1 Introduction to Agro-chemicals Use

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Introduction

Efficiency gains in agricultural production as a result of agro-chemicals (chemical pesticides and fertilizers) are reported to be significant. That is obviously important given the projected growth of world population, though in many countries there is an increasing concern about the public health risks and negative environmental effects of agro-chemicals application. These contrary positions – the positive contribution of agro-chemicals to food production versus their real and perceived negative impacts on health and the environment – justify a careful analysis of the role of agro-chemicals within sustainable agriculture. For agriculture to become more sustainable, the relationships between agro-chemical use, crop response and environmental quality and human health need to be studied. Many factors are involved in these interrelationships and their dynamics: agro-ecology and climate, crops and rotations, socioeconomic conditions, farmers' knowledge and their preferences, the influence of research, education and extension, and developments within the chemical industry.

Against this complex background a conference on the economics of agro-chemical use was held under the aegis of the International Association of Agricultural Economists in April 1996 in Wageningen, The Netherlands. The objective was to bring together experts from both industrialized and developing countries to exchange experience and information. This book

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presents a selection of the papers presented at the conference.

This first chapter presents an introduction to agro-chemical use. Information is provided on the growth of fertilizer and pesticide use and on their productivity during recent decades both by region and globally. Environment and health problems related to agro-chemical use are described and their nature is indicated. Finally, we highlight some of the most urgent research questions and major findings emerging from the conference. The text contains many references to the basic literature which readers might find useful as further reading.

Developments in the Use and Productivity of Agro-chemicals

Chemical Fertilizers

The objective of fertilizer use is to limit reductions in crop yield due to shortage (temporal or spatial) of nutrient supply. All crops remove nutrients nitrogen, phosphorus and potassium (NPK) from the soil and, unless these are replaced, the fertility of the soil declines. Nutrients can be produced from different sources: chemical (manufactured or mined), recycling (green manure, animal waste), mineralization in the soil and atmospheric deposition. Here we focus on chemical fertilizers, where average application varies enormously throughout the world (Table 1.1).

Compared with 1951, total use is now almost nine times greater. This is particularly due to increases in the consumption of nitrogen fertilizers. Table 1.2 shows that, in 1994/95, by far the largest share of fertilizers was used in Asia, North and Central America and in Europe. There are differences among these regions in the relative importance of the three types of chemical fertilizers. In Asia, nitrogen fertilizers in particular are important, whereas Europe and NC America have a relatively larger share in the consumption of

Table 1.1 Comparison of world consumption of fertilizers, 1951/52 and 1994/5

	Volume/share			
	1951/52 (m. tons)	(%)	1994/95 (m. tons)	(%)
Nitrogen (N)	4.2	29.1	73.5	59.7
Phosphate (P_2O_5)	5.7	39.5	29.7	24.1
Potash (K_2O)	4.6	31.4	20.0	16.2
Total	14.5	100.0	123.2	100.0

Source: *FAO Production Yearbook: Fertilizers*, several years.

Table 1.2 Regional shares in total consumption of chemical fertilizers, 1994/5

	Share in world consumption						
	N/C America	S America	W Europe	Africa	Asia	Oceania	World
Nitrogen (N)	18	3	16	3	55	1	100
Phosphate (P_2O_5)	17	8	15	3	50	4	100
Potash (K_2O)	26	10	23	2	29	1	100
Total	19	5	17	2	49	1	100

Note: Because of rounding off, row entries might not add up to world total.

Source: *FAO Yearbook: Fertilizers* (1994).

potash. As indicated by Hiremath and Singh and by Li in Chapters 2 and 6, in Asia there has been an emphasis on nitrogen use, enhanced by subsidies. This excessive use of nitrogen has led to distortions in the supply of nutrients in balanced proportions and declining yields. The differences in average application rates per unit of area among the regions are as significant as those with respect to differences in total consumption. In some parts of Western Europe and Asia, application rates exceed 300 kg per hectare (see Chapters 5 and 7). In West Africa average use is less than 10 kg per hectare, which leads to significant soil nutrient depletion (see Chapter 4).

