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# ENERGY USE IN AGRICULTURE: AN OVERVIEW

**By**

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## INTRODUCTION

Humans have found ways to secure their food from the Earth's land, beginning more than a million years ago with the hunter-gatherers. Much of the world's agriculture was -- and still is -- carried out by hand (Pimentel and Pimentel, 1996). Once fossil energy supplies became available about 200 years ago, intensive agricultural production developed. Although contemporary, energy-intensive agricultural systems are highly productive, their sustainability is questionable because : (1) rapid population growth necessitates continued increases in the use of cropland and water resources; (2) fossil energy resources that are essential for supplying fertilizers, pesticides, irrigation, and mechanization are non-renewable; and (3) the agricultural environment is being degraded by both soil erosion of cropland and pasture land and by the pollution of fresh water resources.

Now, at the turn of the century, we are faced with meeting the food needs of a rapidly expanding human population. Currently, more than 3 billion people in the world are malnourished due to outright food shortages and poor distribution of some foods (WHO, 1996). In addition, shortages of cropland, fresh water, fossil energy (fertilizers and irrigation), and biological resources now plague agricultural production in many parts of the world. The supplies of various grains -- staples that makes up more than 80% of world food -- have been declining since 1984 (Pimentel et al., 1998a). Stores of fossil energy also have begun to decline; this trend will intensify after the year 2000 (Pimentel et al., 1998a).

To meet the basic food needs of our expanding human population, a productive, sustainable agricultural system must become a major priority. From analyses of various agricultural systems, we can understand the use of all forms of energy and learn how to preserve essential land, water, and biological resources for future generations.

In this study, the energy flow in diverse food production systems is analyzed. The evolution from sustainable low-input systems to high-input systems with questionable sustainability is examined.  This information is needed if the sustainability of agricultural systems is to be achieved for us and for future generations.

## SOLAR ENERGY

The foundation of all agricultural production rests on the unique capability of plants to convert solar energy into stored chemical energy.  The success of agricultural production is measured by the amount of solar energy that is captured and converted into food per unit land area as a result of manipulating, plant, land, water, and other resources. Agricultural success can be enhanced by finding ways to augment solar energy using human, animal, and fossil energy power.

The incident solar energy radiated during the year in temperate North America averages about 14 billion kilocalories (1 kcal = 4,186 joules or 4 BTUs; 1 quad = $10^{15}$ BTUs) per hectare (Reifsnyder and Lull, 1965).  During a 4-month summer growing season in the temperate region, nearly 7 billion kcal of solar energy reach an agricultural hectare.

An estimated 30% of the total solar energy reaching the earth is harvested by humans as food and forage, while an additional 20% is harvested as forest products. Thus, humans are harvesting for their use approximately half of the solar energy reaching the earth.  This enormous biomass harvest reduces the amount of biomass and energy that is essential to maintaining natural biota populations and their biodiversity.  Preserving the biodiversity of plants and animals is vital to the integrity of the entire human environment, including agriculture and forestry.

For humans to produce and harvest sufficient food they must manipulate the natural ecosystem and contribute energy with their own hands, draft animals, machines and mechanization, and/or chemicals.  The managed agroecosystem enables the established  plants to capture solar energy and convert it into chemical energy (food) suitable for humans and/or their livestock. In many systems, including intensive agriculture with grains, there is a net energy return to human society.

## SLASH-AND-BURN AGRICULTURE

One of the major factors that caused humans to move from hunting and gathering to slash-and-burn agricultural production was the continual expansion of the human population (Figure 1). The increased number of people to feed required a higher and more dependable yield than was possible with hunter-gatherer systems.

Early slash-and-burn agriculture, with a 20-year rotation, was sustainable (Table 1). A minimum of 2 hectares were needed per person (10 hectares per family of 5 persons) for food production. This system required about 10 hectares of land to provide sustainable food supply from about 1 cultivated hectare of land. The cultivated hectare of land could be used for about 2 years before the nutrients were depleted and the land had to be returned to fallow. Then, solar energy and the absence of cultivation in the natural ecosystem over a 20-year fallow period restored the nutrients and productivity for a piece of land to be used for food production again. Today, a shortage of cropland, and even arable land, is a major constraint to using this technology.

The only fossil energy input used in slash-and-burn agriculture is in the production of the ax and hoe. However, these tools could be produced using charcoal, making the system totally dependent on solar energy. About 1,144 hours of manpower is required to produce about 1,944 kg/ha of maize in this system (Lewis, 1951; Pimentel and Heichel, 1991). The only other input is for 10.4 kg/ha of maize seed. The 1,144 hours of labor represent approximately 60% of the total labor output for one adult per year. The farmer is assumed to consume about 3,000 kcal/day of food and requires about 6,000 kcal/day of fuelwood for cooking and preparing food in a tropical environment. No other input for the farmer is charged in this system. The energy output per input for this system is 8.4:1 (Table 1), using energy budget methods previously described (Lewis, 1951; Pimentel and Heichel, 1991).

