southern one because of orbit, lifetime, and seasonal constraints (2). There is virtually no useful high-resolution coverage of the thickened area of the north polar cap.
35. Improved limits on the presence or absence of planet-wide seasonal pressure fluctuations probably can be obtained from refined analyses of the results from (i) the Mariner 9 radio occultation and ultraviolet and infrared spectroscopy experiments, and (ii) the Soviet Mars 2 and Mars 3 orbital experiments (as well as Mars 4, 5, 6, and 7 experiments now under way). Direct measurements of surface pressure from future U.S. and Soviet landers, as well as further measurements from orbit, could provide sufficiently long-term, precise pressure observations to permit a decisive determination of how the seasonal variation in the mass of the frost caps interacts with the atmosphere. This information, in turn, has important implications for transport of heat, dust, and water vapor by the atmosphere.
36. For example, pressure buffering of the seasonal CO_2 cycle in excess of that calculated by Leighton and Murray (4) might arise through additional semiannual heat exchange by direct conductive transfer of heat into and out of thick water-ice deposits in the residual cap. Water-ice might be a much more effective seasonal heat reservoir than solid CO_2 because of its great stability. Alternatively, Fanale and Cannon (*21*) suggest buffering by a large reservoir of adsorbed CO_2 in the martian regolith.
37. G. Briggs (personal communication) has proposed an extreme but interesting extension of our concept of a CO_2 reservoir capped with water-ice. Briggs wondered if the water-ice could effectively and indefinitely seal off the solid CO_2 from atmospheric interaction. We do not think this is likely for reasons based on long-term climatic changes on Mars. Obliquity variations occur on Mars (*23*) which will cause extreme short-term variations in the insolation received at the poles—so large, in fact, that the equilibrium pressure regime for CO_2 (solid) varies by nearly two orders of magnitude on a 50,000-year time scale. We believe that this is too rapid and too major a variation to allow isolation. Similarly, if we assume that the meteorite flux at Mars is equal to or ten times larger than the rate of the moon, we estimate impact rates at the polar regions that would produce at least one 100-m crater in 1000 years. This would effectively break any water-ice seal of the CO_2 reservoir.
38. D. Milton, *J. Geophys. Res.* **78**, 4037 (1973).
39. C. Sagan, O. B. Toon, P. J. Gierasch, *Science* **181**, 1045 (1973).
40. We exclude any hypothetical early martian episode when enormous quantities of the substance were somehow lost through escape or surface combination. Furthermore, the present earthlike abundance of CO_2 in the atmosphere of Venus argues for the persistence of CO_2 in the gaseous phase. If the maximum ad hoc estimates of Fanale and Cannon (*21*) for adsorbed CO_2 in the regolith were correct, the total CO_2 budget of Mars would be increased to approximately 2 percent of that of the earth—still a small fraction. Furthermore, this CO_2 would not be accessible to become part of the atmosphere under current conditions; the atmospheric equilibria would be virtually unchanged, and our limits on past atmospheric history would still apply.
41. A. P. Ingersoll and C. B. Leovy, *Annu. Rev. Astron. Astrophys.* **9**, 147 (1971).
42. W. H. Pickering, *Pop. Astron.* **24** (No. 4), 236 (1916).
43. We wish to acknowledge G. Biggs and J. Cutts of Jet Propulsion Laboratory, Pasadena; A. P. Ingersoll, R. B. Leighton, and R. P. Sharp of California Institute of Technology, Pasadena; and H. Kieffer of the University of California at Los Angeles for discussions, criticisms, and helpful debates concerning early drafts of this paper. S. C. Yeung, Princeton University, contributed to the early development of some of the ideas presented here. Supported in part by the National Aeronautics and Space Administration. Contribution No. 2248 of the Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena 91109.

Food Production and the Energy Crisis

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By 1975 the world population is expected to reach 4 billion humans (*1*). As it continues to grow, there is increasing concern about ways to prevent wholesale starvation (*2*). Concurrently, an energy crisis (due to shortages and high prices) is expected as finite reserves of fossil fuels are rapidly depleted (*3, 4*). The energy crisis is expected to have a significant impact on food production technology in the United States and the "green revolution," because both systems of crop production depend upon large energy inputs.

Both the U.S. type of agriculture and the "green revolution" type of agriculture have been eminently successful in increasing crop yields through improved technology. The ratio of persons not on farms to each farm worker in the United States increased from 10 in 1930 to 48 persons in 1971 (*5, 6*). This has lead to great social change as numbers of unemployed, untrained farm laborers migrated to our cities (*7*). In addition, the costs to the natural environment have been great, as is reflected in depleted soils, pollution, disruption of natural plant and animal populations, and natural resource shortages. One nonrenewable resource fast being depleted is fossil fuel—the most important element in the impressive yields and quality of agriculture in the United States. Energy is used in mechanized agricultural production for machinery, transport, irrigation, fertlizers, pesticides, and other management tools. Fossil fuel inputs have, in fact, become so integral and indispensable to modern agriculture that the anticipated energy crisis will have a significant impact upon food production in all parts of the world which have adopted or are adopting the Western system.