Additional information on aggregate changes in chemical fertilizer use by major regions of the world for a period of four decades is shown in Table 1.3. The huge increase in world use has already been mentioned. Within that, however, there are marked differences. At the beginning of the period the bulk of use was in NC America and Europe, with both areas showing considerable increases to around the mid-1970s. Since then there has been no change in NC America, while European use has marginally declined. Oceania, with its naturally small aggregate use, broadly follows that pattern.

The striking difference is in Asia. There was a steep increase from 1969–71 to 1975–77 (3.87 to 17.60 million tonnes), which has continued. The 1990–92 figure is up by a further 41.22 million tonnes, or by more than three times the 1957–1977 share in the total consumption of N, P_2O_5 and K_2O by region. That experience has not been shared by South America, where use from 1957 to 1977 is only about 50 per cent higher, while Africa lags behind with a much smaller increment of 35 per cent.

Analysis of the productivity of fertilizer use is, of course, a complex exercise which cannot be attempted here. However, attention is drawn to one feature of Table 1.3 which is of interest in the general context. Though fertilizer is used in many farming applications, much of it contributes to cereal production, which is illustrated in the table, along with a figure of

Table 1.3 Development in chemical fertilizer (NPK) use and productivity, by region, 1950-91

Year	N/C America			S America			Europe			Africa		
	Cereal production (1) (m. tonnes)	Chemical fertilizer use (2) (m. tonnes)	Average yield (1)/(2) (tonnes)	Cereal production (1) (m. tonnes)	Chemical fertilizer use (2) (m. tonnes)	Average yield (1)/(2) (tonnes)	Cereal production (1) (m. tonnes)	Chemical fertilizer use (2) (m. tonnes)	Average yield (1)/(2) (tonnes)	Cereal production (1) (m. tonnes)	Chemical fertilizer use (2) (m. tonnes)	Average yield (1)/(2) (tonnes)
1948–52[a]	169.4	4.59	36.9	24.8	0.17	145.9	112.4	6.97	16.0	33.9	0.31	109.4
1954–56	179.2	5.98	29.9	31.2	0.31	100.7	124.9	8.84	14.1	37.3	0.47	78.2
1961–65	210.0	9.25	22.7	40.2	0.55	73.1	158.6	14.62	10.8	51.0	0.82	62.2
1969–71	261.6	17.68	14.8	50.9	1.61	31.6	197.8	24.87	7.9	61.3	1.62	37.8
1975–77	316.9	23.43	13.5	63.0	3.4	19.5	224.1	29.10	7.7	66.8	2.67	25.0
1980–82	391.2	24.11	16.2	72.0	3.67	19.6	257.2	31.66	8.1	74.0	3.55	20.9
1985–87	395.9	23.10	17.1	79.9	5.50	14.5	289.3	32.35	8.9	82.0	3.69	22.2
1990–92	398.7	23.77	16.8	75.3	4.95	15.2	281.4	22.27	12.6	90.2	3.60	25.1

Table 1.3 continued

Year	Asia: Cereal production (1) (m. tonnes)	Asia: Chemical fertilizer use (2) (m. tonnes)	Asia: Average yield (1)/(2) (tonnes)	Oceania: Cereal production (1) (m. tonnes)	Oceania: Chemical fertilizer use (2) (m. tonnes)	Oceania: Average yield (1)/(2) (tonnes)	World total: Cereal production (1) (m. tonnes)	World total: Chemical fertilizer use (2) (m. tonnes)	World total: Average yield (1)/(2) (tonnes)
1948–52[a]	263.3	1.12	235.0	6.8	0.50	13.6	691.9	13.73	50.4
1954–56	353.4	1.66	212.9	6.8	0.71	9.5	732.7	17.98	40.7
1961–65	393.8	3.61	109.0	11.4	1.00	11.4	987.3	32.49	30.4
1969–71	482.8	3.87	124.7	14.6	1.40	10.4	1 237.9	75.32	16.4
1975–77	562.6	17.60	31.9	17.5	1.62	10.8	1 430.3	94.63	15.1
1980–82	654.0	31.36	20.8	18.8	1.69	11.1	1 637.1	115.27	14.2
1985–87	765.2	40.22	19.0	24.0	1.64	14.6	1 832.1	132.25	13.8
1990–92	875.9	58.82	14.9	23.1	1.70	13.5	1 928.4	134.32	14.4

Note: [a]For the yield of cereals, the average of the period was used; fertilizer use indicates the use in the middle year of the period.
Source: FAO, *Yearbook Production*; FAO, *Yearbook Fertilizer*, several years.