The manpower input of approximately 1,200 hours/ha to produce maize by hand is typical for many crops, especially grains, throughout the world (Pimentel and Pimentel, 1996). Interestingly, in modern China, where more fertilizers and pesticides are used per hectare than even in the intensive grain production of the United States, about 1,200 hr/ha of manpower is still required for their grain production (Wen and Pimentel, 1998).

The large land requirement of a slash-and-burn system limits it usefulness as a widespread agricultural practice at present and in the future. With the current world population at about 6 billion, only slightly more than 0.25 ha/person of cropland is available worldwide (Pimentel et al., 1998a). This represents only one-eighth of the land needed per person for a sustainable slash-and-burn system.

## DRAFT ANIMAL AGRICULTURAL SYSTEM

If some of the 1,144 hours of human labor in the slash-and-burn system are replaced with about 200 hours of ox power per hectare, then the human labor input can be reduced to 380 hours/ha (Table 2). Even with the help of animal power, though, this human labor input of 201,000 kcal still remains a large input in this system.

The feed needed to supply the ox for about 200 hours of work is 150 kg of concentrate (maize) and 300 kg of forage (Morrison, 1956). The concentrate consumed by the ox is derived from the 1,944 kg of maize produced per hectare and reduces the net yield. In addition, the ox consumes forage from 2 hectares of pasture on marginal land. About 20% (2,000 kg) of the dung produced by the ox is applied to the maize hectare without depleting the nutrients and continued productivity of the pasture. Human wastes from the family of 5 also are applied to the maize land.

In this system, maize is grown in rotation after a legume green-manure crop with agronomic characteristics of clover or vetch, and this increases the land requirement by 1 hectare. The legume provides the minimum nitrogen needs (60 kg/ha) of the maize (Troeh and Thompson, 1993) and also helps control soil erosion and adds organic matter to the soil (Pimentel et al., 1995).

The total energy input in the hectare of maize production in this system is estimated to be 1.7 million kcal; based on this value and a yield of 1,944 kg/ha, the output/input ration is 4.1:1 . This value is less than half that achieved in the hand-powered slash-and-burn agricultural system (Tables 1 and 2).

However, about 4 ha is the minimum amount of land area needed to keep this system sustainable. While this is less than the 10 ha required for the slash-and-burn system, it is still land extensive.

## DRAFT-ANIMAL AGROFORESTRY SYSTEM

This agroforestry system is similar to the draft-animal system in terms of labor, ox power, machinery, and seeds (Table 2). By using the agroforestry system, however, 0.5 ha is planted to maize and the other 0.5 ha to the leguminous tree, Leucaena (Torres, 1983; Kidd and Pimentel, 1992). The contour planting design includes 2 rows of maize alternated with 2 rows of trees. The maize in this system is planted at twice the plant density used in the draft-animal system and a similar yield of 1,944 kg/ha is assumed (Pimentel and Pimentel, 1996).

Competition between the Leucaena and maize is reduced at planting by cutting the tree back to an 8 cm stump before the maize is planted. Each year the trees produce 4,500 kg/ha of biomass (Rachie, 1983). About two-thirds of the nitrogen in the Leucaena biomass is contained in the 2,500 kg of leaves and twigs (Rachie, 1983). When applied to the soil, about 60 kg/ha of nitrogen is applied to the land, which is similar to the amount of nitrogen added in the draft-animal system. Of this total biomass, about 2,500 kg of leaves and small twigs are worked into the soil for biological nitrogen nutrients and organic matter to enhance soil and water conservation. Planting Leucaena on the contour, plus mulching with 2,500 kg of leaves and twigs, limits soil erosion to an estimated 1 t/ha/yr (Kidd and Pimentel, 1992). The remaining 2,000 kg of Leucaena are harvested as stems for fuelwood. By providing about 80% of the fuelwood needs of one family, this system has an advantage compared with the previous draft-animal system.

Similar to the draft-animal system, the forage for the ox is provided by 2 ha of forage from marginal land, with concentrate needs subtracted from the maize grain yield. The total energy expended in this system is calculated to be about 1.7 million kcal, with an assumed 1,944 kg/ha maize yield. Note, the ox has to be fed about 150 kg of maize from this yield. The 4.1:1 ratio in this system is similar to the draft-animal system described earlier (Table 2). To help maintain phosphorus and potassium fertility of the cultivated hectare, about 20% of the ox dung is applied to the maize crop. The leguminous tree roots supply some phosphorus and potassium from deep in the soil, and human wastes also are recycled (Kidd and Pimentel, 1992).

Although the total land area needed to keep this system sustainable is 3 ha, less than the 4 ha needed for the draft animal system, it is still relatively land extensive. The agroforestry system, however, has the added benefits of providing some fuelwood and improving soil quality by limiting soil erosion.

## INTENSIVE MAIZE PRODUCTION

The energy flow in tractor-powered agriculture, typical of the United States and other developed nations, is distinctly different from that of all the hand- and draft animal-powered agricultural systems analyzed. The labor input is dramatically reduced to only 10 hours, very low compared with all the hand-powered systems discussed (Tables 1,2, and 3).

