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Pesticides: Energy Use in Chemical Agriculture (**)

Introduction

Worldwide, pests destroy about 35% of all food and fiber crops before harvest (Pimentel and Pimentel, 1979). These significant losses are primarily caused by insects, plant pathogens, and weeds. Then after the crops are harvested, an additional 10 to 20% of the crops are destroyed by insects, microorganisms, rodents, and birds. Thus, from 42 to 48% of the potential world food supply is being destroyed each year by pests. This occurs despite all efforts to control pests with pesticides and alternative nonchemical controls.

In the United States present estimates are that about 37% of all crops are lost to pests before harvest, and an additional 9% is lost to pests after harvest (Pimentel, 1986). A major reason why U.S. losses are similar to those of the world average is that these estimated losses are based on the quality or "cosmetic standards" that exist for each particular country. The allowed and/or acceptable quality standards are considered high in the United States compared with many developing nations, and if used in all nations, average world food losses to pests would be significantly greater than the 35% mentioned earlier.

Both pesticides and nonchemical biological and cultural controls are employed to reduce pest insect, plant pathogen, and weed losses in world crop production. An estimated 4.5 MMt (million metric tonnes) of pesticides are applied annually to world agricultural crops. Of this total, about 500,000 t are used in the United States (Pimentel and Levitan, 1986). Growth in the amount of pesticide produced and used in the United States has been rapid, but recently the quantities have declined. Part of the reason for the decline is that more highly toxic pesticides are being used. Thus, this tends to suggest that pesticide use has been reduced.

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In spite of the availability of chemicals, nonchemical biological and cultural controls are the dominant methods of pest control throughout the world (Pimentel *et al.*, 1978). At least twice as much U.S. cropland is managed by nonchemical controls as by pesticidal controls, while elsewhere in the world the ratio of nonchemical to pesticidal controls probably ranges from 2- to 10-fold to 1.

The nonchemical pest management practices include biological cotnrols, host plant resistance, cultural controls (rotations, crop diversity, planting times, burning, etc.), soil and water management, genetic controls, and behavioral and hormonal chemicals (Pimentel *et al.*, 1984). Although these pest management practices usually cause fewer environmental problems than pesticides, they do cause some problems.

This paper focuses on pesticide and other chemical use in world agriculture and the projected future for chemical agriculture. This information should help agriculturalists and policy makers to understand better the energetic and economic costs and benefits of chemical agriculture.

Pesticide Use on Crops

An estimated 4.5 MMt of pesticides are used in world agriculture, as mentioned. Approximately 90% of this amount is insecticides and herbicides, with about equal shares of each. Fungicides represent about 10% of the total. These proportions differ from those in the United States (USA), which include 60% herbicides, 24% insecticides, and 16% fungicides (Table 1).

Approximately 70% of the 4.5 MMt of pesticides used in the world is applied in developed countries; the remaining 30% is used in the developing countries. In all nations, pesticide use is concentrated on a relatively small portion of the total crops. For example, in the United States 93% of all the hectarage planted to row crops — corn, cotton, soybeans, sorghum, and tobacco — is treated with some type of pesticide (Tables 1 and 2); in contrast, less than 10% of the hectarage in forage crops is treated. Herbicides for weed control are currently being used on more than 100 million hectares in the United States, more than half of the nation's cropland. About 74% of these herbicides is applied to just two major crops, corn and soybeans. Corn grain alone accounts for 53% of the agricultural herbicide use. In developing nations, most pesticides are used on crops like cotton, rice, and peanuts.

Of the total of 500,000 t of pesticide applied on 150 million U.S. hectares, each hectare receives an average dosage of about 3 kg (see Table 1). About 16% of the total area of the United States thus receives some direct pesticide application each year.

Application of Pesticides

Pesticides are applied to destroy undesirable plants and animals. To combat some insects and pathogens, a protective coat of pesticide is placed on the

TABLE 1 - U.S. hectarage treated with pesticides (Pimentel and Levitan, 1986).

Land-use category	Total hectares ($\times 10^6$)	ALL PESTICIDES Treated hectares ($\times 10^6$)	ALL PESTICIDES Quantity ($\times 10^6$ kg)	HERBICIDES Treated hectares ($\times 10^6$)	HERBICIDES Quantity ($\times 10^6$ kg)	INSECTICIDES Treated hectares ($\times 10^6$)	INSECTICIDES Quantity ($\times 10^6$ kg)	FUNGICIDES Treated hectares ($\times 10^6$)	FUNGICIDES Quantity ($\times 10^6$ kg)
Agricultural lands	473	114	341	109	199	34	74	5	68
Croplands	185	113	337	108	195	34	74	5	68
Pasture	288	<1	4	1	4	—	<1	—	—
Government and industrial lands	150	28	55	30	44	—	11	—	—
Forest lands	290	2	4	2	3	<1	1	—	—
Household lands	4	4	55	3	26	3	25	1	4
Total	917	148	455	144*	272	<38	111	11	72

* Total for hectarage treated with herbicides, insecticides, and fungicides exceeds total treated hectares because the same land area can be treated with several classes of chemicals.

