within the same country. For example, estimates of losses in the Philippines ranged from 25 percent in 1973 to between 35 and 44 percent in 1991, and then as low as 9 percent in recent years. Some of the differences in these estimates of crop losses, such as those in the Philippines, can be traced to differences in methodologies for making estimates. Other differences in the estimates between countries and over time stem from the changes in climatic and ecological conditions that prevailed in different countries and years; yet other differences can be explained in good part by the short-term impact of introducing pest-resistant varieties and pesticides in some countries but not others.

The authors of the IRRI study contend that, based on their own experience, most estimates tend to exaggerate losses. In their experience, researchers and policymakers perceive pest losses to be higher than do farmers, who, in turn, usually perceive pest losses to be higher than they actually are. Their view, which is consistent with the views of the authors of this paper, is that "despite rapid changes in pest ecology from the intensification of low-land rice production and the perceived importance of pest losses for crop production, surprisingly little systematic work has been done to assess yield-loss relationships (even by IRRI)." Rola and Pingali suggest that, "barring major infestations, less than 10 percent of yield losses in rice in the Philippines can be attributed to insect pest damage in a normal year. Studies that show very high pest-related yield losses have invariably covered too short a time period to determine the damage distribution or have failed to differentiate adequately between resistant and susceptible varieties." The authors go on to add that "both farmers' and policymakers' perceptions of pest-related yield losses are anchored around exceptionally high losses during major infestations even when the probability of such infestations is low." They conclude, not surprisingly, that efforts should be made to improve policymakers' perceptions of yield losses in order to avoid the introduction of misguided policies such as those that encourage the use of pesticides through subsidies (Rola and Pingali 1993).

Other estimates of crop losses, especially in regions where much of the production is for subsistence, are problematic. In parts of Africa, agencies concerned with the marketing of internationally traded crops such as tea, sisal, cotton, coffee, and cocoa, have their own agents keep track of losses and the size of harvests. Estimates of losses of food crops grown primarily by smallholders for their own consumption and sale on local markets, however, are usually based on casual observations by field officers or by visiting experts. Most of these estimates have little scientific validity. Nonetheless, once an estimate of losses has been made, it tends to become entrenched. Estimated losses from pests in a number of African countries have been "fixed" at about 30 percent for several decades (Yudelman 1998a).

Global Estimates

The fragility of estimates of losses in a major crop such as rice confirms that estimates of global losses from all crops indicate, at best, only some order of magnitude. There have been a handful of valiant efforts to provide *some* measure of global losses, notably by Cramer in 1967 and, more recently, by the Food and Agriculture Organization of the United

Table 1 Crop loss due to rice pests in various countries

Pest and country	Crop loss	Reference
Stem borers		
Bangladesh		
Outbreak	30–70%	Alam et al. 1972
No outbreak	3–20%	Alam 1967
India	3–95%	Ghose et al. 1960
Indonesia	up to 95%	Soenardi 1967
Malaysia (North Krian District)	33%	Wyatt 1957
Philippines	6.6%	Barr et al. 1981
Leafhoppers and planthoppers		
Bangladesh (leafhoppers)	50–80%	Alam 1967
Malaysia (brown planthoppers)	M$10 million	Lim et al. 1980
India	1.1–32.5%	Jayaraj et al. 1974
Rice bugs and gall midge larvae		
India	10%	Pruthi 1953
India	12–35%	Reddy 1967
Viet Nam	50–100%	Reddy 1967
Blast		
India	1% (1960–61)	Padmanabhan 1965
Japan	3% (1953–60)	
Korea	epidemic levels (mid-1970s)	
China	8.4% in 1980, 14% in 1981	Teng 1986
Philippines	50–60% (1963)	Nuque 1963, Nuque et al. 1983
Philippines	70–85% in certain cultivars (1969–70)	Nuque 1970
Tungro		
Malaysia	1% (1981–84)	Heong and Ho 1987
Malaysia	M$21.6 million in 1982	Chang et al. 1985
Indonesia	21,000 hectares in 1969–71	Reddy 1973
Bangladesh	40–60%	Reddy 1973, Wathanakul and Weerapat 1969
Thailand	50%	Reddy 1973, Wathanakul and Weerapat 1969
Philippines	30% (1.4 million tons) per year (1940s)	Serrano 1957
Philippines	456,000 tons of rice (1971)	Ling et al. 1983
Bacterial blight		
Japan	300,000–400,000 hectares per year (recent years) (20–30% in severely affected areas)	
India	6–60%	Srivastava 1967
China	6% (1980), 4.9% (1981)	Teng 1986
Sheath blight		
Japan	24,000–38,000 tons per year	National Institute of Agricultural Sciences 1954
Japan	20%	Mizuta 1956
Japan	25%	Hori 1969
Philippines	7.5–22.7% in high-N plots planted to a susceptible variety and 0.4–8.8% and 2.5–13.2% with moderately resistant varieties	Ou and Bandong 1976
Sri Lanka	10% of rice tillers in one district	Abeygunawardane 1966
China	12% in 1980; 9.1% in 1981	Teng 1986

Source: Rola and Pingali 1993 and Teng et al. 1990.
Note: All tons are metric tons unless otherwise noted.

Nations (FAO) 1975, Pimentel 1992, and Oerke et al. 1996.

The most recent and comprehensive of these estimates are those made by Oerke and his colleagues in 1995. They studied eight important crops (wheat, corn, rice, barley, soybeans, cotton, potatoes, and coffee) that together accounted for half of the area used to grow crops worldwide and more than US$300 billion in annual output between 1988 and 1990. Their estimates are of the average annual value of losses of attainable production attributable to pests in 1988–90. Although the number of crops covered in this analysis is limited to eight, the depth of the analysis is much greater than that of previous studies. The estimates of crop losses were derived from published and unpublished literature, including a substantial volume of data from pesticide manufacturers, expert opinion, and data from developed countries modified to reflect conditions in developing countries. The values in this study were adjusted to take account of the standards of acceptability of pest-damaged products. These standards are much stricter in upper-income countries, such as the United States, than in poorer countries.

The study concluded that "despite the cultural, manual, biological, and chemical methods being used to protect these eight crops, about 42 percent of attainable annual production is a loss as the result of pests." The largest losses of potential output were caused by insects (15 percent), followed by pathogens (13 percent), and weeds (13 percent). With postharvest losses due to pests adding a further 10 percent to the preharvest annual losses, pest-induced losses of these important crops were estimated to be more than half of attainable output.

The study's analysis of crop losses by region showed that production losses as a percentage of attainable production in Europe (28 percent), North America (31 percent), and Oceania (36 percent) were well below the averages for Africa and Asia, which had losses just below 50 percent—the highest proportion of losses for developing countries (Table 2). By far, the largest losses of attainable production were for rice (51 percent), with estimated losses in the rice harvest from insects being much higher than the "normal" average loss of 10 percent postulated in Rola and Pingali 1993. The second largest losses were for coffee (40 percent). Losses from crops grown predominately in tropical developing countries were higher than those from crops such as wheat, maize, barley, and soybeans that are largely grown in the temperate regions (Table 3).

The earlier studies by Cramer, Pimentel, and FAO, each with different coverage of crops and using differing methodologies, give somewhat similar orders of magnitude of crop losses. Pimentel 1992, for instance, placed global crop losses at about 35 percent, with insect pests causing an estimated 13 percent of crop loss, plant pathogens another 12 percent, and weeds 10 percent. FAO (1975) also placed global losses at around 35 percent, as did Cramer (1967) (counting 60 crops). FAO estimated that preharvest losses in developing countries were around 40 percent, while postharvest losses added a further 10 to 20 percent.

Table 2 Actual production and estimated losses for eight crops during 1988 90, by pest and region

Region	Actual Production	Losses due to: Pathogens	Insects	Weeds	Total	Total attainable production
		(US$ in billions)				
Africa	13.3	4.1	4.4	4.3	12.8	26.1
North America	50.5	7.1	7.5	8.4	22.9	73.4
Latin America	30.7	7.1	7.6	7.0	21.7	52.4
Asia	162.9	43.8	57.6	43.8	145.2	308.1
Europe	42.6	5.8	6.1	4.9	16.8	59.4
Former Soviet Union	31.9	8.2	7.0	7.0	22.1	54.0
Oceania	3.3	0.8	0.6	0.5	1.9	5.2

Source: Oerke et al. 1995.
Note: Actual production plus total losses equals total attainable production (see the last column).

Many questions can be raised about the data, scope, and methodology used in deriving these global estimates, which should be seen as pioneering efforts giving some order of magnitude of losses. In the absence of evidence to the contrary, the estimates do indicate that crop losses in the world are anywhere between one-third and one-half of attainable crop production; they also indicate that crop losses are a higher percentage of output in the developing countries than in the developed countries—with a substantial absolute value of crop losses in Asia (Table 2). The largest pest-induced losses in food crops seem to be in rice, along with substantial losses in corn and potatoes—important food crops, especially for the poor in Africa and Latin America. The largest pest-induced damage seems to be caused by insects, followed by pathogens and weeds (Table 3).

Table 3 Actual global production of eight major crops and estimated losses, 1988 90

Crop	Actual production	Losses due to				Total attainable production
		Pathogens	Insects	Weeds	Total	
		(US$ billions)				
Rice	106.4	33.0	45.4	34.2	112.5	218.9
Wheat	64.6	14.0	10.5	14.0	38.5	103.1
Barley	13.7	1.9	1.7	2.0	5.7	19.4
Maize	44.0	7.8	10.4	9.3	27.4	71.4
Potatoes	35.1	9.8	9.6	5.3	24.8	59.9
Soybeans	24.2	3.2	3.7	4.7	11.6	35.8
Cotton	25.7	4.3	6.3	4.9	15.5	41.2
Coffee	11.4	2.8	2.8	2.0	7.6	19.0

Source: Oerke et al. 1995.
Note: Actual production plus total losses equals total attainable production (see last column).

3. Chemical Pesticides: Past and Future Growth and Their Impact on Reducing Losses

Current Pesticide Use

Farmers use a wide range of chemical pesticides to limit losses from pests in agriculture (Box 2). Inorganic agents such as copper and sulphur were used in Europe in the 19th century to control mildew and other fungi. The first synthetic pesticide used was dinitro cresol, marketed in 1892. During World War II, dichloro-diphenyl-dichloro-ethane (DDT) and a few other synthetic pesticides were used primarily for killing vermin to protect public health. Immediately after the war, farmers in developed countries started using DDT and related hydrocarbon insecticides. Parathion, a by-product from efforts to develop a war gas, was also found to have suitable properties as an insecticide, and its use quickly spread in world agriculture. The first herbicide developed was 2–4D, the use of which also began shortly after the war. Over time, chemical pesticides became part of most intensive agricultural packages, along with high-yielding varieties, irrigation, fertilizers, and mechanization.

Box 2 Pesticides

There are close to 50,000 pesticide products now registered for use with the United States Environmental Protection Agency. Pesticides are commonly classified according to their intended target organism: insecticides, herbicides, fungicides, nematicides, rodenticides, and miticides. They are also classified according to their intended use: defoliants, desiccants, fumigants, and plant growth regulators.

Before World War II, pesticides consisted of products made from natural sources such as nicotine and pyrethrum, as well as from inorganic chemicals such as sulphur, arsenic, lead, copper, and lime. After World War II, synthetic pesticides were made from chemical compounds that included “active ingredients” that killed pests.

Since the 1950s, the use of organic pesticides has been superseded by synthetic chemical pesticides. The introduction of new active ingredients has extended the range of available crop agents. Over the past 50 years, the pesticide industry has attempted to develop pesticides that are less toxic and more selective in their targets, require lower dosage per hectare, and have less persistence, all of which reduce the contamination of the soil. The industry has made considerable progress in this area with the introduction of less persistent compounds as a substitute for organo chlorinu in insecticides; the introduction of systemic fungicides that allow fungi to be controlled within plant tissues even when those tissues have not been sprayed directly; and the introduction of herbicides that have a broad spectrum of action and can be used against the reemergence and postemergence of weeds.

In general, the compounds used in pesticides have been characterized as having passed through three generations, with each generation providing greater environmental security. The use of the third generation compounds, with their greater safety, is confined primarily to the developed countries, while compounds of the first and second generation are still widely used in most developing countries.

The most striking advances have been made in the decrease of application rates per hectare, thereby reducing the volume of pesticide needed and the potential for exposure to the chemical. These advances have been made possible because of greater toxicity per kilogram than in earlier pesticides such as DDT. Improved formulation and application techniques have contributed to a fall in the typical application rates of herbicides from 3,000 grams per hectare in 1966 to 100 in 1987, with insecticides falling from 2,500 grams per hectare in 1965 to 20 in 1982, and fungicides from 1,200 in 1961 to 100 in 1991. Since the persistence of most of the newer compounds is lower than those in use 50 years ago, there has been less contamination of soils; however, there is some question as to whether the less persistent pesticides are more harmful to the natural enemies of pests—especially insect pests—than are the older, more persistent pesticides like DDT (Waage 1995).

At present, pesticides are mainly used in the form of herbicides, insecticides, and fungicides. As shown in Table 4, herbicides account for the largest share of total pesticide sales. In 1992 herbicides made up more than 40 percent of all sales, followed by insecticides (30 percent) and fungicides (20 percent). The largest amount of herbicide use was in North America, while the largest amount of fungicide use was in Western Europe, followed by Japan. Insecticides are the main form of pesticides used in the developing countries. About 85 percent of the total pesticides used in the world are used on fruits and vegetables, rice, maize, cotton, and soybeans. In the developing countries, pesticides are used primarily on high-value crops, most of which are export crops. Cotton is a large consumer of pesticides—95 percent of the pesticide used in West Africa and 50 percent of that used in India is applied to cotton. In recent years, pesticides have been used increasingly on rice. As yet, though, relatively little pesticide is used on most of the basic, subsistence food crops (other than rice and, to a lesser extent, potatoes) grown primarily by small-scale producers. At present many millions of these producers, especially in South Asia and Africa, are too poor to purchase agrochemicals of any kind.

The Growth and Distribution of Pesticide Consumption

The consumption of pesticides has increased rapidly over the past 50 years. Starting from a very low base in the 1950s, consumption grew by more than 10 percent a year until the early 1980s. Since 1983, consumption has grown from around US$20 billion a year to US$27 billion in 1993—an annual average increase of 3 percent a year. One set of projections suggests that consumption will reach around US$34 billion by the end of 1998, an increase of 4.4 percent a year since 1983 (Table 5). While the current economic crisis in East Asia may dampen the demand for pesticides in the near future, there is every reason to expect the growth rate to rise by 2020, especially in the developing countries.

While pesticide use has spread very rapidly since the 1950s, the spread has been uneven. At present, pesticides are used only on about one-third of the cropped areas of the world. More than 50 percent of the global consumption of pesticides takes place in North America and Western Europe, regions that contain about 25 percent of the global cropland; on the other hand, around 20 percent of this global consumption occurs in developing countries on 55 percent of the world's agricultural land. The actual and projected patterns of distribution and consumption of pesticides have changed marginally over the past 15 years (Table 5). By and large, the only significant changes in the market between 1983 and 1998 are the projected increase in North America's share of the global market from 15.4 percent in 1983 to an expected 26.3 percent in 1998, and the projected drop in Western and Eastern Europe's shares from 28.5 percent and 14.1 percent in 1983 to an expected 26.3 and 9.3 percent, respectively, in 1998. Latin America's share is ex-

Table 4 Regional pesticide market shares, 1992

Region	Herbicides	Insecticides	Fungicides	Other	Total
			(US$ millions)		
Western Europe	2,921	1,180	2,030	597	6,728
Eastern Europe	440	450	210	60	1,160
North America	4,825	1,600	554	368	7,347
Latin America	1,140	710	460	100	2,410
Japan	1,095	1,200	1,170	80	3,545
Far East	801	1,250	359	190	2,600
Others	218	1,010	117	65	1,410
Total	11,440	7,400	4,900	1,460	25,200

Source: Wood MacKenzie Co., Ltd., 1993, cited in USAID 1994.