Balanced against this low labor input is the significant increase in fossil energy input needed to run the machines that reduce labor input and that are used to produce the fertilizers and pesticides. In 1997, the total energy inputs (mostly fossil fuel) required to produce 1 ha of maize in the United States averaged about 10.0 million kcal, or the equivalent to 1,000 liters of oil (Table 3). Even with the large maize grain yield of 8,000 k/ha, the out/input ratio is about 2.8:1 (Table 3). Based on U.S. production, the total costs of these inputs average approximately $550/ha.

Under favorable moisture and soil nutrient conditions, maize is one of the most productive food and feed crops. For example, maize yields are nearly 2,000 kg/ha under slash-and-burn agriculture (Pimentel and Pimentel, 1996) and upward of 8,000 kg/ha in the intensive system (USDA, 1997). An equal amount of biomass as stover is produced in both systems. Converting the maize grain and stover into heat energy, the slash-and-burn and intensive systems produce about 18 million kcal and 72 million kcal, respectively. This represents from 0.1 to 0.5% of the incident solar energy annually.

Often overlooked in the assessment of agricultural production systems is the diverse environmental costs that accrue over time. These costs are significant, especially for intensive, highly mechanized systems (Table 4). For example, the cost of lost fertilizer nutrients averages $113/ha. This is based on data from Troeh et al. (1991) that suggests $20 billion in nutrients are lost annually from U.S. agriculture by soil erosion and water runoff. In addition, the off-site environmental damage caused by erosion in the United States is calculated to be $17 billion per year (Pimentel et al., 1995). The yearly environmental costs of damages by pesticides were calculated to be $50/ha, based on an estimated $9 billion/yr ecological damage caused by these pesticides (Pimentel et al., 1998b). Taken together, these environmental damages total at least $300/ha for intensive maize production. If these environmental costs are added to the production costs of maize, then the total costs of intensive maize production rise to $850/ha ($550/ha of production inputs for maize plus $300/ha of environmental costs).

Even if we ignore this economic appraisal, the contemporary U.S. maize production system is of questionable sustainability compared with the less technologically developed systems discussed earlier (Pimentel and Pimentel, 1996). The major difficulties associated with the intensive system are: (1) high economic costs of production; (2) serious environmental resource degradation; (3) instability of crop yields; and (4) dependence on non-renewable energy resources (Pimentel, 1993).

## MAKING INTENSIVE MAIZE PRODUCTION MORE SUSTAINABLE

Fortunately, numerous agricultural technologies already exist that, if implemented, will make maize production more sustainable and ecologically sound than it is today. These technologies would reduce chemical inputs (including commercial fertilizers and pesticides), reduce soil erosion and rapid water runoff, and make more effective use of livestock manure (NAS, 1989; Paoletti et al., 1989). To illustrate this, the economic and environmentally sound agricultural practice of the ridge-planting-rotation system is compared with the intensive system of producing maize (Tables 3 and 5).

First, selecting an appropriate crop, such as soybeans, for rotation with maize reduces the corn rootworm problem (Pimentel et al., 1993), maize diseases (Pearson, 1976; Mora and Moreno, 1984), and the weed problems that typically plague maize production (NAS, 1968; 1989; Mulvaney and Paul, 1984). Furthermore, a maize and soybean rotation system is more profitable than raising either crop alone (Helmers et al., 1986; Dobbs et al., 1988; NAS, 1989). In large measure this is because the maize rootworm problem is eliminated when maize is grown in rotation and insecticides are eliminated. Average maize losses to insects in intensive maize production are 12%, whereas losses to insects for maize grown in rotation are only 3.5% (Pimentel et al., 1993). For that reason, about 8% was added to the yield in the ridge-rotation system for this analysis (Table 5).

To make effective use of the grain produced on the farm, frequently livestock are kept. The recycling of livestock manure on the farm and the use of a cover crop are ecologically sound practices included in this sustainable system. Effectively using farm manure reduces the pollution of ground and surface waters, adds valuable nutrients to the soil, enhances soil organic matter and reduces soil erosion (Pimentel et al., 1987). Use of cover crops after harvest, especially legume crops, like winter vetch, reduce soil erosion and water runoff, reduce weed problems and help conserve soil nutrients. In addition, soil nutrients are picked up and stored by the cover crop, which is subsequently plowed under to recycle these nutrients to the soil. The labor input was increased from 10 hours/ha to 12 hours/ha to include the time required to recycle the manure and plow under the cover crop.

These modifications increased the maize yield from the 8,000 kg/ha of the intensive systems to 8,640 kg/ha in the ridge-rotation system (Table 5). Total energy input for this system was only 3.7 million kcal, considerably less than the intensive system. The total cost of production, that included the added labor, was $340/ha or 38% lower than the intensive system. If, however, the environmental costs associated with the intensive system had been included (Table 4), the production costs in the ridge-rotation system would be even lower.