TABLE 2 - U.S. croplands treated with pesticides (Pimentel and Levitan, 1986).

Land-use category	Total hectares ($\times 10^6$)	All pesticides Treated hectares ($\times 10^6$)	All pesticides Quantity ($\times 10^6$ kg)	Herbicides Treated hectares ($\times 10^6$)	Herbicides Quantity ($\times 10^6$ kg)	Insecticides Treated hectares ($\times 10^6$)	Insecticides Quantity ($\times 10^6$ kg)	Fungicides Treated hectares ($\times 10^6$)	Fungicides Quantity ($\times 10^6$ kg)
Croplands alone	185	113	337	108	195	34	74	5	68
Cotton	5	4.8	45	4.2	0.8	3	29	0.5	<1
Tobacco	0.5	0.5	2	0.3	0.5	0.4	1.4	0.5	<1
Corn	34	32	118	31	103	13	15	—	—
Soybeans	20	18	50	18	41	1.4	3.6	—	—
Vegetables	1.2	<1	11	—	9	1	5	0.5	6
Fruit	1.2	<1	89	—		1	10	1	60
Alfalfa & hay	24	1	5	0.2	1	0.4	2.7	—	—

susceptible portions of desirable plants and animals. For weeds and some insect pests, the goal is to get enough herbicide or insecticide onto the pest itself.

In fact, the amount of pesticide impinging on target pests is generally an extremely small percentage of the amount applied. For example, our calculations of pesticide consumed by *Pieris rapae* caterpillars in collards showed that only 0.003% of the 1 kg/ha of pesticide applied was consumed by the target pests. These calculations were based on an infestation of 150,000 caterpillars/ha, each eating 0.1 cm^2/day, and included factors for plant leaf area and pesticide drift. This is about one-tenth the quantity calculated by Graham-Bryce (1975), who reported that aphids on field beans received only 0.03% and mirids on cocoa only 0.02% of the insecticides applied for their control. Even more striking, Joyce (1982) reported that only 0.0000001% of the DDT applied for *Heliothis* control reached the pests.

The amount of fungicide reaching target plant pathogens in a crop is probably even less than the proportion of insecticides reaching target insects because fungal targets are so small. In contrast, the amount of herbicide reaching target weeds is generally much higher. From 0.1 to 5% of postemergence herbicide applied to corn fields is calculated to reach the target weeds. When the herbicide is applied directly to a target weed tree, the proportion of the spray impinging on the tree might be as high as 80% (Haverty *et al.*, 1983).

Aircraft are used to apply a significant portion of the pesticides in the world today. Spray drift from aerial application is about five times greater than from ground-rig applications for row crops (Medved, 1975; Ware *et al.*, 1969). For this reason, up to 30% more pesticide is sometimes applied per hectare from aircraft than from the ground (Bull, 1982). In most situations, however, sufficient pesticide is applied so that if even as little as one-quarter of it reaches the target crop, it will be effective. Dosages recommended by manufacturers usually compensate for variation in application techniques and conditions.

Even under ideal aerial application conditions, only about 50% of the pesticide reaches the target area. In a carefully controlled test in cotton fields in Central America, for example, only 44% of the spray fell within the target area; the remainder fell beyond the borders of the 20-ha field or stayed in the air (ICAITI, 1977). Similar results came from tests with cotton and alfalfa in Arizona; Ware *et al.* (1970) reported that less than 50% of the pesticide applied during the season landed in the target area.

The use of new ultra-low-volume (ULV) technology in aircraft application of pesticides has reduced the amount of pesticide reaching the target area to only 25% (Mazariegos, 1985). The trend with aircraft application now is to use ULV equipment. The advantage of this equipment is that aircraft carries concentrated pesticide instead of pesticide diluted with water. This means that to obtain adequate coverage of the vegetation for effective pest control the spray droplets must be extremely small. The smaller the droplet size, of course, the greater the drift. Thus, instead of getting approximately 50% of the pesticide into the target area, the new ULV application technology only gets 25% into the target area.

