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Pesticide Use in Agriculture

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During the last three decades, the use of modern organic synthetic pesticides has increased about 40-fold. Total U. S. production, for domestic and export use, in 1976 was about 1.4 million pounds. Crops receiving the most intensive application of various pesticides were cotton for insecticides, corn for herbicides, and fruits and vegetables for fungicides.

Examination of use trends of pesticides indicates that the volume in pounds of herbicides used on crops is increasing, whereas the quantities of insecticides and fungicides remain stable. New chemical classes of compounds such as the synthetic pyrethroid insecticides are being introduced, but are not yet significant in terms of their share of the market.

The increased usage of pesticides, together with knowledge of some of their adverse effects, has alerted the public to the need for regulation. To assist in the regulatory decision-making process, emphasis is being placed on benefit-cost analyses. Additional and improved biological inputs and methodologies are needed to provide accurate analyses.

Introduction

Chemicals are continually becoming a more intricate part of modern society. Pesticides used in agriculture constitute less than 3% (1,500 out of over 63,000) of the commonly used commercial chemicals in the United States (*1*) but are often highlighted as being of special concern because of their relatively high intrinsic toxicity and direct application to food crops. This presentation reviews pesticide use in agriculture, with emphasis on crop use in the U. S., and includes discussions of mutagenicity of pesticides and of benefit-cost analysis. Pesticide use on crops in the U. S. is discussed within the framework of land use and crop production, though significant quantities of pesticides are used for control of pests of livestock, man, stored products, structures, home gardens, lawns and ornamental plants, and in industrial processes.

Crops were produced on about 467 million of the 2.3 billion acres of land in the U. S. in 1974 (*2*) (Table 1). The major crops in terms of acreages harvested were corn, wheat and other small grains, hay, soybeans, and cotton; the major crops in terms of value were corn, soybeans, wheat, hay, fruits and nuts, vegetables, and cotton (*3*) (Table 2).

Pesticides are used in varying amounts on crops to maintain yield and quality. Although complete and accurate analytical data concerning losses are lacking, the most comprehensive estimate was published by the U. S. Department of Agriculture for the years 1951–1960 (*4*) (Table 3). Some efforts have been made to update and expand upon these loss estimates and to assemble similar experimental data on pest losses from various parts of the world (*5–7*). These various estimates indicate that losses to crops from insects, weeds, plant diseases, and

Table 1. Major uses of land in the United States, 1974.[a]

Use	Acres (millions)
Forests	718
Grassland	598
Cropland	467
Recreation and wildlife	87
Urban	35
Public installations and facilities and farmsteads	35
Transportation	27
Other	297
Total	2,264

[a] USDA data (*2*).

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and mechanical methods and the use of harvest-aid chemicals (desiccants and defoliants) on cotton followed by mechanical harvesting to replace manual harvesting. Also, it has been suggested that increased pesticide use in reduced tillage systems may reduce the total energy requirements in the production of crops such as corn (*9*). Others question this conclusion as it relates to energy requirements, but support the increased use of pesticides to reduce soil erosion (*10*).

Pesticides are therefore an essential part of current agricultural production technology; however, we should also be cognizant of the increasing interest in the development of an alternative agriculture which is labor intensive and emphasizes use of biological methods of pest control (*11*).

Pesticide Production and Use

In the present discussion of pesticides, major emphasis is placed on insecticides, herbicides, and fungicides, which constitute about 90% of all pesticide use in agriculture. Fumigants including most nematicides, growth regulators, desiccants and defoliants, miticides, rodenticides, and repellents, are discussed when relevant data are available.

Table 6. U. S. production of synthetic organic pesticides, 1945–1976.[a]

Year	Quantity (1000 lb)
1945	34,000
1954	149,274
1955	506,376
1956	569,927
1957	511,552
1958	539,396
1959	585,446
1960	647,795
1961	697,972
1962	729,718
1963	763,477
1964	782,749
1965	877,197
1966	1,013,110
1967	1,049,663
1968	1,192,360
1969	1,104,381
1970	1,034,075
1971	1,135,717
1972	1,157,698
1973	1,288,952
1974	1,417,158
1975	1,609,121
1976	1,400,000[b]

[a] USDA data (*3, 12, 13*).
[b] Preliminary.

