THE ENERGY ANALYSIS OF FOOD PRODUCTION SYSTEMS AND THE ROLE OF ANIMAL PRODUCTION: A REVIEW[1] /

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Resumen

Este trabajo comienza con una breve descripción de los principales insumos de los sistemas de producción de alimentos y discute su disponibilidad en el futuro. A este panorama se opone una descripción de las perspectivas en la demanda mundial de alimentos. Se enfatiza más la calidad que la cantidad de alimentos necesarios para satisfacer los requerimientos de las próximas décadas.

Se compara los distintos sistemas de producción de alimentos desde el punto de vista energético. Así surgen los sistemas de producción de granos como los más eficientes y los sistemas de producción animal como los menos eficientes. Se distingue entre los sistemas de producción animal que no usan alimentos utilizables por el hombre (forraje) y aquellos que consumen recursos, como los granos, que de otra manera serían utilizables por el hombre y por lo tanto compiten con él. Se cuantifica esa competencia, y se resalta el papel del ganado como convertidor de forraje de baja calidad en proteína consumible por el hombre.

Se compara distintas técnicas de utilización de los pastizales, que son la principal fuente de este recurso de baja calidad. El agregado de energía de subsidio en forma de fertilizantes, herbicidas, semillas y otros determina un aumento en la producción pero una disminución en la eficiencia. Finalmente se compara la energía utilizada en la producción de alimentos con el consumo total de energía tanto en países en desarrollo como en aquellos desarrollados. Se concluye que en el futuro próximo las técnicas de producción de alimentos más eficientes en el uso de la energía de subsidios van a ser las más rentables económicamente. Probablemente se dependerá en gran medida de la producción de los pastizales naturales y será necesario desarrollar formas de aprovecharlos que sean eficientes en el uso de la energía.

Introduction

The food production system, whether national or worldwide, consists of several systems, such as the animal production system or the grain production system. Each has distinctive features regarding its inputs and products with respect to other food production systems.

The objective of this paper is to describe the characteristics of the production system from an energy viewpoint and to define the role of animal production. This paper will briefly survey the characteristics and perspectives of the major inputs and outputs of the food production system in the world. It will compare the efficiency of different systems and will estimate the role of animal production and its different components in a future which presents serious constraints. Finally, the possibility of different range utilization techniques will be evaluated in light of the outlook for resource availability.

Inputs of the food production system

From the viewpoint held in this paper, energy (including fertilizer, machinery, fuel and others), land and labor will be considered the prime resources used

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for crop and animal production. These factors are interrelated and each can be partly substituted for the others. For example, energy can be used to reduce the labor input, and viceversa. The land area needed to produce a certain amount of food can be reduced by increasing the intensity of land management through various energy inputs such as fertilizer and tractors. This approach can be reversed also.

Both arable land and fossil energy reserves are finite resources. Estimates of fossil energy reserves, mainly petroleum, vary among different authors. Pimentel *et al.* (15) mentioned that the known reserves of petroleum have been estimated to be 86 912 billion liters, which can be converted to 66 053 billion liters of fuel assuming 76 percent efficiency. The time these reserves will last depends directly on the rate of usage. Cook (2) pointed out that at the present rate of usage there is only a 50-year supply of gas and a 75-year supply of oil. Pimentel *et al.* (15) stated that the known world reserves of petroleum and natural gas are expected to be more than half depleted within the next 25 years. Their projection took into account the demand imposed by the increasing world population.

Nor does land, the other finite resource, face a very optimistic future. About three quarters of all human food comes from the world's cropland. Only 11 percent of the land surface is arable and naturally suitable for crop production. Although reclamation techniques every year put new areas under cultivation by means of drainage or irrigation, land lost to highways, urbanization and erosion processes greatly offset those efforts. Each year more than one million hectares of arable cropland are lost to highways, urbanization and other special uses (16). This loss is partially offset by the addition of 0.5 million hectares of newly developed cropland per year; thus the annual net loss is 0.5 million hectares of arable cropland. Since 1945, the total loss to highways, urbanization and other special uses in the United States alone was about 18 million hectares (16).