Table 5 World pesticide consumption, 1983 98

				Compound annual growth rate	
Region	1983	1993	1998	1983 93	1993 98
		(US$ millions)		(percent)	
North America	3,991	7,377	8,980	6.3	4.0
Latin America	1,258	2,307	3,000	6.3	5.4
Western Europe	5,847	7,173	9,000	2.1	4.6
Eastern Europe	2,898	2,571	3,190	–1.2	4.4
Africa/Mideast	942	1,258	1,610	2.9	5.1
Asia/Oceania	5,571	6,814	8,370	3.0	4.4
Total	20,507	27,500	34,150	3.0	4.4

Source: Fredonia Group, cited in Agrow 1995c.

pected to rise by around 2 percent, while that of Asia/Oceania is expected to fall modestly from 27.2 percent of global consumption in 1983 to 24.5 percent in 1998. African and Middle Eastern shares of global consumption in 1998 are expected to remain at around 4.7 percent. At present, Holland and Japan, with their highly intensive agriculture, use more insecticides per hectare of arable land (21 kilograms per hectare per year for Holland and 20 for Japan) than other countries. The lowest amount used (less than 1 kilogram per hectare per year) is in Sub-Saharan Africa with its extensive, low-yielding agriculture. Insecticide use appears to be high in Central America. Costa Rica, where intensive agriculture occupies a limited area of arable land, is one of the largest users of insecticides in the developing world on a per hectare basis (7.7 kilograms per hectare)—despite that country's very strong commitment to safeguarding the environment. El Salvador and Honduras also apply pesticides at a high rate (3.7 and 1.6 kilograms per hectare, respectively), primarily in support of intensive fruit and vegetable production (FAO 1986–1996).

The actual increase in the use of all pesticides may be larger than it appears from tonnage or value figures. The toxicity and biological effectiveness of these pesticides has increased at least 10-fold from 1945. For example, in 1945 DDT was applied at a rate of about 2 kilograms per hectare. Similar pest control can be achieved through today's pesticides at the rate of 0.1 kilogram per hectare and even 0.05 kilogram per hectare. In addition, many modern pesticides are less persistent than the older pesticides, while others, such as some insecticides and miticides, are more specific than the older, broad-spectrum products (Box 2). Furthermore, newer herbicides used in conjunction with genetically modified crops are more effective in controlling weeds than earlier products of this kind. Thus, because of improvements in the quality of pesticides, the actual change in the impact or effectiveness of the pesticides may be much greater than the change reflected in the increased rate of pesticide consumption.

However, the change in volume of consumption does not necessarily reflect the amount of pesticide that is actually applied to pests. Partly because pesticide delivery systems are inefficient, the amount of pesticide actually reaching its target varies. Some estimates conclude that only a small percentage of applied pesticides actually reaches the targets. The amount depends on the application technique—aerial spraying has been widely used in developing countries such as Sudan and Egypt (for cotton) and Indonesia (for rice)—but even under ideal conditions less than half the pesticide released in the atmosphere reaches its target and, very often, aerial spraying is carried on under far less than ideal conditions (Backman 1997). Indeed, according to Pimentel and Levitan (1986) less than 1 percent of applied pesticides actually reaches the target pests. There have been efforts to improve delivery systems, including the development of ultra-low-volume sprayers that can be used by small-scale producers. These sprayers apply pesticides in the form of droplets rather than fine spray and can reduce wastage. The effectiveness of this technology, though, depends on the interaction between pesticides and the climate, including the external temperature. Because of difficulties in fine-tuning the equipment, considerable wastage still occurs. Little information exists as to whether the increase in usage of pesticides has led to a parallel increase in the actual amounts applied to pests.

Future Growth in Pesticide Use

A number of prognosticators of the longer-term demand for chemical pesticides anticipate rapidly growing sales in the larger developing countries in Asia and Latin America, as well as in Eastern Europe and the former Soviet Union once they establish a path for agricultural recovery. For instance, one large-scale manufacturer, Zeneca Agrochemicals, projects that developing countries will increase demand for pesticides far more rapidly than will the maturer developed countries. The share of global consumption by developing companies is expected to rise substantially above the current level of 20 percent by early in the next century (Morrod 1995). Others, such as the Pesticide Action Network, a major critic of the pesticide industry, have also projected a steep increase in the developing-country market for pesticides in the years ahead (Dinham 1995). These and other estimates tend to agree that global growth will be driven by increased demand from those larger developing countries that are already among the most rapidly growing markets in the world. These countries include Brazil, which consumes more than US$1.5 billion a year of pesticides, and China, which consumes US$1.3 billion a year and is expected to increase its share of the Asian market substantially in the near future. Demand is also expected to increase in India, where pesticide consumption is relatively low (US$650 million) but has been doubling every five years. African demand, around US$500 million in the early 1990s, is also expected to grow, because a very small proportion of farmers currently use pesticides (a 1991 survey in Uganda, for example, found that only 15 percent of farmers used pesticides and these were mainly the larger farmers) (Kiss and Meerman 1991). Even so, demand in Sub-Saharan Africa is expected to represent a small share of total and developing-country demand.

The prospects for further rapid growth in pesticide consumption will depend on macroeconomic conditions, such as the rate of growth of the global economy and the rate of increase in the demand for agricultural products, including foodstuffs. If demand is strong, increased output will have to come from the intensification of production and increased yields. So long as chemical pesticides are the preferred technological means for reducing crop losses and thereby increasing yields, the consumption of these pesticides will continue apace.

The growth in consumption will also depend on the efforts by governments and other groups to influence farmers on their choice of preferred pest management technologies. Until recently, governments, international funding agencies, and some bilateral donors encouraged the use of chemical pesticides as part of the technology available for raising yields and, in some instances, as part of a process whereby export products could meet international standards. The factors that worked to increase pesticide use included the following:

1. A chemical bias existed in promoting technological change at the farm level. Over the years, many government and international agencies committed themselves to agrochemical solutions to raising yields. They promoted a standard package that included fertilizers and pesticides, with credit and other facilities being made available to producers on the condition that they use the prescribed package.
2. Many governments subsidized pesticide prices directly and indirectly in order to encourage pesticide use (Repetto 1985). Some countries reduced these subsidies in recent years, but the practice of subsidizing pesticide use continues to be widespread, especially in Africa.
3. There was and continues to be a good deal of research, largely sponsored by major agrochemical companies, that demonstrates the direct value to farmers of using pesticides. The pesticide manufacturers and their distributors have aggressive and effective sales campaigns and demonstrations of the efficacy of their product, while the private or public sector appears to have done much less research on alternatives to pesticides.
4. Extension services have promoted the use of pesticides because these chemicals are relatively easy to apply and produce immediate results. Farmers see the immediate gains from using pesticides and, in the absence of any educational efforts, apply the chemicals assiduously, frequently using a far greater volume of pesticides than necessary.
5. There have been only limited efforts outside of Cuba and Indonesia to promote IPM programs intended to reduce the use of chemical pesticides (see Chapter 6). However, even in Indonesia, the site of one of the largest and most aggressive current IPM programs, imports of chemical pesticides have risen substantially.

Thus, while macroeconomic conditions will have a strong bearing on the demand for chemical pesticides in the years ahead, so will government actions intended to influence the choice of pest management. These actions could include vigorous steps by governments to limit the use of chemical pesticides and encourage the spread of integrated pest management.

The Paradox of Increased Pesticide Use and Increased Losses from Pests

The effectiveness of pest management over the past 40 years is linked, in large part, to the effectiveness of chemical pesticides. Oerke et al. (1995) cite several hundred cases where chemical pesticides have reduced losses of many crops. For example, without chemical control of weeds in wheat production, U.S. yields would fall by 30 percent, and without fungicides and herbicides, wheat yields would fall by 5 percent (Knutson et al. 1990). Experiments in Pakistan concluded that herbicides prevented crop losses of 23 percent from weed competition (Qureshi 1981). Other studies make it evident that some crops would have been completely destroyed without the use of chemical pesticides (Farah 1994). Finally, according to the analysis by Oerke et al. (1995), global losses would have risen from present levels of around 42 percent to close to 70 percent in the absence of chemical pesticides.

Pesticide use has been profitable for many farmers and economies. One estimate is that, in the United States in 1997, each US$1 invested in pesticides returned US$4, so that the US$6.5 billion invested in pesticides saved US$26 billion in crop losses (Pimentel 1997). All other things being equal, pesticides have been effective in reducing crop losses. However, despite the substantial increases in the volume and value of pesticide use since the 1950s, there appears to have been very little, if any, decline in the proportion of agricultural output being lost to pests. Some analyses indicate that there have actually been increases in the proportion of crop being lost to pests. According to Pimentel, data from the U.S. Department of Agriculture (USDA) show a 10-fold increase in both the amount and toxicity of insecticide use in the United States from the early 1940s to the 1990s. During the same period, though, crop losses from pests rose from 30 to 37 percent, losses from insects increased from 6 to 13 percent, and losses to plant pathogens from 10 to 12 percent, while losses from weeds decreased from about 14 percent to 12 percent. Increases in losses from pests in the corn crop confirm a perverse ratio between increased use of pesticides and an increased proportion of pest-induced losses. In 1945, when very little insecticide was used, losses were estimated to be around 3.5 percent of the crop, but by the late 1990s when insecticide use had increased 1,000-fold to 14 million kilograms a year, corn-crop losses were estimated to be around 12 percent (Pimentel 1995).

The trend of an increasing proportion of crop output being lost to pests, despite a multi-billion-dollar investment in pesticides, appears to be a global phenomenon. Oerke et al. (1994) compared the estimates of global pest-induced losses between 1965 and 1990 for the eight major crops they studied. The comparison between Cramer 1965 and their own 1990 estimates showed that losses increased during the 25-year period for all crops except coffee, with wheat, potatoes, and barley suffering the largest increases in percentage lost. Given differences in assumptions and methodologies, not too much should be read into the comparisons, but they do tend to confirm that the proportion of crop losses has increased during a period of time when the use of chemical pesticides has rapidly increased.

Despite this perverse relationship, a marginal increase in pesticide use still appears to be profitable. A partial explanation for the paradox is that the industrialization of agriculture and the reliance on agrochemicals has led to changed farming systems that have produced higher yields, but have also led to an increased vulnerability of crops to pests. These changes in production systems include an increase in monoculture and reduction in crop diversity, a reduction in crop rotation, reduction in tillage with more crop residues left on the land surface, the production of crops in climatic regions where they are more susceptible to insect attack, and the use of herbicides that alter the physiology of crop plants, making them more vulnerable to insect attacks (Pimentel 1995). In addition, the increase in use of pesticides has resulted partly from the increased resistance of some pests to pesticides. A further factor contributing to the paradox is that the increased use of pesticides has led to a greater rejection of pest-damaged products as quality controls in the marketplace have become more demanding.

The resolution of the paradox may well come from integrated pest management, which would modify cropping patterns and favor a judicious use of pesticides (see Chapter 6). Reducing the proportion of output lost to pests should enhance food security, though it is wholly unrealistic to attempt to have a "pest-free" agricultural environment. The dynamic relationships that underlie agricultural ecosystems are such that changes in one part of an ecosystem affect the rest of the system. Nature abhors a vacuum, so that eradicating currently recognized pests (if this were possible) would soon lead to the emergence of new and possibly more virulent pests. A more realistic goal would be to reduce pest losses to a socially and economically acceptable level. Such a level, or threshold, could well be where marginal gains from added efforts to control pests would be equal to, or close to, the added costs of implementing these efforts. (Gains in costs would encompass both direct and external components.) Thus, an acceptable threshold of crop losses could well be substantially above zero.

So far, most of the threshold analysis has focused on decisionmaking at the level of the farm, that is, at what level of losses does it pay farmers to apply added inputs of pesticides (Nutter et al. 1993). Sectorwide threshold analyses are beginning to appear, but they are still at the embryonic stage (Rola and Pingali 1993; Vorley and Keeney 1995). They need to be encouraged. But whether analyses of these kinds will be able to guide policymakers in their resource allocations for improving pest management remains to be seen.

Looking ahead, one of the issues that should concern policymakers is that despite the current annual expenditure of more than US$30 billion on pesticides, global crop losses from pests are still relatively high. Losses in developing countries appear to be higher than the global average, possibly being close to half of attainable output. Most of these losses appear to be in the preharvest stages of production rather than in the postharvest stages. While much more needs to be known about the economics of improving pest management, such improvement can and should contribute to increasing the food supply in many developing countries and therefore should be an integral part of national strategies for meeting global food security by 2020. However, the possible gains in production from improved pest management have to be tempered with realism. It is sobering to note that the USDA reports that around 37 percent of crop production in the United States is lost due to pests—thus, losses are relatively high even in the most sophisticated and productive agricultural economy in the world.

4. Negative Aspects of Pesticide Use, and New Technologies and Future Trends

Emergence of Pest Resistance

Pesticides have reduced crop losses, but pesticide use has often led to increased and unnecessary pest outbreaks and additional crop losses because of the inadvertent destruction of natural enemies of the pests and the emergence of both pest resistance and secondary pests. Resistance and increased outbreaks have put farmers on a pesticide "treadmill," leading them to use ever-increasing and stronger pesticides to kill mutating pests. The problem of resistance has worsened over time. In 1938, there were seven insect and mite species known to be resistant to pesticides. In 1984, 477 pests were known to be resistant—several of these being the most destructive pests. Resistant weeds, of which none were known before 1970, numbered near 48 toward the late 1980s (Farah 1994). Some 900 species of insects, pathogens, and weeds exhibit resistance to commonly applied pesticides. To reduce losses farmers in parts of Asia are spraying as much as 800 times the original recommended dosage of pesticides (Farah 1994). Increased spraying to overcome resistance is also common in parts of Central America and Africa (Thrupp 1996).

The use and abuse of pesticides has disturbed the ecological balance between pests and their predators in developed and developing countries. Destruction of beneficial natural enemies of pests that damage U.S. cotton and apple crops has led to the outbreak of numerous primary and secondary pests, including cotton bollworm, tobacco budworm, cotton aphid, cotton loopers, European red mites, San Jose scale, and rosy apple aphid. The additional pesticide applications required to control these pests, plus the increased crop losses they cause, are estimated to cost the United States about US$520 million per year (Pimentel 1995). Even with recommended dosages of 2–4D used on corn in the United States, the impact on nontarget pests has led to a threefold increase in aphids, 35 percent increase in corn borers, fivefold increase in corn smut disease, and total loss of resistance to southern corn leaf blight.

Pest resistance seems to develop more rapidly and is more serious in the tropical climate of most developing countries than in the temperate climates of the developed countries. Nonetheless, there are few illustrations of the harmful use of pesticides that can surpass the damage wrought in the cotton processing areas around the Aral Sea in Russia. Excessive use of pesticides led to increased resistance, which led to increases in the use of stronger pesticides, subsequent increases in costs of production, declines in yields, and finally to the near destruction of the productive capacity of the area. In China, the excessive use of pesticides also increased resistance to many insecticides, so much so that in the worst-affected areas in the Yellow River Valley, cotton production has become completely uneconomical (van Veen 1997). Indiscriminate use of pesticides in countries such as Mexico and Nicaragua has also resulted in the destruction of the cotton crop. In Mexico in the 1960s, the budworm developed resistance to all pesticides and decimated the crop so that land under cotton fell from 280,000 hectares to 400 hectares. In Nicaragua, after indiscriminate amounts of insecticides had been used on cotton crops for 15 years, yields fell by 30 percent over the next four years owing to the development of pest resistance to pesticides (Farah 1994). A further graphic illustration of the harmful effect of pesticides on natural predators comes from Indonesia, where the resurgent brown plant hopper wreaked havoc on the rice harvest in the early 1980s (see Chapter 6, Box 7).

