ON ENERGY AND AGRICULTURE: FROM HUNTING–GATHERING TO LANDLESS FARMING

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SUMMARY

An energy analysis of agricultural practices shows very coherent patterns of evolution from the Neolithic Age up to this century. All technical advances were in fact exploited toward intensification, and the ratio of food output to energy input was held remarkably constant over such a long stretch of time.

New agricultural practices in developed countries linked to massive energy "subsidies" from fossil fuels have disrupted the trend, substantially altering the ratio. A more rational use of energy in agriculture is going to be necessary when the developing countries adopt these practices. Low-tillage techniques, hormonal and genetic pesticides and herbicides, nitrogen fixing in grains, and other emerging technologies satisfying this constraint are briefly described and assessed in this paper.

PREFACE

IIASA's Energy Systems Program devotes itself to the analysis and synthesis of energy systems in a long-term time horizon. Agriculture, now a relatively modest consumer of fossil fuels, may become an important one when industrial practices will spread outside developed countries. To assess the impact of these practices on the energy system, and to suggest what trend should be supported in order to cushion it, is one of the objectives of the Program.

The paper was prepared for and presented at the conference, *Science and Technology for Agriculture*, that took place in Bari, Italy, from October 27 to October 29, 1978.

INTRODUCTION

God said to Adam, "In the sweat of thy face shalt thou eat bread . . . ." With the poetic image of evaporative cooling, God obviously adumbrated muscular exertion and the central importance of a mechanical input in order to run the agricultural system.

Since then, things have not changed drastically. Three-fourths of humanity still operates agriculture in a way only marginally different from the Neolithic one, with draft animals associated with the toil of man. The last fourth, the evolutionary tip, tamed machines for the same purpose and started the large-scale use of synthetic chemicals.

The effect of these two innovations, and especially the latter, has been a noticeable increase in the specific productivity of land. The price to be paid, however, has been a disproportionate increase in the amount of energy expended per unit of product generated.

As this ratio keeps increasing with time, and the still Neolithic agriculture will soon enter the energy game, it may pay to pause for a moment and reflect on the consequences of what we are doing and where we are going. The argument of my analysis is the study of this interface between energy and agriculture.

HISTORICAL PATTERNS

Plants are defined as organisms capable of tapping solar energy through their capacity to split water into hydrogen and oxygen using solar light. This hydrogen is used to reduce CO_2 first, and then to feed the production of a vast array of energetic chemicals. Virtually all of the biosphere finally depends on them for its energetic input, through a complex web of hierarchical parasitism.

When man differentiated from the apes, he was well knitted into this web, as a hunter–gatherer. In this form, he did not differ from many other animals. The pressure to grow had to be met by extending on the one side the geographical habitat, and on the other the range of digestible foods.

Here came the first breakthrough, with the use of energy. Plants defend themselves against predators with an impressive panoply of weapons. The most important ones are chemical and tend to make the plant indigestible, in one way or another, and occasionally poisonous. Animals developed counterweapons, but these tend to be sophisticated and specialized, consequently restricting the range of edible material. Man's stroke of genius was to apply thermal treatment in order to upset or destroy the delicate organic chemistry of defense. Fire has to be seen first of all as the tool for a breakthrough in food technology, in most cases improving and sometimes just making possible the digestion of plant material and seeds in particular.

There are still populations living on the Paleolithic, nonagricultural technology, and they do not fare as badly as is usually imagined. A detailed study of the "work–leisure" distribution of time in a primitive tribe made by Eibl-Eibesfeldt (1976) shows that these primitive men work the equivalent of 2 days a week and spend the rest of the time relaxing or socializing. The wildest dream of the unions made real!

Energy-wise, the situation then appears to be excellent. If we suppose that our man supports an extended family of 4, then the ratio of the energy he gets as food to the energy invested to procure it must be on the order of 50 (Eibl-Eibesfeldt 1976, Leach 1976). This ratio will be the common yardstick in the rest of this paper. It is defined as the energy ratio (E_r):

$$E_r = \frac{\text{Energy out}}{\text{Energy in}} .$$

Conceptually, agriculture operates in the reverse direction. It explicitly modifies the ecosystem in order to amplify the production of biological material, assimilable directly or by thermal treatment (cooking). On the one hand, man becomes the ally of certain plants by collaborating in their reproduction cycle and by fighting their natural enemies. On the other hand, he puts himself first in the list of selective forces, by picking the plants most profitable from his point of view. Neolithic man operated with extreme patience and cleverness. Our "green revolutionaries" have added very little to the splendid job he did.