The other major source of cropland loss has been erosion. Large areas have been impaired and are no longer suitable for crop production, while others, still under production, have been degraded and lost productivity. According to Handler (5), during the last 200 years, at least one third of the topsoil on United States croplands has been lost. On the basis of erosion surveys and various soil surveys, he estimated that in 1935 erosion had already ruined approximately 40 million hectares for practical cultivation, and that 40 million additional hectares had lost from one-half to all their topsoil. Thus 80 million hectares in the United States were ruined or seriously deteriorated by soil erosion before 1940. Musto (10) estimated that 40 million hectares are subjected to different degrees of erosion in Argentina. Water erosion accounts for half of the affected area, and the figure grows at a rate of 160 000 hectares per year. Soil is not only lost, but also formed. According to Pimentel *et al.* (16), 3.7 tons of topsoil are formed per hectare per year, but the average annual loss of topsoil from agricultural land is estimated at 30 tons per hectare. This resulted in what he estimated as an annual gross transfer of 5 billion tons of soil to streams, with a corresponding serious impact on the habitat of those streams. The potential for producing food has been reduced 10 to 15 percent in 80 million hectares of United States croplands, according with the same author. Panigatti (13) reported a 25 percent decrease in crop production in 30 percent of the best farmlands of Argentina. Higher inputs of fossil energy are needed to offset the soil erosion loss on croplands.

Labor is the third resource used in the food production system. The world's population is now 4 billion, and is estimated to reach 16 billion for the year 2000 (19). A report of the National Academy of Science of the United States (11) has projected 7 billion for the same year. Reduction in 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. According to these data, labor will not be a scarce resource in the near future, and except in the highly developed countries, this resource will have a low opportunity cost.

Outlook for food demand

Obviously, the rapid growth in the human population is resulting in an increased demand for food. Pimentel *et al.* (15) estimated that half a billion people are at present protein-calorie malnourished. At least a twofold increase in food will be needed to feed this rapidly expanding world population by the year 2000. Protein and calorie shortages in much of the world's population are resulting in poor growth and development and increased disease, particularly among children. Protein and calorie malnutrition are interrelated, because if the body has a calorie deficit, it will convert protein into calories; but the reverse does not occur. Protein has a very important role in human nutrition and is expected to be the first food substance to experience shortages (9). That means that the food production system should be analyzed not only from the viewpoint of the amount of product, but also in terms of the quality of production.

Quality of animal-based food products

Protein in the diet must contain a minimal amount of each of the eight essential amino acids to meet the minumum daily needs of the human body. For this reason, animal proteins are of higher quality than plant proteins because they are composed of relatively large amounts of the eight essential amino acids required by man. Lofgren and Speckmann (8) pointed out that animal protein is higher in nutritional quality than plant protein, because the assortment and amount of amino acids in animal protein more closely match the needs of the human body. Eggs, milk and meat, for example, provide all the essential amino acids in a single source of protein food.

Vegetable proteins are of poorer quality than animal because most are deficient in one or two of the essential amino acids. By selecting combinations of cereals and other vegetable food sources and consuming large quaintities, adults can obtain sufficient quantities of the essential amino acids to meet the daily needs of the body. However, other nutrients, such as vitamin B_{12} and some of the essential trace minerals, may be lacking in a vegetarian diet. Pimentel *et al.* (19) stated that, currently, calcium and iron represent two nutrients whose consumption frequently falls below the recommended daily allowance. Dairy products represent one of the major sources of calcium in the human diet. He also stated that reduced consumption of dairy products could have deleterious effects on the calcium status of the population. Similarly, animal products account for 37 percent of the iron available for consumption (19). Animal sources of iron are generally at least twice as available as plant sources.

Comparative analysis of different food production systems

Energy, land and labor needs are known to vary significantly according to the kind of crop cultivated or animal produced. The amount and quality of the product also vary widely. Efficiency indices are constructed as the output/input ratio of the system. Inputs and outputs of different components of the same system may be measured and different units utilized. As a consequence, several different efficiency indices can be found in the literature.

Steinhart and Steinhart (20) reported data on the energy inputs to different food production systems for one calorie of food output. The input the authors considered is the energy subsidy. According to Odum (12), this energy subsidy includes the energy utilized in the process as fuel, electricity, fertilizer, irrigation, tractors, etc., but does not include the solar energy involved in photosynthesis and responsible for maintaining the narrow range of temperatures which allows life on the earth. Figures for secondary producers do not include the energy of their feed. Food production systems which involve secondary producers usually require a larger energy subsidy. They need between 1 and 20 calories for producing 1 calorie of food. Among the least efficient are feedlot beef and distant fishing. On the other end are range-fed beef, low intensity egg production and milk production using grass-fed cows, which require less than 5 calories per calorie of subsidy. On the other hand, systems which take place at the trophic level of primary producers are more efficient, and the energy content of the product is usually higher than the energy subsidy for producing it. Steinhart and Steinhart (20) demonstrated how sensitive our present food production system may be to a fossil energy shortage.