Production and Value

During the period 1945 to 1976, production of synthetic organic pesticides in the U. S. increased from less than 35 million pounds per year to over 1.4 billion pounds with a high of 1.6 billion pounds produced in 1975 (*3, 12, 13*) (Table 6). In recent years, about one-third of this production has been exported, 596 million pounds in 1975 and 574 million pounds in 1976; while quantities of pesticides equal to less than 5% of U. S. production were imported, 53 million pounds in 1975 and 65 million pounds in 1976 (*13*). World production of pesticides in 1975 was an estimated 3.7 billion pounds; thus in 1975, the U. S. produced nearly one-half of the world's pesticides (*14*). Also, pesticide sales by manufacturers in the U. S. (valued in 1970 dollars) were reported to have increased from $0.9 billion in 1970 to $1.7 billion in 1975 with herbicides accounting for 62%, insecticides for 32%, and fungicides 6% of the total sales (*13*) (Table 7). In another report, U. S. domestic sales (valued in 1976 dollars) have been estimated at $2.7 billion in 1976 with world sales estimated at $7 billion (*14*).

It is important to emphasize that the increase in both production and value of pesticides sold is probably associated with increased production of existing pesticides, since the number of new pesticides being introduced annually has declined from nearly 30 per year to less than 10 per year since 1965 (*15*).

Table 7. Value of pesticides sold (by type) in the United States (domestic and exports) 1970–1975.[a,b]

	Value in constant dollars (in 1000's) (1970 = 100)[c]			
Year	Fungicides	Herbicides[d]	Insecticides[e]	Total
1970	65,178	497,954	307,182	870,314
1971	70,543	539,311	328,864	938,718
1972	76,290	583,991	353,376	1,013,656
1973	95,524	668,172	411,763	1,174,459
1974	96,774	824,935	507,765	1,429,474
1975[f]	102,397	1,047,327	552,182	1,701,906

[a] USDA data (*13*).
[b] Classified by the International Trade Commission according to the most important use; many chemicals actually have uses in more than one major class; herbicides involve some repetition.
[c] Deflated by using the consumer price index, nonfood items, other goods and services (1970 = 100).
[d] Includes plant hormones.
[e] Includes fumigants, rodenticides, and soil conditioners (a grouping required by the International Trade Commission to meet its need for separate data on cyclic chemicals; fumigants included may be fungicidal, nematicidal, and/or herbicidal as well as insecticidal).
[f] Preliminary.

Table 2. Estimates of acres harvested, production and value of major crops in the United States, 1974.[a]

Crop	Harvested acres (millions)	Production (millions)	Value (millions)
Corn[b]	77.8	4,664 (bu)	14,122
Wheat	65.6	1,796 (bu)	7,338
Hay	60.6	127 (ton)	5,827
Soybeans	52.4	1,215 (bu)	8,070
Sorghum[b]	15.4	629 (bu)	1,743
Oats	13.2	614 (bu)	933
Cotton[c]	12.6	11,540 (bale)	2,985
Barley	8.2	304 (bu)	834
Fruits and nuts	3.3	[d]	3,262
Vegetables	4.9	[d]	4,249
Other[e]	153.0	[d]	[f]
Total	467.0	[d]	[f]

[a] USDA data (*3*).
[b] Includes land estimates for grain, forage and silage. The value is for grain sold only.
[c] Includes value of lint and seed.
[d] Not measured in comparable units.
[e] Includes acreage in fruits, nuts, and some pasturelands as well as other commercial field and seed crops.
[f] Estimates not available.

Table 3. Estimated losses due to pests in the United States, 1951–1960.

	Loss, %				
Crop	Insects[a]	Weeds[a]	Diseases[a]	Nematodes[b]	Total
Corn	12	10	12	5	39
Wheat	6	12	14	5	37
Alfalfa	15	12	9	5	41
Soybeans	3	17	14	10	44
Grain sorghum	9	13	9	6	40
Oats	4	17	21	5	47
Cotton	19	8	12	5	44
Barley	5	12	14	6	37
Fruits and nuts	22	8	20	12	62
Vegetables	15	8	18	11	52
Ornamentals	11	[c]	13	10	34

[a] USDA data (*4*).
[b] Society of Nematologists data (*5*).
[c] Not available.

nematodes are probably in excess of 30% of total production. Information is even more limited on the extent to which actual pest losses have been reduced as a result of evolution of pest control technology. Nevertheless, the development of pesticide technology, together with the increased use of improved varieties, fertilizers, irrigation and other new technologies have resulted in enormous increases in crop yields since 1900 (*3*) (Table 4).

