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GENETIC ENGINEERING AND ENERGY EFFICIENCY IN HUMAN FOOD SYSTEMS

by

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I. INTRODUCTION

Energy is a necessity for human food systems. In fact, a human food system is an energy conversion and consumption system, in which soral energy is converted to human food,and some supplemental energy is consumed in the conversion process. The efficiency of energy conversion or utilization in human food systems depends on technology used in the systems. One of the major objectives of improving technology in human food systems is to increase energy efficiency of the systems. Genetic engineering, or reconbinant DNA (R-DNA) technology, has the potential for improving human food systems. The potential benefits include increasing yields and enhancing nutritional value from crops and livestock, reducing pesticide and fertilizer use,and improving conservation of soil and water (Pimentel, 1989a; Hansen et al, 1986; Buttel and Youngberg, 1983). Then the energy efficiency of human food systems would be improved through genetic engineering implementation. Nevertheless, some releases of genetically engineered organizms may have sobering ecological, social, and economic effects (Pimentel, 1989a).These effects would diminish the energy efficiency of human food systems. Obviously, our objective should be to maximize the energy efficiency of human food systems rather than to minimize the efficiency. In the article, I assess the potential effects of genetic engineering on energy efficiency of human food systems. Some suggestions of improving energy efficiency of future genetically engineered food systems are discussed.

Food crop systems are the most important and essential components of human food systems in today and future. Even though animal husbandry is also very important for human food supply, its production mostly depends on crop production. The assessments and discussions in the article will focus on food crop systems.

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II. FOOD CROP SYSTEMS AND ENERGY

Crops, as green plants, convert sunlight into stored chemical energy for human food and other use. Almost all or 90 % of the plant protein/calories utilized by human for food is provided by fifteen major crops. These crops are rice, wheat, corn, sorghum, millet, rye, barley, cassava, sweet potato, potato, coconut, banana, common bean, soybean, and peanut (Pimentel and Pimentel, 1979). Green plants are able to capture only a small percentage of sunlight reaching the earth. In food crop systems, an estimated 15 MKCal of light energy (net production) is fixed per hectare per crop season. This amount is only about 0.1 % of the total solar energy reaching a hectare during the year and equals about 3500 kg/ha of dry biomass. The amount varies with crops and ranges from 200 kg/ha to 11000 kg/ha of dry biomass (Pimentel and Pimentel, 1979).

The basic climatic limitation to crop photosynthetic production in any locality is the seasonal distribution of solar energy, but the use of this energy by a crop cover can be limited by other constraints such as extremes of temperature, water shortage, or the supply of soil nutrients. So it is necessary to manage land, water, nutrients and other environmental conditions for a better crop production. In fact, the efficiency of converting solar energy into stored chemical energy in crop systems depends on the human management to crop systems. All human management, sach as planting, weeding and fertilizing, are actually to input supplementary energy into crop systems. In traditional crop systems,labor and animal power were used as the major supplementary energy. Instead of labor and animal power inputs, large amount of fossil energy in the form of inputs such as machinery, diesel, electricity, synthetic fertilizers, pesticides etc. are used in current crop systems (Table 1). For most grain productions, 1 KCal of fossil energy input produced 1--5

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KCal of grains in the United States (Pimentel, 1984) and 3--8 KCal of grains in Northeast China (Dazhong, 1988). Producing other types of food products, however, is not as energy efficient as grain production. For example, yields of apple and orange production range from 0.9--1.7 KCal output/KCal input of fossil energy; vegetable yields range from 0.2--1.4 KCal output/KCal input of fossil energy (Pimentel, 1984).

Energy efficiency for a food crop system is commonly defined as the food energy output divided by some energy input in the system. The energy inputs in food crop systems include solar energy input and different kinds of supplementary energy inputs. So we can have different energy efficiencies for a food crop system, such as solar energy efficiency, fossil energy efficiency and so on. Obviously, the energy efficiency of food crop systems would be improved through either to increase crop yields without increasing some energy inputs, or to reduce some energy inputs without reducing crop yields. Better resource management and sophisticated use of new techniques, such as genetic engineering, will offer many opportunities for improving the energy efficiency of food crop systems.

