Energy and Land Constraints in Food Protein Production

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This year the world population is expected to reach 4 billion and for the year 2000 the projected figure is 7 billion (*1*). Reduction of the death rates through effective public health measures without a concurrent reduction of birthrates is considered one of the prime causes of the rapid increase in population numbers (*2, 3*). Because birthrates and family planning are intimately interwoven with the social systems and cultures of individual nations, population control does not immediately follow a fall in the death rate. History suggests that population control occurs because of numerous factors, including social and economic change (*3, 4*).

Obviously, the rapid growth of the human population is resulting in an increased demand for food (*1, 5, 6*). Experience has shown that augmenting food supplies is not as easy as controlling disease (*1, 7*). Assuming the figures that suggest an estimated half-billion people are at present protein-calorie malnourished (*8, 9*) are correct, then great concern is justified about our ability to provide adequate food for the increasing numbers of people that are projected for the future.

An integral part of the population-food equation is the use of fossil energy. Energy is consumed in most food and fiber production, in public health activities, and in most endeavors to improve the quality of human life.

As we prepare for the future with its rapidly growing world population, concern has been expressed about the limited energy and land resources that are available to increase food production, especially food protein production. In this article we analyze the energy and land demands for both animal and vegetable protein production in the United States, and then examine world food supply as it relates directly to world population density, dietary standards, and food production technology.

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Animal and Vegetable Protein Consumption

The majority of the world population lives on about 2100 kilocalories per capita per day and obtains most of its protein from grains (*5*). For example, in the Far East about 56 grams of protein per capita are consumed daily, of which only about 8 grams are animal protein (mainly milk) (*10*). In contrast, in the United States the protein consumed per capita per day totals 96 grams, with about 66 grams of animal origin (*11*).

In the United States per capita meat consumption is one of the highest in the world (*12*). In 1974 annual per capita meat consumption was 114 kilograms (250 pounds) or about 312 grams per day (*11*). Beef consumption amounted to 53 kg; pork, 30 kg; fish, 6 kg; chicken and turkey, 23 kg; and veal and lamb, 2 kg (*11*). Per capita milk and milk product consumption was 129 kg. An average of 285 eggs (36 kg) was consumed (*11*).

Health difficulties are sometimes associated with high animal product consumption. For example, coronary heart disease has been associated with high serum cholesterol, which in turn is influenced by the animal products that are consumed. Animal product foods high in saturated fats and cholesterol include liver, eggs, shrimp, beef, and many dairy products. Some persons on high cholesterol diets may be more than normally susceptible to coronary heart disease (*13*). Another problem associated with high protein diets is the production of large amounts of uric acid, which may result in gout (*14*).

Protein Shortages and Needs

Protein and calorie shortages in a large portion of the world population are resulting in poor growth and development and increased disease, particularly among children (*15*). Protein and calorie malnutrition are interrelated, because, as Altschul (*16*) points out, "there is a protein-calorie trade-off." That is, if the body faces a calorie deficit it will convert protein into calories but not the reverse. Most of the instances of protein deficiencies occur in parts of the world where caloric intakes are also inadequate (*16, 17*).

Protein in the diet must contain a minimal amount of each of the eight essential amino acids to meet the minimum daily needs of the human body. The United Nations Food and Agriculture Organization and World Health Organization (FAO/WHO) Expert Group in Protein-Calorie Requirements suggested a daily safe practical allowance for a 70-kg male adult can be met with about 41 grams of FAO's reference protein (egg). These requirements are for the average adult, but vary according to age, activity, and condition of the individual.

Animal proteins are of higher nutritional quality than plant proteins because proteins from animal sources are composed of relatively large amounts of the eight essential amino acids required by man (*18*). Eggs, milk, and meat, for example, provide all the essential amino acids in a single source of protein food. Also, valuable minerals and vitamins are supplied by these animal products.

Vegetable proteins are of poorer quality than animal protein because most are deficient in one or two of the essential amino acids. For example, proteins provided by rice, wheat, and corn are low in lysine (*5, 18, 19*). With the amino acid composition of whole egg as the standard (100 percent), whole rice contains 52 percent lysine; whole wheat, 44 percent; and whole corn, only 38 percent. Conversely, soybean meal (low fat) contains 111 percent of lysine compared with the egg standard; however, soybean contains only 53 percent as much methionine (*5*).

By selecting combinations of cereal and other vegetable food sources and consuming large quantities, adults can obtain sufficient quantities of the essential amino acids to meet daily needs of the body. For example, consuming sufficient quantities of rice and soybean will provide adequate amounts of the essential amino acids. However, other nutrients, such as vitamin B_{12} and some of the essential trace minerals, may be lacking in a vegetarian diet. Young children need more than vegetable food sources (*20*).

Energy, Labor, and Land Resources in Protein Production

Fossil energy (including fertilizer, machinery, fuel, and others), land, and labor are the three prime resources used for crop and animal production. These factors are interrelated and each can be partly substituted for the others. For example, fossil energy power can be used to reduce the labor-manpower input, and vice versa. Increasing the intensity of land management through various energy inputs (such as fertilizers and tractors) can reduce the land area needed, and the approach can be reversed. The accounting procedures used in this analysis are based on these interrelationships among land, labor, and energy.

Although manpower can be substituted for machinery and fuel, the use of machinery and fuel frees a large number of people from agricultural production. This proportion of the population can then produce a greater amount and variety of other goods and services for society. For example, raising corn in the United States requires only 22 man-hours per hectare (*21*), whereas raising corn by hand in parts of Mexico requires as much as 1144 man-hours per hectare (*22*). A U.S. grower with current crop production technology can manage more than 50 times more corn than a farmer producing corn by hand, and thus the U.S. grower has a higher production rate and income.