As agriculturalists, we feel that a careful analysis is needed to measure energy inputs in U.S. and green revolution style crop production techniques. Our approach is to select a single crop, corn (maize), which typifies the energy inputs for crops in general, and to make a detailed analysis of its production energy inputs. With the data on input and output for corn as a model, an examination is then made of energy needs for a world food supply that depends on modern energy intensive agriculture. Using corn as an example, we consider alternatives in crop production technology which might reduce energy inputs in food production. Other than recognizing the high costs of U.S. energy intensive agriculture, we make no effort to examine any of the projected economic, sociological, or political "trade-offs" in the United States or other countries when the energy crisis upsets the world community (*8*).

Energy Resources

As fossil fuel resources decline, the costs of obtaining fuels both from domestic and foreign sources will rapidly increase. If current use patterns continue, fuel costs are expected to double or triple in a decade (*4*) and to increase nearly fivefold by the turn of the century (*9, 10*). When energy resources become expensive, significant changes in agriculture will take place.

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High energy use correlates closely with high gross national product (GNP) (*11*). In 1970, the United States consumed a total of 1.6×10^{16} kilocalories, or more than one-third of the total world energy consumption (*3*) and 35 percent of the world's petroleum (*12*)—for only one-seventeenth of the world population. This country's energy use has doubled during the past 20 years. In some types of agricultural production, the rate of energy use has increased more than threefold during the same period.

Hammond (*3*) reported that about 96 percent of the United States' energy "comes from fossil fuels: petroleum, 43 percent, mostly for transportation; natural gas, 33 percent; and coal, 20 percent. Hydroelectric energy accounts for about 3 percent of present production, and nuclear energy for about 1 percent." Peak petroleum consumption is expected to occur by the end of the century (*13*). Hammond (*3*) estimated that, if the United States were to use petroleum exclusively to provide all of its energy needs at present rates of consumption, the known, recoverable U.S. reserves would be depleted in only 5 years.

As was mentioned, crop production depends heavily on energy inputs just to produce the raw product. In addition, large amounts of energy are consumed as the raw products are transported to centers to be processed, frozen, canned, dehydrated, ground, baked, and so forth. Farmers process little of their own food, being dependent themselves upon the food processing, wholesaling, and retailing industries. They also depend on a multitude of other industries to supply machinery, fertilizers, pesticides, improved crop varieties, and other supplies. For every farm worker, it is estimated there are two farm-support workers (*14*). Thus, about 20 percent of the nation's work force and industries are involved in supplying food (*14*). The farm-support and food processing industries may use more energy than farming itself, further emphasizing the dependence of our food system upon energy. The oft-quoted statistic that one farm worker feeds 48 persons (*5*) is misleading because the farmer depends on a complex of support industries.

Table 1. Average energy inputs in corn production during different years (all figures per acre).

Inputs	1945	1950	1954	1959	1964	1970
Labor*	23	18	17	14	11	9
Machinery (kcal $\times 10^3$)†	180	250	300	350	420	420
Gasoline (gallons)‡	15	17	19	20	21	22
Nitrogen (pounds)§	7	15	27	41	58	112
Phosphorus (pounds)§	7	10	12	16	18	31
Potassium (pounds)§	5	10	18	30	29	60
Seeds for planting (bushels)‖	0.17	0.20	0.25	0.30	0.33	0.33
Irrigation (kcal $\times 10^3$)¶	19	23	27	31	34	34
Insecticides (pounds)#	0	0.10	0.30	0.70	1.00	1.00
Herbicides (pounds)**	0	0.05	0.10	0.25	0.38	1.00
Drying (kcal $\times 10^3$)††	10	30	60	100	120	120
Electricity (kcal $\times 10^3$)‡‡	32	54	100	140	203	310
Transportation (kcal $\times 10^3$)§§	20	30	45	60	70	70
Corn yields (bushel)‖‖	34	38	41	54	68	81