III. SOME POTENTIAL EFFECTS OF GENETIC ENGINEERING ON ENERGY USE IN FOOD CROP PRODUCTION

The initial research of improving crops through genetic engineering has been focused on the engineering of traits of crops, such as the control of insects, weeds, and plant diseases. Progress has been rapid, and genes conferring these traits have already been successfully introduced into several important crop species. Genetically engineered soybeen, cotton, rice, corn, oilseed rape, sugarbeet, tomato, and alfalfa crops are expected to enter the marketplace between 1993 and 2000 (Gasser and Fraley, 1989). The cereals have proved more difficult

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for genetic engineering than have such plants as tobacco, tomato, potato, and petunia. But the prospect for genetically engineered cereal crops is improved. In recent years, cereal research has passed several major milestones. The gap between cereals and other crops is closing. The basic techniques for genetically engineering cereals are now available (Strange, 1990).

Before discussing the effects of genetic engineering on energy use in food crop production, I would like to emphasize a key assumption that the applications of genetic engineering to agriculture still are embryonic. I'm not going to predict these effects exactly,but rather to highlight some possibilities. The discussion will focus on the potential effects of improving crop photosynthetic efficiency, crop resistance to herbicides and pests, and nitrogen fixation of cereal crops.

1. IMPROVING PHOTOSYNTHETIC EFFICIENCY OF CROPS.

The ultimate value of plants is their ability to convert solar energy into stored chemical reserves through the processes of photosynthesis. Obviously, one of the basic goals of genetically engineered breeding, as the conventional breeding, is to have higher yield varieties through improving photosynthetic efficiency of crops. Genetic variation in photosynthetic efficiency has been reported within many crops including corn, rice, and soybeans with, in some cases, significant effects on crop growth rate and crop yield (Wallance, et al., 1972; Cooper, 1982). As more becomes known of photosynthetic pathways, many areas of potential improvement may be envisaged. Because many enzymes function coordinately during photosynthesis, it is likely that species variation will be found at critical reactions. Transfer of more efficient Calvin cycle enzymes (the pathway responsible for CO_2 fixation) between plant varieties may well provide for higher retes of carbon fixation (Barton and Brill, 1983). Genetic engineering will help to make crop varieties with the traits of high photosynthetic efficiency and economic yield. However, some environmental constraints, such as extremes of temperature, water shortage and the supply of soil nutrients, particularly nitrogen, can limite the photosynthetic efficiency and yield of these varieties (Cooper, 1982).

In order to have high yield with the varieties, large amount of supplemental fossil energy in the forms of machines, chemical fertilizers, pesticides, herbicides and electricity are used to overcome these environmental constraints. Most recent increases in crop yields have been achieved by using improved crop varieties and enormous amounts of fossil energy to supply fertilizers, pesticides, irrigation, and fuel for machinery. During the past few decades plant geneticists, supported by agronomists, have enabled American farmers to produce over three times more corn per hectare (Myers, 1989; Pimentel et al., 1990). It was not until about 1945 that corn yields started to increase. At about the same time, it was started to use hybrid corn varieties (Pimentel et al., 1973). From 1945 to 1983, corn yields increased 3-fold in the United States. Concurrently, total fossil energy input has increased about 4- fold (Pimentel et al., 1990). The cereal crop production in China doubled from 1965 to 1983 because of using new crop varieties, but the synthetic fertilizer inputs increased 7.5-fold, insecticide inputs increased 2-fold, diesel input increased 6-fold, and electricity input increased 11-fold. The current crop systems in China have became energy intensive and heavily rely upon fossil energy inputs (Dazhong, 1988). Obviously, improving photosynthetic efficiency of food crops through either genetic engineering or conventional breeding will cause more and more fossil energy consumption to overcome the environmental constraints.Even the solar energy conversion efficiency will increase, but the fossil energy use efficiency will decrease rapidly.

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2. IMPROVING CROP RESISTANCE TO HERBICIDES.

Engineering herbicide tolerance into crops represents a new alternative for conferring selectivity and enhancing crop safety of herbicides. The development of herbicide tolerant crops would provide more effective, less costly, and more environmentally attractive weed control. Two general approaches have been taken in engineering herbicide tolerance: (1) altering the level and sensitivity of the target enzyme for the herbicide, and (2) incorporating a gene that will detoxify the herbicide (Gasser and Fraley, 1989; Gressel, 1986).