Both arable land and fossil energy are finite resources. The FAO estimates that about 11 percent of world land (1.5 billion hectares) is suitable for cultivation and nearly all of this land is already in cultivation (*23*). About 22 percent (3.0 billion hectares) of the world land area is now used for livestock production and is in pastures, ranges, and meadows (*23*). Forest covers another 30 percent (4.1 billion hectares) of the land area (*23*), while the remaining 37 percent is either too dry, too cold, or too steep for any agricultural production.

Arable land (potential) can be increased by irrigation and the use of other inputs, but these require increased energy or labor (or both). Also, the quality of arable land is slowly being degraded by erosion. For example, in the United States, which has the most modern agricultural technology, about 36 metric tons of topsoil are lost annually per hectare in corn production in Iowa (*24*). For the United States as a whole, about 3.6 billion metric tons of topsoil are lost annually, that is, about 31 metric tons per hectare of cultivated land (*25*). To replace this annual loss would take nearly 11 years [about 100 years are required to produce 25 millimeters of topsoil or about 2.9 metric tons per hectare per year (*26*)].

Fossil energy is rapidly being depleted. Known world reserves of petroleum and natural gas are expected to be more than half depleted within the next 25 years (*27*). This projection takes into account the demand imposed by the increasing world population. Meanwhile, it is expected that new energy sources will be developed, but the speed of these developments is unknown. Thus the timetable of energy development is uncertain, while the use of present energy resources is expected to increase.

Vegetable Protein Production

On the basis of inputs of labor, land, and energy, vegetable protein can be produced efficiently. For example, an average of 710 kg of alfalfa protein can be produced per hectare with inputs of only about 9 man-hours and about 2.7 million kcal of fossil energy. Unless the protein is extracted (at an additional energy and labor cost) this protein (as well as that from corn silage and hay) is unavailable to man (Table 1). Soybeans produce an average of 640 kg of protein per hectare and Brussels sprouts yield 604 kg (Table 1). Wheat, rice, and corn produce an average of from 274 to 457 kg of protein per hectare. Corn is an efficient crop as judged by the inputs of labor and fossil energy and food calorie output (Table 1). Corn is also efficient in collecting solar energy (about 1.26 percent) and converting this light energy into plant protoplasm (*28*). Field crops such as alfalfa, corn silage, and hay are included in Table 1 because they are used as feeds for livestock.

In the production of vegetable protein described above, average U.S. agricultural technology with relatively large inputs of fossil energy and small amounts of labor (Table 1) is used. Corn, rice, wheat, and other crops can be produced with relatively large amounts of manpower and small amounts of fossil fuel (Table 1). The inputs of labor range from 240 to 1284 man-hours per hectare (*29*). Cassava (the source of tapioca) requires 9 to 12 months for production, but the yield in food energy is exceptionally large (19.2 million kcal) per hectare with an input of 1284 man-hours. However, cassava contains about 1 percent protein when it is dried (*5*). Sorghum grown in the Sudan required only 240 man-hours per hectare while yielding 900 kg of grain that contained 99 kg of protein per hectare (Table 1).

Currently, people of the world obtain about 70 percent of their dietary protein from cereals, vegetables, and legumes (Table 2). Of the estimated 122 million metric tons of protein available for world consumption in 1975, about 86 million metric tons are vegetable protein. Most of this protein (47 percent) comes from cereal

Table 1. Analysis of vegetable protein production per hectare for various crops in the United States and elsewhere requiring different amounts of labor and energy.

Crop	Crop yield in protein (kg)	Crop yield (kg)	Crop yield in food energy (10^6 kcal)	Fossil energy input for production (10^6 kcal)	Labor (man-hours)	Kcal fossil energy input/kcal protein output
Alfalfa*	710	6,451 (dry)	11.4	2.694	9	0.95
Soybeans†	640	1,882	7.6	5.285	15	2.06
Brussel sprouts*	604	12,320	5.5	8.492	60	3.51
Potatoes*	524	26,208	20.2	8.907	60	4.25
Corn*	457	5,080	17.9	6.644	22	3.63
Corn silage*	393	30,200	24.1	5.493	25	3.49
Rice*	388	5,796	21.0	15.536	30	10.01
Dry beans*	325	1,457	5.0	4.478	15	3.44
Oats*	276	1,900	7.4	2.978	6	2.70
Wheat*	274	2,284	7.5	3.770	7	3.44
Hay*	200	5,000 (dry)	8.6	3.115	16	3.89
Corn (Mexico)‡	175	1,944	6.8	0.053	1,144	0.08
Rice (Philippines)‡	111	1,654	6.0	0.582	576	1.31
Wheat (India)‡	99	821	2.7	0.256	615	0.65
Sorghum (Sudan)‡	99	900	3.0	0.079	240	0.20
Cassava (Tanga)‡	58	5,824 (dry)	19.2	0.016	1,284	0.07

*Data from Pimentel (*43*). †Data from Pimentel (*43*). The inputs include about 1.1 million kcal for processing the beans to make them edible for livestock. ‡Data from Pimentel *et al.* (*29*).

grains, and this agrees well with Roberts' estimate of 50 percent (*30*). Legumes account for an estimated 20 percent of the protein available to man (Table 2). Thus, cereals and legumes account for most of the protein and calories consumed by the majority of the peoples of the world [in the United States, 69 percent of the protein is derived from livestock sources (*11*)].

Examples of typical high-vegetable diets can be found in several parts of the world. In a survey of 12 rural villages in India, the average daily consumption per family member was between 210 and 330 grams of rice and wheat, 140 milliliters of milk, and 40 grams of pulses and beans (*31*). This provided a maximum of about 1400 kcal and 48 grams of protein per day.

In Central America, where corn is the staple food, laborers commonly consume about 500 grams of corn and 100 grams of black beans per day, which provide about 2118 kcal and 68 grams of protein daily (*32*). The corn and beans complement each other in essential amino acid patterns.

The people of Ireland from the 17th through the 19th century relied primarily on potatoes for both calories and protein. During this period, the daily diet for the adult working peasant was 4.5 kg of potatoes and about half a liter of milk (*33*). This provided about 3852 kcal and 64 grams of protein per day, of which 45 grams was from potatoes.