'average yield' per unit of fertilizer employed. It hardly needs to be stated that its use is only one factor which may account for changes in production. What the crude 'productivity' measure shows, however, is the importance of deeper study of use within the developing world. In Asia, for example, the marked increase in output, which has more than doubled in the years from the start of the 1960s, has also been accompanied by a change in average yield, which is declining. Production per tonne of fertilizer applied is now relatively low, at 14.9 tonnes. The importance of Asia within the world totals, allied to the fact that the 'average yield' in the developed world and in South America is of broadly similar magnitude, accounts for the lack of major change in the 'world total' average yield over the past two decades.

The outlier is again Africa. Though the production figures may be distorted by drought, its relatively poor performance in raising output, and the apparently higher fertilizer 'yield' (it is about double the Asian figure), could be an indicator of unused potential for agricultural production through additional, more effective, fertilizer use. As stressed by Koffi-Tessio in Chapter 11, there are many features of the African situation, including the need for innovation and extension services to alter cropping systems and optimize application rates and the timing of use, which deserve attention as means of increasing income and food production.

Chemical Pesticides

Whereas fertilizers are used throughout the world and the chemical compounds they contain are easy to define, chemical crop protection is much more complex. There are mechanical, chemical and biological methods of crop protection. Chemical crop protection agents can be defined as substances that protect plants from diseases, pests and weeds, or which are used to secure yields and facilitate harvesting (growth regulators, haulm-killing chemicals).

Pesticides can be classified in many different ways. One might classify them according to intended use: disease and weed control, haulm killing, soil disinfecting, growth regulation, grassland enhancement, and so on. One might also use biological classification: herbicides, nematicides, bactericides and fungicides, herbicides, insecticides and acaricides (to control mites). In practice, usually a mixture of classifications is used. It is common to indicate use figures, by category or in total, in kg of active ingredient (ai); that is, by the weight of the toxic substances.

Since the 1960s, the market for chemical pesticides has increased appreciably, and in this case a value measure can be used (Table 1.4). Sales of chemical pesticides worldwide have doubled since the 1970s, with herbicide sales showing the greatest rate of increase.

Table 1.4 Comparison of the world market value of chemical pesticides by category, 1972 and 1991

	Market volume/share			
	1972 (US$ bn)	(%)	1991 (1972 US$ bn)	(%)
Herbicides	4.5	36	11.9	44
Insecticides	4.5	36	7.8	29
Fungicides	2.7	21	5.6	21
Others	0.9	7	1.6	6
Total	12.6	100	26.9	100

Source: Modified from Dehne and Schönbeck (1994).

The importance of chemical pesticides varies from region to region (Table 1.5). Currently, more than three-quarters of them are used in the USA, Western Europe and Asia. Herbicides are the principal pesticides used in the USA; fungicides are least important in this region. In the temperate regions of Western Europe fungal diseases dominate and fungicides account for about half of chemical pesticide usage. In Asia the main problems are insect pests and fungal disease, so insecticides and fungicides are most important here (see Chapter 3). This use is still rather localized; more than two-thirds of all cropland in the world is not treated with any chemical pesticide at all (Dehne and Schönbeck, 1994).

Since the 1930s, when the first chemical pesticides were introduced (dithiocarbamate fungicides), there have been substantial developments in the synthesized active ingredients, particularly in herbicides and fungicides, though the spectrum of insecticides available is comparatively limited. This increases the chances of the emergence of insects resistant to the active ingredient.

Table 1.5 Regional market share of pesticides, 1991

Product group	USA	Western Europe	Eastern Europe	Latin America	Asia	Others	World total
Herbicides	34	30	6	8	15	7	100
Insecticides	18	20	8	9	31	14	100
Fungicides	9	48	5	6	28	4	100
Total share by region	20	33	6	8	25	8	100

Source: CountyNat West WoodMac, in Dehne and Schönbeck (1994).

