PEST CONTROL IN WORLD AGRICULTURE

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Summary

Insect, plant pathogen, and weed pests destroy more than 40% of all potential food production each year. This loss occurs despite the application of approximately 3 million tons of pesticide per year plus the use of a wide array of non-chemical controls, like crop rotations and biological controls. If some of this food could be saved from pest attack it could be used to feed the more than 3 billion people who are malnourished in the world today.

The causes of pest outbreaks and losses of crops to pests are due to a wide array of changes in the agricultural ecosystem that encourages pest outbreaks. Some of the changes include the planting of introduced crops into new ecosystems. For example, more than 99% of the crops grown in the United States are introduced crop plants. A similar pattern exists in most countries in the world. Native insects, plant pathogens, and weeds move into the agroecosystems simplified for crop production.

The use of pesticides also destroys beneficial natural enemies and this allows known pests or new pests to occur in the agricultural ecosystem and damage crops. In addition, some pesticides, like herbicides, can alter the physiology of the crop making it more susceptible to pest attack.

Many of the known pest control technologies provide significant economic benefits when employed in a satisfactory manner. For instance, pesticides on average provide about $4 in benefits for every dollar invested in pesticide control. Effective biological controls provide more benefits per dollar invested than pesticides. These benefits range from $30 to $100 per dollar invested in biological controls.

The estimate is that pesticide use could be significantly reduced 50% or more through the implementation of known pest controls available today. Pest problems and pest control are exceeding complex because of the wide array of crops, agricultural systems, and more than 70,000 species of pests in the world. However, many opportunities exist to improve pest control in all nations and in most crops.

1. Introduction

The control of diverse animal and plant pests that damage and/or destroy the food crops needed by humans for their survival continues to be critical, especially as the world population continues grow rapidly. Consider that each person in the world consumes an average of 479 kg of food each year; in the United States an average of 818 kg is consumed (Table 1). The production of large quantities of food the more than 6 billion people in the world and 275 million people in the U.S. is seriously stressing our natural resources including land, water, energy, and biota (Pimentel et al., 1999). Not only does agriculture use vast quantities of land, water, and energy resources but its influence on the stability and indeed survival of natural biodiversity is more widespread than any other human activity in the world. Clearing vast natural ecosystems to increase the needed food crops and livestock production, pumping immense quantities of water, application of agricultural chemicals plus other human manipulations are all contributing to the vast changes in ecological systems of world agriculture (Pimentel et al., 2000).

Food/Feed	**USA**	**China**	**World**
Food Grain	100	387[a]	171
Vegetables	105	198[a]	69
Fruit	125	35[a]	57
Meat and fish	137	62[a]	45
Dairy products	247	7[b]	70
Eggs	14	14[a]	6
Fats and oils	28	5[b]	11
Sugars and sweeteners	62	7[b]	19
Total food	818	406[b]	448
Feed grains	663	70[b]	166
Grand total	1481	476[b]	614
kcal/person/day	3644	2734[b]	2698

[a] Wan Baorui (1996); [b] Agrostat Data Base (1992).

Table 1. Foods and feed grains supplied per capita (kg) per year in the United States, China, and the world.

Worldwide each year, despite the use of nearly 3 million tons of pesticides in the world, pests (insects, diseases, and weeds) destroy more than 40% of the potential world food production. In the U.S. where more than 0.5 million tons of pesticides are applied each year, pests destroy about 37% of the potential food production. Both the quantity of food crops lost to pests and the cost of pest control in terms of dollars and human health are significant (Pimentel and Greiner, 1997). Of the agricultural chemicals currently used throughout the world, pesticides have the most serious and far impacts on natural ecosystems and biodiversity.

Included in this article is an analysis of the basic resource requirements in crop production. An assessment is made of the ecological causes of pest outbreaks as well as the immediate and long range social costs of attempting to control pests of agriculture with pesticides and other pest control methods.

2. Natural Resources used in Agriculture

In order to fully understand the role of pest control in agriculture, it is relevant to analyze the major natural resources required for a productive and sustainable agricultural system.

2.1 Land

Approximately 40% of the total land area (13 billion ha) of the world is managed by farmers for various kinds of agricultural production in the world (Pimentel et al., 1999). Most of this land (3.7 billion ha) is used for livestock production, because it has relatively low rainfall and generally is not suitable for crop production. Crop production takes place on about 1.5 billion ha.