When vegetable protein is used as the primary food source, large numbers can be fed per hectare. For example, in the United States the following crops will provide protein for the listed man-years per hectare when corrected for net utilizable protein (*34*): soybean, 16; potatoes, 16; corn, 12; rice, 10; and wheat, 8 (1 man-year = 60 grams of protein per day for 1 year).

Energy inputs necessary to produce a kilocalorie (1 gram protein = about 4 kcal) of protein varied with the vegetable protein (Table 1). An input of 2.06 kcal of fossil fuel energy is used to produce 1 kcal of soy protein. Included in this 2.06 kcal is the energy (about 20 percent) that is needed to process the soybeans to make them edible for livestock. Per protein-kilocalorie produced, rice required the largest fossil energy input, or 10.01 kcal (Table 1).

Although corn requires 3.63 kcal of fossil energy per protein-kilocalorie, corn as a human food yields the most food calories per input of fossil calorie used in production, that is, about 2.7 kcal per input kilocalorie (Table 1). These energetics are similar to those of Leach (*35*) for corn that is produced in the United Kingdom (3.5 and 2.3, respectively). The second most efficient crop in the production of food calories is the potato, with a yield of 2.3 kcal of energy output per kilocalorie of input (Table 1).

Outside of the United States, corn yields of 175 kg of protein per hectare have been recorded in areas where manpower was the primary input (Table 1). This yield would provide sufficient protein for 4 man-years, as was defined above. Ordinary corn protein, of course, is deficient in lysine and would have to be supplemented with either animal protein, other appropriate vegetable protein, or synthetic amino acids to offset this deficiency. New corn varieties are being developed with the Opaque-2 factors that provide corn with higher levels of lysine and tryptophan and, therefore, improved protein quality (*36*).

Table 2. Estimated and projected vegetable and animal protein produced (million metric tons), fed to livestock, and available to man for 1975 (population 4 billion), year 2000 (projected population of 7 billion), and year 2135 (projected population of 16 billion) for the United States (1975 only) and the world. Per capita protein available to man for the years 2000 and 2135 is held at the 1975 level.

Item	U.S.	World			
	1975	1975	2000	Alternative for 2000	2135
Total cereal protein produced	17.0*	95†	166	134	409
Fed to livestock	15.5‡	38§	49	0	49
Available to man	1.5‖	57	117	134	360
Total legume protein produced	9.3*	30¶	50	36	82
Fed to livestock	9.0*	6#	8	0	8
Available to man	0.3‖	24	42	36	74
Total other vegetable protein produced	0.8*	6**	12	9	20
Fed to livestock	0.1††	1‡‡	2	0	2
Available to man	0.7‖	5	10	9	18
Total livestock protein produced	6.0*	33§§	43	25	43
Fed to livestock	0.7‖‖	3¶¶	4	0	4
Available to man	5.3‖	30	39	25	39
Total fish protein produced	1.0*	9##	12	12	12
Fed to livestock	0.8*	3***	4	0	4
Available to man	0.2‖	6	8	12	8
Total protein produced	34.1	173	283	216	566
Fed to livestock	26.1	51	67	0	67
Available to man	8.0	122	216	216	499

*Data from USDA (*42, 63*). †Cereal grain production is estimated to be 1050 million metric tons for 1975 (*8*) and this grain contains an estimated 9 percent protein (*64*). ‡Data from USDA (*8*). §An estimated 40 percent of cereal protein is fed to livestock (*65*). ‖Data from USDA (*11*). ¶Legume food-crop production (beans, peanuts, and so forth) is estimated to be 122 million metric tons for 1975 (*23*) and these foods contain an estimated 25 percent protein (*64*). #An estimated 21 percent of legume protein is fed to livestock (*42, 65*). **Estimated protein from other vegetable sources such as white and sweet potatoes, cassava, and cabbage. ††Estimated as to the amount of apple pomace, sugar beet, and other vegetable matter fed to cattle, sheep, and hogs. ‡‡An estimated 15 percent of other vegetable protein is fed to livestock. §§Includes total meat (109 million metric tons), milk (415 million metric tons), and egg (22 million tons) production for 1975 (*23*). Percentage protein estimated at 15 percent for meat, 3.5 percent for milk, and 13 percent for eggs (*64*). ‖‖Estimated as meat and milk by-products fed to livestock. ¶¶An estimated 10 percent is fed to livestock as meat and milk products and by-products. ##Fish includes all seafoods harvested from the ocean and for 1975 is estimated at 66 million metric tons (*62*) that contain an estimated 14 percent protein (*64*). A reduction from 17.5 to 14 percent in total fish protein available is included for cleaning the fish consumed by man. ***An estimated 33 percent of the fish harvest is fed to livestock (*39, 62*).

Animal Protein Production

To produce the 114 kg of meat consumed annually per capita in the United States, an estimated 68 kg of livestock biomass must be maintained per hectare (interestingly, human biomass is only about 16 kg per hectare). In other words, our livestock population outweighs by more than fourfold the human population.

In the United States, 91 percent (24.6 million metric tons) of the estimated 27.1 million metric tons of cereal, legume, and vegetable protein suitable for human use is fed to livestock to produce the 5.3 million metric tons of animal protein that humans consume annually (Table 2). Thus, for every 5 kg of vegetable and fish protein fed to livestock in addition to the large forage intake, we obtain 1 kg of animal protein. In addition, the estimated 100 million pets (dogs and cats) (*37*) consume an estimated 5 percent of the total vegetable and animal protein that is fed to livestock.

Livestock consume vegetable protein to produce high-quality animal protein. The "costs" of animal protein production include: (i) the protein-calorie inputs fed to the livestock selected for food production and (ii) the protein-calorie inputs necessary to maintain the breeding herd population.