Pesticides and Farm Management

Although benefits associated with pesticide use are most frequently identified as a reduction in losses due to pests, other less apparent factors contribute to the dependence of modern agriculture on the use of pesticides. An example is the use of pesticides in lieu of costly and frequently unavailable labor. For instance, the alternatives to the use of herbicides are either mechanical or manual methods of weed control. Mechanical methods may require more energy, lead to increased soil erosion and sedimentation in water, and are often not as effective. Manual methods require an able and willing labor force. Due in part to pesticide use, the labor required to produce agricultural products has been markedly reduced over the past 40 years (*8*) (Table 5). Notable examples are the increased use of herbicides for weed control on corn to replace manual

Table 4. Yield trends for some major crops in the United States, 1900–1975.[a]

Year[b]	Cotton, lb/acre	Corn, bu/acre	Wheat, bu/acre	Potatoes, cwt/acre
1900	187	28	13	56
1910	191	27	15	58
1920	160	27	12	63
1930	179	26	14	65
1938	236	28	13	73
1941	251	32	17	80
1944	267	32	17	86
1947	266	34	18	121
1950	275	40	16	145
1953	310	39	18	152
1956	405	42	20	175
1959	459	49	22	185
1961	445	60	25	192
1964	502	67	26	202
1967	490	75	27	211
1970	436	80	32	225
1973	485	86	31	236
1975	453	86	31	251

[a] USDA data (*3*).
[b] Based on moving average around the year cited; 1900-1930 in 10-year intervals, 1938-1973 in 3-year intervals, and 1975 as a 2-year interval.

Table 5. Index of labor hours per unit of production for selected crops in the United States for indicated periods, 1935–1939 to 1971–1975.[a]

	Index of labor hours in production (1935–1939 = 100)				
Crop	1935–39	1945–49	1955–59	1965–69	1971–75[b]
Corn (per 100 bu)	100	49	19	6	5
Wheat (per 100 bu)	100	51	25	16	13
Hay (per ton)	100	68	41	21	18
Soybeans (per 100 bu)	100	83	66	47	30
Cotton (per bale)	100	70	35	14	11

[a] Data of Delhaf and Wysong.
[b] Preliminary.

Crop Use

In 1964, the U. S. Department of Agriculture initiated a survey of farmer usage of pesticides; subsequent studies have been conducted for 1966, 1971 and 1976 (*16–18*). These surveys indicate that pesticide use on farms has about doubled since 1964 and in 1976 was an estimated 663 million pounds of active ingredients (Table 8). When this quantity is compared with net U. S. production (less exports and plus imports), agricultural uses account for only about 70% of the pesticides produced in the U. S. (*13, 16–18*).

Estimates of the crops receiving the most poundage of pesticides in the U. S. in 1976 show that 41% of total 1976 farm use of insecticides was on cotton; 54% of herbicide use was on corn; and 84% of fungicide use was on fruits, nuts, and vegetables (*16–18*) (Tables 9–11). Likewise, total pesticide use based on expenditures by crops throughout the world indicates that pesticide use on cotton, corn, and fruits and vegetables accounts for over 70% of all pesticide use (Table 12). U. S. crop-use trends of pesticide types expressed in pounds of active ingredients for insecticides, herbicides, and fungicides show the volume of herbicides used on agricultural crops has increased five times since 1964 while insecticide and fungicide usage remained relatively stable (*16–18*) (Tables 9–11).

When farm use in the U. S. of the major pesticides is categorized by chemical classes, some major changes are evident during the period 1964–1976. There has been a significant decline in chlorinated hydrocarbon insecticide use and corresponding increase in the use of organophosphate and carbamate insecticides (Table 13). Among the herbicides, there have been major increases in the use of triazines and amides, but use of phenoxy

Table 8. Quantities of pesticides used on farms by type, U. S. 1964–1976.[a]

Type of pesticide	Active ingredients (millions), lb			
	1964	1966	1971	1976[b]
Fungicides[c]	33	33	42	44
Herbicides	84	115	228	384
Insecticides[d]	156	149	170	158
Fumigants, growth regulators, desiccants, and defoliants	44	46	52	57
Subtotal	317	343	492	643
Others not included[e]	4	10	2	20
Total	321	353	494	663

[a] USDA data (*16–18*).
[b] Preliminary data, 1976 USDA/ERS Pesticide Survey for estimates of pesticide use on field crops and livestock. Estimates of quantities used on vegetables and fruits are from adjusted 1971 data.
[c] Does not include sulfur.
[d] Includes use on crops and livestock.
[e] Includes miticides, rodenticides, repellents, and others.