* Mean hours of labor per crop acre in United States (*6, 25*). † An estimate of the energy inputs for the construction and repair of tractors, trucks, and other farm machinery was obtained from the data of Berry and Fels (*63*), who calculated that about 31,968,000 kcal of energy was necessary to construct an average automobile weighing about 3400 pounds. In our calculations we assumed that 244,555,000 kcal (an equivalent of 13 tons of machinery) were used for the production of all machinery (tractors, trucks, and miscellaneous) to farm 62 acres of corn. This machinery was assumed to function for 10 years. Repairs were assumed to be 6 percent of total machinery production or about 15,000,000 kcal. Hence, a conservative estimate for the production and repair of farm machinery per corn acre per year for 1970 was 420,000 kcal. A high for the number of tractors and other farm machinery on farms was reached in 1964 and continues (*64, 65*). The number of tractors and other types of machinery in 1945 were about half what they are now. ‡ DeGraff and Washbon (*66*) reported that corn production required about 15 gallons of fuel per acre for tractor use—intermediate between fruit and small grain production. Because corn appeared to be intermediate, the estimated mean fuel (gallons) burned in farm machinery per harvested acre was based on U.S. Department of Agriculture (*22, 64*) and U.S. Bureau of the Census (*65*) data. § Fertilizers (N, P, K) applied to corn are based on USDA (*25, 26, 61, 62*) estimates. ‖ During 1970, relatively dense corn planting required about one-third of a bushel of corn (25,000 kernels or 34,000 kcal) per acre; the less dense plantings in 1945 were estimated to use about one-sixth of a bushel of seed. Because hybrid seed has to be produced with special care, the input for 1970 was estimated to be 68,000 kcal. ¶ Only about 3.8 percent of the corn grain acres in the United States were irrigated in 1964 (*67*), and this is not expected to change much in the near future (*68*). Although a small percentage, irrigation is costly in terms of energy demand. On the basis of the data of Epp (*69*) and Thorfinnson *et al.* (*70*), an estimated 905,600 kcal is required to irrigate an acre of corn with an acre-foot of water for one season. Higher energy costs for irrigation water are given by ***The Report on the World Food Problem*** (*2*). Since only 3.8 percent of the corn acres are irrigated (1964–1970), it was estimated that only 34,000 kcal were used per acre for corn irrigation. The percentage of acres irrigated in 1945 was based on trends in irrigated acres in agriculture (*55, 67*). # Estimates of insecticides applied per acre of corn are based on the fact that little or no insecticide was used on corn in 1945, and this reached a high in 1964 (*28, 51*). ** Estimates of herbicides applied per acre of corn are based on the fact that little or no herbicides were used on corn in 1945 and that this use continues to increase (*28, 51*). †† When it is dried for storage to reduce the moisture from about 26.5 percent to 13 percent, about 408,204 kcal are needed to dry busheds (*71*). About 30 percent of the corn was estimated to have been dried in 1970 as compared to an estimated 10 percent in 1945. ‡‡ Agriculture consumed about 2.5 percent of all electricity produced in 1970 (*24*) and an estimated 424.2 trillion British thermal units of fossil fuel were used to produce this power (*72*); on croplands this divides to 310,000 kcal per acre for 1970 (*6, 51*). The fuel used to produce the electrical energy for earlier periods was estimated from data reported in *Statistical Abstracts* (*73*). §§ Estimates of the number of calories burned to transport machinery and supplies to corn acres and to transport corn to the site of use is based on data from U.S. Department of Commerce (*74*), U.S. Bureau of the Census (*65, 67, 72*), Interstate Commerce Commission (*75*), and U.S. Department of Transportation (*76*). For 1964 and 1970 this was estimated to be about 70,000 kcal per acre, it was about 20,000 kcal per acre in 1945. ‖‖ Corn yield is expressed as a mean of 3 years, 1 year previous and 1 year past (*55, 59, 60*).

Corn Production and Energy Inputs

To investigate the relationship of energy inputs to crop production, we selected corn for the following reasons. (i) Corn generally typifies the energy inputs in U.S. crop production for it is intermediate in energy inputs between the extremes of high energy-demand fruit production and low energy-demand tame hay and small grain production. (ii) Corn is one of the leading grain crops in the United States and the world. (iii) More data are available on corn than on other crops. Concerning corn data, we have had to rely heavily on Department of Agriculture survey data and estimates provided by various other studies. Although the best available, some of these data have inherent limitations. Despite these shortcomings, this analysis provides a valuable perspective concerning the large energy inputs in U.S. agriculture.

Corn, the most important grain crop grown in the United States, ranks third in world production of food crops (*15*). In terms of world cereal grains, it ranks second to wheat. During 1971, world corn production on 279 million acres was 308 million metric tons (*16*).

Corn yield per acre (1 acre = 0.405 hectare) in the United States has increased significantly from 1909 to 1971 (Fig. 1). During 1909, the corn yield averaged 26 bushels per acre, and during 1971 it averaged 87 bushels per acre. A sharp rise in production per acre started about 1950—a time when many changes, including the planting of hybrid corn, were taking place in corn culture (*17–19*). The planting of hybrid corn probably accounts for

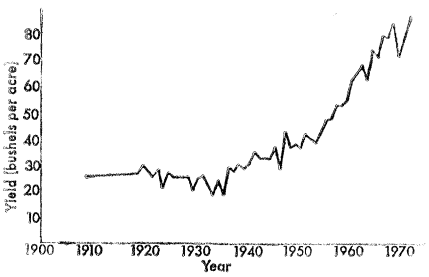

Fig. 1. Corn production (bushels per acre) in the United States from 1909 to 1971 (*55, 59, 60*).