Environmental Aspects of Pesticide Use

Because of the drift problem from aircraft applications and because generally less than 0.1% of all pesticides actually reach target pests, more than 99% of all pesticide has an impact on soil, water, air, humans, and other beneficial biota (Pimentel and Levitan, 1986). Human pesticide poisonings are a major concern in producing and using pesticides in agricultural and public health programs. It has been estimated that annually in the world, there are about 500,000 reported pesticide poisonings (WHO, 1981). The exact proportion of these that are fatalities is unknown, but it could be about 5,000 annually. In Central America (Guatemala, El Salvador, Honduras, and Nicaragua) the estimate was about 3-4,000 pesticide poisonings annually with about 10% as fatalities (ICAITI, 1977). In the United States the best estimate is 45,000 human pesticide poisonings annually, with about 3,000 of these serious enough to require hospitalization (Pimentel *et al.*, 1980). An estimated 200 fatalities occur annually due to pesticides, with slightly less than 50 as actual accidental pesticide poisonings (EPA, 1974; Barrons, 1986).

The humans that are poisoned come in contact with pesticides by various means. Workers are exposed during the production of pesticides, and others are exposed when these materials are formulated, often in small formulation plants. Other important means of human exposure are during the application of the pesticides, both in loading sprayers and in actual crop application, and when workers are exposed to pesticide drift during aircraft application. Also, workers may enter treated crops soon after the treatment to weed crops or harvest food and fiber products. In this situation they obtain pesticides by rubbing against the contaminated foliage with the unprotected portions of their bodies, such as arms and legs (ICAITI, 1977).

When pesticides are applied in agriculture, numerous changes can occur in agroecosystems and adjoining natural ecosystems. Many of these changes can have a detrimental effect on agricultural production. For example, parasites and predators attack a great variety of pests and in some cases provide the primary means of control (Huffaker, 1980). When insecticides and other pesticides are employed, the poisons not only destroy the pest, but also have a severe impact on natural enemies of the target pest. In some cases the natural enemies that are destroyed are important in controlling certain other pests. When these natural enemies are eliminated, it may result in outbreaks of pests that were previously not a problem in the target crop (Pimentel and Edwards, 1982; Adkisson *et al.*, 1982). In cotton, for example, it has been estimated that at least 4 to 5 additional treatments have been used to control the cotton bollworm and tobacco budworm due to the fact that the natural enemies of these two pests were destroyed when pesticides were applied to control the boll weevil. The use of pesticides against pests sometimes results in populations developing resistance to these chemicals. The best estimate is that 430 insect and mite species are now known to be resistant to some pesticides (Georghiou and Saito, 1983). A high level of pesticide resistance in crop insect and mite populations often results in additional sprays of the pesticide and/or the use of more expensive substitute pesticides, giving rise to significant environmental and social costs. For example, malaria is growing rapidly throughout the world because mosquito populations have developed a high level of insecticide resistance (Spindler, 1983).

Energy Inputs for Pesticides

Pesticides require fossil energy for their production (Pimentel, 1980). In the manufacturing process, the active pesticide ingredient uses direct energy inputs from the fuels like oil that make up the hydrocarbon stocks used in manufacture. The energy inputs for each pesticide range from 13,810 kcal/kg for methyl parathion to 109,520 kcal/kg for paraquat (Table 3). These inputs vary according to the hydrocarbon feed stocks used and the amount of heat and electricity used in the manufacturing process.

Herbicide production averages about 57,000 kcal/kg of energy, ranging from 19,080 to 109,520 kcal/kg (Table 3). Energy requirements of insecticide production average slightly less than those for herbicides or 44,000 kcal/kg ranging from 13,810 to 108,100 kcal/kg. Fungicides appear to be the most

TABLE 3 - Energy inputs for the basic production of selected pesticides (Pimentel, 1980).

Pesticides	Kcal for production (1 kg active) ingredient)
Herbicides	
Atrazine	45,240
Paraquat	109,520
2,4-D	24,200
Dinoseb	19,080
Glyphosate	108,100
Diquat	95,240
Insecticides	
DDT	24,200
Methyl parathion	13,810
Carbofuran	108,100
Carbaryl	36,450
Fungicides	
Ferbam	15,250
Maneb	23,570
Captan	27,380
Sulfar	26,620

economical, requiring about 22,000 kcal/kg and ranging from 15,250 to 27,380 kcal/kg for production.

Additional energy inputs are required to formulate the pesticide, to package it, and to transport it to the farm for use (Table 4). The least energy intensive means of supplying a pesticide appears to be a wettable powder formulation (Table 4). Miscible oil formulations and granules are both relatively energy intensive. The energy inputs for formulating, packaging and transporting are presented in Table 4. These inputs represent about a third of the total inputs.