Table 9. Use of insecticides on crops in the United States, 1964, 1966, 1971, 1976.[a]

Crop	Active ingredients (millions), lb			
	1964	1966	1971	1976[b]
Cotton	78.0	64.9	73.3	59.7
Corn	15.7	23.6	25.5	32.0
Soybeans	5.0	3.2	5.6	7.9
Other field crops	10.1	8.7	17.5	11.9
Vegetables	9.7	11.1	11.1	11.1
Fruits	16.7	18.0	14.2	14.2
Other	8.0	8.1	7.1	9.2
Total	143.2	137.6	154.3	146.0

[a] USDA data (*16–18*).
[b] Preliminary data, 1976 USDA/ERS Pesticide Survey for estimates of pesticide use on field crops and livestock. Estimates of quantities used on vegetables and fruits are from adjusted 1971 data.

Table 10. Quantity of herbicides used on crops in the United States, 1964, 1966, 1971, 1976.[a,b]

Crop	Active ingredients (millions), lb			
	1964	1966	1971	1976[c]
Cotton	21.6	6.5	19.6	18.3
Corn	25.5	46.0	101.1	207.1
Soybeans	4.2	10.4	36.5	81.1
Other field crops	21.0	20.5	39.0	42.0
Vegetables[d]	4.8	5.7	5.6	5.6
Fruits and nuts[e]	1.0	3.6	2.4	2.4
Other	15.2	19.7	21.5	27.8
Total	76.3	112.4	225.7	384.2

[a] USDA data (*16–18*).
[b] Does not include petroleum.
[c] Preliminary; quantities used on vegetables and fruits were estimated based on 1971 data.
[d] Includes potatoes.
[e] Includes citrus.

Table 11. Use of fungicides on crops in the United States, 1964, 1966, 1971.[a,b]

Crop	Active ingredients (millions), lb[c]		
	1964	1966	1971
Cotton	0.2	0.4	0.3
Vegetables[d]	8.0	7.6	9.8
Fruits and nuts[e]	16.7	16.9	23.4
Other	5.8	5.6	6.1
Total	30.7	30.5	39.6

[a] USDA data (*16–18*).
[b] Does not include sulfur; Does not include use on livestock on farm commodity storage.
[c] 1976 survey did not include fruits and vegetables and, consequently, did not identify major uses of fungicides.
[d] Includes potatoes.
[e] Includes citrus.

Table 12. Percent of total expenditures for pesticides by type and crop, world, 1976.[a]

Crop	Portion total dollar expenditure by type of pesticide, %			
	Insecticide	Herbicide	Fungicide	Total, %
Cotton	71	26	3	21
Corn	20	78	2	20
Rice	47	35	18	8
Soybeans	6	92	2	4
Wheat	10	75	15	7
Fruits and vegetables	38	10	52	32
All crops	37	43	20	100

[a] Data of Cook (*14*).

Table 13. Farm use of insecticides by chemical class in the United States.[a,b]

Chemical class	Active ingredients (millions), lb[c]			
	1964	1966	1971	1976[d]
Organic				
Botanical	0.5	0.2	0.2	2.1
Carbamate	14.9	12.9	25.4	30.1
Organochlorine	98.2	89.2	69.9	41.0
Organophosphate	33.9	40.0	70.7	79.0
Other	0.8	0.8	0.3	2.1
Total	148.3	143.1	166.5	154.3
Inorganics[d]	7.7	5.8	3.2	3.5
Total	156.0	148.9	169.7	157.8
Petroleum	—	11.4	74.0	

[a] USDA data (*16–18*).
[b] Includes crop and livestock uses.
[c] Preliminary. Quantities used on vegetables and fruits were estimated based on 1971 data.
[d] Primarily arsenicals.