20 to 40 percent of the increased corn yields since the 1940's with energy resource inputs accounting for 60 to 80 percent (*17, 20, 21*). Hybrid corn and energy inputs toward increased yields overlap because corn plants are often selected for characteristics that make the plant perform well under specific environmental conditions as, for example, with high fertilizer inputs. Without the appropriate genetic background, the corn plant will not respond to the fertilizer inputs and, of course, the corn plant cannot respond if fertilizer is absent.

While corn yields increased about 240 percent from 1945 to 1970, the labor input per acre decreased more than 60 percent (Table 1). Intense mechanization reduced the labor input and, in part, made possible the increased corn yield.

Machinery in agriculture has increased significantly during the past 20 years; the mean rate of horsepower per farm worker has increased from 10 in 1950 to 47 in 1971 (*5*). The number of tractors increased (88 percent) from 2.4 million in 1945 to 4.5 million in 1972 (*6, 22*). Concurrently, the rated horsepower of these tractors increased 2.6-fold from 18.0 to 46.6 horsepower (*6, 22*). The mean number of acres farmed per tractor was 62 in 1963 (*22*). In our estimates we assumed that tractors and other machinery were used to farm 62 acres and assumed to function for 10 years (Table 1).

Fuel consumption for all farm machinery rose from slightly more than 3.3 billion gallons (1 gallon = 3.8 liters) in 1940 to about 7.6 billion gallons in 1969 (*22, 65*). For total U.S. corn production, fuel consumption for all machinery rose from an estimated 15 gallons per acre in 1945 to about 22 gallons per acre in 1970 (Table 1). Indeed, farming uses more petroleum than any other single industry (*24*).

The use of fertilizer in corn production has been rising steadily since 1945 (Fig. 2). An estimated 7 pounds (1 pound = 0.4 kilogram) of nitrogen, 7 pounds of phosphorus, and 5 pounds of potassium were applied per acre to the acres fertilized in 1945 (*25*). By 1970 the application of fertilizers had risen to 112 pounds of nitrogen, 31 pounds of phosphorus, and 60 pounds of potassium per acre (*26*). The increase in nitrogen alone has been about 16-fold.

Other inputs in corn production include seeds, irrigation, and pesticides (Table 1). The use of pesticides in corn has been increasing rapidly during the past 20 years and this parallels the general increase in pesticide use in the United States (*27*) (Table 1).

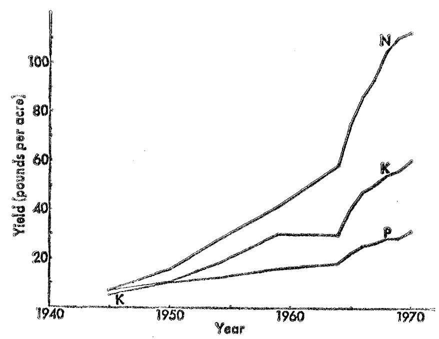

Fig. 2. Fertilizer (nitrogen, phosphorus, and potassium) applied per acre in corn production (*25, 26, 61, 62*).

About 41 percent of all herbicides and 17 percent of all insecticides used in agriculture are applied to corn (*28*).

Hybrid corn that is currently harvested has a higher moisture content because the newer varieties have growing seasons which extend further into the fall when drying conditions are poor (*19*). Moisture content above 13 percent (the maximum suitable for long-term storage) causes spoilage, and a drying process is used to reduce moisture (Table 1).

Agriculture consumed about 2.5 percent of all electricity produced (Table 1). The energy input for transportation is an important feature of modern intensive agriculture (Table 1). Machinery, pesticides, seeds, gasoline, and other supplies must be transported to the farm. Then the corn harvest must be transported to the place of use for animal feed or processing.

To gain an idea of the changes occurring over a period of time in corn production energy inputs, the years

Table 2. Energy inputs (kilocalories) in corn production.