The fossil energy comsumption through the use of herbicides in crop production has increased rapidly. The total fossil energy input for chemical weed control in corn production increased 267-fold from 1950 to 1985, and the current energy consumption of herbicides accounts for about 3 % of the total fossil energy consumption in corn production of the United States (Pimentel et al., 1990). Genetic engineering to create herbicide-resistant crops has the advantage of expanding the array of herbicide types for weed control (NAS, 1987). In some instances, herbicide resistance may make possible the use of a more effective herbicide, thus reducing the number of herbicide applications and encourage the use of a wider array of herbicides on a variety of crops (Pimentel et al., 1989). The relatively low dosage herbicide in crop production would reduce fossil energy comsumption for herbicides in crop production on per hectare base. The use of a wider array of herbicides on a variety of crops would make the possibility of selecting some herbicides, which would be produced with less fossil energy, to reduce fossil energy comsumption in crop production. The two aspects for saving energy consumption would improve the efficiency of fossil energy use in food crop production.

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However, there is a potential loss of yield following selection for a trait such as herbicide resistance. The histories of more than 40 cases where fitness of herbicide resistance material was measured have been exhaustively summarized, and the picture looks depressing (Gressel, 1985). Recently, the eighth backcross of triazine resistant Brassica napus cv Regent (rape-seed) was checked against the parent variety (Gressel, 1986). When the resistant biotype was grown separately from the parent biotype, the yield was about 30 % less. When they were grown mixed together at 5 cm spacing, the yield of the resistant biotype was 25 % that of susceptible parent cultivar. Similar results were found in Canada (Gressel, 1986). Obviously, the energy efficiency of crop production with a genetically engineered variety would be reduced if the yield of the variety lost due to herbicide resistance. Of course, no yield loss should be a criterion of successful genetic-engineered variety of herbicide resistance. This may be much difficult.

In addition,some ecological problems would be intensified because of the use of a wider array of herbicides on a herbicide resistant variety (Pimentel et al., 1989). This might cost much more fossil energy for dealing with these problems.

3. IMPROVING CROP RESISTANCE TO PESTS.

Engineering crop resistance to insect and plant pathogen pests offers opportunities to reduce the use of insecticides and fungicides in crop production. This approach can be expected to reduce problems from pesticides and improve the economics of pest control (Pimentel et al., 1989). Progress in engineering insect resistance in transgenic plants has been achieved through the use of the insect control protein genes of Bacillus thuringiensis (B.t.), and transgenic tomato, tobacco, and cotton plants containing the B.t. gene exhibited torelance to caterpillar pests in laboratory tests (Gasser and Fraley, 1989). The significant resistance to tobacco mosaic virus (TMV) infection has been achieved by expressing

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only the coat protein gene of TMV in transgenic plants (Powell-Abel et al., 1986). Obviously, genetically engineered pest-resistant cultivars could help limit the use of pesticides, which would be benefits not noly for enveronmental protection, but also for saving some fossil energy use in food crop production. The synthetic pesticides require fossil energy for their production, formulation, packing and transportation. The total fossil energy input is 75,000--100,000 KCal per Kg of active pesticide ingredient (Pimentel, 1980).

However, there would be some potential side effects from the use of the engineered resistant crops. For example, the successful engineering of highly resistant crops could lead to the elimination of IPM techniques, and some pests that outbreak sporadically may adapt to a widely planted resistant cultivar before the resistance factor has ever been useful in reducing economic losses due to the pest (Fred ,1988). This would lead to reduce energy efficiency of food crop production somewhat.

4. NITROGEN FIXATION FOR CEREAL CROPS.

As the current food crop systems become more developed and more productive, they become more fossil energy intensive. For an increasing quantities of these energy, the energy used in the synthesis of nitrogen fertilizers accounts for a large propertion. For example, the energy input in the form of nitrogen fertilizers in current crop productions accounts for 31 % of the total fossil energy input in the United States (Pimentel et al., 1990) and 50 % in China (Dazhong, 1988). The new genetic engineering technology would undoubtedly be applied to solve the problems of nitrogen fixation for cereal crops. The genes from the free-living nitrogen fixer <u>Klebsiella pneumoniae</u> have been mapped, individual genes have been cloned, and these are now being used as genetic probes to locate the equivalent

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genes in Rhizobium. Progress is optimistic in this area with the longer term view of inserting these genes into " non-fixing " crops: wheat, rice, corn and grasses (Dunican, 1982; Barton and Brill, 1983).