Growth in Pesticides and Other Chemicals Used in Agriculture

The Green Revolution and chemical revolution in agriculture started about the same time. The Green Revolution included the use of both agricultural chemicals and new high-yielding crop varieties. This combination has had a tremendous effect in raising crop yields throughout the world, but especially in developed nations where yields have increased about 3-fold over the past three decades (Pimentel and Hall, 1984). The growth in the use of pesticides and fertilizers in the United States illustrates this. For example, little or no pesticide was used in corn production in 1945 (Table 5). The quantity of insecticide applied to corn rose from 0.1 kg/ha in 1950 to 2 kg by 1983. The insecticides

TABLE 4 - Energy inputs (production, formulation, packaging, transport) for various pesticides (Pimentel, 1980).

	kcal Input					% Energy types		
Pesticide	Production Active Ingredient	Formulation	Packaging	Transport	Total	Oil	Gas	Coal
Herbicide								
Miscible oil	57,000	33,300	8,500	1,110	99,910	60	23	17
Wettable powder	57,000	2,500	2,600	670	62,770	43	37	20
Granules	57,000	3,600	20,000	6,720	86,600	42	37	21
Insecticide								
Miscible oil	44,000	33,300	8,500	1,110	86,910	61	23	16
Wettable powder	44,000	2,500	2,600	670	61,470	43	37	20
Granules	44,000	3,600	20,000	6,720	74,300	42	37	21
Dust	44,000	3,600	20,000	6,720	74,300	42	37	21
Fungicide								
Miscible oil	22,000	33,300	8,500	1,100	64,910	70	15	15
Wettable powder	22,000	2,500	2,600	670	27,770	42	37	21
Granules	22,000	3,600	20,000	6,720	51,600	41	37	22
Dust	22,000	3,600	20,000	6,720	51,600	41	37	22

TABLE 5 - Quantities of various inputs to produce corn using only labor, draft animals, and mechanization from 1910 to 1983 (All units per hectare) (* means greater than 0).

Years	Hand-produced	1910	1920	1945	1950	1954	1959	1964	1970	1975	1980	1983
Labor (hours)	1,200[a]	120[b]	120[b]	57[f]	44[f]	42[f]	35[g]	27[g]	22[g]	17[h]	12[h]	10[d]
Machinery (kg)	1[c]	15[b]	15[b]	22[g]	30[g]	35[g]	42[g]	49[g]	49[g]	50[h]	55[h]	55[d]
Draft animals (hours)	0	120[b]	120[b]	*	*	*	*	*	*	*	*	*
Fuel (liters) Gasoline	*	*	*	120[i]	135[i]	150[i]	155[i]	125[i]	120[j]	60[h]	50[b]	40[d]
Diesel	*	*	*	20[i]	25[i]	30[i]	35[i]	65[i]	80[j]	70[h]	75[b]	75[d]
Manure (kg)	*	4,000[n]	4,000[n]	3,000[n]	2,000[n]	1,000[n]	1,000[n]	1,000[n]	1,000[n]	1,000[n]	1,000[n]	1,000[n]
N (kg)	0	0	0	8[g]	17[g]	30[g]	46[g]	65[g]	125[g]	118[j]	146[j]	152[j]
P (kg)	0	0	0	8[g]	11[g]	13[g]	18[g]	20[g]	35[g]	65[j]	74[j]	75[j]
K (kg)	0	0	0	6[g]	11[g]	20[g]	34[g]	32[g]	67[g]	75[j]	96[j]	96[j]
Lime (kg)	0	10[d]	10[d]	145[e]	193[e]	124[e]	158[e]	203[e]	220[e]	220[h]	426[k]	426[d]
Seeds (kg)	11[d]	11[d]	11[d]	11[g]	13[g]	17[g]	19[g]	21[g]	21[g]	21[h]	21[h]	21[d]
Insecticides (kg)	0	0	0	0[g]	0.1[g]	0.3[g]	0.8[g]	1.1[g]	1.1[g]	2[h]	2[h]	2[h]
Herbicides (kg)	0	0	0	0[g]	0.05[g]	0.1[g]	0.3[g]	0.4[g]	1[g]	4[h]	4[h]	4[h]
Irrigation (%)	0	*	*	1[l]	1[l]	2[o]	3[o]	5[p]	9[q]	16[r]	17[s]	18[s]
Drying (kg)	0	0	0	43[d]	48[d]	77[d]	271[d]	725[d]	1,880[e]	2,290[d]	3,200[d]	3,300[d]
Electricity (10^3 kcal)	0	*	1[d]	8[d]	16[d]	24[d]	36[d]	60[d]	80[d]	90[d]	100[d]	100[d]
Transport (kg)	*	25[m]	25[m]	170[m]	210[m]	262[m]	287[m]	325[m]	305[m]	298[m]	326[m]	322[m]
Yield (kg)	1,880[c]	1,880[e]	1,880[e]	2,132[g]	2,383[g]	2,572[g]	3,387[g]	4,265[g]	5,080[g]	5,143[t]	6,500[t]	6,500[u]