Clearly, the substantially lower production inputs of fossil energy and dollar costs/ha of the ridge-rotation system, plus the 8% higher yield of this system, generate great profits for the farmer, as well as benefiting society. Specifically, soil and water conservation, as well as reduced fertilizer and pesticide inputs, are major benefits to the environment and contribute to the overall sustainability of production.

In the ridge-rotation system (Table 5), soil erosion is reduced from approximately 17 t/ha for intensive system to less than 1t/ha. Note, the 1 t/ha soil erosion rate equals the soil reformation rate under most agricultural conditions (Pimentel et al., 1995). Also, sound soil and water conservation technologies increase the maize yields from 15% to 30% over maize grown under intensive systems that usually experience moderate to severe soil erosion (Follett and Stewart, 1985).

Ridge plantings, the crop rotation and the other techniques included in this particular analysis may not be appropriate for all soils, all crops, all pests and all farming systems. However, these technologies were selected to illustrate the potential available technologies have to enhance the sustainability of agricultural production and reduce fossil energy use. Various combinations of these and other technologies, like intercropping, have been developed for particular crops and farming systems (NAS, 1989; Pimentel, 1993).

In summary, the ridge planting-rotation system has the following advantages over the intensive system: 1) soil erosion and rapid water runoff is reduced; 2) smaller tractors can be employed and less tractor fuel is used; 3) mechanical cultivation is substituted for the herbicides, but this is not essential; 4) the rotation essentially eliminates the need for all insecticides; 5) on-farm livestock manure is substituted for all the nitrogen and a large portion of the phosphorus and potassium nutrients; and 6) a cover crop protects the soil and nutrients from loss during the non-growing season.

## THE STATUS OF WORLD FOSSIL ENERGY RESOURCES

Although about 50% of all the solar energy captured by photosynthesis worldwide is used by humans, it is still not enough to meet all the energy requirements to provide food, fiber, forest products, and support diverse human activities (Pimentel and Pimentel, 1996). To make up for this shortfall, about 365 quads (1 quad = $10^{15}$ BTU or 383 x $10^{18}$ Joules) of total energy, including fossil (oil, gas, and coal = 345 quads) and solar energy (biomass, hydroelectric, wind power, and numerous other technologies = 20 quads) are utilized throughout the world each year (International Energy Annual, 1995).

Industry, transportation, home heating, and food production account for most of the fossil energy consumed in the United States (DOE, 1991; DOE, 1995a). The per capita use of fossil energy in the United States is about 8,740 liters of oil equivalents per year, more than 12-times the per capita use in China (Table 6). In China, most fossil energy is used by industry, though a substantial amount, approximately 25%, is used for agriculture and the food system (Wen and Pimentel, 1992, 1998).

Developed nations annually consume about 70% of the world's fossil energy, while the develop*ing* nations -- which have about 75% of the world population -- use only 30% (International Energy Annual, 1995). The United States, with only 4% of the world's population, consumes about 22% of the world's fossil energy output (Pimentel and Pimentel, 1996). Fossil energy use in the various U.S. economic sectors has increased from 20- to 1,000-fold in the past 3 to 4 decades, attesting to America's heavy reliance on this finite energy resource to support its affluent lifestyle (Pimentel and Hall, 1989; Pimentel and Pimentel, 1996).

Current fossil energy expenditure is directly related to many factors, including rapid population growth, urbanization, and high per capita consumption rates (Table 7). Indeed, energy use has been growing even faster than world population growth. From 1970 to 1995, energy use was increasing at a rate of 2.5% per year (doubling every 30 years) whereas the world population only grew at 1.7% (doubling about 40 years) (PRB, 1996; International Energy Annual, 1995). From 1995 to 2015, energy use is projected to increase at a rate of 2.2% (doubling every 32 years) compared with a population growth rate of 1.5% (doubling every 47 years) (PRB, 1996; International Energy Annual, 1995).

Fossil fuel energy has enabled a nation's economy to feed an increasing number of humans and improve the general quality of life for people in many ways, including reducing numerous diseases in humans (Pimentel and Pimentel, 1996). But continued heavy reliance on fossil fuels for food production systems will adversely affect the sustainability of food production. Already, fertilizer production on the whole has declined by more than 23% since 1985, especially in the developing countries, due to fossil fuel shortages and high prices (IFDC, 1998).

The world supply of oil is projected to last approximately 50 years at current production rates (BP, 1994; Ivanhoe, 1995; Campbell, 1997; Duncan, 1997; Youngquist, 1997; Duncan and Youngquist, 1998). Worldwide, the natural gas supply is adequate for about 50 years and coal for about 100 years (BP, 1994; Bartlett and Ristinen, 1995;

Youngquist, 1997).   These projections, however, are based on current consumption rates and current population numbers.  If the world population continued to grow at a rate of 1.5% and If all people in the world were to enjoy a standard of living and energy consumption rate similar to that of the average American, then the world's fossil fuel reserves would last only about 15 years (Campbell, 1997; Youngquist, 1997).