Table 14. Farm use of herbicides by chemical class in the United States.[a,b]

Chemical class	Active ingredients (millions), lb			
	1964	1966	1971	1976[c]
Organics				
Arsenical	1.1	0.9	8.0	3.5
Phenoxy	38.4	44.1	40.0	47.3
Phenylurea	1.7	3.7	6.6	15.0
Amide	4.9	5.9	46.3	111.3
Carbamate	5.3	10.2	18.3	38.9
Dinitro	3.2	5.0	7.2	6.8
Triazine	11.3	24.3	63.8	114.9
Benzoic	3.5	7.0	10.1	8.1
Other organics	4.2	9.5	22.7	37.7
Total	73.6	110.4	226.1	383.5
Inorganics[d]	10.4	4.9	1.8	0.7
Total	84.0	115.3	227.9	384.2
Petroleum	—	80.7	145.6	

[a] USDA data (*16–18*).
[b] Includes crop and noncrop usage.
[c] Preliminary. Quantities used on vegetables and fruits were estimated based on 1971 data.
[d] Includes sodium borates and sodium cacodylate.

Table 15. Farm use of fungicides by chemical class in the United States.[a,b]

Chemical class	Active ingredients (millions), lb			
	1964	1966	1971	1976[c]
Organics				
Dithiocarbamates	12.8	15.1	13.0	12.4
Phthalimide	5.8	7.5	7.5	7.7
Dinocap, karathane, dodine and quinones	2.0	1.1	1.2	5.6
Phenols	0.4	0.3	0.2	0.1
Other	2.9	1.5	3.9	3.0
Total	23.9	25.6	25.7	28.8
Inorganics[d]	9.3	7.6	16.0	15.4
Total	33.3	33.2	41.7	44.1
Sulfur	136.8	57.1	112.5	73.5

[a] USDA data (*16–18*).
[b] Includes crop and livestock uses.
[c] The 1976 USDA/ERS Pesticide Survey did not include fruits and vegetables the major users of fungicides. Quantities of fungicides by chemical class for 1976 include estimates of use on fruits and vegetables based on 1971 data.
[d] Includes copper, mercury, and other metal compounds.

Table 16. Quantity of insecticides used on livestock in the United States, 1964, 1966, 1971, 1976.[a,b]

Livestock class	Active ingredients (millions), lb			
	1964	1966	1971	1976[c]
Beef cattle	7,563	6,154	6,806	7,436
Dairy Cattle	1,682	2,895	4,925	1,932
Hogs	814	680	1,408	711
Poultry	345	906	1,428	334
Sheep	150	77	77	20
Other	[d]	69	140	318
Total	10,554	10,781	14,784	10,751

[a] USDA data (*16–18*).
[b] Includes use on livestock buildings, including milkrooms, and replacement livestock.
[c] Preliminary.
[d] None reported.

compounds has remained about the same (Table 14). Only fungicides have not experienced any sigificant changes; dithiocarbamate and the phthalimide compounds are still the principal chemical classes (Table 15).

Noncrop Use

The most important noncrop farm use of pesticides is on livestock. Insecticides, used both externally and systematically for the control of livestock parasites, remained relatively stable over the 1964–1976 period (*16–18*) (Table 16).

Substantial quantities of pesticides also are used for other noncrop activities including stored products, structures, (termites, cockroaches, etc.), home gardens, forestry, ornamental (lawns, trees,

shrubs), industrial processes, and mosquito and fly control. Information on quantities used for these purposes is limited. However, it is obvious from data on farm use and from information on total sales, that these uses are substantial. For example, in one study conducted in 1972 on the use of pesticides in suburban homes and gardens in three representative cities, a population of 5.5 million people was reported to have used 759,000 pounds with the average per acre of application between 5.3 and 10.6 pounds. One must exercise caution extrapolating the results of this one study into broader suburban home and garden use of pesticides, but anything near such a rate would represent 30 or 40 million pounds of use in the U. S. for this noncrop activity (*19*).

Since available data apparently are not adequate to provide a good understanding of total pesticide use in the U. S., there is a need to gather more information particularly on noncrop pesticide use.

Mutagenicity of Pesticides

The use of pesticides in agriculture generates considerable benefits. At the same time, the potential of adverse effects of pesticides must be recognized. While the benefits of pesticides are usually quantified from an analysis of direct costs associated with pesticide use and of relative crop production, a quantitative evaluation of risks is often much more difficult to obtain. The difficulty of obtaining reliable quantitative risk estimates is particularly formidable in the case of mutagenic and carcinogenic risks for a variety of technical reasons which have been discussed elsewhere (*20–22*).