All the interfering, however, did cost time and energy, and the analysis of primitive agricultures that still preserve Neolithic characteristics tells us what man really gained in the operation. Table 1 and Figure 1 show that the energy ratio E_r for primitive agriculture is still on the order of 50, showing no gains and no losses with respect to the case of the hunter–gatherer.

One may then ask what the driving force of the laborious development of agriculture was? Simply this: After having filled the available niche geographically, the only way left to expansion was *intensification. Agriculture just reduces the amount of land necessary to support a man, and it consequently supports the human population's natural drive to expansion.* The entire development of agriculture up to now can be interpreted in this key.

The introduction of draft animals, for instance, did not reduce the toil of man. Peasants with animals worked as hard as the ones without. Nor did it drastically increase the productivity per man. By having a stronger impact on the ecosystem, it essentially increased the specific productivity of land. It was again a transition moving in the same direction, increasing the intensity of human life. Ruminants were the most successful symbiotic draft animals, mostly because they do not compete with man for food, being able to digest all sorts of roughage and poor pasture, extracting energy from cellulose and properly managing nitrogen through the rumen's flora.

The apex of this evolution was probably reached by Chinese agriculture at the turn of the century. Billions of men cleverly devised and carefully checked all sorts of tricks to maximize output. As a result, the amount of (fertile) land necessary to support a man was reduced to 100 m^2, a great leap forward in respect to the few square kilometers necessary to support a hunter–gatherer. A factor of more than 10^4 in intensification! And with a very honorable energy ratio of 40 (Leach 1976).

The ecological system so created, however, although still very appealing aesthetically, does not bear any resemblance to any natural ecosystem, if only because of its great structural simplification. As a consequence, equilibrium and resilience are lost, and the system becomes very unstable and difficult to manage. The wits and toil of most of the Chinese population are just employed to do that. Chinese agriculture is the brilliant pinnacle of a monumental enterprise started about 10,000 years ago.

THE THIRD INPUT

As we have seen, up to the turn of the century, agricultural development followed a very consistent path of progressive intensification, keeping energy ratios more or less constant. As all food energy came from agriculture,

TABLE 1 Energy inputs and outputs per hectare for corn production.

	Neolithic agriculture (Mexican farmer)	Modern agriculture (American farmer)
Time	1,150 hr	17 hr
Energy		
Labor	115 Mcal	
Machinery	15 Mcal (ax and hoe)	1,500 Mcal
Seeds	36 Mcal (10 kg)	140 Mcal
Fuel		2,100 Mcal
Nitrogen		2,500 Mcal
Phosphorus, potassium, pesticides		500 Mcal
Irrigation		780 Mcal
Electricity and drying		700 Mcal
Transportation		180 Mcal
Miscellaneous		200 Mcal
Total energy	166 Mcal	8,600 Mcal
Corn yield	6,700 Mcal (2,000 kg)	18,700 Mcal (5,400 kg)
E_r	40	2.16

Adapted from Pimentel (1977).

a value of 40 for E_r was more or less necessary to allow a certain level of social activities. In fact, with $E_r \approx 50$, about 20 percent of the population can live decoupled from direct agricultural activity. As E_r remained constant over time and is fairly similar to that of the hunter–gatherers, we may conclude from pure energy considerations that agriculture was not the cause of the formation of cities and finally of the modern form of our civilization because it provided a surplus, as is often said, but because it could provide a *critical population density* through its continuous improvement in intensification.

The summit having been reached by Chinese agriculture, evolution could continue only by a qualitative breakthrough. It came at the turn of the century with the introduction of fossil fuels. I said fossil fuels and not machines, because machines are one of the elements of the breakthrough, but all innovations are finally related to fossil fuels.