Over many centuries changes in the agricultural production system imposed on ecosystems in the world, soil erosion has become a major environmental problem in the world (Pimentel et al., 1995; Pimentel and Kounang, 1998). The most damaging practice has been the removal of vegetative cover of soil to plant crops. This exposes the soil to wind and water erosion. Worldwide soil loss from cropland averages about 30 t/ha/yr or about 30 times the level of soil formation and sustainability (Pimentel et al., 1995; Pimentel and Kounang, 1998).

Soil loss adversely affects crop productivity by reducing organic matter and the fine clays, which provide plant nutrients and suitable soil structure (Pimentel et al., 1995; Pimentel and Kounang, 1998). Erosion reduces water availability and water holding capacity of the soil. Then as the topsoil layer is thinned, this restricts the rooting depth. In these ways, erosion diminishes the productivity of agricultural land, and is a serious threat to maintaining a sustainable agriculture now and in the future.

2.2 Water

Not only is water vital for all human life, its availability is the major limiting factor for all crops, livestock, and forest production (Pimentel et al., 1997a). All plants require enormous amounts of water for photosynthesis. For example, a corn crop producing about 8 tons/hectare (t/ha) will utilize about 5 million liters of water during the 3 month growing season.

In areas where rainfall is scarce, crops must be irrigated. An irrigated hectare of corn requires about 10 million liters of water because only about half of the water is utilized by the crop, the remainder is lost through evaporation and leaching (Pimentel et al., 1997a). Then too enormous amounts of fossil energy are required to move water from the source to the crop field for irrigation. For instance, pumping water from a depth of only 30 m requires about 3 times more fossil energy than to produce the same quantity of corn under rain-fed conditions (Pimentel, 1980). In California with abundant agriculture, 85% of the water is consumed by agriculture while only 15% is used by the public and industry (Postel, 1997).

Water is held in rivers, lakes, reservoirs and in enormous underground aquifers. Worldwide, underground aquifers are being mined primarily by agriculture at an alarming rate. The refilling of aquifers is extremely slow, or ranging from only about 0.1% to 0.3% per year (Pimentel, 1997a). Thus, all groundwater resources must be carefully managed, if they are to remain sustainable. Irrigation is expensive in terms of equipment and energy and should be restricted to high value crops, like tomatoes.

2.3 Energy

Beyond solar, human power, and animal power, fossil energy has become an essential resource in world agricultural production. Fossil energy is used to produce fertilizers and pesticides and run machinery and irrigation systems. While solar energy is free, fossil energy is finite expensive and becoming more so. At present from 20% to 25% of total fossil energy in the world is used to supply food to feed the present human population Pimentel et al., 1999). This includes the energy expenditure in production, processing, packaging, transport, preparation, and washing utensils. For each calorie that humans consume, approximately 10 calories of fossil and biomass energy are utilized (Pimentel, 2000).

At a time when the human population continues to grow rapidly, world oil reserves are projected to last from 40 to 50 years (Youngqukist, 1997; Ableson, 2000; Duncan, 2000). Thus significant problems are projected for agriculture because oil is a major resource used throughout the world agricultural production system.

2.4 Biological Resources

Essential for successful agricultural and forestry production are most of the estimated 10 million species of plants, animals, and microbes that exist in the world (Pimentel et al., 1997b). For example, about one-third of the crops in the world depend upon insect pollination. This free service that is being negatively affected as human numbers and their activities are intruding on vital bee habitats. The widespread use of pesticide throughout agriculture is also killing many bees Pimentel and Greiner, 1997). In fact, in some regions pollinated crops now depend on the culture and/or the rental of honeybees and other pollinators to carry out the activities of pollination of major crops.

In addition to pollinators, some natural enemy species help in the control of many serious insect and weed pests worldwide. For example, many of the pest insects in cotton and apples are controlled by natural enemies (Pimentel, 1991). Worldwide, natural enemies provide more control of agricultural pests than all the pesticides applied in the world today.

Several species of microbes help fix nitrogen, thus providing vital nitrogen nutrients for food crop production. An estimated $50 billion per year of useable nitrogen is provided to world agricultural crop by the action of nitrogen-fixing microbes (Pimentel et al., 1997b).

The diversity of genetic material utilized in crops and livestock are obtained from natural ecosystems and vital to increasing the productivity of agriculture. This has been well demonstrated in rice and wheat production.