[a] Estimated from Lewis, 1951.
[b] Estimated from Pimentel, 1984.
[c] Pimentel and Pimentel, 1979.
[d] Estimated.
[e] USDA, 1970.
[f] USDA, 1954.
[g] Pimentel *et al.*, 1973.
[h] Pimentel and Burgess, 1980.
[i] Quantities from Pimentel *et al.* (1973) and proportions estimated.
[j] USDA, 1979; USDA, 1982b.
[k] USDA, 1981.
[l] Percentage of corn acreage irrigated (USBC, 1952).
[m] Transport of machinery, fuel, and nitrogen fertilizer.
[n] Estimated amount of livestock manure containing 80% moisture.
[o] Percentage of corn acreage irrigated (USBC, 1962).
[p] Percentage of corn acreage irrigated (USBC, 1967).
[q] Percentage of corn acreage irrigated (USBC, 1973).
[r] Percentage of corn acreage irrigated (FEA, 1976).
[s] Estimated percentage of corn acreage irrigated.
[t] Three year running average yield (USDA, 1976; USDA, 1982a).
[u] Estimated.

used in the early 1950's and 1960's were primarily chlorinated insecticides. Starting with the ban of some chlorinated insecticides in the early 1970's, there was a gradual shift from the chlorinated insecticides to carbamate and phosphate insecticides. With this change in the chemical makeup of insecticides, the energy inputs per kilogram of pesticide produced rose about 50% and the total inputs for chemical insect control rose nearly 30-fold (Table 6).

Changes in herbicide use also occurred in corn production starting in 1950. The first herbicide used in corn production was 2,4-D, a phenoxy herbicide that was relatively efficient to produce in terms of energy input per kilogram. The newer triazines and other herbicides that were added during the 1960's and later were 50% more energy costly to produce (Table 6). The total energy input for chemical weed-control increased 133-fold from 1950 to date. Hence, not only were there changes in the quantities of pesticides applied but there were significant changes in the kinds of insecticides and herbicides utilized.

Fertilizers (N, P, K, Ca) were the other major chemical input in agriculture. Again, this can be illustrated with corn production. Early hand-produced crops depended upon the nutrients that accumulated in the soil and wild vegetation growing on the uncultivated land. For example, in early slash/burn agriculture, the vegetation was cut and burned to release the nutrients to the soil for crop production. Usually the land had to lie fallow for about 20 years before sufficient nutrients would accumulate in the soil and vegetation. The land could then be tilled and planted to crops for 2 years out of 22 years.

Early U.S. agriculture was primarily organic based; that is, nutrients for crop production were provided primarily by livestock manure, green manures, and other natural means. In most cases, the farming system required 2 hectares of land to produce one hectare of a crop. For example, one hectare would be planted to a legume such as clover or vetch and the following year this legume would be plowed under and planted to corn. This 2-year rotation system did provide an adequate amount of nitrogen for the corn crop each year; however, the soils were slowly being depleted of phosphorus, potassium, and calcium.

In 1945 only 8 kg/ha of nitrogen and phosphorus were applied and 6 kg of potassium. By 1983 nitrogen application rates had reached a high of 152 kg/ha. This was nearly a 20-fold increase in application rates from 1945 to 1983.

Note that the energy inputs for nitrogen alone in 1983 were greater than the total energy inputs for all items used in 1945 corn production (Table 6). This is a clear example of how U.S. agricultural technologies have changed from 1945 to 1983.

During this 38-year period there was a reported 30% improvement in efficiency of producing nitrogen fertilizer (Smil *et al.*, 1983); however, these improved efficiencies have been offset by uses of new larger, more complicated equipment (Dovring and McDowell, 1980).

Although the amounts of phosphorus and potassium applied per hectare rose significantly from 1945 to 1983, the amounts clearly did not grow as rapidly as

TABLE 6 - The energy input for various items used in corn production from 1700 to 1983 (1,000 kcal per hectare) (* means greater than 0).