Machines were introduced marginally, e.g., as steam engines to run threshers, at the end of the last century. They really flourished, however, only after World War II, when the automobile industry produced a solid, cheap, and dependable tractor. The effect of introducing the tractor was

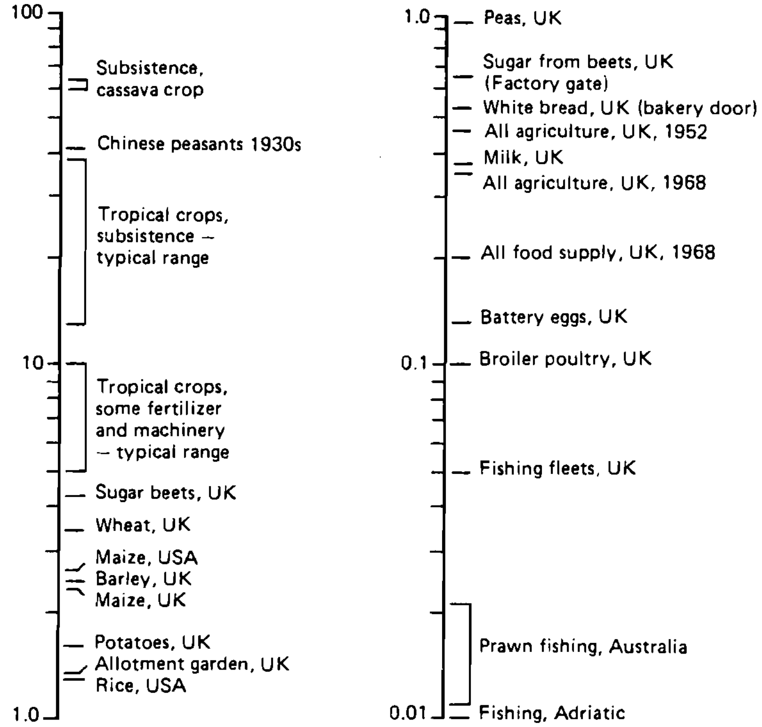

FIGURE 1 Energy ratios for various food sources at farmgate or dockside. From Leach (1976).

to replace the oxen team by a horsepower team 10 to 50 times more powerful. This led to a roughly proportionate increase in the productivity of the laborer, without, however, substantially intensifying production. Consequently, instead of 20 percent perhaps 80 percent of the population could move from the land. Through the machine, with *its external energy input*, evolution branched away from the previous trend.

Being unconstrained by tight energy balances, however, the machine also permitted an extension of the cultivable land somewhat in the direction of the previous trends. The effect of the use of chemicals, on the contrary, fits the original trend perfectly. Fertilizers are intensifiers and they have always been used, but only the external energy input from fossil fuels has permitted their production in significant quantity.

Significant is also their impact on energy consumption. Very careful energy analysis of all the energy inputs going into fertilizer production (including the energy necessary to build the plants to make them) shows that they load the agricultural energy budget by more or less the same amount as the machinery itself (Pimentel 1977). Table 1 illustrates the situation with two typical examples.

THE NEW TRENDS

As Figures 1 and 2 and Table 1 show, the consequence of these new trends has been a precipitous decrease in E_r, falling, on the average, from about 50 to about 2, for "modern" agriculture. On the right side of Figure 1, many fairly important crops are well below the mean, and winter lettuce does not even appear, having an extravagant $E_r < 0.01$. We spend more than 100 calories of fossil energy to produce 1 calorie of lettuce! Chasing for fish in the Adriatic, which is not an agricultural operation but is reported for comparison, would certainly not have lured a Neolithic fisherman, who had to be very attentive to keeping E_r at the proper level in order to survive.

The recent breakthrough of "external" energy inputs has made the expansion and intensification in agriculture develop much faster than the growth of population, particularly in the United States. This has led to an important surplus capacity, especially for grains, and to a queer evolution in eating habits in order to get rid of that surplus.

Here we must consider man's use of animals. Animals have, since the beginning, been the companions of *Homo agricola*, in various symbiotic configurations, which can be reduced to basically two:

(a) Transforming and storing food
(b) Providing mechanical energy

Function (a) has usually been prevalent, and the logic is that an animal can have a food spectrum not overlapping with that of man, consequently expanding the potential for the human input via its products and its carcass. Another rationale is that seasonal inputs of easily degraded foods can be stored in the form of meat and fat for the low season.