Of all the livestock systems, milk production is the most efficient in the conversion of feed protein (mostly vegetable protein) into animal protein (*5*) (Table 3). In the United States about 31 percent of the feed protein is converted into milk protein (59 kg of milk protein is produced from 188 kg of feed protein). Of the 188 kg of feed protein, about 98 kg was grain protein that is usable by man and 90 kg was from forages that are unsuitable for man. On the basis of only the grain protein that is consumable by man, the efficiency of the conversion increased to 60 percent.

Turning to energy accounting, we find that about 7.0 million kcal of feed energy is needed by dairy cattle to produce the 59 kg of milk protein, or about 30 kcal of feed energy per kilocalorie of milk protein produced (Table 3). These results agree favorably with those of Reid, who reported a ratio of 28 : 1 for milk protein (*38*). In addition, the production of milk requires trucks, tractors, manure movers, and other equipment. The fossil fuel input for feed and animal production required about 36 kcal per kilocalorie of milk protein (Table 3); for the United Kingdom, Leach estimated about a 20 : 1 ratio for milk protein production (*35*). The 36 : 1 ratio per kilocalorie of protein is about average for the input-output ratio of animal protein production (Table 3); generally animal protein production averages about tenfold that of plant protein production (Tables 1 and 3). The milk protein production per man-hour of labor was about 2.6 kg (Table 3).

Egg protein production is the next most efficient (27 percent) means of converting vegetable protein into animal protein (Table 3). Unlike the protein fed to cows, most of the protein that is fed to chickens is in a form suitable for man. Broiler production is similar to egg production but the efficiency of protein conversion is only 18 percent (Table 3).

Table 3. Animal protein (kg) produced per hectare in the United States (except for the last item) with various inputs of feed, labor, and energy.

Animal product	Animal protein yield (kg)	Feed protein input (kg)	Feed energy input (10^3 kcal)	Fossil energy input (10^3 kcal) for the production of:			Labor (man-hours)	Kilocalorie ratio	
				Feed	Feed and animal	Animal		Feed input/ protein output	Fossil energy input/ protein output
Milk*	59	188	6,963	2,382	8,561	6,179	23	30	35.9
Eggs†	182	672	14,406	6,070	9,560	3,490	174	20	13.1
Broilers‡	116	651	8,886	6,446	10,233	3,787	38	19	22.1
Catfish§	51	484	5,007	2,180	7,068	4,888	55	25	34.6
Pork‖	65	689	17,021	6,774	9,212	2,438	28	65	35.4
Beef (feedlot)¶	51	786	24,952	7,129	15,845	8,716	31	122	77.7
Beef (rangeland)#	2.2	33	1,420	0	89	89	1	164	10.1
Lamb (rangeland)**	0.17	3	128	2	11	9	0.2	188	16.2
Milk, blood, and Zebu cows (rangeland)††	0.76	1	40	0	0	0	34	159	—