Years	1700	1910	1920	1945	1950	1954	1959	1964	1970	1975	1980	1983
Labor [a]	653	65	65	31	24	23	19	15	12	10	7	6
Machinery [b]	19	278	278	407	555	648	777	907	907	925	1,018	1,018
Draft animal [c]	0	886	886	0	0	0	0	0	0	0	0	0
Fuel: Gasoline [d]	0	0	0	1,200	1,350	1,500	1,550	1,250	1,200	600	500	400
Diesel [d]	0	0	0	228	275	342	399	741	912	912	878	855
Manure [e]	0	0	0									
N	0	0	0	118[f]	250[f]	440[f]	676[f]	955[f]	1,837[f]	1,734[f]	3,066[i]	3,192[i]
P[g]	0	0	0	24[g]	33[g]	39[g]	54[g]	60[g]	105[g]	195[g]	466[j]	473[j]
K[h]	0	0	0	13[h]	18[h]	32[h]	54[h]	51[h]	107[h]	120[h]	240[k]	240[k]
Lime [l]	0	3	3	46	61	39	50	64	69	69	134	134
Seeds [m]	44	44	44	161	322	421	470	520	520	520	520	520
Insecticides [n]	0	0	0	0	7	20	54	74	110	200	200	200
Herbicides [o]	0	0	0	0	3	7	20	40	100	400	400	400
Irrigation [p]	0	*	*	125	125	250	375	625	1,125	2,000	2,125	2,250
Drying [q]	0	0	0	9	10	15	54	145	376	458	640	660
Electricity [r]	0	*	1	8	16	24	36	60	80	90	100	100
Transport [s]	*	25	25	44	58	67	79	89	84	82	90	89
Total	716	1,301	1,302	2,414	3,107	3,867	4,667	5,596	7,544	8,315	10,384	10,537
Ratio [t]	10.5	5.8	5.8	3.5	3.1	2.7	2.9	3.0	2.7	2.5	2.5	2.5
Yield [u]	7,520	7,520	7,520	8,528	9,532	10,288	13,548	17,060	20,320	20,575	26,000	26,000

[a] Food energy consumed per laborer per day was assumed to be 3,110 kcal from 1700 to 1970, 3,300 kcal for 1975, and 3,500 kcal for 1980-1983.

[b] The energy input per kilogram of steel in tools and other machinery was 18,500 kcal (Doering, 1980).

[c] The food energy per hour of draft animal use was calculated to be 7,380 kcal (Pimentel, 1984).

[d] A liter of gasoline and diesel fuel was calculated to contain 10,000 and 11,400 kcal (Cervinka, 1980). These values include the energy input for mining and refining.

[e] No charge was made for the manure input. This input was assumed to be included in either the draft animal input or the machinery and fuel inputs.

[f] Nitrogen = 14,700 kcal/kg (Pimentel, 1980).

[g] Phosphorus = 3,000 kcal/kg (Pimentel, 1980).

[h] Potassium = 1,600 kcal/kg (Pimentel, 1980).

[i] Nitrogen = 21,000 kcal/kg (Dovring and McDowell, 1980).

[j] Phosphorus = 6,300 kcal/kg (Dovring and McDowell, 1980).

[k] Potassium = 2,500 kcal/kg (Dovring and McDowell, 1980).

[l] Limestone = 315 kcal/kg (Terhune, 1980).

[m] From 1700 to 1920, it was assumed that each kilogram of corn equalled 4,000 kcal, whereas when hybrid seed was used from 1945 to 1983 the cost was 24,750 kcal/kg (Heichel, 1980).

[n] Chlorinated insecticides dominated use from 1945 to 1964 and the energy input was calculated to be 67,000 kcal whereas from 1970 to 1983 carbamate and phosphate dominated use and the energy input for these was calculated to be 100,000 kcal/kg (Pimentel, 1980).

[o] Phenoxy herbicides dominated use from 1945 to 1959 and the energy input was calculated to be 67,000 kcal/kg whereas from 1964 to 1983 other types of herbicides dominated use and the energy input for these was calculated to be 100,000 kcal/kg (Pimentel, 1980).

[p] Water used per irrigated hectare was assumed to be 37.5 cm from 1945 to 1970 and 45 cm from 1974 to 1983. The percentage of corn acreage receiving irrigation is shown in Table 1. The energy required per centimeter of irrigation water pumped from a depth of 100 meters was calculated to be 300,000 kcal/cm.

[q] The quantity of corn per hectare that required drying is shown in Table 1. The energy required per kilogram dried was 200 kcal (Peart *et al.*, 1980).

[r] Includes energy input required to produce the electricity.

[s] For the goods transported to the farm, an input of 275 kcal/kg was included (Pimentel, 1980).

[t] Ratio = output/input.

[u] An input of 4,000 kcal/kg of corn.

TABLE 7 - Energy inputs per hectare of rice, Grand Prairie, Arkansas (Rutger and Grant, 1980).