Youngquist (1997) reports that current oil and gas exploration drilling data has not borne out some of the earlier optimistic estimates of the amount of these resources that have yet to be found in the United States.  Both the production rate and proved reserves have continued to decline.  Reliable analyses suggest that at present (1998) the United States has consumed about three-quarters of the recoverable oil that was ever in the ground,  and that we are currently consuming the last 25% of our oil resources (Bartlett, 1998).  Projections suggest that U.S. domestic oil and natural gas production will be substantially less in 20 years than it is today.  Even now oil is not sufficient to meet domestic needs, and oil supplies are imported in increasing yearly amounts (DOE, 1991;BP, 1994; Youngquist, 1997).   Importing 60% of its oil puts the United States' economy at risk due to fluctuating oil prices and difficult political situations, like those that occurred in the 1973 oil crisis and the 1991 Gulf War (U.S. Congressional Record, 1997).

All of the chemical and nuclear energy that society uses ultimately adds heat to the Earth's environment.  The Second Law of Thermodynamics limits the efficiency of heat engines to about 35%.

## RENEWABLE ENERGY TECHNOLOGIES

By developing and using available renewable energy technologies, such as biomass, hydropower, photovoltaics, wind power, and other technologies, an estimated 200 quads of potential renewable energy could be produced by using 20% to 26% of the world land area (Pimentel et al., 1994; Yao Xlang-Jun, personal communication, Cornell University, 1998). A self-sustaining renewable energy system producing 200 quads of energy per year is sufficient for about 2 billion people (Pimentel et al., 1998a) and would provide each person with 5,000 liters of oil equivalents per year. This is about half of an American's current yearly consumption, yet would be an increase for other individuals in the world (Pimentel et al., 1998a). Obviously for the project to be successful, the world population would have to be reduced form the current 6 billion to about 2 billion (Pimentel et al., 1998a).

Furthermore, the appropriation of over 20% of the world's land area for renewable energy production not only would remove land that will be needed for an expanding agriculture and forest production, but will further limit the integrity and resilience of the vital ecosystem that humanity depends on for its life support system (Daily, 1996; Pimentel et al., 1997).

Liquid fuels are extremely important in the economy. One potential liquid fuel that merits attention is hydrogen but, it is neither as economical nor as versatile as oil and oil products (Pimentel and Pimentel, 1996).

A possible liquid fuel that has received considerable attention is ethanol, produced from maize, sugarcane, and woody biomass. Because of the variable claims made concerning ethanol, it is relevant to analyze its production in terms of energy yield and economics.

Another biomass energy system that differs from ethanol is the use of triticale to produce heat energy for direct use and the production of electricity.

**Ethanol Production**

The conversion of maize and some other food/feed crops into ethanol by fermentation is a well known and established technology. In a large and efficient plant with economies of scale, the yield from a bushel (25.5-kg) of maize is about 2.5 gallons (9.45 liters) of ethanol.

As mentioned, the production of maize in the United States requires significant energy and economic inputs; this basic fact highlights the energy and dollar cost of producing ethanol (Pimentel, 1991; Giampietro et al., 1997). As mentioned, to produce an average of 8,000 kg per hectare of maize using intensive production technology requires more than 10,000 liters of oil equivalents and costs about $550 (excluding the environmental costs) (Pimentel, 1992). The major energy inputs in U.S. maize production are oil, natural gas, and/or other high grade fuels. Fertilizer production and fuels for mechanization account for about two-thirds of these energy inputs for maize production (Table 3).

Once maize is harvested three additional energy expenditures in ethanol production raise the total costs. These include energy to the transport maize grain to the ethanol plant, energy expended to provide the capital equipment requirements for the plant, and energy expended in the plant operations for the fermentation and distillation processes.

The average costs in terms of energy and dollars for a large modern ethanol plant (230 - 280 million liters/yr) are listed in Table 8. The largest energy inputs are for maize production and fuel energy expended in the fermentation/distillation process. The total energy input to produce 1,000 liters of ethanol is about 8.3 million kcal. However, when used as a fuel, 1,000 liters of ethanol has an energy value of only 5.0 million kcal. Thus, a net energy loss of 3.3 million kcal occurs for each gallon of ethanol produced. Put another way, about 65% more energy is required to produce 1,000 liters of ethanol than the energy that is in 1,000 liters of ethanol (Table 8). If new technology is developed that would reduce the specific energy in the fermentation/distillation process --even with no change in the cost of the capital equipment -- the energy inputs for this process might be reduced from 4.9 million kcal to approximately 3 million kcal (Gulati, et al., 1996). Though this would reduce the total energy input for 1,000 liters from 8.3 million kcal to 6.3 million kcal, the production of ethanol would still require the expenditure of 26% more fossil energy than is available in 1,000 liters of ethanol produced.