The excessive and indiscriminate use of pesticides also led to development of resistance to pesticides in India. First reported in the case of DDT and benzine-hexachloride (BHC) in 1963, resistance soon spread to chlorinated hydrocarbons and organophosphate-based pesticides. A high degree of resistance in *Herlithesis armigera*, which preys on cotton, chickpea, and pigeonpea, has also developed in recent years. Pesticide use has also contaminated foodstuffs. The average Indian meal is laced with high amounts of toxic pesticide residues; the daily intake of chemicals in the form of pesticide residue is reported to be about 0.51 milligram, well above accepted levels (Alam 1994).

There are cases, also, where pesticides can damage crops. This occurs when the recommended dosages suppress crop growth, development, and yield, or when pesticides drift from the targeted crop to damage adjacent crops. Also, residual herbicides can prevent chemical-sensitive crops from being planted in rotation or inhibit the growth of rotation crops that are planted. Excessive pesticide residues may accumulate on crops, necessitating the destruction of the harvest (Pimentel 1995).

The increase in resistance adds substantially to the indirect costs of using pesticides and lends weight to those who favor pest management systems that pay adequate attention to pest ecology, biological agents, and farmer training, rather than focusing solely on chemical agents to control pests.

Health and Environmental Effects

There is a widespread presumption that chemical pesticides are harmful to human health and the environment (Conway 1995; Backman 1997). As with so many facets of pesticide use, much remains to be learned about the long-term effects of the use and abuse of different pesticides on pesticide users as well as the consumers of products treated with pesticides. Most pesticides, especially insecticides, contain toxic compounds and their impact on health can occur through inhaling, ingesting, contact while spraying, or eating crops with pesticide residues on them. Some pesticides, especially the older types, can cause cancer, birth defects, male sterility, genetic mutations, and behavioral changes. Pesticides can affect human health by causing allergies or breathing trouble or by affecting the liver, kidneys, and nervous system. Airborne pesticides can travel far in the atmosphere and can result in concentration of chemical residues in mothers' breast milk (Repetto and Baliga 1996). Concentration of persistent organochlorine compounds like DDT in the fat of mothers' milk can create health problems for future generations (Repetto and Baliga 1996; Farah 1994). More recently, there has been increasing concern about the effects of pesticides on the endocrine system of both humans and wildlife (WWF 1996; Repetto and Baliga 1996).

A study by the World Health Organization (WHO) in 1972 estimated 500,000 annual pesticide poisonings globally and about 5,000 deaths (Farah 1994). A subsequent WHO and United Nations Environment Programme (UNEP) report estimated that there are 1 million human pesticide poisonings annually, with about 20,000 deaths (WHO/UNEP 1989 in Farah 1994). Another study suggested that occupational pesticide poisonings may affect as many as 25 million people, or 3 percent of the agricultural workforce worldwide each year, and may include 3 million severe poisonings a year with 220,000 fatalities (Jeyaratnam 1987). Poisonings from pesticides appear to be high in developed countries as well as developing countries. The American Association of Poison Control Centers reports about 67,000 pesticide poisonings each year in the United States, including some fatalities (Pimentel 1995), and the Environmental Protection Agency estimates that there are between 10,000 and 20,000 physician-diagnosed cases of pesticide poisoning of agricultural workers each year in the United States. Since many cases go undiagnosed, the actual number of cases of pesticide poisoning may well be higher (Hoppin, Liroff, and Miller 1996).

The estimates presented by the WHO have been criticized for being extrapolations based on a very limited data set. Furthermore, it is reported that WHO itself admits that there is no scientific basis for the early figures, nor for those produced subsequently. Indeed WHO is said to be "so concerned about the lack of reliable figures that they are trying to put the data collection system on a more accurate basis" (Pearson 1998). Critics also contend that the data presented for the number of pesticide-related poisonings in the United States can be misleading. The vast majority of calls to the American Association of Poison Control Centers are either inquiries or relate to minor irritations, but they are used by many to reflect casualties from pesticide poisonings. Furthermore, critics also point out that there are relatively few fatalities from pesticide poisoning, and most of these are people who have committed suicide by drinking pesticides (Leisinger 1998). Hopefully, the ongoing efforts at WHO to improve the quality of data will lead to more reliable information on the size and seriousness of "pest-induced" health problems. In the interim, though, organizations such as the World Wildlife Foundation contend that, while better data are needed, potentially harmful effects of pesticide use are such "that public policies should be more preventive and protective, and taking account of existing evidence together with the opportunities for reducing pesticide use there is ample reason to accelerate reduced reliance on pesticides" (Hoppin, Liroff, and Miller 1996).

While the overall estimates of casualties may be questioned, there are a number of on-site studies and observations that report that farmers and others have had health problems arising from pesticide exposure. Many of these studies are cross-sectional rather than longitudinal, giving a picture at a moment in time rather than showing trends. Nonetheless, the available information points to pesticide-related health problems. Detailed field-level studies among rice growers in the Philippines in the 1980s, for example, indicate that around half of the rice farmers in rainfed and irrigated rice lands claimed sickness due to pesticide use (Rola and Pingali 1993). Other studies among Philippine vegetable growers, who use pesticides intensively, indicate that a very high proportion of growers with prolonged exposure to pesticides developed eye, skin, pulmonary, neurological, and renal problems. The same general conclusion about pesticides being harmful to users has been arrived at about places as disparate as India, Central America, Malaysia, Uganda, Northern Brazil, and parts of the former Soviet Union where pesticide use—especially in cotton-producing areas—has been very heavy (Repetto and Baliga 1996; WRI 1997). Casual observations in many other areas confirm that many smallholders fail to take basic precautions when using pesticides, exposing themselves to possible injury and ill health as a result. A potentially devastating effect involves the possibility of pesticides interfering with the endocrine and hormone systems of animals and humans. This is particularly worrisome because the endocrine system regulates the production and function of hormones, which control everything from reproduction to the development of the young (Repetto and Baliga 1996; WWF 1996).

The other side of pesticide contamination occurs through consumption of food with pesticide residue in it. In a high-income country such as the United States, 35 percent of marketed food is found to have detectable levels of pesticide residue, and 1 to 3 percent of this food is above the legally defined tolerance level. At the other end of the spectrum, in low-income India, 80 percent of food has detectable levels of residue (Pimentel 1995).

The greatest potential impact of pesticide use on health appears to be in the developing countries. This is due, in part, to the fact that farmers in developing countries use a high proportion of the global total of the "dangerous" older pesticides, and they do not follow instructions in the "safe use" of these pesticides. Many of these older pesticides have long been banned in the United States and elsewhere, but are still sold in relatively large volumes in developing countries (Dinham 1995). Regulations and enforcement of quality control in pesticide manufacture, imports, and distribution in many of these markets are either very weak or nonexistent, and the instructions for the safe use of pesticides are either ignored or are unrealistic (for example, wearing heavy protective gear in the tropics). While the available data must be treated with caution, it is estimated that some 50 percent of all pesticide poisonings and 80 percent of deaths (including suicides) through the mid-1980s were occurring in developing countries, even though these regions were consuming only 20 percent of global pesticides used (Pimbert 1991 in Farah 1994).

Pesticide use has also had a harmful effect on the environment. Pesticides persist in the soil and water table, and sometimes break down to even more toxic components, contaminating crops and water systems (WWF 1996). Pesticides washing into streams, lakes, and bays cause fishery losses.

Pesticides also kill aquatic insects and small invertebrates that are food for fish.

Ground and surface waters have been contaminated by applied pesticides. It is difficult to predict the overall damage to water resources because there is no systematic monitoring of the impact of pesticides on these resources. However, Pimentel (1995) estimates that nearly half of the well- and groundwater in the United States is contaminated or has the potential for becoming contaminated by pesticides. In addition, recent studies have indicated very serious environmental effects on the Great Lakes area in the United States due to the runoff from the use of pesticides, including herbicides, which also leach into groundwater in considerable amounts (Hoppin, Liroff, and Miller 1997).

Birds, mammals, and other wildlife are also killed by pesticides. An Environmental Protection Agency analysis of recent studies and mortality rates estimates that the use of the pesticide carbofuran alone has resulted in 1 to 2 million bird deaths in the United States annually, including some endangered and threatened birds (Hoppin, Liroff, and Miller 1997). Pesticides frequently kill honey bees and wild bees that are essential for the annual pollination of about 30 billion fruits and vegetables in the United States. The losses incurred due to the destruction of honey bees and subsequent loss of pollination are conservatively estimated to be about US$320 million a year (Pimentel 1995). There are other scattered illustrations of pesticides harming the environment. In Southeast Asia, for example, fish production in rice field areas is falling drastically due to the use of chemicals on the high-yield rice varieties. Elsewhere in places such as Surinam, tens of thousands of fish died after the rice fields were sprayed to kill pomacea snails (Farah 1994). In Amazonian Brazil, pesticide use is killing fish, damaging agriculture, poisoning land ecosystems, and “affecting the quality of life of the area’s inhabitants” (de Oliveira 1995).

A Growing Problem in Developing Countries

There is a high probability that pesticide-induced side effects will grow more rapidly in developing countries as a whole than in the developed countries. In the first instance, the rate of consumption of pesticides in developing countries, especially in Latin America and Asia, is expected to grow more rapidly than in developed countries. This increased consumption will be taking place in countries and societies where there is less awareness and concern about the side effects from increased use of pesticides than there is in most developed countries. Furthermore, even where there is some awareness about possible side effects, policymakers, the public, and farmers place a high premium on attaining short-run food security. This further discourages checks on the use of pesticides.

The environmental movement in the developed countries has been important in increasing the public’s awareness about issues related to the use and abuse of pesticides. The nongovernmental organizations (NGOs) that lead the environmental movements in developing countries are relatively weak. They have had some modest successes in places like India, Indonesia, and Kenya, but they are far less influential than their counterparts in the developed world. The environmental movement in Western Europe and North America has had a profound impact on shaping attitudes and subsequent government regulations on the manufacture, control, and use of pesticides. These movements will continue to act as “watchdogs” and will continue to bring pressure on governments and industry to reduce levels of pesticide use and minimize any harmful side effects from pesticides. They will also continue to bring pressure to bear on their host governments to follow environmentally benign policies in their bilateral aid programs, and on the policies of international agencies such as the World Bank. Thus far, the NGOs in developed countries have been singularly successful in influencing the pesticide-related policies and programs of bilateral and multilateral donors (Tobin 1994; Kleiner 1996). It is an open question though whether the environmental movement in most developing countries will grow to the point where they will have comparable influence. Without their countervailing influence, it is almost axiomatic that increases in the use of pesticides will be accompanied by worsening side effects.

The lax controls in many developing countries have also led to an increase in the use of a number of broad-based toxic chemicals that have been banned in developed countries. Manufacturers in developed countries have exported these earlier and more harmful chemicals to less-regulated developing countries where these products are relatively cheap and can be used against a wide range of pests. These exports have continued despite the existence of several different voluntary codes intended to limit the spread of hazardous pesticides. In addition to imports from the industrialized countries, pesticide production of the old-fashioned, more toxic types is also growing rapidly in newly industrialized and developing countries, including China, Brazil, India, and South Korea. Some of the local production facilities are subsidiaries of transnational corporations; most, though, are indigenous corporations or companies.

International codes have not been effective in halting the international trade in banned pesticides (Dinham 1995). One such international code was created with considerable help from the organizations—the FAO and the UNEP—most responsible for international efforts in this field. This formal code, which was published in 1990, provided guidelines to all public and private institutions involved with the pesticide sector for a volunteer code of conduct for the regulation of trading, testing, registration and viability, packaging, labeling, distribution, advertising, training, and the like. After the code was introduced, FAO conducted a country-level survey to determine the level of compliance. The survey found a lack of capacity in most developing countries to create and implement a regulatory system that would ensure safe and correct use of chemicals and encourage alternative technologies. It also found a lack of effort on the part of manufacturers and exporting countries to regulate exported pesticides and prevent damage to crops, health, and the environment in developing countries (Farah 1994).

The lack of will and capacity to regulate the manufacture and distribution of pesticides will probably lead to a greater use of harmful chemicals and an increased incidence of harmful side effects. There are many thousands of small-scale distributors in the rural areas—86,000 in India alone—who do not follow guidelines on the marketing of pesticides (van Veen 1997; de Oliveira 1995). There are also more general socioeconomic conditions, such as persistent rural poverty, that cannot be overcome in the short run and that contribute to pesticide-related health problems. Poverty-related factors include illiteracy, which prevents peasants from following complex label instructions on pesticides, lack of training in application methods or alternatives, poor access to clean water for washing after routine spraying or for washing insecticide-stained clothes, no separate storage facilities for pesticides (containers are scarce among the poor, and pesticide bottles and drums are reused to store food), and poor access to health care or transport to treatment centers.

Some of the partial solutions envisaged to reduce the harmful side effects from pesticides include special educational programs, regulations limiting (or banning) the importation and use of harmful chemicals, and the development of alternative approaches to improving the management of pests. One innovative market-oriented approach would be to levy a moderate flat fee per kilogram of active ingredients in all pesticides sold. This would help shift pesticide usage away from the more dangerous compounds, including older organochlorine, organophosphate, and carbonate compounds, some of which pose the most serious chronic health risks. The higher costs of these ingredients would (in theory) encourage farmers to substitute newer pest control products, many of which are safer than the more dangerous, older types. However, all of the activities related to improving the quality and use of pesticides require governments that are prepared to make changes in policy and develop a capacity and will to implement these changes. In addition to governments instituting changes, the private sector, especially the pesticide industry, can contribute to reducing harmful side effects from pesticide use by developing improved and safer products with easy-to-understand instructions for their safe use.

Newer and Safer Pesticide Technology?

The pesticide industry has invested billions of dollars on research and development. It has been and continues to be the source of new pesticides that are used by tens of millions of farmers throughout the world. The industry is dominated by a small number of research-based transnational corporations headquartered in Europe, North America, and Japan that control around 70 to 80 percent of the global market. The other 20 to 30 percent is controlled by a large number of smaller firms that have little or no capacity for research, but rely largely on manufacturing and trading pesticides that have gone "off-patent" (Dinham 1995).

The large transnational corporations, with their substantial capacity for research, have responded to the criticisms of the environmental, health, and resistance problems that have followed from the use of pesticides primarily to safeguard their shares of the US$30 billion pesticide market. Many of the larger corporations have also responded to criticisms by assuming "product stewardship," which promotes the testing and marketing of branded products in a socially acceptable manner. Moreover, standards have been imposed by the regulatory agencies in Europe and North America that take into account the effects of pesticide use on producers, consumers, and the public at large. As a result, the major manufacturers are investing more heavily in research than in the past, with an increasing share of these costs being allocated to ensuring that the end product meets health and environmental standards. In 1956, manufacturers were spending about US$1.2 million to develop new pesticides; in 1987, costs of developing new pesticides had risen to US$45 million (Postel 1987 in Farah 1994). According to a 1997 assessment by the European Crop Protection Association, it now takes 10 years to bring a new product to market at an average cost of around 125 million ecus (approximately US$120 to 125 million), of which an estimated 40 million ecus are used on chemicals and 35 million go for biological development. The largest share, though, is allocated for safety, including tests that check for toxicity and ensure that the product meets stringent health and environmental safeguards (Kaufmann 1998).

The next several decades will probably see an increase in the trend toward the production of more narrowly targeted, less persistent, and less toxic products, and a consistent reduction in the use of broadly targeted products. There probably also will be an increase in more narrowly targeted products to deal with an increasingly diverse spectrum of local pest problems. A closer relationship between the producers of pesticides and the scientists working on genetic engineering can also be expected. This symbiosis may well result in greater crop protection being provided by genetically engineered plants using smaller quantities of pesticides than before (see next chapter). It is conceivable that the newest generation of pesticides may have even lower usage rates than at present, be well screened for environmental effects, and be nontoxic (functioning instead by triggering a crop's natural plant defense mechanism) (Backman 1997).