Item	Quantity/ha	kcal/ha
	Input	
Labor	29.5 hr	18,130
Machinery	35.3 kg	686,364
Gasoline	86.1 l	870,385
Diesel	205.4 l	2,344,436
Electricity	29.7 kwh	85,031
Nitrogen	134.5 kg	1,977,150
Potash (units K_2O)	33.6 kg	53,760
Zinc	3.9 kg	19,500
Propanil	4.5 kg	449,595
Molinate	3.4 kg	294,440
2,4,5-T	1.1 kg	109,901
Insecticide	1.1 kg	95,601
Seed	156.9 kg	627,600
Irrigation	61.0 cm	3,803,139
Drying	5,074.0 kg	1,014,800
Transportation	431.4 kg	110,870
TOTAL		12,560,702
	Output	
Rice yield	4,742.0 kg	13,998,384
kcal output/kcal input		1.12

occurred with nitrogen, and both potassium and phosphorus require significantly less energy per kilogram to produce (Table 6).

The quantities of lime applied to agricultural land also rose about 3-fold from 1945 to 1983, but lime is the least energy costly of the fertilizers that are used in corn production (Table 6).

Concerning pesticide use in corn, the energy input represents only 6% (Table 6). This is a small percentage when compared with rice, potato, and apple production in the United States. With rice the percentage is 8% (Table 7), apples 20% (Table 8), and potato 29% (Table 9).

In a developing country, usually the labor input is high but other fossil energy inputs are low. However, the percentage of energy for pesticides is similar when rice production in the United States and Philippines was compared (Table 7 and 10). The percentage of energy for pesticides in Philippine rice production was 10%.

Pesticide Chemicals and Economics

Pesticides are generally effective in pest control and therefore return benefits greater than the investments in these chemicals. Although a worldwide

TABLE 8 - Energy input per hectare for low density (165 trees/ha) hand or mechanically harvested nonirrigated apples for the twentieth year after establishment, Eastern Region U.S. (Funt, 1980).

Item	Quantity/ha	kcal/ha
	Input	
Labor		
Hand	385 hr	235,200
Mechanical	138 hr	83,750
Machinery		
Hand	88 kg	1,029,385
Mechanical	151 kg	1,730,557
Gasoline		
Hand	1346 l	13,606,714
Mechanical	1531 l	15,768,879
Diesel	483 l	5,512,962
Electricity	20 kwh	57,260
Nitrogen	45 kg	661,500
Phosphorus	114 kg	627,000
Potassium	114 kg	231,408
Lime	682 kg	1,437,656
Insecticide	47 kg	2,889,090
Fungicide	49 kg	1,360,730
Herbicide	6 kg	599,460
Transportation		
Hand	2974 kg	787,448
Mechanical	3222 kg	851,184
Building (450 sq ft)		14,250
TOTAL		
Hand		29,049,973
Mechanical		31,827,596
	Output	
Yield		
Hand	54,743 kg	30,656,080
Mechanical	54,743 kg	30,656,080
kcal output/kcal input		
Hand		1.06
Mechanical		0.96

figure is not available, the return per dollar invested for pesticidal controls has been calculated for the United States (Pimentel, 1986). An estimated $3 billion dollars are spent for pesticides annually, including both the costs for the chemicals and costs for application. This investment is calculated to save about $12 billion in crop yields — thus, for each dollar invested for pesticidal control there is a $4 return. Certainly, this is an excellent return on the investment.

However, when compared to some nonchemical controls like biological control the return is relatively small. In the United States, it has been calculated

TABLE 9 - Energy inputs and outputs per hectare for potatoes in New York (Schreiner and Nafus, 1980).

Item	Quantity/ha	kcal/ha
	Input	
Labor	35 hr	21,560
Machinery	14 kg	252,000
Gasoline	261 l	2,638,449
Diesel	152 l	1,734,928
Electricity	45.7 kwh	130,839
Nitrogen	229 kg	2,748,000
Phosphorus	390 kg	1,170,000
Potassium	222 kg	355,200
Seed	2134 kg	1,309,347
Insecticides	31.4 kg	2,678,200
Herbicides	18.0 kg	1,798,380
Transportation	2473 kg	635,561
TOTAL		15,472,684
	Output	
Total yield	34,468 kg	21,156,291
kcal output/kcal input		1.37

TABLE 10 - Energy input per hectare of rice, wet season, Philippines (Rutger and Grant, 1980).

Item	Quantity/ha	kcal/ha
	Input	
Labor	814.4 hr	428,400
Machinery	4.5 kg	81,000
Gasoline	131.3 l	1,327,312
Nitrogen	33.0 kg	485,100
Herbicide	0.7 kg	69,937
Insecticide	3.2 kg	255,664
Seed	88.0 kg	352,000
Irrigation	15.0 cm	227,090
TOTAL		3,226,503
	Output	
Rice yield	3,232.0 kg	9,540,864
kcal output/kcal input		2.96

that for each dollar invested in biological control about $30 is returned in increased crop yields (Pimentel, 1986). This return is about 7 times greater than that for pesticides.