3. Ecological Causes of Pest Problems

Over many decades, agricultural technology has changed the dynamics of the ecology and economics of pest control. Some of these changes in agroecosystems have resulted in pest outbreaks. Although this assessment of the effects of diverse ecological changes on pest problems focuses on individual ecosystem alterations, pest outbreaks usually are the result of a complex combination of changing factors in a given agricultural ecosystem.

3.1 Introduced Crops

Approximately 99% of all crops produced in the world and the United States are introduced from various parts of the world (Pimentel et al., 2000). All too frequently, some native insects and plant pathogens move from being parasitic on native plant species to attack and feed on the introduced crop (Pimentel, 1997). Not surprisingly, most of the introduced crops lack any natural resistance to the native pests because they have never been exposed to them. For example, when the potato (*Solanum tuberosum*), which originated in Bolivia and Peru, was introduced into the southwestern United States, it was attacked by the native Colorado potato beetle (*Leptinotarsa decemlineata*). This beetle had originally coevolved with and fed on wild sand bur (*Solanum rostratum*). But when the potato was introduced into the Southwest, the beetle spread onto the potato, which lacked any natural resistance to the beetle. Soon the insect became the most serious pest of potato in the U.S. and throughout the world. The beetle continues to be the major pest of potato today.

3.2 Introduced Pests

Sometimes pest species of insects, pathogens, plants (weeds), mammals, and birds are introduced into a new ecosystem, where they become the major pest species in their new ecosystem. Unfortunately, the introduced crop pests often are introduced without their natural enemies which normally control the invading pest species in their native habitat. If an introduced crop plant lacks natural resistance, then the introduced pest population can and often does increase to outbreak levels and the crop suffers.

A classic example of this is the damage done by the gypsy moth (*Lymantria dispar*) which was brought from Europe into the eastern United States (Pimentel et al., 2000). Once released and established the moth reached outbreak levels and inflected severe damage on its new plant hosts, primarily oaks and related hardwoods. Subsequently, the moth has spread westward in the United States where it continues to damage valuable trees.

Dutch elm disease a continuing problem throughout the U.S., is the result of a chance introduction of a fungal pathogen associated with European elms to the American elm (*Ulmus americana*) population (Matthysse, 1959). Unfortunately the American elm lacked resistance to the new pathogen, so it continues infect American elms and to cause widespread destruction of these beautiful trees. In addition, the spread of this disease has hastened by the introduction of the European bark beetle (*Scolytus multistriatus*), which also increased quickly to outbreak levels in its new American habitat (Matthysse, 1959). Together, these two introduced species have been responsible for decimating the beautiful American elms throughout U.S. cities and countryside.

3.3 Monocultures

Biotic communities in natural ecosystems normally consist of a complex group plant, animal, and microbe species. In crop production, however, the natural plant community and most other organisms are removed and replaced with a single crop–plant species. This greatly reduces the natural species diversity within the habitat. Planting vast areas of a country with one crop to the exclusion of other plant species, enabled the insect pests feeding on the crop plant's favorable conditions for their explosive increase (Pimentel, 1997). There were few other plant species and especially few natural enemies in the simplified habitat to help control the pest populations. Frequently, outbreaks of insect, plant pathogen, and weed pests follow the practice of monoculturing crops.

Although some combinations of plants, like cotton and alfalfa, may reduce pest problems, planting other crops, like cotton and corn, in combination helps increase pests (Pimentel, 1991). For example, planting cotton and corn crops close together increases certain insect pest populations, like *Heliothis zea*. Clearly knowledge of the ecology of pest populations and the specific crop plants can help reduce or prevent some pest problems.

3.4 Regional Climatic Differences

Sometimes, the distribution of plants, animals, and microbes in nature is the result of the differential survival of parasite, predator, and host in specific climatic region (Elton, 1927). This means that some plants are able to escape severe attack from their usual parasites and predators if they can be grown in a climatic region unsuited to their natural enemy populations.

In agriculture, as well as in the wild, climatic conditions influence the degree of pest attack on a particular crop or animal. For example, potatoes grown in northern Maine or in North Dakota have fewer insect pests and experience less damage than potatoes grown in warmer regions of the United States. This occurs because the potato aphid (*Macrosipum euphoribae*), potato stalk borer (*Trichobaris_trinotata*), and potato tuberworm (*Phthorimaea_operculella*) are more serious pests in the warmer Southeast than in the cooler northern and mountainous regions (Pimentel, 1977). One indication of the differences is the severity of the pest problem related to climate is that 100% of the potato acreage in the Southeast U.S. is treated with insecticides, whereas only 65% is treated in the cooler regions of the North (Pimentel, 1977).