Because the chemicals used are so heterogeneous, assessing their productivity is far more difficult than in the case of fertilizers. In Table 1.6, an estimate is presented for six major food and cash crops that are grown worldwide. The intensity of crop protection is best quantified in terms of expenditures on crop protection agents per unit area. However, it must be pointed out that in many parts of the world farmers control weeds by hand or by machine, whereas elsewhere weeds are controlled almost exclusively by herbicides. Direct control of pests and of diseases is impossible without the use of agro-chemicals, however. Table 1.6 shows expenditure per hectare of arable land for the total of herbicides, insecticides and fungicides used. This does not give the total costs of crop protection because the costs of application and the costs of labour and so on are not included, but it does give an overall picture of the intensity of use. On a per unit area basis, use is highest for cotton (US$80.5/ha), followed by potato (US$39.6/ha) and soybean (US$34.3/ha). In cereals the intensity of use is less than US$20/ha on average.

The effectiveness of crop protection is difficult to assess, not least because the concept has both a physical and an economic dimension. Estimates have been made of 'attainable production' and 'production without protection' for each of the crops, on the assumption that they could be either fully protected or not protected at all (Oerke *et al.*, 1994). The difference between the two then measures the full extent of 'potential loss'. Actual production (which always falls between the two limits, as would be expected) is also known, hence it can be presumed that crop protection has limited the losses; the actual size of the limitation is the difference between the 'attainable production' and its observed level. The effectiveness of protection, at least in its physical connotation, is the ratio of the 'potential loss minus the actual loss' to the 'potential loss'. In Table 1.6 (which also has some details for crop loss due to three types of causes, and estimates of the crop saved by the three types of chemical inputs), the overall effectiveness, calculated by the method described, is highest for cotton at 55 per cent, while for soybean and potato, it is around 45 per cent. The other three cases fall in the range 34–38 per cent. On a regional basis (Table 1.7) the figures are high for Western Europe (always greater than 50 per cent) and for North America and Oceania, but the performance is less impressive in other regions of the world except in the case of cotton.

It has to be borne in mind that the level of potential loss rate, and any measure of effectiveness that stems from it, could be misleading. It does have a financial equivalent measured in terms of the value of output that is saved, although the important issue is whether that saving is worth achieving given the cost of the chemicals and the labour and other costs of their application. The goal of crop protection is to prevent economic loss. If the

Table 1.6 Productivity of crop protection for six major food and cash crops, 1988-90

	Rice	Wheat	Potato	Maize	Soybean	Cotton
Use						
Total expenditure (m. US$)	2 400	4 718[a]	704[b]	2 463	1 930	2 722[c]
Per group (%)						
herbicides	36	50.4	31.3	74.3	81.9	18.2
insecticides	38	6.6	36.9	21.9	10.7	64.0
fungicides	24	38.8	31.7	3.1	6.5	3.9
Area harvested (m. ha)	145.8	231.5	17.8	129.1	56.3	33.8
Use ($/ha)	16.5	20.4	39.6	19.1	34.3	80.5
Attainable production, world total (m. t)	1047.1	830.7	464.7	728.6	152.0	84.1
Production without crop protection (m. t)	184.0	399.6	122.6	294.6	62.9	13.8
Potential yield loss[d] (%) due to						
weeds	34.0	23.9	22.8	28.8	36.3	36.3
animal pests	29.0	11.3	26.4	19.1	12.7	37.0
diseases	20.0	16.7	24.4	11.7	10.5	10.2
Actual production (m. t)	508.9	547.9	272.6	448.8	102.7	52.4
Actual yield loss[d] (%) due to						
weeds	16.0	12.3	8.9	13.1	13.0	11.8
animal pests	21.0	9.3	16.1	14.5	10.4	15.4
diseases	15.0	12.4	16.3	10.9	9.0	10.5
Crop saved (m. t) by the use of						
herbicides	192. 7	68.2	64.7	114.7	33.9	20.6
insecticides	86.5	26.3	47.9	33.5	3.1	18.2
fungicides	51.7	36.9	37.4	6.1	2.3	0.8
Effectiveness of crop protection (%)[e]	38	34	44	36	45	55
Average physical return of crop protection (crop saved in t/expenditure in US$)						
herbicides	0.23	0.03	0.09	0.06	0.02	0.04
insecticides	0.10	0.08	0.18	0.06	0.02	0.01
fungicides	0.09	0.02	0.17	0.08	0.02	0.01
Average financial return of crop protection (crop saved in US$/expenditure in US$)[f]						
herbicides	48.1	4.1	11.6	5.9	4.7	19.6
insecticides	10.9	10.9	223.2	5.9	4.7	4.9
fungicides	18.8	2.7	21.9	7.8	4.7	4.9