David Pimentel is one of the authors who have made major contributions to analyzing the efficiency of different food production systems. He centered his work on the efficiency of producing protein foods, because he believed that their response to various environmental conditions was representative of all foods contributing to the food supply. Pimentel in his book **Food, Energy and Society** (18) analyzed energy use in livestock production. He reported that egg and broiler production was the most efficient converter when only energy and land were considered. Broilers are also extremely efficient in labor use. When only forage is available, then egg, broiler and pork production are eliminated and only milk, beef and lamb are viable systems. Of these three, milk production is the most efficient converter, because forage can be used, and relatively small amounts of energy, land and labor are needed for production. Livestock is less efficient than grain, legumes, fruits or vegetables (19). Of these, grains and legumes such as soybeans are produced more efficiently than fruits and vegetables.

The role of animal production

Two species compete only when their ecological niches overlap. In other words, they have similar requirements for a specific resource which is a limiting factor for both species. The competition concept may be applied to animals and man. Animals may be fed with resources unsuitable for human consumption or suitable for it. In the first case, animals and man do not compete; in the second they do, because the resources which do not go to animals would increase the availability of resources for the human population.

Pimentel and Pimentel (19) reported the present status of such competition. They said that on a worldwide basis, about 25 percent of the protein consumed, or 30 million tons, was animal protein. They estimated that more than 60 percent of this livestock protein came from animals fed with grasses and forage that could not be utilized by man. The remainder came from livestock fed with protein suitable for human consumption. Specifically, the 50 million tons of plant and animal protein suitable for man and used for animal feed yield only an estimated 13 million tons of livestock protein. This means that in addition to large amounts of forage, 4 kg of dry plant protein suitable for human consumption is converted into 1 kg of animal protein. Obviously this plant to animal protein conversion is relatively inefficient when compared with direct consumption of plant protein by humans.

In highly industrialized countries where diets are high in animal protein, intensive livestock production systems are maintained to supply large quantities of animal products. Basic to maintaining these systems is the use of large amounts of cereal grains which, though useful to animals, are also nutritious human food. In the United States, an estimated 1 300 kg of grain is produced per person per year (21). Of this, man eats only 110 kg, while the remaining 1 190 kg are fed to livestock. Put another way, in addition to forage consumed, an estimated 26 million tons of plant and animal protein quite suitable for human consumption are fed to animals, which in turn produce 6 million tons of animal protein. A relatively large amount of this plant protein comes from various grains and legumes. As a result, on the average, for every 5 kg of plant and fish protein fed to animals, only 1 kg of animal protein is produced.

Taking into account the constraints on the availability of fossil energy and land, as well as the future of food demand in the world, as described above, it can be expected that animals fed with resources suitable for human consumption will decrease drastically. One of the major roles of animal production will be to convert roughage or feed high in cellulose into needed food and fiber for human sustenance, despite their low efficiency in converting dietary energy into such products as meat or milk (4). This cellulosic feed is plentiful throughout the world and has no alternate use for food, other than through transformation by herbivores. Forage from pasture land and forest range is fed to ruminant animals because they can convert forage cellulose into utilizable nutrients through microbial fermentation. Total plant protein produced on pasture and forest range in the United States is 1.4 times the total grain protein production. Current yield from pasture and rangeland is 53.4 kg per hectare (19), while the energy input per kilogram of protein is 2.6 Mcal. This is nearly one-quarter of the fossil energy input expended in producing grain protein.

High protein foods are essential for human diets, and the amino acid balance necessary for good nutrition is not found in most of the cereal grains. Therefore, man cannot take the step of abandoning meat sources altogether. As a consequence, the major role of animal production will be to produce high protein foods utilizing forest range or pastures. This can be complemented with wastes, including byproducts of harvesting or processing food crops, or byproducts of processing animal products. Moore (9) stressed the importance of using urea and byproducts inedible to humans to produce palatable proteins for humans. He stated that even though these byproducts were low in protein, they provided energy needed in the production of animal proteins. One of the most important byproducts is dried sugar beet pulp from sugar beet extract. Approximately 169 000 tons are consumed annually by livestock in the United States. In the meat packing industry, inedible portions of carcasses, including meat scraps, intestines and blood, are exposed to high temperatures and rendered into livestock feed. Urea, a nonprotein nitrogen source which humans cannot utilize in their diets, can be converted to animal protein by ruminants. It is being used extensively for dairy and beef cattle.