*Milk yield data are for New York State dairy farms (*66*). The average milk yield per cow was 5541 kg per year and 1698 kg per hectare. Feed for the cattle was both produced on the farm and purchased. Protein content and food energy of the feed were estimated from the total feed that was provided to the cattle (*43*, *67*). Feed inputs include that provided to dry cattle and replacement heifers. Total fossil energy input for feed production was calculated by using the data on quantities of feeds that were consumed (*67*) and the data on fossil fuel inputs that were used producing the crops (*43*). The fossil energy input for dairy milk production was estimated from the expenditures for the operation and maintenance of machinery, equipment, buildings, and for feed transport (*66*, *67*). The labor input includes the labor for producing the crops as well as for managing the dairy (*66*, *67*). In this and the other animal production systems, all fossil energy inputs were estimated one step back from the farm and cropland. †Each hen is assumed to produce 220 eggs per year (*68*). Each egg weighs an estimated 57 grams (*69*). Yield per 119 birds per hectare was 1483 kg of eggs (*67*). Feed for the chickens was purchased (*68*, *70*) and protein content and feed energy of the feed were estimated from the total feed provided the hens (*43*, *67*). Feed inputs do not include the maintenance of the breeding flock for the reason that per hen this is an extremely small input. Total fossil energy input for feed production was calculated by using the data on quantities of feeds that were consumed by 119 birds (*67*) and the data on fossil fuel inputs that were used in producing the feeds (*43*). The fossil energy input for egg (animal) production was estimated from expenditures of New Jersey poultry farms for operation and maintenance of machinery, equipment, buildings, and for feed transport (*67*, *71*). The labor input includes the labor for producing the crops as well as for managing the poultry operation (*67*, *69*). ‡For broiler production we assumed a liveweight product of nearly 1.6 kg at about 10 weeks (*68*). All feed was purchased (*68*, *70*) and protein content and food energy of the feed were estimated from total feed that was provided to the broilers (*43*, *67*). Feed inputs include an additional 5 percent for the maintenance of the breeding flock. Total fossil energy input for feed production was calculated by using the data on quantities of feeds that were consumed by about 973 broilers (*67*) and the data on fossil fuel inputs that were used in producing the feeds (*43*). The fossil energy input for broiler (animal) production was estimated from the expenditures of broiler farms for operation and maintenance of machinery, equipment, buildings, and for feed transport (*67*, *71*). The labor input includes the labor for producing the crops as well as for managing the broiler operation (*67*, *71*). §About 1.5 years are required before catfish fingerlings are of sufficient size (0.5 kg) to be harvested (*72*). The yield per hectare was 771 kg. Feed that was provided to the catfish was purchased (*72*), and the protein content and feed energy of the feed were estimated from the total feed that was provided (*43*, *67*). Feed inputs include an additional 5 percent for the maintenance of the breeding stock and production of catfish fingerlings (*72*). Total fossil energy input for feed production was calculated by using the data on quantities of feeds consumed by the approximately 1540 catfish (*67*) and the data on fossil fuel inputs used in producing the feeds (*43*). The fossil energy input for catfish production was estimated from expenditures of catfish farms for operation and maintenance of machinery, equipment, buildings, and for feed transport (*67*, *73*). The labor input includes the labor for producing the crops as well as for managing the catfish operation (*67*, *73*). ‖Live hog yield including cropland was 865 kg per hectare (*67*, *74*, *75*). The feed that was fed to the hogs (*74–76*) and its protein content and food energy were estimated from total feed that was provided (*43*, *67*). Feed inputs include that used for maintenance of the breeding herd. Total fossil energy input for feed production was calculated by using the data on quantities of feeds that were consumed by the hogs (*67*) and the data on fossil fuel inputs that were used in producing the feeds (*43*). The fossil energy input for pork production was estimated from expenditures of Illinois hog farms for operation and maintenance of machinery, equipment, buildings, and for feed transport (*67*). The labor input includes the labor for producing the crops as well as for managing the hog farm operation (*67*, *75*). ¶The beef production data are for California feedlots (*77*). Protein content and food energy of the feed were estimated from the total feed that was provided to the beef animals (*43*, *67*). Feed inputs include that purchased for the feedlot operation as well as the feed that was consumed by the breeding herd in producing the feeder animals. Assumptions used for producing feeders from the breeding herd were those of Reid (*38*). Breeding herd input represented about a third of the food energy input required for beef production (*67*). Total fossil energy input for feed produced was calculated by using the data on quantities of feeds consumed (*67*) and the data on fossil fuel inputs used in producing the crops (*43*). The fossil energy input for the beef feedlot operation was estimated from the expenditures for the operation and maintenance of machinery, equipment, buildings, and for feed transport (*67*, *78*). The labor input includes the labor for producing the crops as well as for managing the beef feedlot operation (*67*, *79*). #Rangeland beef production data are for good range grasses (70 cm of rainfall per year) of Texas that yield about 24 kg beef per hectare (*80*). Protein content and food energy of the feed were estimated from the forage consumed by the animals (*81*). The forage that was consumed was estimated at 15 kg of dry forage per day per 455 kg of animal (*81*). The feed that was consumed includes that eaten by the breeding herd in producing the calves. We assumed that the breeding herd consumed a quantity equal to about 30 percent of the food energy consumed by the harvested calves. Total fossil energy input for feed produced was included in the animal production input. The fossil energy input for managing this rangeland operation included machinery, fences, and buildings (*67*, *80*). The labor input is only that for managing the rangeland operation (*67*, *80*). **Rangeland production data (36 cm of rainfall per year) are for Utah, with a yield of about 2.8 kg of lamb per hectare (*82*). Protein content and food energy of the feed were estimated from the total feed (forage plus supplements) that was provided to the sheep (*43*, *67*, *82*). Feed that was consumed on range was estimated at 1.3 kg of dry forage per head per day (*81*). Feed inputs include that provided to the breeding herd. Total fossil energy input for feed production was calculated by using the data on the quantities of feeds that were consumed (*67*) and the data on fossil fuel inputs that were used in producing the crops (*43*). The fossil energy input for lamb production was estimated from the expenditures for the operation and maintenance of machinery, equipment, buildings, and for feed transport (*67*, *82*, *83*). The labor input includes the labor both for producing the crops and for managing the range and animals (*67*, *82*). ††Zebu cows (about 75,000 head) are herded by the Dodos tribe in Africa for milk, blood, and meat (*84*). Milk yield was assumed to be 2485.7 million kcal, meat 2320.5 million kcal, and blood 631.5 million kcal per year for the area that was grazed (about 780,000 hectares) (*84*). Protein content and food energy of the feed were estimated from the total feed (forage) that was consumed by the cows (*67*, *84*). Feed that was consumed on range was estimated at 8 kg of dry forage per head (estimated 250 kg animal) per day (*81*). Feed inputs include that provided to the breeding herd. No significant fossil energy input was used in this production system. The Dodos population is estimated at 20,000 (*84*). We assumed that 40 percent were working males who worked an 8-hour day, and 40 percent were working females contributing 1 hour/day to maintenance. Thus the estimate of 34 man-hours per hectare per year.

The commercial production of catfish also requires the feeding of grains and similar protein suitable for man and animals. The rate of protein conversion by catfish is about 11 percent (Table 3). Hogs are also fed protein that is suitable for man, and their conversion rate is 9 percent (Table 3). The feed energy input in kilocalories per kilocalorie of protein output for pork production is 65 : 1 or about twice that of milk production. This estimate is somewhat greater than Reid's estimate of 51 : 1 (*38*).

Feedlot beef protein production has an efficiency of conversion of feed protein of only 6 percent (Table 3). The feed protein in this case consisted of 42 percent forage. A total of about 25 million kcal of feed energy is needed by beef animals to produce the average 51 kg of beef protein; or about 122 kcal of feed energy is consumed per kilocalorie of beef protein produced (Table 3). This result agrees favorably with that of Reid, who reported a ratio of 123 : 1 (*38*). About 78 kcal of fossil energy was required for each kilocalorie of beef protein produced (Table 3); the estimate for beef in the United Kingdom was less, or about 45 : 1 (*35*). Protein production with beef cattle is energetically expensive "mainly because of the cost of maintaining the breeding herd" (*38*).

The conversion of forage grasses and shrubs on pastureland and rangeland into animal protein (milk and meat) by cattle, sheep, and goats is extremely important to man, and pastoral systems vary in their effectiveness. Under exceptional rangeland conditions in Texas, for example, with good rainfall of 70 centimeters per year, about 2.2 kg of beef protein is produced per hectare (Table 3). Under the Texas rangeland conditions, the fossil energy input is still about 4 kcal per kilocalorie of beef protein produced. The fossil energy in this case is for pickup trucks and other machinery used in herding and management.

Lamb (sheep) production on Utah rangeland with a rainfall of 36 cm per year requires large areas; this is documented by the extremely small amount of protein produced per hectare (0.17 kg) (Table 3). About 200 kcal of feed energy is used by the animals to produce each kilocalorie of lamb protein. However, sheep also produce wool, and if wool production were included, the calculation of sheep protein production would be higher.