In general, pesticides are becoming more and more efficient (see Box 2) and presumably will continue to improve during the next 20 years. An industry view is that advances in plant biochemistry, molecular modeling, and organic chemistry have already delivered molecules that are active and selective at rates of application that are much lower than earlier pesticides. Pesticide-use rates have dropped from 2 to 5 kilograms per hectare to 0.01 to 0.2 kilogram per hectare. Knowledge of toxicology and the relationship between the laboratory and the field (ecotoxicology and soil science) are now being utilized in screening tests to avoid or limit adverse effects from new chemicals. In addition, the probability that resistance will develop is now an integral part of the evaluation of candidates for development as pesticides, and resistance management programs are planned before new products are commercialized (Morrod 1995).

Studies undertaken by the chemical companies have shown that the greatest extent of human exposure to pesticides occurs during the mixing and loading processes prior to application. As a result, steps have been taken to limit potential harm from these stages. Recent developments in formulation technology, such as water-soluble sachets, tablets, dust-free granules, and microencapsulated active ingredients, offer significantly reduced exposure and should make the handling of chemical pesticides safer (Morrod 1995).

New technologies also are being developed that reduce the wastage and negative environmental effects due to inefficient placement of pesticides. A carefully adjusted boom sprayer places up to 90 percent of the pesticide in the target area. Granular pesticides, where appropriate, place nearly 99 percent in the target area. The use of rope-wick application for herbicides is successful in placing 90 percent of the herbicide on the target weeds. Spot treatment, that is, treatment of only those areas of the fields where the pest problem is serious, further reduces the amount of pesticide applied (Pimentel 1995). Herbicide use can be reduced from the previous 10 pounds per acre to about 10 grams per acre for the same level of protection (Morrod 1995).

By 2020, vastly improved systems for placing pesticides where needed should be available. For instance, satellite technology is beginning to be used for farming and will have a beneficial effect on both pesticide application and ecological risk assessment. Experimental systems are already being built that guide machinery to apply pesticides where appropriate—for instance, to patches of perennial weeds or to matching soil types (Morrod 1995). Geographical Information Systems will soon be utilized to gauge more precisely the proximity of pesticide application to sensitive natural habitats (Morrod 1995).

To minimize soil erosion, increased use of conservation or ecotillage techniques will be required in the future—increasing the need for alternative weed management techniques. For instance, it is predicted that 70 percent of the U.S. cropping cycle will be supported by conservation tillage or "no-till" by the year 2000 (Morrod 1995). This implies that the demand for herbicides will increase. Biotechnical solutions are not expected to control weeds within the next 25 years. Nevertheless, genetic engineering will continue to be used to build in crop selectivity to herbicides, so that the use of herbicides will not harm the crop (Morrod 1995).

In general, the industry view is that there will be better pesticides tailored for specific uses and improved application and delivery. As it is, farmers in developed countries are moving away from heavy reliance on chemical pesticides and toward a mix of strategies that includes nonchemical components. The volume of chemical pesticides needed may well be reduced. In line with this, several developed countries, including Denmark, Sweden, and the Netherlands, have declared explicit policies and defined targets for pesticide use reduction, generally aiming to cut consumption by 50 percent or more by the year 2000.

The province of Ontario, in Canada, has also set quantitative pesticide reduction goals. Since 1988, through its Food Systems 2002 program, the province has assisted growers in efforts to cut pesticide use by 50 percent over a 15-year period, while maintaining on-farm profitability. The provincial government has mounted a vigorous educational program requiring farms and vendors to be certified if they want to use pesticides. As of 1993, Ontario had achieved a 28 percent reduction over the preceding 10 years (Hoppin, Liroff, and Miller 1997). At present, 1998, the program is reported to have reduced pesticide use to 35 percent of the levels used in 1988 (Jewett 1998).

Most of the foreseen innovations in the manufacture and use of pesticides will be in the developed countries, with their well-regulated environmental controls, innovative industries, and higher purchasing power of farmers. But the bulk of the increase in demand for pesticides over the next 25 years is expected to be in the developing countries, where there will have to be substantial growth in food production to provide food security. In the absence of national and international action, it is probable that current trends in the manufacture, import, and use of harmful, generic, and broad-spectrum pesticides will continue. All other things being equal, these lower-cost, more toxic pesticides will have a continued appeal to the small- and medium-scale farmers who will provide much of the increased supply of food in the years ahead.

The actual and potential negative effects from the use of pesticides indicate that there are many advantages to be gained from shifting away from crop protection that relies almost exclusively on chemical pesticides—even the modern, improved pesticides that, after all, are still toxic—toward approaches that reduce reliance on chemicals. For this to happen, government policies as well as international donor action have to encourage and support moves toward ecological and management-based approaches, for example, IPM, and to regulate the manufacture, distribution, and use of harmful chemical pesticides. Such moves should be promoted not only in areas where problems from the use of pesticides are already apparent—as in Indonesia—but also in other areas, including those vast areas in Asia, Latin America, and Africa where intensification of agricultural production and the use of pesticides is beginning or is yet to occur.

5. Nonchemical Technological Approaches

There are technological approaches to improving pest management that do not necessarily depend on chemical pesticides. These include plant breeding, the use of biological control agents, and biotechnology, all of which are discussed separately below though elements of all these technologies are often used together—frequently with chemical pesticides.

Plant Breeding

For centuries, plants in the ecosystem have had some natural resistance to plant pathogens. Over time, professional and amateur plant breeders have crossed varieties of plant species to produce improved varieties with increased pest resistance. In this century, breeders have had considerable success in improving the resistance of crops, more to diseases, less to insects, and least to weeds. Breeders have been able to breed many crop varieties that exhibit resistance to fungal diseases affecting the parts of the plants outside of the soil, as well as to nematodes and viruses. However, only about 5 to 10 percent of the crops grown today have significant built-in insect resistance and only about one percent have significant weed resistance. Nonetheless, the breeding of high-yielding varieties of crops such as wheat, rice, and corn with built-in resistance to a number of pests has been an important part of the strategy to increase and stabilize yields.

Over the past 50 years, agricultural scientists at national and international agricultural research stations and, more recently, in the private sector have played a major role in developing pest-resistant varieties in the important food crops grown in developing countries. The initial focus of most of these early breeding efforts, based on Mendelian principles, was to increase yields of basic food crops. The first high-yielding varieties of wheat and rice, and to a lesser extent maize, that were intended for use in the tropics were produced in the 1960s: they provided the underpinning for the Green Revolution, giving high yields when used with fertilizers and ample supplies of water and pesticides. As the Green Revolution technology spread, however, the high-yielding varieties became increasingly susceptible to attacks by pests, because of changes in plant structure, increased biomass, the changed taste of the plants, an increased density of planting, and the spread of monoculture. Moreover, continuous cropping gave pests a continuous, year-round habitat. As a result, the scientists' attention shifted to increasing the resistance of modern varieties so as to stabilize yields at a high level. This was done, in large part, by crossing the modern, high-yielding varieties with selected varieties of plants with natural genetic resistance to pests.

Plant breeders from developed and developing countries, including India, China, Mexico, Brazil, and Zimbabwe, have all contributed to producing genetically improved germplasm with increased resistance to diseases. Noteworthy contributions have also been made by international scientists working under the aegis of the CGIAR, which was created in 1972 to strengthen the research capacity for working on food crops in developing countries. Scientists from CGIAR centers have helped produce disease-resistant varieties of food crops grown in developing countries. The oldest of the centers, the International Maize and Wheat Improvement Center (CIMMYT), working with national agricultural research centers in developed and developing countries, has invested heavily in producing improved varieties that could perform well in areas where production is limited by insects and diseases. Some of CIMMYT's contributions have included the development of maize varieties with resistance to the maize streak virus. Before these new varieties were available, producers had no effective way to protect their crops from this disease, which is widespread in many parts of Africa. Scientists at CIMMYT have also made remarkable progress against major diseases of wheat. Losses to stem rust, formerly a major pest, have been negligible since the early 1960s, and no major outbreaks of leaf rust have been reported for more than a decade. The built-in resistance of many of the newer varieties has also given yields as high or higher than varieties treated with fungicides. These newer varieties not only cost less to produce than the older varieties, but they remove the potential environmental damage from the use of fungicides.

Scientists at another CGIAR center, the International Rice Research Institute (IRRI), have developed a succession of improved varieties of rice since the introduction of IR-8, the first of the high-yielding varieties released by the institute. Most of these modern varieties of rice released since the 1970s have been designed to resist the major rice insect pest, the brown plant hopper, now the most destructive of all pests, and the green leaf hopper and stem borer. Breeders have been only partially successful in limiting the damage from these pests, partly because the spectrum of pests and diseases and their importance has tended to change with each change of rice-growing technology. Producers using modern varieties and more intensive cultivation, including some excessive use of pesticides, have enabled previously unimportant damage-causing agents to come to the fore, while others have disappeared and new ones have appeared. In many respects, the resistance that has been built-in to improve rice varieties has provided a temporary respite, as pests (especially insect pests) have mutated around earlier built-in resistance. Continued resistance can be maintained only by constantly breeding further improved varieties and by using these improved varieties with other pest management elements such as selective chemicals, crop rotation, and the like.

There has also been significant progress in breeding higher and more stable yields into other food crops—potatoes, sorghum, millet, and cassava. The International Potato Center (CIP) has had outstanding success in developing improved blight-resistant potatoes. Had these been available at an earlier time, the course of Irish history may have changed. As in the case of other plants, however, there is a constant need to develop improved products to withstand new and more resistant pests as they evolve over time.

It is important for policymakers to recognize that plant breeding requires a sustained and long-term commitment. In this regard, plant breeding to limit losses from pests, classified as "maintenance research," is now taking an increasing proportion of agricultural research budgets. In the case of the CGIAR, as much as 40 to 50 percent of the US$300 million budget is used for maintenance research. This research is competing with funds available for work on other important aspects of plant development, for example, yield increases. It is important that national governments and international donors recognize the critical need to sustain and increase maintenance research in the years ahead. Without adequate resources, plant breeding will be restricted and unable to continue to play an important role in improving and sustaining pest resistance in the major food crops grown in the tropics. Indeed, without adequate funds for maintenance research, pest losses could rise as pests evolve to overcome the "temporary" successes achieved from developing many pest-resistant varieties currently in use.

Biological Control Agents

Biological control agents are naturally occurring enemies of pests and include insects, anthropoid predators, and pathogens. Biological control uses these natural enemies in a directed manner to control pest populations and follows three strategies:

- classical biological control, where ecologically adapted natural enemies are introduced from the area of origin of the pest to the target area;
- conservation of natural enemies present in the ecosystem using cultural practices or habitat management that enhance their activity; and
- artificial augmentation of local natural enemy populations.

Biological control has the advantage of eliminating the need to use chemicals and being low in cost. In addition, it is self-sustaining, may not require inputs from farmers, and is safe for the environment and human health. Biological control agents seem to be particularly effective in controlling the populations of exotic or alien pests, which tend to proliferate in the absence of natural predators in a new ecosystem (see Box 3). The spread of alien pests and diseases has been growing with increasing world trade. Some of the pests that have spread through trade include coffee rust in South America, black sigatoka on bananas in Latin America, fire blight in Europe, and rizomania in sugar beet (Oerke et al. 1995).

One of the first known cases of modern biological control was the introduction in 1888 of a predatory beetle from Australia for the control of the cottony cushion scale, an invasive alien species from Australia that was infesting citrus crops in California (CABI 1994). Some more recent cases, other than in the case of cassava, include the use of *Anagyrus spp*. to control *Planococcus kenyae* on coffee in Kenya and parasitoid insects to control pests on cereals in New Zealand (Oerke et al. 1995). A parasitic wasp was introduced to Togo from India in 1987 to control the population of the mango mealybug, an alien pest from Asia that was decimating the mango crops in West Africa. The benefit to Togo was estimated at around US$3.9 million per year, whereas the cost of the program was US$175,000 (CABI 1994). An alien water fern in Sri Lanka in the 1980s was controlled through the introduction of a South American weevil with help from the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO).

In certain cases, biological control may be the only solution to the pest problem. The gumwood in St. Helena is threatened by an alien scale insect, but use of chemical pesticides is not possible due to steep terrain and high winds. A specialized beetle from the area of origin of the scale insect was introduced in 1993 and 1994, and the pest population soon began to decline (CABI 1994).

Between 1888 and 1994, more then 5,000 different introductions of biological control agents into an alien ecology have taken place. Few of these are reported to have caused any problems. However, the effectiveness and environmental

Box 3 Biological Control: Cassava in Africa

One of the best known cases of biological control concerns the cassava mealybug in Africa. Cassava was an exotic crop in Africa, and when it was first introduced it left behind in its neotropical area of origin most, if not all, diseases and pests. With time, endemic diseases and arthropods in Africa overcame the defensive strategies of cassava through adaptation or mutation, and added it to their list of hosts. In other instances, modern transport technology facilitated the movement of neotropical pests to Africa, where they created havoc in the absence of coevolved natural control mechanisms.

Several years ago, the cassava mealybug and cassava green mite began devastating the cassava crops in large areas of Africa. The International Institute of Tropical Agriculture (IITA) had long been involved in research on cassava diseases. Following the pattern of the other CGIAR centers, IITA had concentrated mainly on genetic improvement and resistance breeding, initially directed to the African cassava mosaic disease and later to cassava bacterial blight and anthracnose. It soon became clear that resistance would not be available against the cassava mealybug and the cassava green mite in time to avoid the disappearance of the crop from most growing areas. The two pests are of South American origin, where they evolved with a complex of natural control mechanisms, including host plant tolerance, but more importantly biotic agents such as pathogens and arthropods as natural enemies. Thus, there was no evolutionary advantage for cassava to have developed a strong resistance to these pests.

The problem required immediate action. It was apparent that chemical pesticides would be ineffective and the time needed to develop host plant resistance was too long. IITA, therefore, started the Africa-wide Biological Control Program in 1979. IITA located and imported natural predators of the cassava mealybug from Latin America. The biological control program using the imported parasitoid against the cassava mealybug was an unprecedented success. The estimated cost-benefit ratio of the program calculated over a period of 22 years is 1 to 200, and shows the tremendous potential of biological control in contributing to efficient pest management. There are now many projects in Africa involving biological control of food (staple and horticultural) and cash crop pests (Herren 1994).

impact of many of these introductions have not been evaluated (CABI 1994). About 30 percent of the biological control programs against alien insects and about 64 percent of the programs against alien weeds have been reported to be successful. The programs that seem to succeed typically reduce the pest level so low that they are no longer a threat needing extensive chemical pesticides (CABI 1994). The biological agents used thus far have come from 98 different countries, 57 percent of which are developing countries. One hundred twenty-one countries, about half of them developing countries, have conducted at least one biological control project (CABI 1994).

Natural enemies compose a significant proportion of the biodiversity in the insect and parasitoid world. Parasitic wasps, or parasitoids that prey on insects that are agricultural pests, account for about 10 percent of the entire species on earth (CABI 1994). For successful biological control in the future, it is important that biological diversity is preserved. Biological control scientists strongly support the Convention on Biological Diversity.

Supporters of biological control feel that natural pathogens and predators should be the first choice for pest control as they are natural and have been tested by nature for eons. There are, however, many concerns about introducing an alien natural predator into an ecosystem: the predator itself might become a pest, become a predator of other desirable species, or otherwise upset the balance in the local ecology. Many countries, therefore, require strict testing to ensure that an introduced species will not lead to such problems. FAO, along with national biological control programs with assistance from the International Institute of Biological Control, has produced a draft Code of Conduct for the Import and Release of Biological Control Agents in order to ensure the safety of biological control (CABI 1994).

Despite its appeal, biological control has not had a broad-based impact on the practice of pest management in the world. It makes up much less than 0.5 percent of the market for pest control solutions (Oerke et al. 1995). In Europe, biological pest control is mainly practiced in greenhouses—which only compose a very small percent of the agriculture in the region. Worldwide, the area under biological control in greenhouses has increased from 400 hectares in 1970 to 14,000 hectares in 1991. Fifteen species of natural enemies have been used to control 18 pests during this period (Oerke et al. 1995). Biological control has also been practiced, as a matter of national policy in Cuba, where the government has promoted organic farming in lieu of using chemicals (see next chapter). The Cuban experience has not led other governments to adopt similar policies.