Analysis of livestock production alternatives

Taking into account the resource constraints and the alternative uses of cereal grains and legumes, several proposals have been made for converting from a system under which livestock are fed both grain and grass to one under which they are fed grass alone. These analyses are also critical for those countries which presently raise livestock on rangelands and are considering the alternative of feedlot systems. Pimentel *et al.* (19) made several projections and analyzed three different alternatives for livestock production in the United States.

The first alternative called for eliminating grain as livestock feed, using only grass on present pasture lands and grazing of forest range. They believed that animal production under this system would include primarily dairy, beef and sheep. The total amount of animal protein produced under this system would be about 2.9 million tons, or slightly more than half the animal protein currently produced. The inputs for this system of grass-fed livestock would be reduced as follows: land 8 percent, labor 34 percent, and fossil energy 59 percent. This system would release most of the grain currently fed to livestock, or 135 million tons of grain.

Another alternative called for improvement in the forest range currently grazed by dairy and beef cattle and sheep. Through better management inputs, the yield of animal protein would increase 7 percent, still significantly less than current production. Compared with the current grain-grass system, the total resource inputs for the "improved grass only" would be reduced as follows: land 8 percent, labor 28 percent and energy 7 percent.

The third alternative was to improve forest range and use 10 million hectares of land for corn and sorghum silage. Total milk, beef and sheep protein production under these conditions is calculated to be 4.4 million tons, compared with current total production of 5.4 million tons. Compared with the current system, the resource inputs for the "improved grass and silage system" decline by 5 percent for land and 8 percent for labor. Energy use, however, rises about 13 percent above the current level. The increased energy input, in a time of scarce energy and high prices, make this system inappropriate. D. Pimentel believed that if there were a change toward a system using only grass, some grain resources and byproducts would continue to be devoted to egg, broiler and pork production. Egg protein is better nutritionally than any other protein available, and it is relatively efficient to produce. Present land input for egg production is less than 1 percent of that for all protein sources, and the energy input is only about 1 percent of that for the total livestock production system. Broiler and pork production would also be continued because of their efficiency and capacity for utilizing byproducts and wastes.

Other authors took another approach to the problem of animal production systems and their energy costs. Instead of using the worldwide scale adopted by D. Pimentel, they compared actual animal production systems requiring different amounts of resources, and looked at the efficiencies of meat or protein production.

Cook *et al.* (3) analyzed different cattle feeding and grazing systems including yearlong total confinement, partial confinement feeding, and conventional range grazing. They determined the cultural and digestible energy expended to produce a kilocalorie of dressed-carcass meat from weaner calves and the protein consumed to produce a pound of red-meat protein. They reported that the yearlong range grazing system with a winter supplement required considerable less cultural energy than other systems. Range livestock produced about 1 Kcal of dressed-carcass meat for each 5 Kcal of cultural energy. Partial confinement, with cows corralled and fed for 5 months during the winter and grazed on the range during the spring and summer, produced 1 Kcal of dressed-carcass meat from weaned calves for an approximate cost of 8 to 9 Kcal of cultural energy. Total confinement required about 15 Kcal of cultural energy for each Kcal of dressed meat, or about three times as much cultural energy to produce 1 Kcal of edible meat from weaned calves, compared to range production.

Digestible energy conversion from feed or forage to meat of weaned calves was measured, showing that total confinement was the most efficient. The range group produced the lowest return of food energy in dressed calf meat per unit of digestible energy consumed, largely because some of the energy was utilized in foraging. The ratio of digestible protein in the diet to meat protein produced was analyzed and the range group showed the lowest ratio; this group therefore produced more edible meat protein from weaned calves per unit of digestible protein consumed. Confined groups were the least efficient systems with respect to protein conversion.

Another approach was taken by Cauhépé *et al.* (1). They analyzed range utilization in the Salado River Basin, Province of Buenos Aires, Argentina. They distinguished four different production systems, which they called: improved 1, improved 2, improved 3 and traditional. In the improved 1 system, the range had been replaced with fertilized pastures and showed a stocking rate of two cows per hectare and an 85 percent to 95 percent calf crop. Annual secondary production was estimated at 300 kg live weight per hectare per year. The improved 2 system did not include fertilization. Pastures were resown more frequently, and primary productivity was lower. Annual production was estimated at 200 kg live weight per hectare per year. The improved 3 system was based on fertilized native grasslands with a primary production of 2 400 kg of dry matter per hectare per year. Animal production was estimated at 96 kg live weight per hectare per year. Finally, the traditional system was based on native grasslands, with a stocking rate of 0.6 cows per hectare and a 75% calf crop. Calf weight at weaning time was 155 kg. Secondary production was estimated at 70 kg live weight per hectare per year.