The quantitation of mutagenic and carcinogenic risks is of particular importance because of recent reports that representatives of the major classes of pesticides are suspect due to mutagenicity and/or carcinogenicity (*23–36*). Included in these studies are triazines, organochlorines, carbamates, dithiocarbamates, organophosphates, phthalimides, amides, phenyl ureas, phenoxyacetic acids, and benzimidazoles. These classes of pesticides represent well over 80% of all synthetic organic pesticides now used in the U. S. (Tables 8, 13–15). It is not unlikely that further experimental scrutiny of structually related pesticides within these classes will reveal additional compounds which exert an adverse genetic effect under some test conditions. This does not imply that these compounds necessarily pose a significant genetic hazard to humans under the conditions of their use, but rather emphasizes the extent to which regulatory decisions related to possible genetic effects of these compounds will influence pesticide technology during the next decade; it also illustrates the need for translation of laboratory findings into quantitative measures of the actual risk to humans under use conditions.

Regulatory decisions related to the use of the above groups of pesticides will be a major determinant of the pesticide technology available during the decade ahead. The importance of basing these decisions on meaningful, quantitative, risk analyses is obvious. It is not our intention to discuss in detail the complex issue of genetic risk assessment. Suffice it to say that the cellular mechanisms for DNA replication and repair, like all major physiological systems, involve a complex set of enzymatically and genetically controlled biological reactions which may be altered in many ways. Not only are several types of genetic damage possible, but each may arise via a variety of mechanisms. Evaluation of findings in terms of risk is often impossible if these mechanisms are unknown. The interpretation of the finding that certain herbicides cause structural abnormalities in plant chromosomes, for example, would be quite different if the effect resulted from direct alkylation of the DNA rather than, as has been suggested, as a secondary effect of severe physiological disturbances in the plant (*37, 38*). Likewise, a reversible increase in repair synthesis in bacteria from a near lethal dose of a compound which exhibited no other adverse genetic effect would not be of the same concern as would a significant increase in the frequency of heritable translocations in mice at a dose near that expected from environmental exposure. Unfortunately, distinctions are seldom so clear-cut in practice. Interpretation of findings with agents that are mutagenic in microorganisms but which do not readily produce observable mutations in mammals are particularly difficult to interpret quantitatively. This occurs because alternative explanations for the results generally lead to markedly different conclusions regarding potential health hazards (*27, 39*). Indeed, the problem of reliably extrapolating into dose ranges approximately environmental exposures is still formidable even if a health hazard of undisputed significance is established in man, due to the wide range of minimal risk levels predicted by the alternative models which might be assumed (*21, 22*).

The major purpose of this workshop is the evaluation of potential uses of higher plants as monitors of mutagens in the environment. Data obtained from such monitoring with higher plant systems can play a valuable role in determining if a pesticide, in the environmental milieu in which it is employed, poses a mutagenic hazard. One example of the value of such data is provided by consideration of

the environmental data obtained on the triazine herbicides. This group of herbicides is used in the U. S. in quantities greater than any other group of organic pesticides (Table 14). Atrazine does not itself induce mitotic gene conversion in yeast, but extracts from maize kernels or seedlings treated with atrazine do induce this genetic effect (*23, 24*). A mutagenic effect is also observed in pollen grains from maize plants treated with atrazine in the field (*25*). This information indicates that laboratory data based on the exposure to test organisms to atrazine *per se* will not necessarily be an appropriate base for a risk assessment of atrazine residues in maize or in field runoff after atrazine use. Monitoring the mutation frequency in field plants thus revealed a mutagenic effect due to environmental conversion products which might not have been appreciated from conventional laboratory tests of the pesticide *per se*, or from chemical determinations of atrazine residues in the field.

Hopefully, future developments will permit the integration of such monitoring data with laboratory and epidemiological data to permit translation into a quantitative measure of health risk. Undoubtedly, the development of substantive risk evaluation methods is one of the most important challenges to environmental health scientists. Fortunately, research in genetic toxicology is moving rapidly toward a better understanding of the fundamental mechanisms of genetic damage and the foundation provided by this work will, hopefully, resolve the major difficulties associated with quantitative risk assessment.

Benefit-Cost Analysis

To aid in the formulation of regulatory policy action a specific decision-making approach is evolving that assesses the benefits and costs (including human health risks) associated with pesticide use. This approach, known as benefit-cost analysis (or benefit-risk analysis), is concerned with the economy as a measure of societal welfare, which refers to the state of well-being of the individuals in the society (*40*).