Biological control is not expected to be a major factor in pest management over the next decade unless funding for its widespread adoption becomes available. Most biological control solutions, such as introduction of alien pests, require institutional rather than farmer action. Currently, biological control is followed where chemical solutions or resistant seeds are not available or usable, as in the case of regionwide pest plagues. Biological control forms one of the foundations of ecological strategies like IPM and is expected to be taken up by farmers as IPM gains popularity. At present, however, biological control is facing the same problem as most other new technologies in pest management—difficulty in overcoming the market appeal of chemical control. Biological solutions require more knowledge by the farmer and are not as consistently effective in killing pests as are chemicals. A major issue, though, is whether the environmental and other advantages of biological control do justify public action in making these chemical-free approaches more competitive in the market.

Biotechnology and Plant Protection

The most dramatic changes in agricultural technology in the last quarter of the 20th century are coming from biotechnology. Agricultural biotechnology involves the changing of traits and characteristics of plants and animals through manipulation of the entire organism, its cells or molecules. The Office of Technology Assessment of the United States Congress defined biotechnology as "any technique that uses living organisms, or substances from those organisms, to make or modify a product, to improve plants or animals, or to develop micro-organisms for specific uses" (Persley 1994).

The use of biotechnology for the improved management of pests encompasses:

1. disease-free planting material produced through tissue culture and micropropagation;
2. diagnostic techniques developed for improved identification and monitoring of pest populations and pesticide residues;
3. biopesticides or microbial pesticides that use microbes like *Bacillus thuringiensis* (Bt) and baculoviruses; and
4. transgenic genetically engineered plants with increased virus, pest, and disease resistance.

Biotechnology thus covers a wide range of technologies, a large number of crops, and a wide spectrum of scientific research. Tissue culture and micropropagation are among the simpler technologies already in use in developing countries. Micropropagation is the process of rapid multiplication of planting material and elite clones, after selecting the most desirable plant types. Through tissue culture, pathogens can be cleaned out from planting material to produce disease-free material that can be rapidly mass-propagated for planting. Tissue culture techniques are simple enough to be used at the local level. Some NGOs in developing countries, working with resource-poor farmers, are exploring the possibilities of setting up local tissue culture and micropropagation enterprises (Messer and Heywood 1990).

Biopesticides

Biopesticides are preferred by many to chemical pesticides, because they (1) do not leave harmful residues, (2) are target-specific and do not destroy beneficial organisms, and (3) promote the growth of natural enemies of pests, thus reducing the need for future pesticide application. Against these advantages, though, are concerns that biological pesticides may not be as efficient or as cheap as chemicals (see the next chapter for a discussion of biopesticide development in India and Cuba).

The agents employed as biopesticides include parasites, predators, fungi, and bacteria, which are the natural enemies of pests. In addition to these, certain plant products such as neem are also valuable as biological pesticides.

The potential of fungi in controlling pests has been known for some time. Fungi are particularly effective because they do not have to be ingested by a pest but can infect through physical contact. They are especially useful against root pests, which are difficult to reach and control with conventional pesticides. Also, they are ideal for treatment of seeds. An example is trichoderma, which is effective against root pathogens and is used for seed treatment. First used in 1930, it is one of the oldest and most widely used fungi-based pesticides in the world. It is particularly effective in the case of groundnut, sunflower, sesamum, blackgram, green gram, and chickpea crops, all of which are particularly susceptible to root rot.

Baculoviruses, which include nuclear polyhidrosis viruses (NPV) and granulosis viruses (GV) are target-specific viruses that can infect and destroy a number of important plant pests. However, large-scale commercial production of NPV requires a substantial number of healthy host larvae. The maintenance of these larvae on a large scale poses serious technical problems because of the possibility of contamination. The problem is particularly serious when labor-intensive techniques are used. The difficulty in maintaining optimum conditions on a large scale and the need to employ a large number of workers have limited the popularity of NPV and other baculoviruses in the past (Alam 1995).

The biopesticide *Bacillus thuringienses* (Bt), among the most widely known and researched biocontrol agents, is a microbe that produces a special protein that is active against a very narrow spectrum of insects. Different strains of Bt are used against different pests. One such strain kills caterpillars and has been available commercially for over 30 years in a powder form that can be dusted onto the surface of plant leaves. Caterpillars that consume sufficient quantities of the powder are killed; natural enemies of the pests eat the powdered leaves but remain unaffected. Bt is currently being used in several developing countries and is widely used in Cuba. The use of Bt (as an alternative to earlier chemical use) in the management of the diamondback moth that infests cabbages in tropical Asian highlands has protected this crop. It has also enabled two or three species of parasitoids of the moth to recover to a point where biopesticide use need only be infrequent, and other cultural methods may suffice (Waage 1995). However, the moth is now showing resistance to Bt in parts of Asia, due to intensive and unnecessary "calendar" application of the biopesticide. The most significant technological advance in the use of Bt has been the successful engineering of the insect control protein from Bt into the host plant itself for better protection for the entire plant (Monsanto 1997).

The neem tree and its various products are among the most important of botanical pesticides. Neem contains several chemicals that affect the reproductive and digestive processes of a number of important pests. Neem also acts as a repellent and antifeedant, and its oil is effective against leaf folders (rice), *Heliothis* (chickpea), and aphids and bollworms (cotton). In fact, 200 species of insects are known to be controlled by neem. However, neem suffers from some problems such as low toxicity and high oil content, and there have been a number of difficulties in commercializing it despite its many attractive natural qualities as a pesticide.

Production of biopesticides as well as tissue culture and micropropagation can be done even at small-scale and local levels. They are neither technology- nor investment-intensive. As has been shown in Cuba, many different products and microbes can be made using local resources with the purchase of a fermenter. Many NGOs, like CARE International, are promoting small-scale biotechnology enterprises at the community level. CARE is promoting biotechnology products as a part of its IPM programs and is working with research groups, including CIP, to develop improved biopesticides. Technologies using baculovirus and the fungus bavaria to combat potato weevil and potato tubermoth have been developed. Mass production of these two biocontrol agents is being carried out in community-managed multiplication centers with technical backstopping from CIP, and the distribution to farmers is being handled by local NGOs and government agents (Hruska 1995).

Biopesticides are reported to have less than 0.45 percent of the market share of the multibillion dollar agrochemical market—most of it coming from sales of Bt. More than half of these sales are in North America and around one-tenth percent in Europe. The main sectors using Bt are forestry and vegetable production. Biofungicides have had even less success. Bioherbicide sales are also very small. Industry sources project that sales of biopesticides will increase by 10 to 25 percent per year. Their use will increase mainly in areas where chemical pesticides are not very effective, such as in the control of soil-borne diseases. It is expected that biopesticides will also be used where pest resistance to chemical pesticides has developed and in small niche markets that are of little interest to chemical manufacturers (Oerke et al. 1995). In general, even if biopesticides are competitive, farmers tend to opt for them only in those rare situations where chemical pesticides cannot be used (Box 4).

Biopesticides may also face the problem of pests developing resistance to them. Bt has been used for about 20 years, and development of resistance in the diamondback moth is now being reported in Hawaii, Asia, and mainland United States (Oerke et al. 1995). Most of this resistance may be due to overuse and inappropriate use of the biopesticide.

Biopesticides can provide a more sustainable solution to improving pest management than chemical pesticides. Efforts aimed at popularizing biopesticides and assisting them to "break" the chemical hold on the market need to have two foci: increasing the demand for biopesticides and encouraging the development and commercialization of suitable products and production technologies. Biopesticides have to compete with established chemical pesticides in terms of both price and effectiveness. Government support in the form of short-term subsidies can improve the price competitiveness of biopesticides. However, in the long term, increased research to improve their effectiveness; the use of modern production, transportation, and storage methods; and strict quality control are essential if biopesticides are to become effective alternatives to chemical pesticides.

Despite all the difficulties involved in instituting and implementing biotechnical controls for pest management, one country, Cuba, has shifted from conventional to chemical-free, organic pest control. This shift was prompted by necessity following the collapse of the sugar market and after a shortage of foreign exchange forced the curtailment of chemical imports. The Cuban authorities appear to have

Box 4 The Case of Biopesticides in India

In India, the rise of biopesticides is being encouraged by the government as part of an integrated pest management (IPM) program. The Ministry of Agriculture and the Department of Biotechnology are largely responsible for supporting the production and application of biopesticides. The Department of Biotechnology has set up an ambitious project to demonstrate the technical viability of various biopesticide production technologies developed in India. The project will also concentrate on training farmers, NGOs, and extension workers in the production and use of biopesticides. The program will run for five years (1995–2000), during which 50 demonstration units in different agroclimatic regions will be set up. The cost of setting up the 50 units is estimated to be about Rs 106 million (US$3.5 million).

Mainly 4 types of biopesticides are being produced or promoted in India: parasites (mainly *Trichogramma*), fungus (mainly *Trochoderma*), Bt, and baculoviruses. In all four, production facilities are very basic and small scale. Production quality is poor and availability uncertain. Most of the biopesticides are produced now by either university departments or state agriculture departments on a very small scale in inadequate facilities. Some private production on a small scale is taking place for *Trichogramma*. There are several concerns over risk of contamination from production of baculoviruses. One of the agricultural universities has entered into a collaboration with the Natural Resources Institute (NRI) of the United Kingdom in order to obtain technology for large-scale and lower-risk production of NPV baculoviruses. Bt, for which there is expected to be a high demand, is not being produced but being imported by a few firms. Local production is expected to begin when the technology for Bt production has been developed and licensed.

Although *neem* has been used in India as a pesticide for a very long time, its large-scale production is of relatively recent origin. At present, 10 firms are producing 37 neem-based pesticides. The Indian market is estimated to be valued at about Rs 300–400 million (US$10–13 million). One of the most ambitious production facilities, with an initial capacity of 20 tons per day, has been established as a joint venture by W.R. Grace and Co. (U.S.A.), and the Indian firm P. J. Margo Pvt, Ltd. Research on improving the effectiveness of neem has also begun recently.

Most biopesticides are being supplied free of cost by the research agencies to farmers through extension services. Commercial channels have not been properly developed.

The present use of biopesticides in India is very limited. Demand from farmers is low due to poor performance of biopesticides, which suffer from low toxicity, poor stability and consistency, and slow action. Biopesticides also show poor tolerance to moisture, temperature, sunlight, and pH. In particular, their target specificity and slow pace of action put them at a disadvantage vis-á-vis chemical pesticides.

Due to the production limitations mentioned above, at present both the quantity and quality of biopesticides available in the market are erratic. Production in small batches means that uniform quality standards are difficult to maintain. In fact, the growth of biopesticides is caught in a vicious circle. The poor quality and performance of these products limit their demand, which in turn has a discouraging effect on investment in research and production facilities.

At present, biopesticides do not have an economic advantage over chemical pesticides for the farmer. Some experiments done on cotton and paddy show marginal improvement in the cost-benefit ratio for cotton but not for rice when biopesticides are used as part of IPM.

When the absence of significant economic benefits from the use of biopesticides is seen against their uncertain effectiveness, the low level of acceptance by farmers is easy to understand. As a result, biopesticides have failed to make a serious impact on the market, which continues to be dominated by chemical pesticides. The small amounts of viral formulations (such as NPV and GV) and egg parasitoids that are being produced currently are being used largely as part of a government-supported IPM program. The use of Bt is even smaller.

Source: Alam 1994

been relatively successful in the artificial manufacture and distribution of biological control agents and in promoting organic farming among the small-scale food-producing sector. The success of biological controls as a substitute for agrochemicals in the large-scale, irrigated sugar-producing sector remains to be seen (Box 5).

Genetic Engineering

Genetic engineering creates transgenic plants and animals, whereby hereditary DNA is augmented by adding DNA from another germplasm source. The incorporation of genes into crop plants to produce toxins for pest control will automatically reduce the

Box 5 Cuba s Technological Change: From Conventional to Alternative Agriculture

Prior to the 1989–90 collapse of its trade relations with the socialist bloc, Cuba had an agricultural system that was "highly modern." Farming methods depended heavily on imported inputs. Around half of the chemical fertilizers and more than 80 percent of the pesticides were imported as were many of the ingredients needed for the domestic manufacture of these inputs. Following the loss of its privileged access to subsidized markets in Eastern Europe, and a subsequent drastic reduction in foreign exchange earnings, the government cut off all imports of chemical pesticides and fertilizers in 1990.

Cuba was faced with a critical situation: it had to substitute domestic production for the inputs formerly imported as well as for the imported food that provided more than half the calories consumed by the Cuban people. One facet of the government's response was to promote organic or near organic agriculture and to substitute "nonchemical" technologies to replace the products formerly imported. These technologies were to include the use of resistant varieties of crops, crop rotations, the use of natural enemies of insects, and the use of domestically produced biopesticides. By the mid-1990s, Cuba was one of the world's leaders in the production and use of many of these biopesticides.

Cuba had already had early experience with a biological control program, based on mass rearing of parasitoids. This program had been successful in using a parasitic fly to control the cane borer in many sugarcane areas. Other natural enemies had also been used to control pests in cattle pastures as well as in tobacco, tomatoes, cassava, and other crops. One of the earlier notable successes was the use of reservoir-raised ants to control weevils in sweet potatoes, a staple food in the Cuban diet.

Cuban researchers are reported to have found technologies for producing, harvesting, formulating, applying, and controlling the quality of various bacteria and fungi used in nonchemical pest control. Cuba is also reported to have a big international lead in the production and use of diseases caused by bacteria, fungi, and virus that are nontoxic to humans but effective in biological control of pests. The table shows the national production figures for biopesticides in Cuba for 1993 and 1994. The two biopesticides produced commercially in the largest quantities are the *Bacillus thuringiensis*, which is available from multinational pesticide companies, and *Beauveria bassiana*, which is not generally available internationally. The fungus *trichoderma spp.* is also produced in substantial volume—it is used as a soil fumigant. Cuba is probably the only developing country producing tobacco that no longer uses *methyl biomide* as a soil fumigant.

The Cuban authorities followed two paths in producing biopesticides. One was through a network of brewers' fermenters that made industrial products for the largest units of production, such as former state farms and large cooperatives. The other route was through "artisanal production." The government created a uniquely Cuban institution, the Centers for the Production of Entomophagens and

Source: This box is derived almost wholly from Rosset 1996.

exposure of nontarget organisms to these toxins. Transgenic insect-resistant seeds could eliminate the need for pesticide application. Biological control agents could also be made more potent by the insertion of engineered toxins.

At present, transgenics are being developed for some 40 crops, including maize, rice, soybean, cotton, tomato, canola, and potato, nearly all for use in developed countries. The crops that have already been commercialized include soybeans, corn, canola, and potatoes, as well as fruits, vegetables, and tobacco. Most of these are herbicide-resistant transgenics released in developed countries.

Recent Trends

In recent years, the private sector has invested heavily in genetic research and development to produce crops with desired traits that could replace the use of some chemical pesticides (without reducing yields). Progress has been rapid: in 1996, after 15 years of research and development, the first significant commodity crops became commercially available. The planting of genetically altered soybeans, corn, cotton, canola, and potatoes has spread dramatically since then in the United States and, to a lesser extent, in Canada, and in Argentina in the case of soybeans. According to information pro-

Entomopathogens, known by the acronym CPEE. Each CPEE is a relatively modest entity that has modern equipment, and is said to be "high-tech" by any standard. It is maintained and operated by local technicians with scientific training. A CPEE produces a number of entomopathogens as well as fungi depending on which crops are grown locally. A CPEE either gives its products to a parent organization (such as a cooperative) or sells them to neighboring producers, using the sales proceeds to help cover costs.