However, every time we filter energy through a transformation, here a hierarchical level in the food chain, the rule of thumb is a loss of one order of magnitude in the energy and protein value of the carcasses with respect to the input. With milk or egg production, the transformation loss is on the order of a factor of 4 to 5 (Figure 3). Strangely enough, ruminants don't fare particularly well, their superiority lying mostly in their capacity to digest very rough inputs rich in cellulose.

Now, by increasing the protein input in the form of animal proteins and in order for these animals to grow rapidly, one feeds them easily digestible grains. Any surplus can be "efficiently" taken care of. The energy ratio,

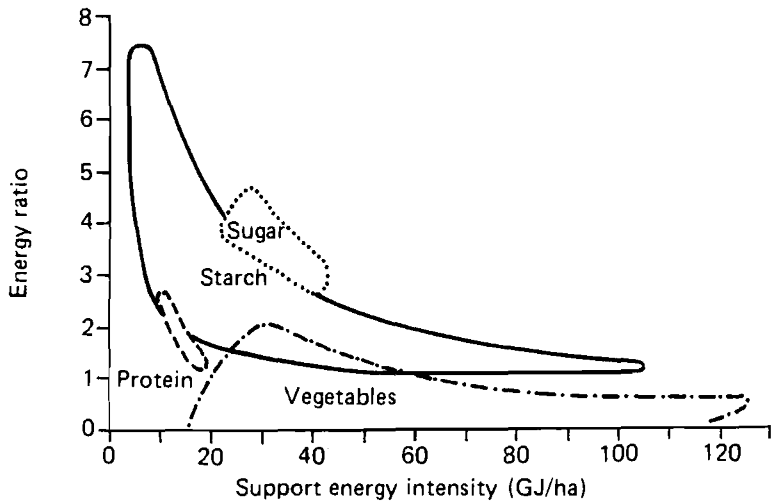

FIGURE 2 Energy ratio versus support energy intensity for various crops. The curves enclose about 50 points from a variety of agricultural systems. From Gifford (1976).

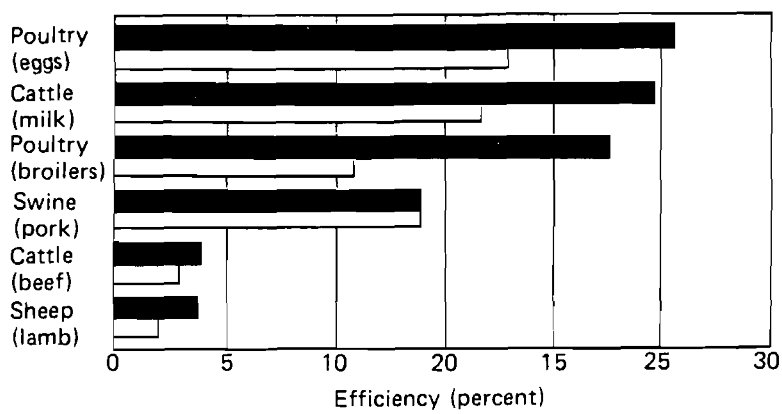

FIGURE 3 Conversion efficiency of animals, defined as the ratio of proteins or calories produced to proteins or calories in the feed. The black bars represent protein and the white ones calories. From Janick *et al.* (1976).

however, plummets to levels well below unity. For feedlot beef, it is in the range of .1, meaning that one needs an input of more than 10 calories of fossil fuels to get 1 calorie of beef. For proteins alone, the ratio is 100 (Slesser *et al.* 1977)! This fact has two consequences. The first one is that the fossil energy input for agriculture may rise extremely rapidly with the increasing welfare of world population. Figure 4 shows how the diet evolves with income, here indexed by energy consumption. Second, energy expenditure increases with intensification of agriculture; this is shown in Figure 5. Five nations are located on the abscissa to indicate where we stand.