The Dodos tribe of northeast Uganda herd cows for milk, meat, and blood. With rainfall of 45 to 62 cm per year the pastures provide thornscrub and perennial grasses. Under these conditions the yield of milk, meat, and blood protein amounts to 0.76 kg per hectare (Table 3). This yield falls somewhere between Utah sheep production and Texas rangeland beef production (Table 3).

On a worldwide basis, total protein produced by livestock amounts to about 30 million metric tons, or about 25 percent of the total protein available to man (Table 2). More than 60 percent of this livestock protein is probably produced from pasture and rangelands that are not useful in producing food for man. The other 40 percent comes from livestock that is fed vegetable and animal protein. The 51 million metric tons of vegetable and animal protein that are fed to livestock are used to produce an estimated 13 million metric tons of the livestock protein. This amounts to about 4 kg of vegetable protein suitable for man that is fed to livestock per 1 kg of livestock protein produced.

In the United States about 6 million metric tons of livestock protein are produced each year by feeding an estimated 26.1 million metric tons of vegetable and animal protein to these animals (Table 2). If the change were made to only grass-fed livestock, livestock protein production would decline from 6 to an estimated 2 million metric tons. This is assuming an effective shift in animal protein consumption from swine and poultry to more milk, beef, lamb, and goat.

Fish protein amounts to only about 5 percent of the total protein available to man (Table 2). Fish has been suggested as an important source of animal protein for the future; unfortunately, most of the common fishes have been overfished (*39*) (Fig. 1). Also, large quantities of fossil energy must be expended to produce this animal protein. Off the coast of England, for instance, about 7920 kcal are required to harvest 1 kg of fish (*40*). This is about 20 kcal of fossil energy expended for each kilocalorie of gutted fish.

World Food Supply

To gain some idea of the challenges that face mankind in the near future to feed a rapidly growing world population (Fig. 2), estimates are made of animal and vegetable protein production relative to the constraints of water, land, and fossil energy. World populations of 4 billion (present) and 7 billion projected for the year 2000 (*1*) and 16 billion projected (high) for the year 2135 are used for this analysis (*41*).

Most people of the world desire to eat and live as we do in the United States. Hence, the first estimate is to feed a population of 4 billion with a U.S. high protein-calorie diet produced with the use of U.S. agricultural technology. About 160 million hectares are planted to crops in the United States (*42*). With about 208 million people in the United States, this averages out to be about 0.77 hectare planted to crops per capita. Since about 20 percent of our crop yield is exported, the estimated arable land per person is about 0.62 hectare (*42*).

World arable land resources are about 1.5 billion hectares (*23*). With 4 billion humans in the world today, the per capita land available is only 0.38 hectare. In the United States, 0.62 hectare of land plus a high-energy agricultural technology are necessary to produce the high protein-calorie diet that is consumed. Hence, in the world today, arable land is not sufficient (even assuming that the energy resources and other technology were also available) to feed the current world population of 4 billion a diet similar to that consumed in the United States.

In the above analysis fossil energy was assumed to be unlimited. Unfortunately, fossil energy is also in limited supply for food production. This can be put into perspective with the following analysis. It has been estimated that from 13 to 15 percent of the total per capita energy used annually in the United States is expended for food (*43, 44*). This amounts to about 1250 liters of gasoline equivalents used for food production, processing, distribution, and preparation. The use of the U.S. agricultural technology to feed a world population of 4 billion a high protein-calorie diet for 1 year would require the equivalent of 5000 billion liters of fuel.

To gain some idea of what the world energy needs would be for a high protein-calorie diet if U.S. agricultural technology were employed, an estimate is made of how long it would take to deplete the known world reserves of petroleum. The known reserves have been estimated to be 86,912 billion liters (*45*). If we assume that 76 percent of the raw petroleum can be converted into fuel (*45*), this would equal a usable reserve of 66,053 billion liters. If petroleum were the only source of energy for food production and if we used all petroleum reserves solely to feed the world population, the 66,053 billion liter reserve would last a mere 13 years.

Both estimates indicate that the world population has already reached a density too great for the arable land and energy resources that are required to feed the world population on a U.S. diet with U.S. technology. Of course, both estimates were made from known arable land and known petroleum resources. If we include potential arable land and potential petroleum reserves, the situation appears to be improved, but we should point out that only a current population of 4 billion was used in the analysis. Numerous estimates, of course, are possible with the use of various combinations of population size, dietary standards, and production technology. The one used suffices as an example of limitations.

With regard to land resources, suggestions have been made that the world's potential arable land might be doubled with irrigation and other significant alterations of parts of the ecosystem (*46*). Only about 12 percent of the world's cultivated land is now irrigated (*47*). Unfortunately, irrigation and other similar environmental manipulations require enormous amounts of energy. For example, about 12.2 million liters or 12,200 metric tons of water are needed to produce 5000 kg of corn per hectare in the subtropics (*48*). The energy cost to pump this water from a depth of a little more than 90 meters is about 20.6 million kcal (*49*). If we use irrigation and this estimate (20.6 million kcal per hectare), doubling the arable land from 1.5 to 3.0 billion hectares would require 3090 billion liters of fuel per year. This amounts to about 5 percent of the known usable petroleum reserves or the equivalent of a 20-year supply if the reserves are used solely for increased irrigation. This appears to be impractical. In addition, this does not include supplying the machinery [an additional 13 percent in energy (*50*)], nor does it consider the salination of soil and other problems associated with irrigation (*51*).

The potential reserves of petroleum are larger than the known reserves, so the 20-year estimate can be increased by a few years. However, fossil energy resources are finite and world use has approximately doubled during the last 10 years (*52*). Furthermore, the human population will not remain at 4 billion as used in these analyses but is rapidly escalating (Fig. 2).