About 60% of the cost of producing 1,000 liters of ethanol in a large plant is for the maize feedstock itself (Table 8). This cost is offset, in part, by the by-product, dried-distillers grain, that can be fed to livestock. However, most of the cost contributions of by-products are negated by the costs of environmental pollution that result from the production processes. These are estimated to be $38 per 1,000 liters of ethanol produced (Pimentel, 1991; Pimentel, 1998).

Using maize for ethanol production is costly in terms of land use, fossil energy, soil erosion, and most importantly it subverts a valued human food and animal feed from direct use. The fact that ethanol production has a negative energy balance further precludes its place as an alternative liquid fuel for the future.

**Triticale Biomass Energy**

Triticale is a highly productive plant crop that was produced by combining the genes of wheat and rye. The following described triticale cultivation and storage system has many ecological and economic benefits as a biomass energy system (Scheffer and Karpenstein-Machan, 1991; Karpenstein-Machan, 1991). The crop is harvested with a moisture level of 50% to 60%, before the triticale actually reaches maturity. This high moisture content is essential for storage of the crop as silage in a silo (Karpenstein-Machan, 1991).

When placed in the silo, the silage produces lactic acids that reduce the pH to a low level of 3 to 4. The lactic acid and low pH prevent further decomposition of the stored biomass (Karpenstein-Machan, 1991). For use as a fuel, the triticale biomass is pressed in a screw press to reduce the moisture level so the biomass is 55% to 60% dry matter. This de-watering requires minimal amounts of energy and increases the quality of triticale biomass as fuel (Karpenstein-Machan and Scheffer, 1998). The liquid effluent resulting from the de-watering process has value as a fertilizer.

Biomass fuels with a water content of about 40% have 7% fewer calories than dry straw with 15% moisture.  The lower energy production of wet triticale results from the evaporation of water during combustion (Karpenstein-Machan , 1997).  However, most of the energy for evaporation can be reclaimed in modern energy plants by steam condensation.

The production and harvest inputs for triticale are about 4.1 million kcal per hectare (Table 9).  The input per output ratio for this biomass-energy system is 13.7: 1, which is a relatively high return.

## DECISIONS FOR THE FUTURE

If, as projected, human numbers continue to increase at the current rate of 1.5%, supplies of fossil energy will be unable to support a secure food supply.  Fossil energy supplies, finite in nature, will no longer be adequate and affordable.  Cropland is growing in short supply and fresh water is already scarce in many regions of the world. Competition for land and water is intensifying because of population growth and degradation of land and water resources.

Emerging evidence suggests that natural forces are starting to control human population numbers through malnutrition and emerging infectious diseases (Pimentel et al., 1998c).  More than 3 billion people worldwide are now considered malnourished (WHO, 1996), and equal number (3 billion) are living in poverty.  As early as 1984, per capita grain production started to decline in 1984; this trend continues today.   It is important to note that grains make up more than 80% of the world's food supply.

Other resource trends suggest more reasons for the growing world malnutrition problem.  During the last decade, per capita declines in the following have been reported: fertilizers, 23%; cropland, 20%; irrigation, 12%; and fish production, 10%.  In addition, the loss of food pre- and post-harvest to pests continues to be slightly more than 50% (Pimentel et al., 1998a).   Pollution of water, air, and land has increased, resulting in a growing number of humans suffering from serious, pollution-related diseases (Pimentel et al., 1998c).

Worldwide, 58 academies of science, including the U.S. National Academy of Sciences, point out that "Humanity is approaching a crisis point with respect to the interlocking issues" of population, natural resources, and sustainability (NAS, 1994, p. 13). The NAS report emphasizes that science and technology have a limited ability to meet the basic needs of a rapidly growing human population with increasing per capita demands.

Certainly more productive and improved food crops will be developed by biotechnology. Hopefully, food distribution throughout the world can be improved so food supplies are more fairly distributed. Perhaps new renewable energy sources will be developed to help as fossil fuel supplies decline.

Clearly many policies need to be changed and improved, if we are to achieve some balance between population numbers and the resources needed for a sustainable agriculture.

Energy use in agriculture is only one dimension of the food problem in the world. Yet agricultural production will be more sustainable when fossil energy resources are conserved. Of major importance is the needed reduction in soil erosion and water runoff from croplands. Improved pest control is necessary to reduce the percentage of the world's food -- currently more than 50% -- destroyed by pests. Many currently available strategies and technologies will, if employed, make such improvement possible.

However, the adoption of these and other sustainable practices in agriculture will be for naught if the world population continues its pattern of rapid growth by adding a quarter million additional people each day. No one can deny that an adequate and reliable supply of nutritional food is basic to human survival and the hoped for progress of human society. Humans will have to find ways to voluntarily control their numbers, or natural limits of the earth's resources will eventually do it for them.