3.5 Breeding Crops

Over time plant breeders have been able to make many crops somewhat resistant to some major pest species. The difference in pest resistance levels that may exist in crop plants and their effectiveness to resist pest attack is well illustrated with pea aphids (*Acyrthosiphon pisum*) pests of alfalfa. For example, five young pea aphids placed on a common crop variety of alfalfa produced a total of 290 offspring in 10 days, whereas the same number of aphids placed on a resistant variety of alfalfa produced a total of only 10 aphids in the same time (Dahms and Painter, 1940). Obviously, a pest population that has 29 fold greater rate of increase on a host plant will inflict significantly greater damage than one with an extremely low rate of increase.

One of the major ecological factors that has increased pest problems is the breeding of susceptible crop genotypes. This occurred during the period 1940 to 1970, when the prime aim of plant breeders was to increase crop yields. When altering the genetic makeup of the crop plant to increase yield, little or no attention was given to its resistance to pest attacks. In fact, the plant breeders were applying large quantities of pesticides to protect their high yielding experimental genotypes from pests. After 1970, there was a dramatic change and the plant breeders started to reduce their use of pesticides to a minimum and increase the resistance of crops to pests (PSAC, 1965). This emphasizes the importance of considering all factors involved in crop production when dealing with the causes of crop pest outbreaks.

3.6 Genetic Diversity

Parasites associated with hosts in nature appear to be fairly stable in terms of population outbreaks and this is related in large measure to genetic diversity inherent in parasite-host systems in natural ecosystems. However, in agricultural ecosystems, when a parasite pest population is stressed by a single factor in the host plant or by a pesticide, it frequently evolves genetically to overcome the single factor resistance and subsequently is able to cause serious damage to crops. For example both parasitic stem rust and crown rust have been able to overcome genetic resistance bred into their oat host. To prevent this from happening in outbreaks of the stem rust, the cultivated oat varieties are changed approximately every 5 years to counter the changes evolving in the races of stem rust and crown rust (van der Plank, 1968). Perhaps by breeding resistant strain with sufficient genetic diversity, the instability of host plant resistance in crops can be reduced.

3.7 Plant Spacings

The feeding intensity of herbivores and the damage it inflicts on its plant host depends upon the relative abundance of herbivores per unit of plant biomass. Thus, plant survival may depend on the spatial pattern of the plants in the field which affects herbivore density per plant.

In cultivated crops, densities of crop plants are carefully controlled to ensure optimal growth and thus a maximum economic yield. The spacings of cultivated crop plants, seldom similar to those in the wild, alter the natural pattern of the ecological habitat and may make it easy for herbivores to find and feed on their host plants (Pimentel, 1961).

Plant hosts, for example, existing in relatively dense stands, may limit the number of herbivores plant. In an investigation of insects and other herbivores on dense and dispersed plantings of cole crops demonstrated that there were one-fifth as many herbivores per unit plant area in the dense than in the dispersed planting.

The total number of herbivores was greater in the dense than the dispersed planting, however, because there was significantly more vegetation in the dense than in the dispersed the herbivores were abundant on the dispersed plants than on the dense plants (Pimentel, 1961).

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Biographical Sketch

David Pimentel is professor of insect ecology and agricultural sciences in the Department of Entomology, Section of Ecology and Evolutionary Biology, Cornell University. He has broad expertise in insect ecology, ecological and economic aspects of pest control, sustainable agriculture, energy use and conservation in agriculture, biological invasions of species, biological control, and soil and water resources management and environmental policy. His past positions include professor and Head of the Department of Entomology and Limnology at Cornell University and Chief of the Tropical Research Laboratory, U.S. Public Health Service in Puerto Rico. Pimentel served on many NRC study committees and panels in various capacities, including chairman of the Panel on Economic and Environmental Aspects of Pest Management in Central America; chairman of the Study Team on the Interdependencies of Food, Population, Health, Energy, and Environment, World Food and Nutrition Study; chairman of the Environmental Studies Board; and chairman of the Board of Science and Technology for International Development, member of the Committee on the Role of Alternative Farming Methods in Modern Production Agriculture. He has chaired and served on committees in the Office of Technology Assessment of the U.S. Congress, U.S. Department of Agriculture, U.S. Department of Energy, U.S. Health Education and Welfare, U.S. State Department, and the National Science Foundation. He received a B.S. degree from the University of Massachusetts, a Ph.D. degree from Cornell University, and an OEEC Fellow at Oxford University.