Another analysis can be made by using the limited land and energy resources while the human population increases from 4 billion to 7 billion, and then to 16 billion. The focus is on both animal and vegetable protein availability (Table 2). Livestock in the world total about 1 billion cattle, 1 billion sheep, 350 million goats, 100 million buffalo, 11 million camels, 550 million pigs, 64 million horses, 15 million mules, and about 40 million asses (*53*). These 3.1 billion livestock graze on an average of 1.6 hectares per head. This estimate is based on about 3 billion hectares of available pasture and range plus about 2 billion hectares or 50 percent of forest land suitable for grazing.

Total animal protein constitutes about 25 percent of the total protein (122 million metric tons) supply that is estimated to be available to man. Cereals, as mentioned, contribute nearly half (47 percent) of the total protein supply (*30*) (Table 2). The 122

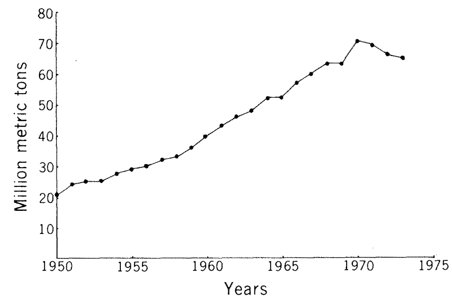

Fig. 1. World fish catch (*61*, *62*).

million metric tons would provide an average of 84 grams of protein per person per day when problems of losses to pests and waste after production are ignored. We estimate worldwide pest losses after harvest to be at least 20 percent [pest losses after harvest in the United States are nearly 10 percent (*54*)]. Even with pest losses and other types of loss, there should be adequate amounts of food protein available if it is equitably distributed.

When projecting to the year 2000 with 7 billion humans, estimates are that fish yield from the oceans might be increased from 66 million metric tons to 100 million metric tons (*55*) (Table 2). This is probably an overly optimistic projection because of the serious overfishing problems in the world fisheries today (*39*). In fact, world fish catches have declined during the past 3 years (Fig. 1). In addition, catching fish, as was mentioned previously, is energy intensive (*40*).

Animal protein (excluding fish) production hopefully can be increased 30 percent through reduced overgrazing, the use of better pasture plant species, and the application of limited amounts of fertilizers under certain advantageous conditions. This might result in a yield of 43 million metric tons annually by the year 2000 (Table 2).

To hold the per capita protein supply in the year 2000 at 1975 levels will require a 66 percent increase in legumes, a 100 percent increase in other vegetables, and a 75 percent increase in cereals (Table 2). The 75 percent increase in cereals during the next 25 years is technically feasible. The 66 percent increase for legumes and 100 percent increase for vegetables might be possible.

To feed the 16 billion humans projected for the year 2135 the same protein diet as in 1975 will require significant increases in vegetable protein, that is, legumes, 173 percent; vegetables, 233 percent; and cereals, 330 percent (Table 2). With the resources available, these increases appear to be doubtful.

One means of increasing the total protein available to man would be to reduce the amount of vegetable and animal protein that is fed to livestock. An estimated 51 million metric tons of protein suitable for man's use will be fed to the world's livestock in 1975 (Table 2). This 51 million metric tons that is fed to livestock is nearly equal to the total cereal protein available to man for 1975.

If the projected 67 million metric tons of protein to be fed to livestock in the year 2000 were diverted directly to human consumption, significant reductions in the projected increases for cereal, legume, and other vegetable protein production might

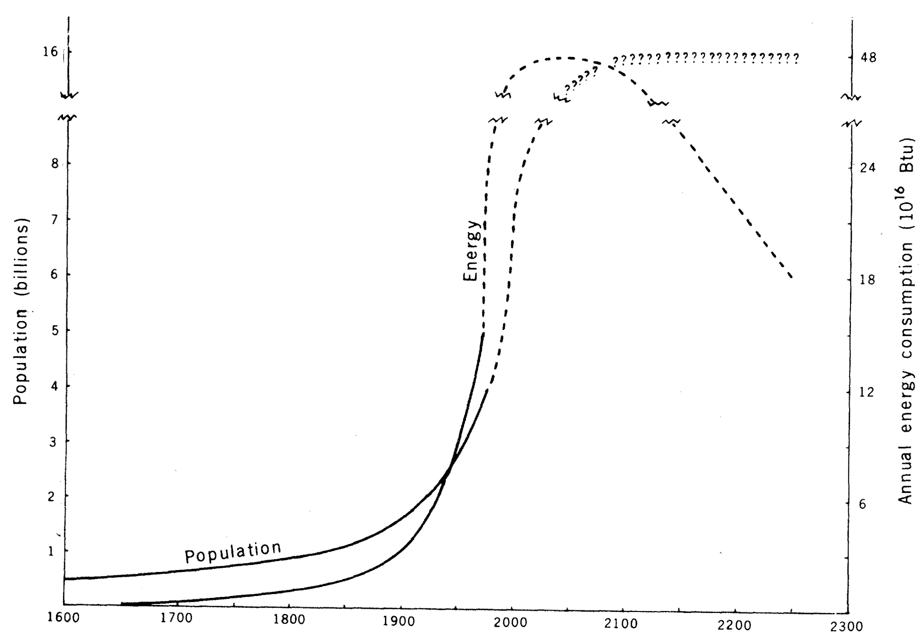

Fig. 2. Estimated world population numbers (______) from 1600 to 1975 and projected numbers (– – –) (? ? ?) to the year 2250 (*1*, *2*, *41*). Estimated fossil fuel consumption (______) from 1650 to 1975 and projected (– – –) to the year 2250 (*27*).

be feasible (see alternative for year 2000 in Table 2). Assuming that improved management of livestock, pasture, and rangeland would yield 25 million metric tons of livestock protein, then the increases needed in the following crops would be: cereals, 41 percent; legumes, 20 percent; and other vegetable protein, 50 percent. All of these estimates for increased crop production are more easily achieved than the estimates for increased production when intensive livestock management is continued at current levels (Table 2).