Input	1945	1950	1954	1959	1964	1970
Labor*	12,500	9,800	9,300	7,600	6,000	4,900
Machinery†	180,000	250,000	300,000	350,000	420,000	420,000
Gasoline‡	543,400	615,800	688,300	724,500	760,700	797,000
Nitrogen§	58,800	126,000	226,800	344,400	487,200	940,800
Phosphorus ‖	10,600	15,200	18,200	24,300	27,400	47,100
Potassium¶	5,200	10,500	50,400	60,400	68,000	68,000
Seeds for planting#	34,000	40,400	18,900	36,500	30,400	63,000
Irrigation†	19,000	23,000	27,000	31,000	34,000	34,000
Insecticides**	0	1,100	3,300	7,700	11,000	11,000
Herbicides††	0	600	1,100	2,800	4,200	11,000
Drying†	10,000	30,000	60,000	100,000	120,000	120,000
Electricity†	32,000	54,000	100,000	140,000	203,000	310,000
Transportation†	20,000	30,000	45,000	60,000	70,000	70,000
Total inputs	925,500	1,206,400	1,548,300	1,889,200	2,241,900	2,896,800
Corn yield (output)‡‡	3,427,200	3,830,400	4,132,800	5,443,200	6,854,400	8,164,800
Kcal return/input kcal	3.70	3.18	2.67	2.88	3.06	2.82

* It is assumed that a farm laborer consumes 21,770 kcal per week and works a 40-hour week. For 1970: (9 hours/40 hours) × 21,770 kcal = 4,900 kcal. † See Table 1. ‡ Gasoline, 1 gallon = 36,225 kcal (*77*). § Nitrogen, 1 pound = 8,400 kcal, including production and processing (*78*). ‖ Phosphorus, 1 pound = 1,520 kcal, including mining and processing (*79*). ¶ Potassium, 1 pound = 1,050 kcal, including mining and processing (*79*). # Corn seed, 1 pound = 1,800 kcal (*33*). This energy input was doubled because of the effort employed in producing hybrid seed corn. ** Insecticides, 1 pound = 11,000 kcal including production and processing (similar to herbicide; see ††). †† Herbicides, 1 pound = 11,000 kcal including production and processing (*31*). ‡‡ Each pound of corn was assumed to contain 1,800 kcal (*33*) and a bushel of corn was considered to be 56 pounds.

1945, 1950, 1954, 1959, 1964, and 1970 were selected for a detailed analysis (Tables 1 and 2). Exact 5-year intervals were not selected because more complete data were available on these specific years than on others.

In 1970 about 2.9 million kcal was used by farmers to raise an acre of corn (equivalent to 80 gallons of gasoline) (Table 2). From 1945 to 1970, mean corn yields increased from about 34 bushels per acre to 81 bushels per acre (2.4-fold); however, mean energy inputs increased from 0.9 million kcal to 2.9 million kcal (3.1-fold) (Table 2). Hence, the yield in corn calories decreased from 3.7 kcal per one fuel kilocalorie input in 1945 to a yield of about 2.8 kcal from the period of 1954 to 1970, a 24 percent decrease.

The 2.9 million kcal input of fossil fuel represents a small portion of the energy input when compared with the solar energy input. During the growing season, about 2043 million kcal reaches a 1-acre cornfield; about 1.26 percent of this is converted into corn and about 0.4 percent in corn grain (at 100 bushels per acre) itself (*29*). The 1.26 percent represents about 26.6 million kcal. Hence, when solar energy input is included, man's 2.9-million-kcal fossil fuel input represents about 11 percent of the total energy input in corn production. The important point is that the supply of solar energy is unlimited in time, whereas fossil fuel supply is finite.

The trends in energy inputs and corn yields confirm several agricultural evaluations which conclude that the impressive agricultural production in the United States has been gained through large inputs of fossil energy (*8*, *30*).

Alternatives

Some alternatives may be needed to reduce energy inputs in agricultural food production when conventional energy resources become in short supply and costs soar. Some of the practical alternatives which might be employed in corn and other crop production are reviewed below.

The energy input from farm labor in corn production is the smallest of all inputs, only 4,900 kcal (Table 2). Increasing some labor inputs can significantly reduce some energy inputs. For example, one application of herbicide to corn requires about 18,000 kcal/acre if applied by tractor and sprayer (*31*) but less than 300 kcal if applied by hand sprayer. Although 1/60 as much energy is used, the labor cost of hand application today is about four times that of the tractor application. Hand application might become economically profitable when fuel costs increase and if herbicides are used in spot treatment only.

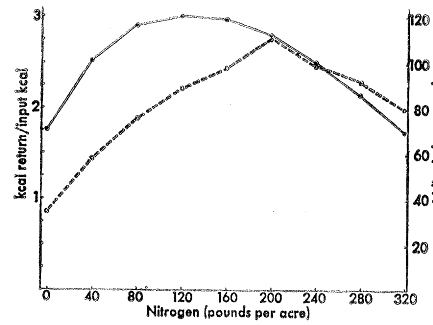

Fig. 3. Corn yields (bushels per acre, dashed line) with varying amounts of nitrogen (phosphorus = 34 pounds per acre) applied per acre (*45*). The kilocalorie return per kilocalorie of input (solid line) was calculated from the data of Munson and Doll (*45*) and from the 1970 input data in Tables 1 and 2.