Nitrogen-fixing cereal grains could make food production saving fossil energy use by reducing chemical nitrogen fertilizer input. However, we could not too optimize about the use of nitrogen-fixing cereal grains to improve the energy efficiency in food crop production. For example, the symbiotic nitrogen fixation will lower yields somewhat (Buttle and Youngberg, 1983), which could offset the effect of nitrogen-fixation on increasing fossil energy efficiency. The availability of nitrogen-fixing cereal grains might further reduce the attractiveness of crop rotations, especially those involving legumes, and lead to the monoculture of the nitrogen-fixing cereal grains, which would have some adverse effects on fossil energy efficiency of the crop systems. For example, the monoculture systems would need more pesticides and herbicides to control insects, diseases and weeds than the rotation systems (Higgs et al, 1990). Moreover, the monoculture of the nitrogen-fixing cereal grains might widely be used on fragile, steeply sloped soils, which would lead severe soil erosion (Buttle and Youngberg, 1983). The serious soil erosion would adversely affect crop productivity by reducing the availability of water, nutrients, and organic matter,and, as the topsoil thins, by restricting rooting depth (OTA, 1982). It is estimated that the total erosion effects will decrease crop productivity from 15 to 30 % (Battiston et al., 1985; Schertz et al., 1985; Pimentel et al., 1987). This means that the benefit of incresing fossil energy efficiency in food production through using genetically engineered nitrogen-fixing cereal crops could be completely offset by the reversed effects in monocultural conditions and on fragile, steeply sloped areas. In addition, the monocultures and continuous croppings induced by nitrogen-fixing cereal crops, as

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current monoculture and continuous croppings, could also cause some pest, disease and weed problems (Sumner, 1982; Altieri, 1987). These adversely effects could be compensated by more fossil energy inputs as pesticides, insecticides and herbicides, which could also offset the benefit effects of nitrogen-fixation of cereal crops on energy efficiency.

IV. THE POTENTIAL EFFECTS OF GENETIC ENGINEERING ON ENERGY EFFICIENCY IN MAJOR FOOD CROP SYSTEMS

The potential effects of genetic engineering on energy efficiency of food crop systems will differ from crop to crop, and from country to country. My discussion will focus on the systems of corn, wheat and rice, which are the most important food crops in the World, in developed countries such as the United States, and developing countries such as China.

1. THE POTENTIAL EFFECTS ON CURRENT FOOD CROP SYSTEMS IN THE UNITED STATES

In developed countries, like the United States, the fossil energy has became as vital a resource for the conventional food crop production (Pimentel, 1984). The fossil energy inputs in corn, wheat and rice systems in the United States are listed in Table 2.

The production of corn, wheat and rice in the United States are heavy reliance on machines, chemical fertilizers and pesticides, but less labor input. These are typical labor saving and fossil energy intensive food crop systems.

As mentioned above, genetic engineering would improve some traits of food crops,and save some fossil energy inputs in the crop systems. In order to assess the potential effects of genetic engineering on energy efficiency of crop systems, let us suppose that the application of genetic engineering in the agriculture of the United States would be successful in the near future, and the engineered varieties

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of food crops would have most ideal traits for nitrogen fixation, herbicide torelance, pest torelance and higher yield, which could reduce 80 % of the utilizations of nitrogen fertilizers, herbicides and insecticides respectively without other side effects and risks. Then we could estimate the effects of the ideal engineered varieties of these major food crops on energy efficiency based on Table 2.

For the corn production system, using the ideally engineered varieties would make the system saving 36 % of total fossil energy input,and increasing 56 % of fossil energy efficiency. For the wheat production system, saving 22 % of total fossil energy input, and increasing 28 % of fossil energy efficiency. For the rice production system, saving 30 % of total fossil energy input, and increasing 43 % of fossil energy efficiency. In fact, this supposition is too ideal to be realistic. The nitrogen fertilizer inputs in the three crop systems represent the largest single input for each system (Table 2). However, the progress of genetic engineering for nitrogen fixation of cereal crops has been very slow, and some side effects with the trait, such as yield reduction and so on, could not be easy to be overcame. So the improvement of crop systems through engineered nitrogen fixation would not be remarkable in the near future. In addition, the inputs of herbicides and insecticides in corn, wheat and rice systems only account for 13 %, 2 % and 9 % of the total energy inputs respectively. Even the engineered herbicide and insect resistant varieties could be developed in the near future, the maximum potential improvement of fossil energy efficiencies would not be over 12 % for corn system, 1% for wheat system and 8 % for rice system.