Pesticides and the Future of Pest Control

Devising pest-control strategies in the future employing minimum amounts of pesticides will require the joint efforts of scientists from several disciplines. Entomologists, plant pathologists and weed specialists will have to work together with agronomists, plant breeders, horticulturalists and others where appropriate. Only this type of interdisciplinary effort is likely to produce a sound Integrated Pest Management (IPM) program for both agriculture and society. Unfortunately, few current IPM programs include this broad type of joint interdisciplinary effort. Most remain *ad hoc* efforts by individual pest-control specialists.

Despite the need for joint interdisciplinary efforts for future IPM, some important achievements have been made in improving pest-control strategies for reducing pesticide use. For example, the quantity of insecticides applied to cotton in Texas has been reduced by about one-third compared with earlier years OTA, 1979). Fungicide use on cotton in this region has also been reduced significantly; however, herbicide use has increased. In contrast, in certain other cotton-growing regions of the United States, pesticide use has increased (OTA, 1979).

In New York State, new IPM strategies for insect and mite control in apple orchards have confirmed the potential to reduce insecticide use by 50% (Tette *et al.*, 1981). Although fruit growers are adopting these new IPM strategies, to date only a small percentage of the growers are relying on this new technology for pest control.

The implementation of IPM is slowing the rapid increase in pesticide use in both the United States and the world. Although IPM has the potential to reduce pesticide use by 35-50%, this goal is unlikely to be achieved in the near future. Although the adoption of IPM control strategies will be slow, the trend should be for more and more farmers to employ IPM.

The reasons for the adoption of IPM by farmers worldwide include the development of pesticide resistance (especially insecticide) in pest populations, the destruction of beneficial natural enemies by pesticides, and greater environmental awareness on the part of the public and farmers. Another major factor encouraging farmers to adopt IPM is the higher prices of the newer pesticides, some of which are sold for as much as $180 per kilogram.

The prices of pesticides will continue to rise because they are produced primarily from petrochemicals. For example, the average amount of fossil energy in a kilogram of pesticide in a miscible oil formulation is about 100,000 kcal or about 10 liters of oil (Pimentel, 1980). As oil prices continue to rise, pesticide prices can be expected to escalate.

Other factors adding to the cost of pesticides are the development and registration procedures. Whereas in 1945 pesticide manufacturers spent about $1 million to develop and market a pesticide (Shotwell, 1975), the cost is now approaching $20 million. Thus, it appears that pesticide costs will probably continue to increase and this will encourage growers to use pesticides cautiously.

Recently, farmers have become concerned about the widespread effects of environmental pollution from agricultural chemicals. This, too, has made farmers more cautious in their use of pesticides and has encouraged them to employ sound pest control practices when these are adapted to their crops.

Conclusion

In this paper I focused on pesticides and other energy inputs in chemical agriculture. These agricultural chemicals contributed to the success of the green revolution in increasing food and fiber production and making many nations self sufficient. However, despite the notable successes of the green revolution, there were several problems, including equity, environment, and increased energy use.

Can these problems be dealt with and at the same time provide increased food and fiber production for socioeconomic development? The findings of my investigation suggest that the prime need for a second green revolution is a holistic approach to agriculture. Agricultural production depends on soil, water, air, energy, and biological resources. Clearly, for a productive, sustainable agriculture for socioeconomic development, the complex interaction among these resources must be understood for each environmental and social situation so they can be managed as an integrated system.

The major principles that underlie a productive, sustainable agricultural system that will benefit society, protect the environment, and reduce energy inputs include the following approach: (1) Adapting and designing the agricultural system to the environment of the region. This means, for example, culturing crops and/or forages (livestock) that are ecologically adapted to the soil, water, climate and biota present at the site. (2) Optimizing the use of biological resources in the agroecosystem. This includes making effective use of biological pest control, green manures, cover crops, rotations, agricultural wastes, and other biological resources. (3) Developing strategies that induce minimal changes in the natural ecosystem to protect the environment and minimize use of fossil energy in manipulating the ecosystem.

Although this ecological resources management approach is complex, it may be simplified by focusing primarily on four factors that are commonly manipulated in agriculture — soil nutrients, water, energy, and pests. The goal is to conserve soil nutrients and water, while at the same time encouraging beneficial organisms and discouraging pests. Soil nutrients (N,P,K, etc.) and water are essential to a productive agriculture. Conserving soil and water resources reduces the energy inputs of commercial fertilizers and irrigation needed and thus decreases costs. Similarly, manipulations of the agroecosystem that encourage biological pest control and make the environment unfavorable for pests reduce the use of pesticides. Combined, these strategies will reduce input costs and help maintain a highly productive, ecologically sound agriculture for socioeconomic development and equity.

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