Machinery and gasoline comprise a large energy input in corn production (Table 2). A viable alternative for reducing this fuel use would be to use machinery precisely scaled for its job and operate it at efficient speeds (*32*). Some of the extremely large tractors and other machinery will do more work per unit time, but this efficiency is offset by greater fuel requirements during operation. In addition, increasing the number of acres tended by a tractor or other machinery (currently about 62 acres per tractor) would help reduce this input. Horses and mules are not satisfactory substitutes for machinery because of the large quantity of energy they consume in feed (*33*).

The single largest input in corn production is fertilizer; nitrogen requires the largest quantity of energy to produce (Tables 1 and 2). A potential fertilizer source is the small percentage of livestock manure that is not now being used in crop production.

We mentioned that chemical fertilizer is applied to corn at a rate of 112 pounds of nitrogen, 31 pounds of phosphorus, and 60 pounds of potassium (Table 1). A like amount of nitrogen is available from manure produced during one year by either 1 dairy cow, 2 young fattening beef cattle, 9 hogs, or 84 chickens (*34*). In addition to the nutrients manure adds to the soil, it adds organic matter which increases the number of beneficial bacteria and fungi in the soil, makes plowing easier, improves the waterholding and percolation capacity of soil, reduces soil erosion, and improves the ratio of carbon to nitrogen in the soil (*35*).

The major costs of using manure for crop production are hauling and spreading. Hauling and spreading manure within a radius of ½ to 1 mile (1 mile = 1.6 kilometers) is estimated to require 1.1 gallons of gasoline per ton [calculated from data of Linton (*36*)]. If the average manure application is 10 tons (production by 1 cow for 1 year) per acre, an estimated 398,475 kcal (11 gallons of gasoline) per acre is necessary to apply the manure and hence to fertilize corn with manure. Producing chemical fertilizer (112 pounds of nitrogen, 31 pounds of phosphorus, 60 pounds of potassium) for 1 acre requires a total of 1,415,200 kcal (Table 2). One gallon of gasoline is used for tractor application, therefore a total of 1,451,425 kcal for chemical fertilizer application is used. Hence, if manure were substituted for chemical fertilizer, the savings in energy would be a substantial 1.1 million kcal per acre.

Current U.S. livestock manure production is estimated to be 1.7 billion tons per year, over 50 percent of which is produced in feedlots and confinement rearing situations (*37*). If 20 percent of the manure produced in feedlots and confinement rearing situations (0.17 billion tons) were available for use in corn production, 17.0 million acres of corn could be fertilized at an average manure application rate of 10 tons per acre. The above acreage would be 30 percent of the 1970 harvested grain corn acreage (*38*). In addition to saving valuable fuel energy, applying this manure to crop land would effectively recycle these animal wastes (*39*).

If some of the livestock manure from feedlots and confinement rearing situations is to be used, then these livestock production facilities would have to be moved closer to cropland where the manure is to be used. Redistributing livestock facilities would itself require a careful analysis of associated costs.

Nitrogen fertilizer inputs can also be reduced by planting legumes or other alternate crops in rotation with corn. For example, planting sweet clover in the fall and plowing it under 1 year later will add about 150 pounds of nitrogen per acre to the soil (*40*). Rotating corn with a legume would also effectively control the corn rootworm (*41*), would reduce corn disease problems (*42*), and would reduce weed problems (*43*).

When rotations are not feasible, it is possible to plant legumes between corn rows in late August and to plow this green manure under in early spring. In the northeast, Sprague (*44*) reports that seeding corn acreage to winter vetch in late August and plowing the vetch under in late April yielded about 133 pounds of nitrogen per acre. A cover crop also protects the soil from wind and water erosion during the winter and has the same advantages as manure in adding organic matter to the soil.

The energy cost of seeding a legume, we estimate, would require about 90,000 kcal/acre (fuel and seeds). For the commercial production of 133 pounds of nitrogen, 1.53 million kcal are needed; thus the energy saved by planting a legume for green manure would be substantial or 1.5 million kcal/acre. Hence, green manure offers a greater saving than livestock manure.

With fertilizer and other alternative inputs, a measure should be made to determine the maximum benefit per input in combination with all other inputs. In an investigation of fertilizer inputs in Iowa, Munson and Doll (*45*) reported that with 34 pounds of phosphorus per acre and 200 pounds of nitrogen per acre, they calculated mean corn yields of about 101 bushels per acre with all other inputs held constant (Fig. 3). Combining most of the 1970 energy input data from Tables 1 and 2 with the nitrogen, phosphorus, and corn yield data of Munson and Doll, we calculated the kilocalorie return per kilocalories input (Fig. 3). Maximum return was 3.0 kcal for 1 kcal input at 120 pounds of nitrogen per acre. A return of 2.8 for 1 was estimated for 1970 with the use of 112 pounds of nitrogen and 31 pounds of phosphorus per acre (Table 2). On the basis of only nitrogen inputs combined with the other inputs listed for 1970, it would appear that 112 pounds of nitrogen per acre provide nearly a maximum kilocalorie return per input kilocalorie.