Moreover, if there could be some side effects and environmental risks happened with the applications of genetically engineered varieties, more fossil energy would

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be required in the food crop systems to deal with these problems. This would reduce the energy efficiency of the engineered food crop systems.

2.THE POTENTIAL EFFECTS ON CURRENT FOOD CROP SYSTEMS IN CHINA.

The food crop production in developing countries, such as in China, is quite different from those in the United States and other developed countries. Even though the current food crop production in China becomes more fossil energy intensive , it is still highly labor and animal power intensive. During the past three decades, the food crop production in China has changed rapidly. Instead of traditional crop systems, which used labor and animal power, organic fertilizers, and traditional crop varieties, the current food crop systems in China use high yield varieties, synthetic fertilizers and pesticides, even more labor and animal power are still used (Dazhong and Pimentel, 1984c; 1990). The crop yield has tripled in China since 1950s (Kong, 1981; DAC, 1989). Although the growing use of fossil energy has been advantageous in raising the yields of essential food crops, this large use of fossil energy makes food crop production more dependent on fossl energy resources and more susceptible to the instability and fluctuations in oil and other energy prices. For this reason, agricultural scientists in China have been searching for alternative agricultural practices that make more effective use of fossil energy , soil, water, biota, and other natural resources , and increase food crop production. The energy inputs in current corn (maize), wheat and rice production systems in some regions of China are listed in Table 3.

The total fossil energy input in Liaoning corn system in China is 40 % of that in the United States, but the labor input in China is 100 times greater than that in U.S. corn system (See Table 2 and 3). The fossil energy input for nitrogen accounts for 60 % of the total fossil energy input in China corn system, but for insecticides and herbicides only 4.5 % (See Table 3).

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The wheat yield in Heilongjiang of China is similar to that in the United States, but the fossil energy input in China wheat system is 75 % of that in the United States. The fossil energy input for nitrogen in China wheat system accounts for 25 % of its total fossil energy input, but for pesticides only 4 % (See Table 2 and 3).

The rice yield in Liaoning of China is 30 % more than that in the United States, but the fossil energy input in Liaoning rice system is only 42 % of that in the United States (See Table 2 and 3). The fossil energy input for nitrogen in Liaoning rice system accounts for 38 % of total fossil energy input in the system, but for pesticides only 4.4 % (See Table 3).

Again, let us suppose that the application of genetic engineering in food crop production in China would be successful in the near future, and the engineered varieties of food crops used in crop systems could have most ideal traits as supposed for the crop systems in the United States. Then we could estimate the effects of the ideally engineered varieties of corn, wheat and rice on energy efficiency of these major food crop systems in China on the base of Table 3.

This improvement would make Liaoning corn system saving 52 % of total fossil energy input, and increasing 110 % of fossil energy efficiency; make Heilongjiang wheat system saving 23 % of total fossil energy input, and increasing 29 % of fossil energy efficiency; make Liaoning rice system saving 34 % of total fossil energy input, and increasing 53 % of fossil energy efficiency.

Obviously, the potential improvement of energy efficiency for major food crop systems in China through genetic engineering would be more remarkable than that in the United States. It would be suggested that the successful genetic engineering would give more benefits to the food crop production in developing countries than that in developed countries in terms of fossil energy efficiency.

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However, if the genetic engineering for cereal nitrogen fixation would not be successful for commercial use in the near future, the improvement of the energy efficiency in the food crop systems in China through the resistances to insects, pathogen and herbicides would not be remarkable. Because the fossil energy inputs for pesticides in these major food crop systems in China only account for about 4 % of the total fossil energy input, it is estimated that the increasing of fossil energy efficiency through the engineered resistances would not be more than 4.3 % for corn, 2.4 % for wheat and 4.8 % for rice. Moreover, if there could be some side effects and environmental risks happened with the applications of the genetically engineered varieties, the energy efficiency of food crop systems in developing countries would also be reduced.