The authors calculated the cultural energy utilized for each system in management, fertilization, herbicides, labor, machinery, etc. They also calculated the energy content of the output of the different systems, which ranged from 500 Mcal ha^{-1} yr^{-1} for the highest technological input, to 115 Mcal ha^{-1} yr^{-1} for the traditional system. The amount of subsidy received by each system showed similar trends. However the efficiency of the energy subsidy use showed exactly the opposite pattern. The traditional system, receiving the smaller subsidy, had the highest efficiency because its low productivity was offset by the small amounts of energy inputs needed for taking care of the herd and for veterinary care. Using one Mcal of subsidy, the traditional system produced 9.6 Mcal of beef, while the improved 1 system produced just 0.78 Mcal. Only the traditional system and the improved 3 system had efficiencies higher than 1, while the other two required subsidies higher than their products.

Klopatek and Risser (7) found a similar pattern in an energy analysis of rangelands and improved pastures on different sites in Oklahoma, United States. They reported a linear decrease in the efficiency of subsidies with an increase in production. Their rangelands in all cases received higher subsidies and their efficiencies were always lower than those reported by Cauhépé *et al.* (1). The rangeland with the highest efficiency in the Oklahoma study produced only 0.15 units per unit of subsidy.

Relative importance of the energy flow through the food production system

Agricultural production is responsible for only 2.9 percent of total United States energy use (6). In contrast, the food system consumes 16.5 percent of all United States energy used. Manufacturing and processing use 4.8 percent, preparation requires 7.1 percent and distribution accounts for 1.7 percent. The absolute numbers for production, however, are large: 30 billion liters of petroleum fuels and 22 billion KWH of electricity. Total energy input is equivalent to 52 billion liters of gasoline. Other authors such as Steinhart and Steinhart (20) and Pimentel (18), have emphasized that in developed countries, the relative amount of energy which goes into food production is small. On the other hand, in developing countries the energy used for producing food accounts for as much as 60 percent of the total energy utilized, because they spend less energy in transportation, heating, etc. Therefore, small improvements in the efficiency of the food production system will have a larger impact on the energy budget of developing countries than of developed countries.

If the economic structure remains at it is today, the utilization of a resource will depend largely on its price. The trend in cattle production in the United States during the past two decades has been for the utilization of forage to decrease and the use of feed grain to increase because of the relatively low price of grain. Fossil energy is expected to become scarce and its price to soar. The energy input to farms and ranches will be more expensive, and some of the present techniques will no longer be economically feasible. With these changes, both developing countries and developed countries will need to possess energy-efficient techniques for producing food.

Present prices of different inputs to the food production system are not strictly related to their energy content. In other words, the relation between energy content and price usually is quite poor. Prices depend mostly on economic variables such as supply and demand. This means that production systems which are not feasible from the energy viewpoint may be feasible economically. As prices rise, especially for fossil energy, systems which utilize less of this resource will be very advantageous. C.W. Cook (4) stated that expenditures of fossil fuel in the future will undoubtedly be closely correlated with the price.

In conclusion, it is probable that in the near future we will rely heavily on rangelands as a source of protein for humans. It will be necessary to maximize their production, but the subsidies most often used to increase production will be scarce and expensive. Therefore, considerable effort will need to be devoted to developing energy-efficient techniques for rangeland utilization. Most of the research required to develop these techniques has its own timing. It is the responsibility of the scientific community to begin their projects now, before decision makers ask for new technologies, so that the new demands can be met.

Summary

This paper begins with a brief description of the major inputs for food production systems and discusses their availability in the future. This picture is contrasted with a description of the outlook for world food demand. Stress is placed more on the quality than on the quantity of the food needed to meet the needs of coming decades.

Different food production systems are compared from the energy standpoint. Grain production systems emerge as the most efficient, and animal production systems as the least efficient. A distinction is made between animal production systems that use food inputs not useful to human beings (forage) and those that use resources, such as cereals, that otherwise would be edible by humans and therefore compete with human nutrition. This competition is quantified, stressing the role of cattle as a mechanism for converting low quality forage into proteins for human consumption.

Different techniques for using pasturelands, the major source of these low quality resources, are

compared. The addition of energy subsidies in the form of fertilizer, herbicides, seeds, etc. can increase production but reduce efficiency. Finally, energy used for food production is compared with total energy consumption in the developed and developing countries. The paper concludes that in the near future, the more energy-efficient food production techniques will be the most profitable. The population will probably depend significantly on the production of natural pasturelands, and it will be necessary to develop energy-efficient ways of using them.

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