In Figure 5 two curves are given, one referring to "Chinese" eating habits, and the other to "European" or, more precisely, North-American habits, in which animals are largely used as intermediate processors. This situation opens up new avenues, as the amount of fossil energy to produce proteins from microorganisms is more or less in the vicinity of $E_r \simeq .1$, with present technology (Slesser *et al.* 1977); a possible asymptotic value of .5 has been considered.

Microorganisms have a long history of domestication by man, providing chemical transformations that improve the preservability, digestibility, and taste of agricultural raw materials. Bread, wine, and tempeh are the three characteristic cases, their use already established in the dawn of history.

Microorganisms are geniuses at handling biochemical problems; and the next problem – whether one can feed them fossil energetic products – has been solved without a hitch. Plants have the privileged position of interfacing the biosphere with solar energy via photoproduction of hydrogen, which then feeds all the chemical chains inside the plant. If, however, agriculture develops in such a way that the energy obtained is substantially less than the energy put in, why then not have microorganisms do the same job and avoid agriculture altogether, the advantage being that land would no longer be required?

Proposals in that direction have been made (Marchetti 1973) in which nuclear reactors are used as primary energy sources, and hydrogen produced by water decomposition is used as a feed. The proper microorganisms able "to do the rest" are under intensive development (Schlegel and Lafferty 1971).

CONCLUSIONS

The menace for agriculture, if not in the very short term, is quite visible, and agricultural practices must start reacting, I think, in the proper direction, to retard, if not to avoid, the defeat. The increase in human population

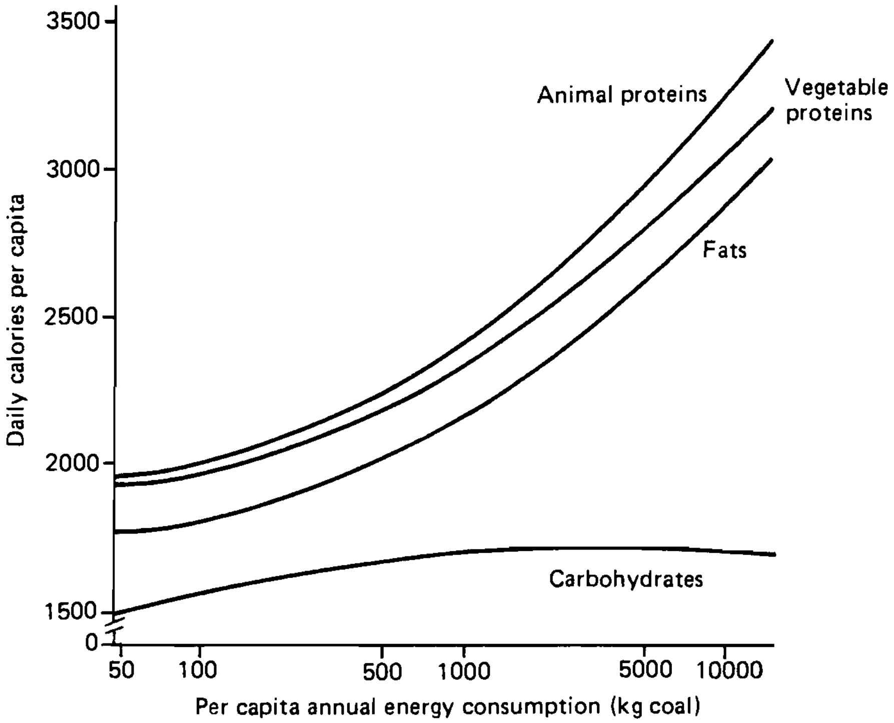

FIGURE 4 Energy consumption per capita, which is taken as an index of wealth, versus feed mix expressed in calories per capita. From Sagan and Afifi (1978).

expected to reach 6 billion in the year 2000, and a ceiling of perhaps 20 billion in 2050, spells in fact a final defeat (Von Voerster *et al.* 1960). Not only will these people ask for better nutrition than now available, but their cities and amenities will eat up agricultural land, pushing the operation points further toward the left in the graphs of Figure 5.

As things are happening now in the United States, and will be in the near future in other countries like Australia, relatively low intensity is exported where high intensity is already the rule. The U.S. export of grains and soybeans to Japan can be interpreted in that way. The energy cost of transportation from the United States to Japan is lower than the energy cost of intensification of agriculture in Japan to get the same result.