Livestock production is vital to man today and will be equally important to us in the future. Cattle, sheep, and goats are of particular value because these animals convert the grasses and shrubs on the pastures and rangelands of the world into food for humans.

With careful management of land, water, energy, and human resources and cooperation among the nations of the world, we believe that it is possible to maintain current per capita levels of food supply for the next 25 years as the world population increases to 7 billion humans. Serious malnourishment, as mentioned, already exists with some half-billion humans, and efforts are also needed to eliminate this deficiency by better food production and distribution.

Of great concern is the degradation of land, water, and other resources and depletion of fossil energy as the human population continues its rapid growth. Agricultural land is being lost and will continue to be lost because of population pressure from housing, roads, other construction, and normal crop cultivation. The growth in human numbers in many parts of the world during the past few decades has resulted in large blocks of farmland being taken out of production. For example, in the United States during the past 20 years some 11 million hectares (an area larger than Ohio) have been converted into urban areas and highways (*56*). This amounts to an annual loss of more than a half-million hectares of cropland, pastures, and forests. Whether the annual loss is due primarily to sprawling urbanization as in the United States, or housing for exploding human numbers as in less developed countries, it is clear that important losses of agricultural land are occurring as a result of rising population pressure. In addition, soil erosion results in a decline in potential productivity of our land.

Another concern is the effect that climatic changes have on the suitability and availability of some world cropland for production. The mean temperature of the Northern Hemisphere reached a maximum in about 1940. Since 1940, temperatures in the Northern Hemisphere have declined about 0.1°C per decade (*57*, *58*). Only a 0.6°C drop in temperature is necessary to shorten the growing season by about 2 weeks (*58*). In marginal crop-growing regions, 2 weeks less in the growing season may significantly reduce yields. In the corn belt, for instance, each day of delay in planting corn after about 20 May results in a reduction in total yield of about 63 kg per hectare (*59*).

Changes in climate and other vital environmental resources are impossible to project. Equally difficult to project are changes in technology. Considerable hope rests with science and technology (*37*). Sir Julian Huxley (*60*), however, warned us to be cautious in totally relying on science. He supported his argument by pointing out that science has been "completely unable to cope with the appalling problems" of the developing world today.

Conclusion

Population pressure for food, energy, water, and land resources is significant at present with a population of 4 billion human beings. With the human population projected to increase to 7 billion within 25 years and 16 billion by the year 2135, food shortages and energy, water, and land limitations will become critical.

Already both energy and land resource limitations make it impossible to feed the present world population of 4 billion a U.S. diet (69 percent animal protein) that is based on U.S. technology. World diets will have to depend mainly on vegetable protein. Over 70 percent of the protein consumed by people outside the United States is of vegetable origin. Currently about two-thirds of the protein available to man comes from cereals (47 percent) and legumes (20 percent). These protein sources will become ever more important in the future.

Ocean fisheries contribute only about 5 percent of the total protein available to man. More than 3 billion head of livestock (mostly cattle, sheep, goats, and buffalo) contribute about 25 percent of the world's protein supply. An estimated 29 percent of the world's protein supply (51 million metric tons) suitable for human food is fed to livestock.

Even if we move toward greater consumption of vegetable protein, protein production from legumes would have to increase an estimated 173 percent, other vegetables more than 200 percent, and cereals about 330 percent over the 1975 levels to feed a population of 16 billion humans in the year 2135. These increases are questionable because: (i) shortages of land, water, and energy resources already exist and these shortages will intensify as the human population continues to increase; (ii) further ecological degradation of land, water, and vital biological resources will tend to reduce the productivity of the agroecosystems; and (iii) crops have physiological limits in their ability to respond to increased amounts of fertilizers and other crop production inputs.

Science and technology will help man overcome some of the food and other crises facing him as his numbers rapidly increase, but the obvious solution is effective, organized population control. Clearly if man does not control his numbers, nature will.

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NEWS AND COMMENT

Methanol at MIT: Industry Influence Charged in Project Cancellation

Cambridge, Massachusetts. Academic institutions in theory provide a testing ground for ideas which is somewhat insulated from the push and pull of the world outside. But, as they take advantage of the energy R & D dollars now so tantalizingly available from government and industry, these institutions may risk compromising or appearing to compromise their academic independence. The cancellation of a research project on methanol (methyl alcohol) as a substitute motor fuel for gasoline at the Massachusetts Institute of Technology's Energy Laboratory offers a case in point. In the opinion of the scientist who initiated and led the project, it was killed because the laboratory yielded to influence from the oil and automobile industries.

Authorities at MIT deny that outside influence had any bearing on the decision, and they say that the project—which was to involve the testing of a blend of methanol and gasoline in 200 faculty and student cars—was terminated because it was technically weak and inappropriate for a university. Yet the attendant circumstances, which include the active involvement of an Exxon employee as well as the fact that the laboratory had received $1 million in grants from Exxon and Ford, put the termination in an ambiguous, and perhaps suspicious, light.

The project in question began some 18 months ago at a time of considerable debate over the feasibility of using methanol in automobiles. Several academic researchers were touting methanol's potential, and among them Thomas B. Reed of MIT's Lincoln Laboratory was perhaps the most vocal. Spokesmen for several oil and automobile companies, notably Exxon, Chevron, and General Motors, were contesting the feasibility of methanol fuels. Reed, a 49-year-old chemist who holds 10 patents and whose specialty is crystal growth and high temperature processes, had in his spare time experimented extensively with his own automobiles and those of his colleagues. He found that adding about 10 percent methanol to a tank of gasoline improved performance, gave better mileage, and reduced pollutant emissions. Results similar to Reed's have since been reported by West Germany's Volkswagen, now generally acknowledged as the leader in methanol research. In this country, however, oil and automobile companies have continued to report that methanol-gasoline blends cause drivability problems.*

Because of the ensuing publicity, Reed received an unsolicited $100,000 grant for methanol research. The money, ironically, came from a Minnesota oilman, John B. Hawley, who had become concerned with