Weeds can be controlled effectively and economically by either mechanical cultivation, herbicides, or a combination (*46*). On the basis of the energy expenditure, herbicidal weed control requires more energy than mechanical cultivation. For example, using 2 pounds of preemergence and 2 pounds of postemergence herbicides per acre requires a total energy input of about 80,225 kcal/acre (11,000 kcal per pound of herbicide plus 1 gallon gasoline for two applications) (*31*). The use of three cultivations (rotary hoe twice) would require an estimated 2 gallons of gasoline or 72,450 kcal/acre. Although the saving is not as large as some, alternatives do exist for reducing energy inputs for weed control.

With postemergence herbicides under certain conditions, it might be possible to spot-treat and therefore reduce the total quantity of herbicide used. To be done effectively, more labor would be necessary. In general, today's high labor and low energy costs would prohibit this, but with high energy costs, spot treatments could become economically feasible.

Rotating corn with other crops such as legumes and small grains may significantly reduce weed problems (*47*) and, therefore, reduce energy inputs for weed control.

Minimum tillage may also offer some opportunity to reduce energy inputs in plowing and disking, but this must be balanced against increased pest problems. A more complete analysis would be necessary to determine the precise costs and benefits of this alternative.

The protein content of corn has changed little since 1910, averaging about 9 percent (*48, 49*). However, the protein content of corn could be increased by selection to 12 to 15 percent (*50*). The value of increasing the quantity of protein in corn by even 1 percent is clear when it is calculated that this would reduce the need for 2 million tons of soybean meal in U.S. mixed feeds (*48*). Some increased energy inputs, such as nitrogen, would be necessary for cultivars of high protein corn, but the benefits would more than offset the costs.

Breeding corn for insect, disease, and bird resistance would in itself reduce the energy inputs of pesticides. At the same time this would reduce problems from pesticide pollution. Also, less energy would be needed for corn production if new corn varieties could be developed for faster maturity, reduced moisture content, greater water efficiency, and improved fertilizer response.

While only a small percentage (3.8 percent) of corn acres is irrigated, transporting water is an operation that demands lots of energy. The only alternative to reduce irrigation costs is to raise corn in regions where irrigation is seldom necessary. In the future, high energy costs may automatically reduce the percentage of corn acres irrigated.

The energy input for transportation of equipment and supplies to and from the farm is considerable. A real opportunity to reduce this input would be to move more of the materials and goods by train than by truck, because trains are significantly more efficient for transport (*8*).

Most of the alternatives mentioned would probably not fit easily into current corn management programs; however, when energy becomes costly, some or all of the alternatives may become practical and necessary. Furthermore, it should be emphasized that in some cases the partial use of one or more alternatives may prove to be the most economical procedure. By employing combinations of several of these alternatives, we estimate that it would be possible to reduce energy inputs by about a half and still maintain present yields. The economic feasibility of this depends of course upon many factors—including future energy costs.

World Food Supply

The shortages of food supplies in some nations (*2*) have prompted the United States to develop various international agricultural programs to aid in the "green revolution." Green revolution agricultural technology requires high energy inputs especially in fertilizers, pesticides, and hybrid seeds. Obviously, as energy shortages occur and costs increase, the success of the green revolution will be affected. For this reason, the problems of food production and energy demand on a worldwide basis are briefly examined.

In estimating the fuel energy needs to feed 4 billion humans, modern crop production technology similar to U.S. and green revolution agriculture is assumed. Energy data on U.S. corn will be used since it approximates average inputs and outputs in modern crop production. Our analysis indicated that about 2.9 million kilocalories of energy was used to raise an acre of corn in 1970—the equivalent of 80 gallons (2.5 barrels) of gasoline per acre (Table 2).

An estimated 330 million acres were planted in crops in 1970 (excluding cotton and tobacco) (*6, 51*). With about 200 million people in the United States, this averages about 1.7 acres per capita; but since about 20 percent of our crops is exported, the estimated acreage is about 1.4 acres per capita. In terms of fuel per person for food, employing modern intensive agriculture, this is the equivalent of 112 gallons of gasoline per person (80 gallons per acre × 1.4 acres per person = 112 gallons). Using U.S. agricultural technology to feed a world population of 4 billion on an average U.S. diet for 1 year would require the energy equivalent of 488 billion gallons of fuel.