Notes:
[a] Figure for 1990 (CountyNatWest WoodMac, 1991).
[b] Figure for 1991 (CountyNatWest WoodMac, 1992).
[c] The category 'others' accounts for 13.9%. This category includes defoliants and/or desiccants that are applied before mechanical harvesting.
[d] Loss in % of attainable yield.
[e] Effectiveness potential minus actual loss in per cent of potential loss.
[f] Trade prices used in US$/t: wheat 136.2; rice 209.1; maize 98.1; potato 128.7; cotton 490.6. (See Oerke *et al.*, 1994: 748.)

Source: Own calculation, based on Oerke *et al.* (1994).

Table 1.7 Effectiveness[a] of crop protection in six principal food and cash crops, by region, 1988–90

Region	Rice	Wheat	Maize	Potato	Soybean	Cotton
Africa	34.0	25.5	26.2	30.7	38.9	49.5
N America	57.3	31.7	45.8	58.9	45.4	64.2
Latin America	36.4	28.6	22.4	44.1	46.6	52.8
Asia	37.5	32.1	30.1	35.8	39.0	51.6
W Europe	51.5	51.3	51.2	54.1	55.2	66.0
E Europe	39.7	24.9	28.9	35.9	37.4	59.0
Oceania	59.3	36.3	52.6	59.6	44.8	66.6

Note: [a]In percentage abatement of the potential loss.
Source: Oerke *et al.* (1994).

anticipated physical yield is low, for instance because it is limited by abiotic factors such as shortage of nutrients or water, it might be uneconomical to apply pesticides. There is an economic optimum between the intensity of pesticide used and the remaining crop losses. Therefore the economics of crop protection in different production systems cannot be concluded from the actual loss rates (see, for example, Campbell and Madden, 1990; Carlson and Wetzstein, 1993; Oerke *et al.*, 1994).

Impacts of Agro-chemicals on Environment and Health

The residuals that are generated as by-products of agricultural activity may be dealt with by the environment in two ways: (1) they may be reallocated and/or accumulated, or (2) they may be processed and recycled. Ecological processes exist with category (2) that result in the breakdown and reuse of chemicals, but are not available in (1). Chemical pesticides, phosphorus (P) and potassium (K) belong to the first category. Initially they are diluted and dispersed, but ultimately they will accumulate in some environmental component such as soil or water. Substances in the second category include nitrogen (N) and organic pesticides. Within limits, the environment can receive and process them without any negative effects. This capacity is constrained, firstly, by the environmental transportation mechanisms that carry that substance from the point of release to the environmental component responsible for its breakdown and, secondly, by thresholds that, if exceeded, will induce ecosystem changes. Nitrogen can only be taken up by crops if it is placed close enough to the root system; if that is not the case, it will for example, leach into groundwater.

The major environmental and health effects of nutrients are caused by eutrophication, which occurs when the concentration of nutrients in the environment is so high that it disturbs ecological processes. Nutrient surpluses (organic and inorganic) can lead to a decrease in the quality of groundwater and surface water and to a reduction in the value of nature. It might affect the quality of drinking water, which may lead to health problems. A well known example of the relation between agricultural intensification and human health is the contamination of drinking water by nitrate, which constitutes a hazard mainly for infants (*methaemoglobinaemia*, or blue baby syndrome). Babies may be at risk with nitrogen nitrate levels of 10 mg per litre of water which is easily exceeded in countries with intensive farming systems (see Chapter 2). Other studies mention nitrate as a cause of stomach cancer in adults (see Chapter 2.2).