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**Table 1**. Material and energy inputs and outputs per hectare for maize production in Mexico using only human labor (Lewis, 1951; Pimentel and Pimentel, 1996).

| Production Factor | Quantity | Kcal |
|---|---|---|
| Inputs: | | |
| Labor | 1,444 hr | 766,500 * |
| Axe and hoe | 16,570 kcal # | 16570 |
| Seeds | 10.4 kg # | 46,800 |
| Total Inputs | | 829,870 |
| Outputs: | | |
| Grain | 1,944 kg | 6,998,400 |
| kcal output/kcal input | | 8.4 |

* Estimated; # See text for assumptions for calculating kcal input.

**Table 2**. Material and energy inputs and outputs per hectare for maize production, plus 2 ha of pasture using an ox (Pimentel and Heichel, 1991).

| Production Factor | Quantity | Kcal |
|---|---|---|
| Input | | |
| Labor | 383 hr | 201,480 |
| Ox | 198 hr | |
| Concentrate | 150 kg | 525,000 # |
| Hay | 295 kg | 885,000 # |
| Machinery | 41,400 kcal * | 41,400 |
| Seeds | 10.4 kg * | 46,800 |
| Total | | 1,699,680 |
| Output | | |
| Grain | 1,944 kg | 6,998,400 |
| Kcal output/kcal input | | 4.1 |

# See text for assumptions used in the calculations; * Estimated

**Table 3**. Average energy inputs for producing a hectare of maize in the United States for 1997 (up dated after Pimentel [1992]).

| **Input** | **Quantity** | **Energy (kcal) x 100** |
|---|---|---|
| Labor | 10 hr | 444 |
| Machinery | 55 kg | 1,300 |
| Fuel | | |
| Gasoline | 40 liters | 320 |
| Diesel | 75 liters | 750 |
| Nitrogen | 160 kg | 2,400 |
| Phosphorus | 75 kg | 227 |
| Potassium | 96 kg | 155 |
| Lime | 426 kg | 135 |
| Seeds | 21 kg | 540 |
| Insecticides | 3 kg | 300 |
| Herbicides | 8 kg | 800 |
| Irrigation | 16% (irrigated) | 1,750 |
| Drying Maize | 4,000 kg | 800 |
| Electricity | 100,000 kcal | 100 |
| Transport | 350 kg | 97 |
| Total | | 10,118 |
| Maize Yield | 8,000 kg | 28,800 |
| Output/Input Ratio | | 2.8 / 1 |

**Table 4**. Environmental costs for both onsite and offsite effects from conventional, intensive agriculture per hectare each year (Pimentel, 1993).

| **Item** | **Costs** |
|---|---|
| Loss of Soil Nutrients | $ 113.00 |
| Loss of Water | 50.00 |
| Manure Pollution | 5.00 |
| Sediments Impacts Offsite | 37.50 |
| Pesticide Impacts | 25.00 |
| **TOTAL** | $230.50 |

**Table 5**. Average energy inputs for producing a hectare of maize in the United States for 1997 employing sustainable technologies (up dated after Pimentel [1993]).

| **Input** | **Quantity** | **Energy (kcal) x 100** |
|---|---|---|
| Labor | 12 hr | 533 |
| Machinery | 45 kg | 1,215 |
| Fuel | | |
| Gasoline | 24 liters | 192 |
| Diesel | 45 liters | 450 |
| Nitrogen (manure) | 30 t | 600 |
| Phosphorus | 34 kg | 103 |
| Potassium | 15 kg | 24 |
| Lime | 426 kg | 135 |
| Seeds | 21 kg | 540 |
| Insecticides | 0 kg | 0 |
| Herbicides | 0 kg | 0 |
| Irrigation | 16% (irrigated) | 1,750 |
| Drying Maize | 4,000 kg | 800 |
| Electricity | 100,000 kcal | 100 |
| Transport | 45 kg | 21 |
| Total | | 6,463 |
| Maize Yield | 8,640 kg | 31,100 |
| Output/Input Ratio | | 4.8 / 1 |

**Table 6**. Resources used and/or available per capita per year in the United States, China, and the world to supply basic needs.

| **Resources** | **USA** | **China** | **World** |
|---|---|---|---|
| Land | | | |
| Cropland (ha) | 0.71[a] | 0.08 | 0.27[e] |
| Pasture (ha) | 0.91[a] | 0.33[c] | 0.57[e] |
| Forest (ha) | 1.00[a] | 0.11[c] | 0.75[e] |
| Total (ha) | 2.62 | 0.52 | 1.59 |
| Water (liters x $10^6$) | 1.7[b] | 0.46[c] | 0.64[c] |
| Fossil Fuel | | | |
| Oil Equivalents (liters) | 8740[b] | 700[d] | 1570[f] |
| Forest Products (kg) | 1091[b] | 40[c] | 70[g] |

a) USDA (1993); b) USBC (1996); c) PRC (1994); Bennett, (1995), d) SSBPRC (1990);
b) e) Buringh (1989); f) International Energy Annual (1995); g) UNEP (1985).