In the mid-1990s, there were more than 220 CPEEs throughout Cuba providing inputs and services to producers. There have been problems involving the shortage of glass jars in 1994 and growing competition with the livestock sector for waste materials such as rice chaff. In addition, there are great differences among CPEEs, including levels of technology, training, and motivation. There are also serious problems in controlling the quality of microbial strains being produced—problems that are difficult to manage in such a highly decentralized system.

Despite these and other problems, the artisanal production of biopesticides in the CPEE and their use by farmers have been deemed a success. The overall production of biopesticides has been impressive by any standard. The dissemination of the new technologies has certainly helped the small farmer sector. The fact that Cuba also has an organization that is generally centralized and strong has helped the application of research results and use of new technologies. Once the technologies have been accepted by the central authorities, there is an almost instantaneous dissemination of results. As with all organic farming, the new technologies are management intensive and best suited to small-scale production. Thus, it is not surprising that the "peasant sector," which had a tradition of low-input agriculture, was best able to use the output of the CPEE to reduce losses from pests. Unlike the large-scale sugar-producing units, the small-scale units have rapidly recovered and their output now exceeds pre-crisis levels. One important by-product of the food crisis in Cuba and the subsequent emphasis on organic farming has been the rehabilitation of the peasant, long scorned by Marxist literature. Factories in the fields do not appear to be amenable to low-input agroecologically sound agriculture.

Production of biopesticides in Cuba

Biological control agents	1993	1994
	(metric tons)	
Insect control		
Bacillus thuringiensis	1,381	1,312
Beauveria bassiana	718	781
Verticillium leucanni	191	196
Metarhizium anisopliae	120	142
Plant disease control		
Trichoderma spp.	2,708	2,842
Nematode control		
Paecilomyces lilacinus	141	173

Source: Beatriz Diaz, "Biotecnologia Agricola: Estudio de Caso en Cuba," paper prepared for presentation at the meeting of the Latin America Studies Association, Washington, D.C., 1995.

vided by Monsanto Corporation, the leading discoverer and developer of these genetically engineered crops, growers planted more than 19 million acres of Monsanto products in 1997, a sixfold increase over 1996. Monsanto expects that 1998 plantings of their genetically improved soybean, corn, and potato will increase sales by a further two-, three-, and fourfold, respectively. Indeed, it is projected that around one-third of the U.S. potato acreage and around 10 percent of the U.S. corn acreage in 1998 will be planted with Monsanto's genetically modified products. The American Soybean Association estimates that 30 percent of the country's soya acreage, 25 percent of its maize, and 40 percent of its cotton will be planted with genetically modified seeds from all sources in 1998 (*Economist* 1998).

There are no independent data on the impact of the use of genetically engineered plants on pest control, and on whether the introduction of these plants has reduced the consumption of chemical pesticides. However, the rapid spread in the adoption of the improved seeds by U.S. farmers seems to indicate that their use gives greater returns than the more traditional seeds. Monsanto has analyzed some of the data derived from farm records. It has concluded that farmers using the improved seeds did indeed get higher yields and did consume substantially less chemical insecticides than would have been the case had they used "traditional" seeds and the earlier technology with its heavy dependence on chemical insecticides (Monsanto 1997).

Biotechnology appears to hold great promise and will probably have a profound effect on pest management in the developed countries in the not too distant future. The ability to encode information in plants opens innumerable, intriguing prospects for protection against pests. Plants can and are being genetically altered to combine resistant herbicides (which kill weeds) with insect resistance (reducing the need for insecticides). This combination can promote "no-till" agriculture and reduce the need (and cost) of using chemical insecticides. Also, experiments are in train to modify plants to use less materials and energy. For example, some crops are being encoded to produce oils with more desirable compositions, eliminating the additional processing or additives that normally provide functional or nutritional benefits to producers and consumers. It is envisioned that other plants (yet to be developed) will work as factories, providing renewable sources of everything from polymers to pharmaceuticals (Monsanto 1997).

There are some major concerns about the rapid spread of genetically engineered crops. These concerns include (1) whether genetically engineered crops will lead to insect-resistance; (2) whether the use of the newer herbicides, as part of weed-control systems based on genetically engineered herbicide-resistant food crops, will lead to the development of herbicide-resistant weeds; and (3) whether the consumption of genetically altered food crops by humans and animals will have harmful side effects. The regulatory agencies in the United States and Europe have given qualified support for the introduction and spread of the initial genetically engineered products. Nonetheless, the "law of unintended consequences" is such that there will have to be constant monitoring of farmers' fields to assess the effects of the new technology on the emergence of any forms of resistance or other side effects. It will be up to the private sector, with its near monopoly on this technology, to provide any technology that might be necessary for ensuring the long-term effectiveness of the new insect-protected crops and sustainable weed control systems. Hopefully, the costs of research and development to promote these aspects of sustainable pest control, should they be needed, will not clash with the desire to generate profits to satisfy stockholders.

The few cases of research on transgenic crops for developing countries include virus-resistant tobacco, tomato, and potato varieties that have been developed at Washington University in St. Louis, Missouri, with help from Monsanto. The Rockefeller Foundation Rice Biotechnology Network is attempting to develop tungrovirus resistance in Asian rice. The program is expected to result in a limited number of insect- and virus-resistant varieties of rice. Virus-resistant cassava is being developed by an international network that includes Washington University, Monsanto, Rockefeller Foundation, the French overseas aid program (ORSTOM), the U.S. Agency for International Development (USAID), and the International Institute of Tropical Agriculture (IITA) in Nigeria. Monsanto has also joined with several Kenyan institutions to develop selected pest-resistant varieties of yams.

In general, biotechnology for crop protection will probably have limited impact in developing countries over the next 10 years. Tissue culture, micropropagation, biological control agents, and biopesticides will probably have a greater impact. However, the effect of biotechnology on developing-country agriculture over the subsequent quarter century will be significant; consequently, it is important for developing-country governments to formulate strategies for future investments in biotechnology.

The decision to invest in agricultural biotechnology for plant protection in developing countries is complex. The cost is high and the need to collaborate with the international private sector further complicates investment decisions. Countries must design a coherent and long-term program with clear decisions on in-house research versus import of the technology and products. In any event, only the economically and technologically more developed countries like Argentina, China, India, Indonesia, and Brazil appear to have the capacity to put together the long-term financial and intellectual resources—biochemists, geneticists, microbiologists—needed for biotechnology research (Oerke et al. 1995). The uncertainties of biotechnology's benefits make the investment decision difficult for most developing countries. In these countries, the ongoing research effort is confined almost exclusively to public institutions. While some new forms of public- and private-sector collaboration are emerging, at present there is little involvement in biotechnology research, development, or diffusion by the private sector in developing countries. For the foreseeable future, the burden of research and development in developing countries will fall on the public sector (Brenner and Komen 1994).

Developing countries can benefit considerably from the advances in biotechnology in developed countries by leapfrogging on the technology, rather than starting from scratch. If the developing countries are to "leapfrog," they need to develop skills to collaborate with the international private sector and negotiate intellectual property rights and biosafety regulations that will facilitate access to the new processes and products. Efforts are also needed to involve the private sector in research, seed production, and distribution, and help it become competitive.

There are also international concerns about potential environmental and health hazards from field testing and release of genetically engineered organisms and plants. Biosafety protocols have been presented and discussed at the international level. They are expected to lead to a code to ensure that biological agents or genetically altered species introduced into an ecosystem are safe. These protocols have been introduced by agencies like UNEP and FAO. As yet, the protocols have not been ratified. In the absence of well-developed biosafety procedures, the testing and introduction of several products are being delayed as countries are unsure about the potential impact of the products on the ecosystem. Ill-defined international biosafety procedures also make countries with looser biosafety laws a "haven" in which companies can test their biological products, possibly endangering national ecosystems. Despite long delays, however, it appears that by early in the next century the lack of protocols will no longer be an obstacle to the spread of biotechnology and its products in developing countries.

6. Integrated Pest Management

The economic and ecological impact of pesticide abuse has prompted attempts to reduce pesticide use and led to an increased investment in alternative technologies and products, a reconsideration of traditional methods of pest management, and a more comprehensive look at the ecological context of pests, including an increased interest in IPM. It is widely believed that if farmers in developing countries adopt IPM, it could contribute substantially to the intensification of agriculture in a sustainable manner (Thrupp 1996).

The concept of IPM varies, with different groups advocating different approaches. One approach focuses on when to apply pesticides, while another emphasizes when not to apply pesticides (Box 6). Everyone agrees, though, that IPM is a flexible approach that draws upon a range of pest control methods to produce a result that combines the greatest value to the farmer with environmentally acceptable and sustainable outcomes. The techniques used for crop protection in IPM may include traditional crop management—crop rotation, intercropping, mulching, flooding, polyculture, scouting, sanitation, input management, tillage, and the like. IPM may also use the products developed through research—resistant crop varieties (hybrid or transgenic), biological control agents, biopesticides, pheremones, diagnostics, and, in some instances, chemical pesticides. The options used by the farmer depend on the local context—agroecological needs, availability, and affordability of the various alternatives.

IPM works through prevention, observation, and intervention. Preventive measures such as intercropping are taken by farmers to preempt pest populations. Observation of pest populations during the vegetation period is done through scouting or the use of diagnostic tools. "Decision tools" are used by the farmer to decide when and how to intervene. If pest losses reach a given threshold, farmers will use biopesticides or natural enemies or, as a last resort, recommended amounts of chemical pesticides consistent with the needs of the moment. IPM poses an educational challenge to producers because it is relatively complex, location-specific, and management-intensive. The farmer must learn ecological and pest management principles and acquire the knowledge and skills necessary to apply them. Training must leave farmers confident enough to make independent decisions based on their specific farm conditions (Matteson and Meltzer 1994).

The move toward IPM in developed countries has been fostered by environmental groups as a reaction to the problems created by heavy pesticide use. The concept of IPM, elaborated in the United States in the 1970s, is based on restricting pesticide use through the imposition of economic thresholds that allow spraying and encourage the replacement of broad-spectrum chemical insecticides with alternatives (Waage 1995). The pesticide industry, faced with a potential reduction in demand, has taken note of the need to adapt to maintain market shares. Presently, IPM products are being expanded to include selective pesticides, biological control agents, engineered microbials, and other biotechnological products. In addition, older products are being "repositioned" so that they can be used in IPM programs (Kaufmann 1995). Besides improving products, the pesticide industry is moving into IPM through its "product stewardship," which involves developing application methods and services that meet the requirements of IPM, assisting in the development and testing of IPM programs, developing diagnostic tools, and training customers by providing appropriate information materials and programs. Many

Box 6 Defining IPM

IPM has been defined in vastly different terms by different types of agencies and interest groups. At the extremes are the "technological" and "ecological" views of IPM. Both of these views base IPM on natural processes of pest regulation, for example, the action of natural enemies.

The technological view is product-oriented and works on the basis of top-down development and delivery of solutions. This view is found mainly in the agrochemical industry and in parts of the agricultural technology research systems at national and international levels. For the technological approach, the natural processes of pest regulation make thresholds for intervention possible. However, these processes remain something of a "black box," and the emphasis is on intervention, particularly with safer products that keep that box intact. This concept of IPM has been implemented mostly in developed countries and in large-scale farms and plantations in developing countries.

The ecological view of IPM is linked with the paradigms of sustainable agriculture and rural development, participatory development, and the principles of integrated crop management. This approach builds knowledge and skills in farmers and provides them with the tools for decisionmaking. The more ecological concept of IPM makes natural processes of pest regulation the central emphasis. This view of IPM does not recognize, *a priori*, the need for pest control interventions, especially with chemicals. This view has developed through experience in developing countries suffering severe pest resistance owing to overuse of pesticides. Pesticide use in these countries could be considerably reduced without significant reduction in yields. The ecological concept of IPM has been implemented mainly by NGOs and international development agencies collaborating with governments and small farmers in developing countries.

From the technological perspective, new, selective products replace old, broad-spectrum ones in a package of continuing pest control made much more sustainable by virtue of IPM. In the ecological perspective, the new, selective products have a clear role in "environmental amelioration," but no necessary role in the future basket of IPM techniques that a farmer may adopt. Asian cabbage farmers moved from expensive chemicals to free parasitoids through an intermediary step of using biopesticides that allowed the natural enemies to recover—making even the need for biopesticides infrequent.

In the technological paradigm, the goals are predetermined. A package for pest management is planned and farmers are motivated to adopt it. The output is a crop protection infrastructure for delivering this package—products, marketing, and extension systems. In the ecological paradigm, the goals are evolving and location-specific. Participation of scientists and farmers is encouraged in the development of a basket of methods from which farmers, empowered and competent in pest management, can choose.

Ideally, IPM would occur through a mix of technologies and products working together, depending on the local ecology. However, a single-technology or single-product solution is the orientation of not only the agrochemical industry, but also the national and international agricultural research communities working on biological control, host plant resistance, transgenic plants, or engineered microbials as the "magic bullet" solution. True IPM would be driven by local processes where many of these technologies may work partially, and solutions may require other IPM components as well (Waage 1995).

of these processes and products involve advanced biotechnology-based tests.

While the major pesticide manufacturers have pledged to support IPM, there are environmental groups that believe that "the contradictory messages and economic leverage of pesticide companies is a major constraint on the widespread use of IPM and related agroecological approaches" (Thrupp 1996, 24). In their view, the pesticide companies' advertising and advice to farmers tend to work against IPM as does the payment of commissions to local distributors based on the volume of sales. In addition, some environmental groups believe that pesticide companies use their financial strength to lobby against government policies that might favor nonchemical approaches to pest management. Finally, many environmentalists whose main concern is the side effects of the use of any chemical pesticides are suspicious that the major pesticide companies support IPM because they are more interested in pesticide management than ecologically based pest management (Thrupp 1996).

Advocates of IPM believe that more widespread adoption of an ecological IPM would produce significant benefits without reducing yields. Evidence to support this view comes from the U.S. experience with maize. Since 1940 insecticide use on maize has increased substantially in the United States, but losses from pests have risen to a relatively high level mainly because of the abandonment of crop rotation. IPM advocates contend that by reinstituting crop rotations with some high-value crops, such as soybeans, yields and net profits could be increased and that pest losses, soil erosion, and rapid water runoff could be decreased. This could be accomplished by combining crop rotations with the planting of corn resistant to the corn borer and chinch bug. This approach should make it possible to reduce insecticide use while concurrently decreasing losses from insects and reducing potential environmental and health hazards (Pimentel 1995).

The technological base and requirements for IPM are available in developed countries. Help with IPM in these countries is available from public-sector research entities and crop consultants and agrochemical firms in the private sector. Most farmers in developed countries can afford to purchase the technological products and knowledge needed for IPM.

A recent report by the World Wildlife Fund (WWF) cites a number of analyses of farming in the United States that show that it is possible to reduce pesticide use without necessarily reducing yields (Hoppin, Liroff, and Miller 1996). The report also cites comparisons between some farmers in the Great Lakes Basin who use very little or no pesticides with other farmers who farm "traditionally." The report concludes that "the best farms practicing sustainable agriculture can be economically competitive with conventional agriculture." Other studies cited in the report indicated that farmers who practiced different versions of IPM generally had favorable results. Some showed an increase in pesticide use, coupled with higher yields and incomes. Others showed a sharp drop in pesticide use with increases in net returns ranging from negligible to as high as 19 percent. In two studies of alfalfa producers, pesticide use under IPM fell 2 percent, but net returns rose by 37 percent. A further survey cited by WWF indicated that, in 1995, 40,000 farmers in the United States subscribed to IPM and collectively they had achieved a significant reduction in the use of chemical pesticides. The survey concluded "It is clear from the data . . . that alternative pest management strategies have had a profound impact on farm profitability, through reduction in pest control cost and improved yields" (Hoppin, Liroff, and Miller 1997, 59).