Environmental problems caused by pesticides are specifically due to the fact that the amount of pesticides coming in direct contact with, or consumed by, the target pest is an extremely small percentage of the total amount applied. In most studies the proportion of pesticides reaching the target pest has been found to be less than 0.3 per cent, with the bulk being emitted into the environment (Pimentel, 1995; van der Werf, 1996). A consensus exists that the environmental impact of a specific pesticide depends on its dispersion, the resulting concentration in the environment and its toxicological properties (van der Werf, 1996).

Apart from environmental and health problems, pesticide use leads also to agricultural or agronomic problems. The most important of these are phytotoxicity (manifested as damaged crops, especially likely to occur when using herbicides), resistance, adaptation (after some years of soil disinfection and other soil treatment the chemicals used are decomposed by micro-organisms before they can become active), the development of secondary pests and changes in quality (Oskam *et al.*, 1992).

Environmental effects of pesticides are caused by emission into groundwater, surface water, air and adjacent fields. The most important routes are evaporation and leaching. Important factors are the characteristics of a pesticide and of the soil and the way in which the pesticide is applied (aerial spraying of crops compared to under-leaf spraying). Natural effects due to pesticide use result indirectly from the environmental effects mentioned. Human health can be affected by the toxic substances in pesticides either in food, drinking water or air.

Notwithstanding the extensive literature on the human and ecotoxicological risks of pesticides (see Chapter 24), data on their actual impact are scanty. At the conference some information was presented on human health risks of pesticide use. An overview of the maximum concentrations of pesticides in shallow and deep groundwater shows that, in about 30 per cent of water supply in EU countries, the European guidelines for drinking water (0.1 μg per litre groundwater for individual pesticides and 0.5 μg for total pesticide concentration) are exceeded (see Chapter 24). One of the few other significant international studies of the human health risks of pesticides is on residues in fruit and vegetables (van Klaveren, 1997). The norm used in this assessment is the acceptable daily intake (ADI), which is the maximum amount of a pesticide that a human being can ingest per kilogram of body weight during a lifetime without damaging health. There are significant differences among countries, as indicated in Table 1.8. Further, it follows that the percentage of vegetables and fruits with a residue higher than the norm in certain countries is still increasing, particularly for imported products. Possible effects of pesticides in the air have not been studied. However, the relative overrepresentation of toxicosis from pesticides in people working in agriculture indicates that they run greater

Table 1.8 International results of residue measurements of plant protection products in vegetables and fruit

Country	Product group	Year	No residue (%)	Residue < norm (%)	Residue > norm (%)
Denmark	Domestic	1993	90.5	7.4	2.1
		1994	87.8	11.7	0.5
	Imported	1993	74.5	23.9	1.6
		1994	74.7	23.0	2.3
Germany[a]	Domestic	1995	59.4	39.9	0.7
	Imported	1995	43.9	51.1	5.0
Greece	Domestic	1995	81.0	11.3	7.7
Netherlands	Domestic	1993	79.2	19.1	1.7
		1995	61.9	36.1	2.0
	Imported	1993	44.7	49.6	5.7
		1995	46.0	49.6	4.5
Spain	Domestic	1995	61.4	36.0	3.6
Sweden	Domestic	1993	84.6	13.9	1.5
		1995	90.2	9.4	0.4
	Imported	1993	41.2	56.0	2.8
		1995	55.8	38.2	6.0
UK	Domestic	1993	73.3	26.1	0.6
	Imported	1994	57.4	41.0	1.7
USA	Domestic	1993	58.3	40.0	1.7
		1994	56.2	42.5	1.3
	Imported	1993	64.9	31.4	3.7
		1994	64.6	31.3	4.1

Note: [a]Baden-Württenburg.

Source: van Klaveren (1997).

risks of damaging their health than others living in the same areas (Oskam *et al.*, 1992).

Summary Observations

The aim of this book is to assess critically the current status of economic research on agro-chemical use. We seek to answer two questions: what have been the main approaches and limitations in recent research; and what are some of the broader conceptual and methodological developments that are needed to enhance the future perspectives of this type of economic research?