Benefit-cost analysis requires that many questions be examined for tradeoffs associated with the effects of regulating pesticide use. The most obvious question addressed by such an analysis is, "do the benefits or gains of the given pesticide use pattern exceed the costs or losses incurred?" This then lends itself to simulating posited changes in the given pesticide use pattern and measuring the potential impacts. In this way, analysts can determine optimal resource use through the allocation of productive inputs, the substitutability between productive inputs or control practices, and the substitutability between commodities produced. Other effects resulting from a policy change are the possible redistribution of social benefits such as impacts to the producers' and consumers' incomes.

Although complete benefit-cost analyses are yet to be conducted, the recent Environmental Protection Agency decision not to suspend trifluralin registration for weed control immediately used such an approach to balance relative cancer risk against the economic benefit of continuing registration pending further evaluation (*41, 42*).

A recent study designed to identify or specify inputs needed for benefit-cost modeling of pesticide use represents perhaps the most complete effort to develop a conceptual framework (*43*). The impact areas identified in this study are summarized in Table 17. The principal areas considered are: agricultural, material and property damage, human health, environmental and aesthetic values, distributional effects, and regulatory control costs.

Table 17. Summary of study areas to be considered in the identification and specification of impacts for the benefit-cost modeling of pesticide use.

1. Agricultural
   a. Yield of crop
   b. Quality of crop
   c. Cost of production
   d. Quality of land
2. Material and Property Damage
   a. Right-of-way maintenance
   b. Structural integrity of buildings
   c. Damage to commodities during storage
   d. Personal belongings
3. Human Health
   a. Manufacturing worker
   b. Formulator worker
   c. Distributor—wholesale and retail
   d. Applicators
   e. Non-occupationally exposed
   f. Disease vector control
   g. Accident attenuation
4. Environment and Aesthetic
   a. Non-renewable resources
   b. Sporting activities
   c. Tourism
   d. Home and gardens
5. Distributional Effects[a]
   a. Geographic
   b. Social
   c. Balance of payments
6. Regulation Control Costs[a]
   a. Legislation
   b. Enforcement

[a] The distributional effects and the regulation control costs were identified by Epp et al. (*43*) as secondary effects, but were included as primary effects for purposes of this paper. See discussion in Benefit-Cost Analysis section.

The first component, agricultural impact, is the focus of most benefit-cost analyses of pesticides. The crop yield, quality of the crop, and cost of production are areas of market-valued benefits resulting from the use of pesticides. On the other hand, the final item within this agricultural component, quality of land, deals with such effects of pesticides as soil erosion, soil compaction, and soil microorganisms. This variable is not intuitively apparent nor easily quantified and evaluated, but integral to the cropping decisions of the farmer. These characteristics are considerations when modeling the agricultural sector to simulate the effects of a change in pesticide use resulting from regulatory action. The biological data necessary to complete the agricultural impact equation involves collaboration between economics and various biological disciplines.

The second component, protection of material and property from damage by pests, is another quantifiable benefit of pesticide usage. The measurement of such an impact is made from the prices or defined values of such goods. Right-of-way maintenance includes the use of herbicides along roadsides, a labor-saving use. The use of pesticides to insure the structural integrity of buildings from pests such as termites extends the life of the buildings, a tangible benefit. Control of pests damaging commodities during storage and personal belongings is, of course, of real value.

The third component, human health, is the major issue in risk identification and quantification. The difficulties of quantifying the risk associated with possible mutagenicity and carcinogenicity discussed in the preceding section will probably constitute the greatest barrier to the practical application of such an analysis. Nevertheless, even at our present state of knowledge, assumption of conservative extrapolation criteria will permit assessment of a maximum feasible risk for many types of agents. The calculated permissible levels may then be adjusted to higher values as more precise risk information becomes available. Such maximum risk estimates may then be balanced against the benefits of pesticide use. If there are measurable health hazards and the total value of these hazards are a function of the size of the population affected, then an estimate of the value of adverse health effects can be made. Conversely, of the various items and groups affected under the human health component, the disease vector control item is a definite benefit. The control of disease carrying insects is often overlooked, but has saved innumerable lives. Biological estimates of human health benefits must be made to insure the safety of the public and, at the same time, allow adequate productive resources to maintain prosperity.