**Table 7**. Fossil and solar energy use in the USA and world (Quads).

| **Energy** | **USA** | **World** |
|---|---|---|
| Petroleum | 33.71 a | 141.2 b |
| Natural Gas | 20.81 a | 77.6 b |
| Coal | 19.43 a | 93.1 b |
| Nuclear Power | 6.52 a | 23.3 b |
| Biomass | 6.80 a | 28.50 c |
| Hydroelectric Power | 3.00 d | 23.81 c |
| Geothermal and Wind Power | 0.30 d | 0.80 c |
| Biofuels (ethanol) | 3.40 e | 7.00 f |
| **Total Consumption** | 93.97 | 395.31 |

a) DOE 1995a; b) International Energy Annual 1995, DOE/EIA-219 (95);
c) DOE, 1995b; d) DOE, 1993 (thermal equivalents for hydropower);
e) Pimentel et al., 1994c; f) Pimentel and Pimentel, 1996

**Table 8**. Energy and dollar inputs for 1,000 liters of ethanol (Pimentel, 1991, 1992; USBC, 1996; USDA, 1996; Giampietro et al., 1997). Note: 1,000 liters of ethanol contain 5.0 million kcal of energy.

| **Inputs** | **Million kcal** | **Dollars** |
|---|---|---|
| Maize Production | 3.4 | $335.40 |
| Fermentation / Distillation | 4.9 (3.0)* | 243.80 |
| **Total** | 8.3 | 579.20 |

Based on experimental data, it is theoretically possible to reduce the energy input to approximately 3 million kcal (Gulati et al., 1996).

**Table 9**. Energy inputs for producing a hectare of triticale for 1997 (Energieconsulting Heidelberg, 1995; Karpenstein-Machan, 1998).

| Input | Quantity | Energy (kcal) x 1000 |
|---|---|---|
| Labor | 5 hr | 220 hr |
| Machinery | 12kg | 272 kg |
| Fuel -- Diesel | 100 liters | 941 liters |
| Nitrogen* | 82 kg | 1,223 kg |
| Phosphorus | 75 kg | 194 kg |
| Potassium | 96 kg | 165 kg |
| Lime | 426 kg | 183 kg |
| Seeds | 114 kg | 109 kg |
| Insecticides | 0 kg | 0 kg |
| Herbicides | 0 kg | 0 kg |
| Silage | 13 t | 56 t |
| Harvest | 13 t | 565 t |
| Transport | 13 t | 151 t |
| Total | | 4,079 |
| Triticale yield | 13,000 kg | 55,714 kg |
| Output / Input Ratio | | 13.7 / 1 |

* 50% of N-fertilization is recycled with effluent.

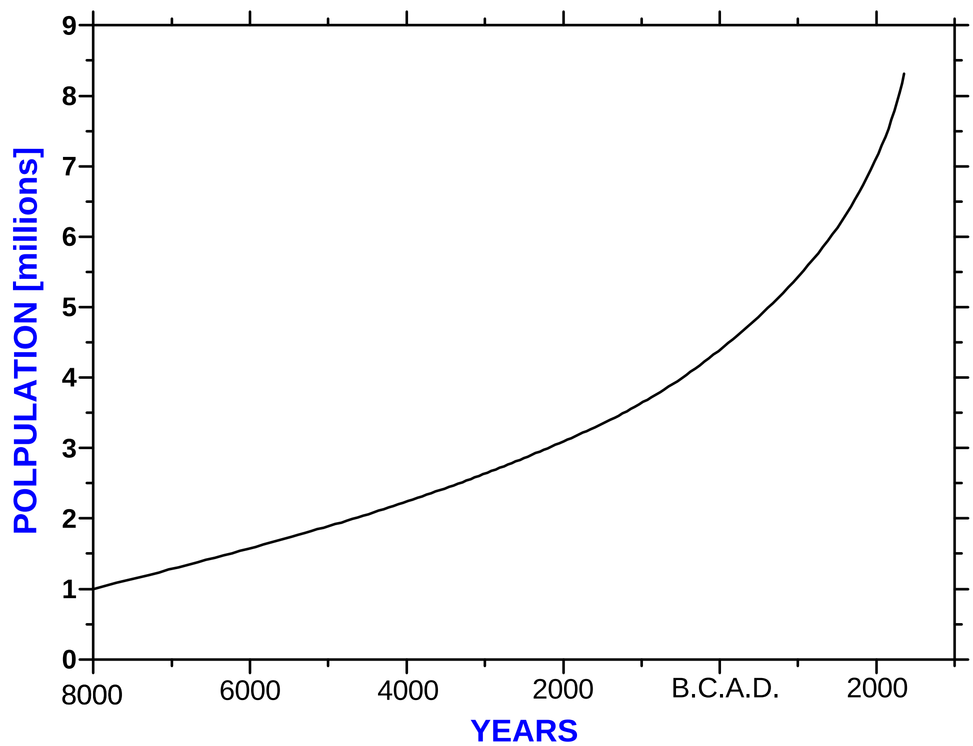


**Figure 1:** World population growth after the introduction of agriculture about 10,000 years ago. The population numbered only about 1 million at the discovery of agriculture (Coale, 1974; Deevey, 1960).