Agro-chemical Use and Sustainable Agriculture

In contrast to conventional inputs (land, labour and capital) agro-chemicals affect output through indirect control mechanisms. These control processes aim to prevent, or reduce, yield loss due to biotic (pests, weeds or diseases) or abiotic (shortage of plant nutrients N, P and K) factors. So yield reduction can be regarded as a function of control actions and the uncontrolled level of the yield-limiting abiotic factors or yield-reducing biotic factors. Inputs that control crop loss act either in a preventive or a curative way. If the limiting or reducing factor is not present, the control input has no effect. This special feature, plus the fact that farmers have limited information on parameters that may vary between and within seasons and plots, makes demand for fertilizers and pesticides more complex than for conventional inputs. Environmental problems have resulted in renewed interest in this topic.

In the economics literature, debates continue about specifications and functional forms to use when studying crop response to pesticides and fertilizer (see Chapter 26). For econometric studies of pesticide use see, for example, Lichtenberg and Zilberman (1986), Babcock *et al.* (1992), Carrasco-Tauber and Moffit (1992), Chambers and Lichtenberg (1994) and Carpentier and Weaver (1995). Literature concerning uncertainty with respect to modelling fertilizer use and crop response includes Ackello-Ogutu *et al.* (1985), Berck and Helfand (1990), Paris and Knapp (1989), Paris (1992) and Chambers and Lichtenberg (1996). Just (1993, pp.11–12) shows that estimates of elasticities vary by more than orders of magnitude for most crops, depending on the functional specifications used.

In Chapter 9, the econometric approach is applied to compare the economics of high and low external input agriculture. Other authors such as Pandey (1989), Blackwell and Pagoulatos (1992) and Fox and Weersink (1995) emphasize that, rather than testing a range of functional specifications and comparing elasticity estimates, the production function should be derived from the biological and ecophysiological processes governing agro-ecosystems. This means that the analysis should start at a disaggregated level - the farm or crop level. By means of crop growth and pesticide and nutrient emission models, crop yields and indicators of pollution can be obtained for different production situations. This information can be used in an ecological-economic farm model to determine impacts of environmental and price policies, and of alternative technologies, on production patterns, farmers' revenue and environmental quality (see Chapters 8 and 21; also Wossink *et al.*, 1992). Both current and innovative production practices can be considered, which is not possible in the econometric approach.

Chapter 10 presents a multiple-criteria method to evaluate and summarize the ecological, economic and social sustainability of different farming systems. Such a method can be used in combination with the econometric or the ecological-economic farm model approach.

Efficiency and Producer Knowledge and Perceptions

All over the world significant differences are found in the efficiency with which farmers use agro-chemicals. Here an important issue is the impact of uncertainty due to limited information given to farmers. For example, Babcock (1992) showed that economically efficient nitrogen application rates for a corn–soybean rotation in the USA are about 35 per cent higher when uncertainty is explicitly taken into account. Risk aversion might further affect the optimal application rate. Chapter 7 discusses interview data for India which show that an increase in fertilizer prices gave a reduction in use and changes in cropping pattern, in line with economic theory, but that total crop production did not decline because of improvements in efficiency. Similar improvements in efficiency of agro-chemical use have been found for European cereal growers after the reduction in EU output prices (Boussemart and Dervaux, 1993). Also a continuing increase in higher-yielding varieties might counteract the expectation of lower yields at higher fertilizer prices (see Chapter 14).

Improvements in efficiency without changing crop varieties or chemical inputs can be achieved by education of farmers to stimulate better use of existing information, or by providing farmers with additional and better information itself. Site specific management or 'precision agriculture', is based on the idea that more detailed information will improve agricultural efficiency. Chapter 12 shows that this innovation can be particularly important as a means of improving the environmental quality of crop production.

Chapters 9 and 26 emphasize that costs and benefits are not the only relevant parameters for the selection of techniques by farmers in developing and developed countries. Utility analysis (farm household modelling) could offer a better methodology to evaluate the impact of agrarian policy instruments on agro-chemical use and land use than estimating crop response elasticities. An alternative would be to use an efficiency frontier approach in combination with a survey of farmers' perceptions and preferences (see Chapter 13).