V. MAKING EFFORTS FOR IMPROVING ENERGY EFFICIENCY OF FUTURE HUMAN FOOD SYSTEMS

The rapidly expanding human population needs more nutrientious food. our ability to produce more food through agricultural production depends on arable land, and various forms of energy (Pimentel and Hall, 1984). With the increasing demand for these limited resources, the agricultural production is facing some serious problems of resource shortage and environmental degradations. There is need to develope a productive and sustainable agriculture to meet the increasing demand for human food and to conserve agricultural resources and environment. More effective use of fossil energy resources is one of the most important aspects in developing productive and sustainable agriculture (Poincelot, 1986; Pimentel et al., 1989).

Genetic engineering would give some opportunities of improving the energy efficiency of human food production. However, the strategy of improving the energy

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efficiency of human food systems will have to do more than simple introduce some genetically engineered varieties to the systems. A successful strategy should be to integrate ecological resource management with the application of genetic engineering in human food systems. The integrations will include following two aspects: (1) Adapting and designing the engineered food crop systems in a certain area to the environment of the area; (2) Using some suitable ecological techniques to reduce some potential side effects and enhance the benefits induced through the application of genetic engineering, such as crop rotation, intercropping and multiple cropping, minimum tillage, cover cropping and mulching, agroforestry, integrated pest management, effective management and use of organic fertilizers, and so on.

Recently, the research on integrated ecological resource management should be emphasized (Dazhong and Pimentel, 1990). This is not only for improving current conventional agriculture, but also for developing genetically engineered agriculture in the near future. Some research on applying traditional ecological techniques and new biotechnology to human food production in developing countries has been emphasized at some research institutions for many years and is likely to become increasingly important in the future (Tangley, 1987; Artieri, 1987). More research cooperation between genetic engineers and agroecologists will enhance the progress of integrated ecological resource management, and will make the human food systems more effective use of energy resources.

VI. CONCLUSIONS

Genetic engineering has the potentials for improving energy efficiency in human food systems. Nevertheless, some potential side effects and risks could happen with the use of genetic engineering in food production, which would also have some

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reversed effects on energy efficiency of human food systems. Based on the analyses and discussions above, we could introduce the following conclusions.

1. Improving photosynthetic efficiency of food crops through genetic engineering could increase solar energy conversion efficiency and crop yields. However the fossil energy efficiency in the crop production might decrease more rapidly with the crop yield increasing.

2. Engineered crop resistance to herbicides would reduce fossil energy consumption for herbicides, and improve fossil energy efficiency in food crop productions. However, some side effects, such as the crop yield reduction with the resistant trait, and other ecological problems, could significantly reduce the energy efficinecy of food crop production.

3. Improving crop resistance to pests through genetic engineering could help limit the use of pesticides, which could be benefits for saving some fossil energy use in food crop production. Some potential side effects could also lead to reduce energy efficinecy in food crop production somewhat.

4. Nitrogen fixation for cereal crops through genetic engineering would significantly save fossil energy use in food crop production by reducing synthetic nitrogen fertilizer input. However the symbiotic nitrogen fixation will lower crop yields somewhat, which could offset the benefit effect of nitrogen fixasion on saving fossil energy. Some side effects induced through the use of nitrogen fixation for cereal crops might lead to reduce the energy efficiency of food crop production.

5. The potential effects of genetic engineering on energy efficiency of food crop systems would differ from crop to crop, and from country to country. There would be more potential benefits of improving energy efficiency through genetic engineering in food crop systems in developing countries than that in developed countries from a long-term view.

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6. It is estimated that the maximum potential energy benefits for current corn, wheat and rice systems in the Unites States through the use of the ideal successful genetic engineering could reduce about 20--40 % of fossil energy inputs, and increase about 30--60 % of fossil energy efficiencies. If considering that the nitrogen fixation for cereal crops would not be successful in the near future, the potential improvement of fossil energy efficiency in these systems would not be over 10 %.

7. It is estimated that the maximum potential energy benefits for current corn, wheat and rice systems in some regions of China through the ideal successful genetic engineering could reduce about 20--50 % of fossil energy inputs, and increase about 30--110 % of fossil energy efficiency. If considering that the nitrogen fixation for cereal crops would not be successful in the near future, the potential improvement of fossil energy efficiencies in these systems would not be over 5 %.

8. It is need to make efforts for improving energy efficiency of future human food systems through integrated use of genetic engineering and ecological techniques.