The environmental and aesthetic impacts also are difficult to measure. Pesticides are formulated to kill or control a wide array of species considered harmful to man. The basic problem with these chemical formulations is that their effects often are not limited to the intended or target organism. Through the use of pesticides, nontarget organisms can be killed either directly or indirectly via the consumption of contaminated foodstuffs. Pesticides can be transferred from the original application sites to other locations by erosion, drift, runoff, and biological transfer.

The final components, distributional effects and regulatory control costs, are treated as secondary effects in the original model specifications (*43*). We feel, however, that these effects, to the extent possible, should be quantified and included in the benefit-cost analysis conducted for pesticide use policy. An example of one of the distributional impacts that has rather significant impact on both the agricultural community and the consumer is the U. S. balance of payments accounts. Over the past four years, agriculture has consistently provided a net contribution to the balance of payments of over $10 billion per year (*3*). Thus, at a time when the U. S. deficit in balance of payments has reached a negative $27 billion per year and has caused the value of the dollar to decline, agriculture's role in the balance of payments is more important than ever. Judicious, objective investigations of pesticide use is warranted since the role of agriculture in the nation's economic welfare is more far reaching than some people realize. Regulatory costs at Federal, State, and local levels are very real costs than can be integrated into models designed to provide a total benefit analysis.

There is perhaps an area of consideration that has been essentially ignored in previous discussions of benefit-cost analysis of pesticides. This is the inclusion of methods of pest control practices other than pesticides. The inclusion in pesticide regulation analyses of nonpesticide control methods such as biological control agents, genetical methods, host plant resistance, cultural and physical methods and attractants and repellents, as alternatives to the use of pesticides also should be considered.

Future Outlook

During the past 20 years, quantities of pesticides used have increased about 10% per year. Pesticide use will likely continue to increase but at a somewhat slower rate. The future use of pesticides can be speculated to be largely a function of changing social mores and subsequent institutional regulation

rather than solely a function of demand for increased production and labor substitution. But, of course, the latter mentioned variables will remain in the pesticide use equation.

Insecticide use in terms of pounds is not likely to increase substantially. However, shifts in compounds used will continue to occur. Continued decreases in chlorinated hydrocarbons and changes among the organophosphates, with emphasis on greater specificity, can be expected. Also, some important new classes of compounds will play a major role in the years ahead. For example, among the insecticides a wide range of highly effective synthetic pyrethroids have been recently introduced (*44*). Also, a group of benzoyl phenylureas that act as insect growth regulators by inhibiting chitin synthesis look quite promising (*45*). These latter compounds are also active against nematodes.

Herbicide use will continue to expand but perhaps at a reduced rate. The amide and triazines will continue to represent the major chemical classes with some significant increases in other classes. Also, regulatory actions will likely have more impact on herbicide use in the future than they have in the past.

Nonsystemic, inorganic fungicides have been in use for over 100 years and continue to be of importance in select instances, especially the copper-based compounds; however, regulatory restrictions have had a major impact on these materials. Of the organic fungicides, dithiocarbamates will continue to be the most important group. Most current research and development into the fungicide area is focused on systemic products, so more fungicides of this type can be expected in the future.

Lastly, new compounds such as plant growth regulators and harvest aids are becoming more important with the advent of the energy shortages. However, there are regulatory issues to be resolved in obtaining approval for at least some of the materials which modify tissue growth (*14*).

Pest Control Policy

Although the use of pesticides in agriculture is the subject here, it should be emphasized that the U. S. Department of Agriculture is not only committed to the safe and effective use of pesticides, but to the development and use of alternatives to pesticides. Perhaps the Department's policy on pest control might be most accurately expressed by quoting from the Secretary's Memorandum No. 1929 dated December 12, 1977 (*46*):

"It is the policy of the U. S. Department of Agriculture to develop, practice, and encourage the use of integrated pest management methods, systems, and strategies that are practical, effective, and energy-efficient. The policy is to seek adequate protection against significant pests with the least hazard to man, his possessions, wildlife and the natural environment. Additional natural controls and selective measures to achieve these goals will be developed and adopted as rapidly as possible."

The Department's new pest management policy should provide a framework for the U. S. Department of Agriculture to work more effectively with all segments of society interested in improving pest control. Certainly, a better understanding of the role of chemical mutagens in our environment and the way their impact might be measured is a critical part of hazard assessment. The exchange of information and the innovation stimulated by this workshop should help all of us carry out our responsibilities more effectively.

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