To gain some idea about what the energy needs would be for different diets if U.S. agricultural technology were employed, an estimate is made of how long it would take to deplete the known and potential world reserves of petroleum. The known reserves have been estimated to be 546 billion barrels (*52*). If we assume that 76 percent of raw petroleum can be converted into fuel (*52*), this would equal a usable reserve of 415 billion barrels. *If petroleum* were the only source of energy and if we used *all* petroleum reserves solely to feed the world population, the 415-billion-barrel reserve would last a mere 29 years [(415 billion barrels/448 billion gallons)/(31.5 gallons per barrel = 29 years)]. The estimate would be 107 years if all potential reserves (2000 billion barrels) (*53*) of petroleum were used for food production. However, if the world population were willing to eat nothing but corn grain, potential petroleum reserves could feed a projected 10 billion humans for 448 years.

Contrary to popular belief, U.S. food production costs are high (*54*). Although only 16.6 percent of a person's total disposable mean income of $3595 in the United States was spent for food in 1970 (*5, 23*), the percentage is small only because U.S. per capita earnings are high. The 16.6 percent of U.S. per capita income of $3595 for food is $597. Since a third of food retail prices is production costs (*55*), it costs about $199 to produce $597 worth of food or 3110 kcal per person per day per year [including 66 g of animal protein and 18 g of animal fat (*2, 56*)]. This is the equivalent of 5280 plant kcal per person per day per year (assuming that 7 kcal of plant product is needed to produce 1 kcal of animal protein and fat with 1 g of animal protein = 4 kcal and 1 g of fat = 9 kcal). Thus, the cost for 1000 kcal of plant product is about $38.

In India about 77 percent of a person's income is spent for food with expenditures per capita averaging about $23 (includes marketing costs) per year (*2*). The calorie intake per person per day averages 2000 kcal, with animal protein being about 7 g per day and animal fats assumed to be 2 g (*2*). This is the equivalent of 2280 plant kcal per person per day per year. Thus the cost for 1000 plant kcal is about $10. Hence, the cost of producing 1000 plant kcal per day per year in India is significantly less than the $38 costs in the United States. This is in part due to the difference between nations in the plant crops used for food.

Conclusions

The principal raw material of modern U.S. agriculture is fossil fuel, whereas the labor input is relatively small (about 9 hours per crop acre). As agriculture is dependent upon fossil energy, crop production costs will also soar when fuel costs increase two- to fivefold. A return of 2.8 kcal of corn per 1 kcal of fuel input may then be uneconomical.

Green revolution agriculture also uses high energy crop production technology, especially with respect to fertilizers and pesticides. While one may not doubt the sincerity of the U.S. effort to share its agricultural technology so that the rest of the world can live and eat as it does, one must be realistic about the resources available to accomplish this mission. In the United States we are currently using an equivalent of 80 gallons of gasoline to produce an acre of corn. With fuel shortages and high prices to come, we wonder if many developing nations will be able to afford the technology of U.S. agriculture.

Problems have already occurred with green revolution crops, particularly problems related to pests (*57*). More critical problems are expected when there is a world energy crisis. A careful assessment should be made of the benefits, costs, and risks of high energy-demand green revolution agriculture in order to be certain that this program will not aggravate the already serious world food situation (*58*).

To reduce energy inputs, green revolution and U.S. agriculture might employ such alternatives as rotations and green manures to reduce the high energy demand of chemical fertilizers and pesticides. U.S. agriculture might also reduce energy expenditures by substituting some manpower currently displaced by mechanization.

While no one knows for certain what changes will have to be made, we can be sure that when conventional energy resources become scarce and expensive, the impact on agriculture as an industry and a way of life will be significant. This analysis is but a preliminary investigation of a significant agricultural problem that deserves careful attention and greater study before the energy situation becomes more critical.

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Species Introduction in a Tropical Lake

A newly introduced piscivore can produce population changes in a wide range of trophic levels.

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By chance or by intention, man has often introduced new species to an ecosystem. The results have ranged from little or no effect to large-scale changes, often accompanied by catastrophic consequences (*1*). Although there have been many such species introductions over the past century, there is little documentation of community effects other than some general information about vertebrate introductions (*2*) and some experimental studies concerning the effects of herbivores on vegetation (*3*). Noticeably absent is the situation in which there has been sufficient qualitative or quantitative information concerning the preceding conditions of the ecosystem to permit a quantitative statement about changes resulting from the species introduction. Even in the field of biological control, where serious studies of this nature have been continuing for more than seven decades, accurate predictions of the effects of a new species on a given ecosystem are, even at the most basic level, not yet possible (*4*).

Historically, fish introduction (or culture) has provided a rich source of protein in many tropical areas. Introductions, however, are not without a

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