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Table 1. Fossil energy requirement for various inputs in crop production

Item	Energy requirement (kcal/ha)	References
1 Kg of steel tools and other machinery	18,500	Doering, 1980.
1 Litre of diesel fuel	11,414	Cervinka, 1980.
1 Kg of gasoline	10,109	Cervinka, 1980.
1 Kwh of electricity	2,863	Cervinka, 1980.
1 Kg of nitrogen (N)	21,000	Dovring and McDowell, 1980.
1 Kg of Phosphorus (P_2O_5)	6,300	Dovring and McDowell, 1980.
1 Kg of Potassium (K_2O)	2,500	Dovring and McDowell, 1980.
1 Kg of herbicides	100,000	Pimentel, 1980a.
1 Kg of insecticides	100,000	Pimentel, 1980a.
1 Kg of transportation	275	Pimentel, 1980b.

Table 2. Energy inputs per hectare for corn,wheat, and rice production in the United States

Item	Corn[1]		Wheat[2]		Rice[2]	
	Quautity/ha	kcal/ha	quautity/ha	kcal/ha	quautity/ha	kcar/ha
INPUTS						
Labor	12 hr.	-	7 hr.	-	17 hr.	-
Machinery	55 kg	990,000	20 kg	360,000	20 kg	360,000
Gasoline	26 l	264,000	-	-	65 l	657,090
Diesel	77 l	881,500	53 l	604,940	286 l	3,264,400
LP gas	80 l	616,400	-	-	46 l	354,430
Electricity	33 kwh	95,500	200,000 kcal	200,000	380,000 kcal	380,000
Nitrogen	151 kg	2,220,000	50 kg	715,000	280 kg	4,116,000
Phosphorus	72 kg	216,000	26 kg	78,000	67 kg	201,000
Potassium	84 kg	134,000	30 kg	48,000	-	-
Lime	426 kg	134,400	35 kg	11,030	35 kg	11,030
Seeds	18 kg	445,500	106 kg	699,600	157 kg	1,139,820
Insecticides	1.4 kg	119,950	-	-	2.2 kg	191,200
Herbicides	7 kg	777,500	0.5 kg	49,960	11.2 kg	1,118,990
Irrigation	-	-	-	-	110 m^3	1,299,430
Drying	7,000 kg	-	-	-	6,160 kg	1,217,220
Transportation	200 kg	51,200	177 kg	45,490	471 kg	121,050
TOTAL		6,951,250		2,812,020		14,431,660
OUTPUT						
Total yield	7,000 kg	24,500,000	2,060 kg	6,798,000	6,160 kg	22,360,800
kcal output/ kcal input	3.52		2.42		1.55	

[1] Adapted from Pimentel and Burges (1980).

[2] Adapted from Pimentel and Pimentel (1979).

Table 3. Energy inputs per hectare for corn,wheat, and rice production in some regions of China[1]

Item	Corn in Liaoning Province		Wheat in Heilongjiang province		Rice in Liaoning province	
	Quantity/ha	kcal/ha	quantity/ha	kcal/ha	quantity/ha	kcal/ha
INPUTS						
Labor	1,252 hr	-	315 hr	-	3,045 hr	-
Animal power	444 hr	-	85 hr	-	332 hr	-
Tools	3.2 kg	66,690	3.5 kg	71,870	4.5 kg	93,200
Machinery	4.0 kg	71,820	9.6 kg	171,900	14.6 kg	263,160
Diesel	38.7 l	441,270	44.4 l	507,580	72.9 l	832,200
Electricity	13.4 kwh	38,300	-	-	121.9 kwh	348,910
Nitrogen	146.9 kg	1,762,920	44.9 kg	538,200	191.1 kg	2,292,600
Phosphorus	80.3 kg	240,840	3.2 kg	9,690	96.7 kg	290,190
Insecticides	1.5 kg	130,370	-	-	0.9 kg	78,220
Herbicides	-	-	0.9 kg	86,000	1.9 kg	187,830
Seeds	37.5 kg	130,500	225.0 kg	739,130	163.6 kg	482,800
Irrigation	-	-	-	-	183.9 m^3	1,170,010
Transportation	40.0 kg	10,300	50.8 kg	13,060	81.1 kg	20,840
TOTAL		2,893,010		2,137,430		6,059,960
OUTPUT						
Crop yield	5,012 kg	17,447,850	1,995 kg	6,553,580	8,094 kg	23,906,480
kcal output/ kcal input	6.0		3.1		3.9	

[1] Adapted from Dazhong (1988), and Dazhong and Pimentel (1984b).