Policy Instruments and Policy Analysis

If all the ecological and health effects can be measured, an ecological cost-benefit assessment can be made (see Chapter 20). Usually ecological processes have a very different space and time dimension compared with economic processes and often ask for an assessment at a wider spatial level than is common in agricultural economics (see Chapter 23). Health impacts may also take a long time to appear and can be difficult to trace back to a specific polluting source. Not only does the appropriate space and time scale need to be decided on before an economic assessment of pesticide and nutrient use is possible, but indicators of environmental quality have to be defined, particularly for pesticides given their diverse environment and health impacts. As long as ecological costs of agro-chemical use tend to be underestimated because of methodological and data problems in economic research, environmental and economic policy will not be able to signal the right price for pesticide and fertilizer use (see Chapter 18).

Chapter 24 provides an example of an environmental-ecological assessment. The indicator used for policy design and evaluation regarding nitrogen and pesticide use is the concentration in water. With such indicators an economic assessment can be made of the costs imposed by restrictions on drinking water, for example.

In Africa ecological effects of nutrient use are related not to over-application but to the opposite. Nutrient depletion is particularly severe in West Africa when agriculture is intensive. In the Sahelian countries, by contrast, there is little that possibly could be depleted. The economics of the ecological effects can be assessed by various methods (see Chapter 4), but actual data are scarce.

After an ecological-economic assessment of agro-chemical pollution or nutrient depletion, the policy issue is how to curb further environmental harm. There is a multitude of factors that determine agro-chemical use, some internal to the farmer (and his family) and others external, depending on economic and institutional conditions. The average outcome of the total of these factors might be different, even between growers of the same crop in two regions within one country (see Chapter 16).

Main Conclusions

Government agricultural programmes in developed and developing countries have been a major contributor to the overuse and inefficient use of agro-chemicals, especially fertilizers. This has been accomplished by both input and output supports that have distorted land use, crop mixes and applications of agro-chemicals. In developing countries there are many complications. Since public infrastructure can be poor, it is often the case that there has been a slow growth in the marketing of crops (farm gate prices are low). This has reduced the demand for fertilizer available from domestic resources, including manure and phosphate rock, while transport problems have made it difficult to move bulky material easily from supplying areas to the point of use. In other cases cheap food policies, used as a means of placating restless urban populations, have had similar effects, since effectively they reduce the profitability of farming. These features are particularly true for Africa. Elsewhere, notably in parts of Asia, there has been emphasis on encouraging the use of standard NPK fertilizers, which have often been subsidized and drawn from imports. In other cases, export crops are encouraged (cotton is a notable example), with the export crop using fertilizers less efficiently than crops produced for the domestic markets.

For the central and eastern European countries in transition, a special situation applies. Here new rules for economic activities are being institutionalized and agricultural policies are being redefined. Environmental concerns are now considered seriously, which was not the case before the political changes began in 1989/90 (see Chapter 25).

Use of agro-chemicals is often inappropriate (inefficient) because farmers do not apply proper amounts, employ less than optimal crop rotations, and so on. This problem exists in both developed and developing countries, but is most pronounced in the latter. Extension services are poor and many farmers are unable to read labels that give directions as to how to use products. A number of contributors to the present volume recommend that greater emphasis be put on extension, improving farm management and encouraging innovation, instead of limiting policy design to output restrictions, emission limits, price changes, subsidies, and so on (see Chapters 15, 17, 20 and 22). Governments need to reconsider their roles with respect to the agricultural sector, avoiding the application of instruments that distort resource use to the detriment of both people and the environment. This applies as well to developing countries as to the industrialized countries.

This volume contains 26 chapters. The remaining chapters are arranged into seven parts that deal with overviews of agro-chemical use for different parts of the world, agro-chemical use and its relation to a sustainable agriculture, farmers' knowledge, price responses, policy instruments and policy analysis in developing and industrialized countries. After considering inventories for different regions, the presentation moves from the farm to the higher, national or supranational level where policy regulations are the main issue. The volume concludes with some perspectives regarding agro-chemical use in the next century.

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