Most of the IPM programs in developing countries are associated with high-input agriculture, such as cotton or horticulture (including fruits and vegetables for export). The important IPM programs dealing with food crops include work on soybean pests in Brazil, the cassava mealybug in Africa, potatoes in the Andes, and rice in Indonesia and other parts of Southeast Asia. Generally, most small-scale farmers in developing countries have little access to the technologies or services needed for IPM, nor could they afford them if they were available in the market. The public sector will have a much larger role to play in promoting IPM among these small-scale farmers than it has had in developed countries. The need for public-sector support applies to research, development, and the provision of supporting services, such as advice, credit, and essential education. IPM programs that have already been implemented in developing countries have relied heavily on support from the public sector, often backed by international development agencies and nongovernmental organizations, rather than private entrepreneurs.

International and national NGOs have been active in supporting IPM in many parts of the world. A number of case studies show promising results. They include the reduction of pesticide use in Bangladesh, along with increased incomes to farmers, the improvement in returns to millet farmers in Mali, and a sharp reduction in losses from pests among potato producers in Ecuador who followed nonchemical approaches to reducing pests (Thrupp 1996). CARE International is an example of one of the prominent NGOs concerned with reducing pesticides. CARE International has contributed its expertise in helping maize farmers in Nicaragua reduce pesticide use by 70 percent in one year without a change in yields (Hruska 1995). CARE's success has led it to mandate that IPM is its official policy, and it is actively promoting IPM in many other regions where it has projects. CARE's success has also encouraged other NGOs to adopt similar policies (Hruska 1995). However, CARE and other NGOs anticipate difficulties in "scaling up" their relatively small, successful projects. Enlarging the scope of these projects requires institutional changes that can only occur with strong governmental commitment to IPM.

Apart from the special case of Cuba (Box 5), the largest national program of IPM is in Indonesia. The program was initiated following heavy pest-induced losses in rice production arising from excessive use of pesticides (Box 7). The program has strong government support. However, the experience in Indonesia highlights the need for governments to recognize the importance of farmer participation. While governments can help in motivating, training, and disseminating knowledge among producers, farmer participation in planning and executing programs and changing the modus operandi of extension services is important for success. IPM training has been found to work well in a number of countries when used on a pilot scale by highly motivated field officers. However, problems in sustaining and expanding farmer interest arise when these programs are expanded. For example, when the responsibility for extension went from those running pilot programs over to national agricultural extension systems in the Philippines, Sri Lanka, and Indonesia, the quality of training fell so much that it had only a marginal impact on changing farmers' practices (Meltzer, Matteson, and Knausenberger 1994).

Some IPM trainers find conventional extension training methods inadequate for carrying out IPM-related training. As a rule, extension systems are usually large, top-down hierarchies, based on trans-

Box 7 IPM in Indonesia

The FAO-supported IPM programs for rice in the 1980s in a number of Asian countries were prompted by national agricultural crises caused by pest resistance. Insecticide application against the brown plant hopper not only caused its dramatic resurgence by eliminating more exposed and slowly reproducing natural enemies, but also led to the breakdown of useful resistance bred into the high-yielding rice varieties. In one year, 75,000 hectares of rice had to be abandoned in Indonesia because of damage by the brown plant hopper. When insecticide use was dramatically reduced, natural enemies recovered and the pest became once more a minor and occasional problem in many areas.

Under the leadership of I. W. Oka and with assistance from FAO, Indonesia began its rice IPM program in 1986 by removing or reducing subsidies for most chemical pesticides and banning others, and by initiating an intensive training effort that, by 1992, had trained approximately 150,000 farmers, 3,000 extension staff, and 1,000 pest observers. The training created expertise in pest ecology and pest control decisions based on threshold rules. Farmers were educated to understand the local ecology and use different crop protection solutions at different threshold levels. The removal of pesticide subsidies (amounting to 85 percent of the price) led to a decrease in pesticide use of about 50 percent between 1987 and 1990 and considerable savings by the government. Rice yields during this period increased by approximately 15 percent. IPM-trained farmers attained an average increase in profits of US$18 per season, with training cost per farmer estimated at US$4. In 1993 a program to expand IPM to the entire country was announced, with US$53 million provided by the World Bank, USAID, and the government.

The rice IPM programs are based on an ecological view of IPM and emphasize farmer participation. IPM training in rice was found to be effective if there was group training and frequent discussions among farmers, field-based instruction, experiments and demonstrations, and periodic follow-up by trainers for one or two seasons.

Some of the training was provided through an innovative system of Farm Field Schools (FFS) that use a farmer-participatory, learning-by-doing training approach for teaching rice IPM. The FFS process changes the roles of the extension agent and farmer, with the agent becoming more of a collaborator, consultant, and facilitator, and the farmer dominating the learning process. Farmers learn to make decisions and not just gain technical knowledge. A weekly analysis of the agroecological situation is done by the extension agent and the farmer to decide actions needed for that week for integrated crop management, including IPM. A result of the training process is that the farmer becomes an "expert" with a capacity for observation, analysis, experimentation, and decisionmaking. This innovation has achieved the best rice IPM results to date in Asia, with FFS farmers using less pesticides than farmers trained through conventional IPM training.

Such intensive training is costly and hard to implement. By March 1993, the IPM program in Indonesia had trained about 18,000 extension agents and over 500,000 farmers, still only a small percentage of the total 5 to 10 million farmers in the country. The number of farmers reached was expected to multiply through farmer-to-farmer training. However, the quality of farmer-to-farmer training has been seen to deteriorate for each succeeding round of trainees. In the absence of training follow-up, there is also a high rate of slippage in the behavior of farmers trained 5 to 6 years back. The lesson learned is that there can be no "let up" in training programs, and that adequate recurrent expenditures for training is an essential part of financing IPM programs.

mitting information to farmers who have little opportunity for participation in decisionmaking. This modus operandi has continued in a number of projects even though experience with pilot projects has shown farmer participation to be one of the important keys to sustainable pest management.

In spite of international, national, and local efforts over the past 20 years, IPM has yet to have a substantial and widespread application in the developing world. Nonetheless, even though there has been a slow spread of IPM, there is a growing consensus that IPM will be the preferred means for coping with pest-induced losses in the years ahead. There are, however, a number of issues that need to be addressed if IPM is indeed to become more widespread and successful than at present. These include the following:

1. Governments may be reluctant to commit and sustain the political support and money needed to field extensive IPM training. It is difficult to get national commitment to IPM in the absence of "shocks" such as economic crises caused by heavy pesticide losses. Increased environmental degradation and health-related problems are seldom considered serious enough to warrant a major change in strategies dealing with crop protection. This is all the more so when environmental lobbies in countries are not very strong. The government of Indonesia made an unusually large investment in training as part of an IPM program because national rice production was threatened by pest resistance due in large part to overuse of chemical pesticides.
2. The institutional structure, subsidies, and extension systems in most countries encourage the use of chemical pesticides and distort incentives so that pesticide use is entrenched in the system. The use of pesticides is a simple process and easy to implement from the top down without requiring extensive interaction with the farmer or knowledge of the local ecology. IPM is difficult to implement as long as there is a prochemical bias and the economic system continues to provide incentives for the use of pesticides.
3. A key impediment to the widespread implementation of IPM has been the difficulty of delivering training of adequate quality on a large scale. IPM implementation requires a considerable commitment because it involves a complex mixture of socioeconomic, political, and scientific solutions. The present extension systems are inadequate for IPM training. There is also the problem of achieving a multiplier effect, whereby the learning process and farmer-to-farmer training can lead to changes in farmer behavior that can be sustained over the long run.
4. IPM is a complex process that has to be tailor-made for local conditions and for different crops. Appropriate methodologies for defining the IPM process and its broad application have yet to be developed.
5. From the farmer's point of view, IPM often may be too complex, expensive, and risky. Not using pesticides or limiting pesticide use may be perceived as high risk. It is hard for a farmer to wait until he or she reaches an economic threshold level when neighboring farmers may be spraying by the calendar. IPM is also much more complex and requires much more knowledge and work from the farmer than does the use of pesticides.

In the past few years, multilateral development banks, which previously supported the use of pesticides as part of Green Revolution technology, have begun to see IPM as a key step in the development of any new agricultural program because of its importance to sustainability. The publication by the Asian Development Bank of its *Handbook for the Incorporation of Integrated Pest Management in Agricultural Projects* (ADB 1995) and the establishment by the World Bank, FAO, UNEP, and UNDP of a global IPM facility in Asia, with a mission to help accelerate the implementation of IPM programs by governments, all represent important steps in the commitment of development institutions to sustainable crop protection. The CGIAR also has an initiative in IPM to improve management of the major food crops produced and consumed by the poor. This initiative has produced promising results with pest-resistant potatoes and chemical-free techniques for reducing otherwise heavy crop losses in the Andes. There are many critics, though, who are not convinced that the international agencies, especially the World Bank, have a true commitment to IPM (Kleiner 1996). For its part, the World Bank points to its staff training programs, recent publications on IPM and guidelines to staff, and the growing volume of support for IPM programs as evidence of its commitment (Serageldin in van Veen et al. 1997).

As yet, the most effective methodology for the promotion of IPM technology has not been fully developed. The future of IPM will depend *inter alia* on the development of methodologies that are environmentally benign and that farmers find to be profitable, along with the ability of governments to create the necessary conditions to convince farmers that it is in their best interests to adopt these methods. A start along this road can be made if governments (and donors) introduce biological concepts in their ongoing programs and projects, and emphasize the importance of these concepts in existing extension systems, even as more comprehensive IPM programs are being developed. As yet, there are very few comprehensive IPM programs that are both effective and chemical free. In the short run, up to 2020, it is highly likely that IPM will focus on improving the management of pesticide use rather than on programs that eliminate the use of pesticides.

An optimistic scenario presented to a symposium on U.S. agriculture over the next 50 years suggests that “pesticide pollution” will decrease (Backman 1997). The reasons given for this scenario are “(a) the use of IPM technologies to apply pesticides only when needed, (b) the replacement of many chemicals with biologically based alternatives, (c) development of pesticides which are active at very low application rates and by uncovering synergies, which further reduce effective usage rates, and (d) improved application techniques which greatly reduce off-target pollution.”

Such a scenario is indeed feasible, but if it is to come about for the world at large, it will require (1) increased commitments by governments to fund research and development of biopesticides, among other things, and (2) sustained investments by the private sector to develop more effective, less hazardous pesticides and delivery systems that minimize wastage. In addition, as this paper has stressed throughout, an optimistic scenario will also require the development of low-cost, innovative systems for encouraging millions of producers to adopt changed methods of pest management. In the final analysis, whatever policies are adopted should be seen in light of the need to raise average yields of most crops to meet the food and fiber requirements of the 8 billion people who will inhabit the earth by 2020.

7. Conclusion

A number of recent studies confirm that there will be a need for a substantial increase in food production in developing countries over the next 20 to 25 years to meet food security needs for the populations of Asia, Africa, and Latin America. The circumstances governing food production and the prospects for expanding production in these regions vary greatly. In the main, though, most of the increased food supply will have to come from the further intensification of production. This applies with special force to Asia, where prospects for expanding acreage under cultivation are severely constrained, and, to a lesser extent, to much of Africa and Latin America. In the latter regions, there are opportunities to expand the areas under crop production. However, unrestrained expansion could well entail pushing the frontiers of crop production into ecologically fragile areas, including biodiverse forest areas, with a high risk of long-term damage to the natural resource base and the environment.

Over the past 50 years, gains in productivity have contributed to the increase in the production of the major grains and tubers that comprise the bulk of the diet of the poor. The increases in productivity have also provided the underpinning for the long-term secular decline in the prices of these basic foodstuffs. However, there is an ever-increasing concern that it will become more and more difficult to sustain a steady increase in productivity over the next several decades. One reason for this concern is that there are fewer opportunities for low-cost expansion of irrigation, a most important factor in producing more than half the rice and wheat grown in developing countries, especially in Asia. Costs of developing irrigation have risen steadily over the past several decades and are likely to continue to do so in the years ahead. In addition, it appears that Green Revolution technology has now been widely adopted so that, after an initial increase in productivity, diminishing returns may well be setting in for additional inputs, especially fertilizers.

The possibilities of rising costs of production and the slowing down of yield increases from the existing technology make it timely to reconsider some of the options and priorities for raising productivity and increasing future food supplies. Any such review should include examining whether higher priority should be given to reducing wasteful and unnecessary crop losses and protecting crops from pests. Higher priority might well be warranted if losses from pests are as substantial as has been reported in some of the studies cited in Chapter 1. Theoretically, higher priority for improving crop protection would be warranted up to the threshold where the marginal costs of reducing losses are equal to the marginal costs of expanding a comparable volume of production by other means. Priorities could also be based on partial analysis that would consider the economic rate of return based on the costs and benefits of improving pest management. The higher the return, the higher the priority.

One of the obstacles to formulating any such strategy is that the current state of knowledge about actual losses from pests and the gains from improved pest management leaves much to be desired. This applies to most developing countries, including all the countries in Sub-Saharan Africa (WIEA 1994). On the face of it, there would be a much stronger case for investing in improved crop protection if pests are responsible for reducing attainable yields by 50 percent rather than 25 percent.

More information is also needed on whether the level of losses is episodic and fluctuates with insect invasions or whether there is a consistent trend in losses. If overall losses from pests are indeed as high as 50 percent, this should signal governments and organizations such as the World Bank and the CGIAR that they need to devote more resources to reducing losses. From a donor perspective, more aid could well be allocated to organizations such as the Kenya-based International Centre of Insect Physiology and Ecology (ICIPE), which focuses on pest management. On the other hand, if losses from pests are much lower than 50 percent, then it may be appropriate to give a lesser priority to pest control relative to other investments in agricultural development.

In the years ahead, there may well be innovations in the use of satellite technology and the GIS that will make it possible to get a better fix on losses from different pests. However, it is most unlikely that any new technology will substitute for field-level monitoring. Any such monitoring would have to be based on standardized criteria in representative areas and would have to cover a reasonable period of time. An initiative could be started during the next decade to generate improved information and create a databank that could help establish the priorities to be given to improved pest management in the early part of the 21st century. Such an initiative could begin with a pilot project in a given region or on a given crop. The conflicting views about the many aspects of the benefits and losses from different aspects of pest management make it important that any such initiative be objective and seen to be objective. It could be organized by an international body, such as FAO or the CGIAR, with their global responsibilities for promoting food security. The organizer should mobilize public and private support and involve as many interested parties as possible. These would include government agencies, agricultural colleges, international research centers, NGOs, and representatives of the pesticide industry. Hopefully, the results of such an initiative would cast much needed light on the size of the problem, the possible contributions that could be made to increasing food production by reducing pest losses, and the costs of reducing these losses.

The major substantive issues that will confront policymakers and others interested in effective crop protection will center on balancing social costs with social gains from the use of chemical pesticides, that is, how to reduce crop losses while minimizing pest-resistance in plants and harmful side effects to health and the environment. While much still needs to be learned about the side effects of chemical pesticide use, the actual and potential social and economic costs from pesticide use make it desirable to reduce the use of chemical pesticides (and so the introduction of toxins into the ecosystem) without reducing needed crop production. Possible technological solutions to this dilemma include the development of new generations of pesticides that may well be more benign than current products, including nontoxics that enhance or trigger the defense mechanisms of plants themselves. However, for the foreseeable future the most pragmatic approach lies in the promotion of integrated pest management, including the use of genetically engineered plants.

The concept of integrated pest management has gained strong support among environmental groups as well as among agriculturists. At present, 20 years or more after the introduction of the concept in the United States, there is still no agreed-upon definition of IPM (see Appendix 1). However, in its broadest sense, IPM involves moving from a chemically based treatment of crops to a biologically based treatment. At present, most systems of crop protection in developing countries, outside of traditional agriculture, are chemically based (especially for cotton, export crops, and rice). Apart from some experimental efforts and the substantial program in Cuba, there are few if any large-scale efforts that are wholly biologically based.

The promotion of IPM requires an effective, easily managed method that can be introduced on a large enough scale to offer what chemical pesticides currently deliver: insurance against pest damages and crop losses, and acceptability among smallholders who can ill afford any losses. For this to happen, international development agencies, governments, and others will have to make major commitments to IPM, including the commitment of resources to develop and promote this form of management. This will involve both acquiring new knowledge about improving pest management through research, as well as disseminating information that is already known. It will also involve educating and organizing producers so that they can apply that knowledge. This will be no easy task. The experience in Indonesia and elsewhere points to the importance of sustained government commitment and support and the introduction of innovative approaches for persuading small-scale, risk-averse producers to adopt new approaches to pest management.

Given the need to have effective crop management, it is highly unlikely that there will be pesticide-free agricultural economies in the developing countries in the years ahead. Rather, the forms of IPM that will be encouraged will probably include the judicious use of some pesticides applied in the right quantities at the right time. It will be important to ensure that the pesticides that will continue to be used do not include the earlier products that have been banned for being hazardous to human health and the environment. Equally important, the international community should continue to seek ways and means to limit the manufacture, export, and distribution of the most harmful products. The phasing out of the manufacture of some products may well be accomplished by international agreement—along the lines established for ozone-depleting gasses.

During the next several decades, the private sector will continue to be the source of new and improved pesticides. These will be developed by the handful of large transnationals that have the resources and capacity to discover, test, develop, and market new products. The costs of bringing these products to market will probably continue to rise because of increasingly stringent standards imposed by the regulatory agencies in North America and Europe (both regions with strong environmental movements). The likelihood is that the newer products, especially insecticides, will be more selective and more expensive than earlier products.

The newer, improved products will have to compete in developing countries with older products that are imported or produced within these countries by domestic manufacturers. The manufacturers and importers in the developing world are either subsidiaries of the transnational corporations or independent corporations that produce for sale within the host country or for export to other developing countries. Many of the products put on the market by these manufacturers and their distributors are off-patent, broad-spectrum pesticides that contain hazardous compounds banned in developed countries. They may also be banned in developing countries, but the enforcement of regulations is so lax that these bans tend to be ignored (WIEA 1994).

Because of the lack of regulations or, more commonly, the weak enforcement of regulations, there is a dual-pricing system in many developing countries, with (1) the cheaper, broad-based, more hazardous products on the one hand, and (2) the more expensive, more specific, less harmful products on the other. Unless action is taken, there will be increasing sales of the cheaper, more hazardous products in developing countries. Market-oriented solutions might include taxing the use of the more hazardous products or subsidizing the more costly, new products. Other actions to limit the use of these products would include bans on their import, manufacture, and use, and, more important, implementing any such ban.

In many respects, the most important issue regarding the future promotion of IPM is whether governments will make the necessary commitments and whether they will adopt appropriate policies regulating the use of pesticides. Policies that support IPM would include removing biases that encourage pesticide use and promoting research and development on the most effective farming systems consistent with IPM. In addition, governments will need to support the massive educational efforts required to inculcate new approaches to IPM among producers. As has been shown in Indonesia, this will not be an easy task. However, since IPM is so knowledge-intensive, education is an essential component if IPM is to be successful. Indeed, the education of thousands, if not millions, of agricultural producers may well be the *sine qua non* for promoting the adoption and spread of effective integrated pest management.

The next 20 years will see a substantial increase in the use of genetically engineered plants, with a substantial impact on crop protection. The first generation of these plants is now in production in the developed countries, most notably in North America. These plants include products that have been engineered to resist herbicides so that the application of herbicides will destroy weed growth but not the economic crop. This achievement has permitted the adoption of no-till farming, which has helped reduce soil erosion, maintain soil fertility, and, it is claimed by industry spokespeople, reduce costs of production. Other genetically engineered plants have been designed to resist certain pests without the need for pesticides. Genetically engineered plants under development are expected to combine herbicide resistance and insect resistance in one seed. Such developments may well increase the demand for herbicides but reduce the demand for other pesticides. Should this be the case, the rapid spread of these genetically engineered crops may reduce some of the harmful side effects that could otherwise arise from the use of insecticides.

The use of genetic engineering is expected to produce plants with other desirable qualities, such as resistance to drought, greater salt tolerance, and higher nutritional content. There are concerns, however, that the rapid diffusion of improved varieties (relying on Bt) will lead to pest resistance and ensuing problems. Other inadvertent consequences from the spread of genetically engineered plants include the possible transfer of genetic qualities from modified plants to weeds, creating new generations of weeds that could resist herbicides and smother crop production. There are also concerns about the long-term effects of increased consumption of genetically altered materials on both humans and animals. Genetically engineered crops will have to be continually monitored and tested. An international body may have to fulfill this role, but which one?

Another issue that will preoccupy policymakers and others in the years ahead is the need to ensure that developing countries are not bypassed by this new technology. Developing countries may indeed lose out because the new technology has been developed in North America and Europe by the private sector, which is interested in making profits under the protection of laws governing intellectual property rights and patents. In addition, the designers of genetically engineered plants have concentrated on market opportunities in the richer countries and on products grown primarily, though not exclusively, in the temperate zones, for example, soybeans, canola, Irish potatoes, wheat, and corn. Moreover, considerable effort has also gone into enhancing the quality of some products to increase their sales appeal in affluent societies.

The developing countries will have a limited number of options if they wish to take advantage of the opportunities afforded by biotechnological research. One is to invest in domestic capacity to develop biotechnology suited to national circumstances. Such an approach, though, would involve a relatively heavy investment in human and financial resources with uncertain returns. It would involve duplicating some of the research and development already concentrated at high cost in the universities and, more significantly, in the private sectors of the developed countries.

Another option would be to “leapfrog” the technological gap by entering into arrangements to share new technologies with the corporations that own the rights to these technologies. This would involve some form of partnership between either the public or private sector in developing countries and the patent owners in the developed countries. Any such partnership could include laboratory and field research to develop and test new products, or it could involve the direct transfer of new products (as appears to be the case with the transfer of genetically altered soybeans from the United States to Argentina). As has been pointed out, technology and new products will be transferred by corporations interested in making profits for their shareholders, and profits may well depend on the recognition of proprietary rights to the technology being transferred. Consequently, transfers may hinge on legal codes in developing countries that recognize the sanctity of patents and intellectual property rights, in addition to the right to repatriate profits. Developed-country corporations would also have an interest in biosafety protocols to insure limited exposure to any damage that might arise from the use of the new products.

Biotechnology will be an important factor in agricultural development and food production in the next quarter century and beyond. It behooves policymakers in developing countries to have strategies that can capitalize on these new technologies, which could well contribute to increasing production and reducing the use of pesticides, especially insecticides, in the years ahead. No single strategy will be appropriate for all developing countries with their different endowments. The most important issue for national policymakers is to recognize the great potential benefit that can come from the use of new technology and then decide on the most appropriate means for encouraging its development and diffusion.

One more issue that will be of consequence over the next several decades is the role of the private sector as the driving force in research and development regarding innovative agricultural inputs. The private sector now invests more than the public sector in agriculturally related research and the major transnational corporations currently provide a high proportion of those investments. This can be a cause for concern because corporate shareholders are presumably interested in profits rather than the social consequences of the use of industry products, especially when the production of socially acceptable products raises costs and lowers profits. Thus, one of the important issues in the years ahead will be what role, if any, can or should governments and others play in encouraging the transnationals to use their vast resources to produce agricultural inputs that lessen the risks of harmful side effects without leading to a decline in output. Attaining this outcome might well involve moving against the trend toward reducing the role of the public sector by encouraging public-private partnerships for specific product development. Alternatively, as environmental groups have suggested, efforts can be made to educate stockholders so that there is “broad-based participation of stockholders in the decision made by corporations to ensure establishment of meaningful goals and systems of accountability” (WWF 1996).

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Appendix 1 Recommendations of a Workshop Held at IFPRI in 1995

The International Food Policy Research Institute (IFPRI), with assistance from the World Wildlife Fund, held a workshop called "Pest Management, Food Security, and the Environment: The Future to 2020," in Washington, D.C., from May 10 to 11, 1995. The participants, who attended in their individual capacities, came from developing and developed countries and a variety of institutional backgrounds, including the environmental community, the chemical and biopesticide industries, nongovernmental organizations dealing with development, and academia (see Appendix 2).

The seminar covered a wide range of topics, and many viewpoints were expressed. However, at the conclusion of the seminar, there was general agreement on a number of recommendations. These included:

- **Recommendations on Roles of Various Players in Pest Management and Allocation of Funds for Research**
  1. *Governments should pass legislation and implement programs to reduce pest losses using IPM.* Priority activities should include:
     incentives for adoption of technologies that are alternatives to chemical pesticides;
     support and extension for biological control;
     development of indicators for IPM and its effectiveness and systems for data collection;
     removal of subsidies for chemical pesticides and consideration of taxation and credit policies that would encourage use of alternative technologies; and
     a ban on pesticides falling in class 1a and 1b and organochlorines.
  2. *Increased investment should be made for research on farmer participation and on integrating the various players in research institutions, farming, NGOs, and public extension services.*
  3. *Linkages and collaboration among national and international players should be promoted in order to implement IPM.*
  4. *Private- and public-sector institutions should consider establishing a pool of funds to be administered by stakeholders in pest management in order to address IPM solutions.*
  5. *NGOs have a role to play* and this should be acknowledged. Other players should accept the fact that NGOs can provide extension services and assistance in technology transfer where public and private agencies have failed to do so.
- **Recommendations on Research and Policy Areas That Need Attention in the Future**
  1. *Document successful stories of alternatives to pesticide use, such as cases of integrated pest management.* There are several well-established and competitive alternatives to pure pesticide use that provide equal or better yield improvements. However, these alternatives have not been documented and studied enough to gain credibility These alternative approaches could define the path of pest management over the next 25 years. This documentation is not altogether a new task—the process has already begun.
  2. *The research field needs to examine yield-limiting factors and set priorities.* There are many yield-limiting factors in addition to pests, and they need to be researched. It is imperative that research funds be allocated according to priorities set. Priorities should ensure that the research agenda is balanced. Currently, for example, allocation of funds

to basic sciences, such as taxonomy and biocontrol, is suffering because more resources have been given to applied areas, such as biotechnology.

3. *More care needs to be given to implementation of pest management because it is a critical process in the successful use of pest management technologies.* More resources need to be devoted to effective ways to secure farmer participation in the development and appropriate application of pest management technology. New technologies are needed, but even some existing technologies are not being effectively used because of the lack of farmer participation in the current extension process.
4. *In donor-funded programs, priority should be given to programs that most or more directly contribute to food security*. Thus, funding of programs that increase overall yields, but only benefit large-scale farmers or plantations, should be given a lower priority than programs that more directly affect the food security needs of the small farmers and the poor.
5. *Sustained and sincere support should be given to promising initiatives in pest management.* An example is the new IPM facility funded by FAO, UNEP, and the World Bank. There is a need to make a meaningful allocation of monetary and personnel resources to such programs, rather than initiating them for the purpose of enhancing one's public image. The relevant agencies should actively promote these programs and provide them with sustained funding to ensure success.
6. *Full cost accounting should be used to measure the economic impact of pest management technologies in order to make funding and program decisions.* Externalities, such as health, environment, and subsidies, should be internalized into economic accounting.
7. *Mismanaged or inappropriate pest control programs should be identified and funds redirected toward finding better solutions.* An example is the outbreak of migratory insects in Africa. Current solutions being used are ineffective and need to be stopped. Resources should be reallocated for researching and implementing alternative solutions.
8. *More attention should be given to postharvest losses.* Postharvest losses in lower-income countries could be significantly reduced simply with more effective utilization of existing and traditional technologies.
9. *The CGIAR system needs to do more research in IPM, biological products, and plant protection biotechnology, but must become more participatory and reach out to stakeholders.*
10. *Interdisciplinary work is important,* not just between technical people, but also between social scientists, community development people, and others involved in pest management.

- **Areas of Disagreement**
  1. *Future role of chemical pesticides:* The group could not come to a consensus over the future role of synthetic pesticides. Some felt chemical pesticides should be banned, at least class 1a and 1b pesticides and organochlorines. However, others felt that some pesticides included in these groups were not harmful or had alternative uses, like malaria control, and banning them would prevent their use in these other areas. Still others felt that chemical pesticides were essential for maintaining yields and that the benefits and risks of various chemical pesticides need to be separately weighted to judge if they are beneficial or harmful.
  2. *The definition of IPM:* The group decided not to use time in trying to define IPM to the satisfaction of all parties. However, the varying concepts of IPM indicated that there was a need to develop a consensus on this issue. IPM is seen by some from an ecological angle, frequently with no role for chemical pesticides, while others see it from an input efficiency angle, with decisions based on economic thresholds. It was agreed that there was a need to have a universally accepted definition of IPM and that this should be the subject of a special workshop.

Appendix 2 Workshop Participants and Papers Presented

Participants

Ghayur Alam, Center for Technology Studies
New Delhi, India

Robert Blake, World Resources Institute
Washington, D.C., U.S.A.

Carlienne Brenner, Organization for Economic Cooperation and Development
Paris, France

Peter Carlson, Crop Genetics International
Columbia, Maryland, U.S.A.

Barbara Dinham, Pesticides Trust
London, England

John Edman, University of Massachusetts
Amherst, Massachusetts, U.S.A.

Robb Farley, Monsanto Corporation
St. Louis, Missouri, U.S.A.

Michael Hansen, Consumer Policy Institute
Yonkers, New York, U.S.A.

Hans Herren, International Center of Insect Physiology and Ecology
Nairobi, Kenya

Polly Hoppin, World Wildlife Fund
Washington, D.C., U.S.A.

Rob Horsch, Monsanto Corporation
St. Louis, Missouri, U.S.A.

Allan Hruska, CARE International
Managua, Nicaragua

David Jessen, Pioneer Hi-Bred International
Johnston, Iowa , U.S.A.

Walter Kaufmann, CIBA-GEIGY Ltd.
Basel, Switzerland

Agi Kiss, World Bank
Nairobi, Kenya

Patricia Matteson, EAP Zamorano
Tegucigalpa, Honduras

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Abou Thiam, ENDA-Senegal
Dakar, Senegal

Lori Ann Thrupp, World Resources Institute
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William T. Vorley, Iowa State University
Ames, Iowa, U.S.A.

Jeff Waage, International Institute of
Biological Control, CAB International
Silwood Park, United Kingdom

Participants from IFPRI

Per Pinstrup-Andersen, Director General
David Nygaard, Research Fellow
Montague Yudelman, Consultant
Mercedita Agcaoili-Sombilla, Postdoctoral Fellow
Annu Ratta, Consultant

Papers Presented at the Workshop

1. Mark W. Rosegrant, Mercedita Agcaoili-Sombilla, and Nicostrato D. Perez. Global food supply, demand, and trade to 2020: Projections and implications for policy and investment.

2. David Pimentel. Pest management, food security, and the environment: History and current status.

3. R. S. Morrod. The future: The role of pest management techniques in meeting future food needs — improved conventional inputs.

4. William T. Vorley and Dennis R. Keeney. Sustainable pest management and the learning organization.

5. Walter Kaufmann. CIBA's experience with integrated pest management (IPM).

6. Patricia C. Matteson. Developing human resources through participatory IPM training.

7. Allan J. Hruska. Resource-poor farmers and integrated pest management: The role of NGOs.

8. Jeff Waage. Divergent perspectives on the future of IPM.

9. Peter S. Carlson. Creating value with agricultural biotechnology: Developing world applications.

10. Ghayur Alam. Biotechnology and pest control: The case of India.

11. Hans R. Herren. The special needs of Africa in pest management.

12. Agi Kiss. Pest management needs and trends in Africa today.

13. Abou Thiam. Situation et problèmes posés par le contrôle des ravageurs en Afrique au sud du Sahara.

Montague Yudelman is a senior fellow at the World Wildlife Fund and a former director of agriculture and rural development at the World Bank; Annu Ratta is an independent consultant; and David Nygaard is director of Rural Development Programmes, Aga Khan Foundation, Geneva.