This may well not be the case in the medium-range future. If only the 6 billion people pretend to live in their cars and eat meat from their refrigerators, the Los Angeles way, there will be no land left. And the attraction of the Los Angeles way of life seems irresistible. In this case, the movement toward landless food production via microorganisms is inevitable, and would come rapidly.

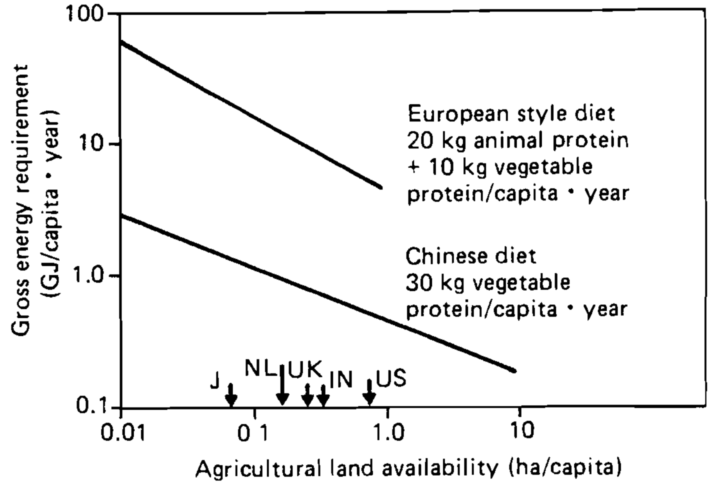

FIGURE 5 Energy from fossil fuels versus agricultural intensification. The positions of Japan (J), the Netherlands (NL), the United Kingdom (UK), India (IN), and the United States (US) are shown. About 150 case points were used to construct the curves. From Slesser (1977).

In the real world, however, situations are rarely so drastic, as proper changes along the way soften their outcome. What then can be a reasonable target for agriculture in the meantime?

As Table 1 shows, the energy cost of modern agriculture can be split equally between machines and chemistry. Most of the work of machines goes into tillage, whose main objective is to kill weeds. Here we have to say first that tractors did improve their mechanical efficiency over the last 30 years (Sahal 1975), but their fuel efficiency has not improved much. As their efficiency at the axle may be perhaps 15 percent, there is a lot of room for improvement there.

Low-tillage techniques are under development and their application is spreading, especially in the United States. Tillage, as mentioned before, has the main objective of modifying the ecosystem, and plants have been doing it all the time by using proper chemicals. The basis of low-tillage techniques is the use of herbicides to control weeds. Seeds are planted by "injecting" them into the soil (Triplett and Van Doren 1977).

Herbicides and *pesticides* that now operate on the principle of carpet bombing may progressively move into the *hormonal or perhaps genetic level*, and require less and less energy, as the amounts necessary will be reduced.

The largest slice of the energy for chemicals is taken by fertilizers, however, with nitrogen in the first place. Nitrogen, though, mostly goes to grains. Consequently, the other line of attack that promises to minimize energy expenditure lies in the development, by genetic engineering (Hollaender 1977), of grains capable directly, or more probably through symbiosis with bacteria, of fixing nitrogen from the atmosphere. *Nitrogen fixing in grains*, contrary to what one would expect intuitively, would not draw upon the energetic resources of the plant. Plants actually use nitrogen in reduced form, but they can draw it from the soil only in an oxidized form, e.g., as NO_3^-. The energy a plant (e.g., wheat) expends to reduce this nitrogen is almost exactly the same as what a legume (e.g., soybeans) spends to extract it from the atmosphere (Hardy and Hawelka 1975, Brill 1977). From a purely chemical angle, this is very plausible, but one tends to think that all the work to make ammonia could be finally saved by the plant.

Back-of-the-envelope calculations show that improved tractors, low tilling, targeted herbicides and pesticides, and an extended capacity for nitrogen fixation have together a potential for reducing energy consumption in agriculture by one order of magnitude, bringing E_r to a safer level of 10 to 20.

The fad of more "natural" eating habits, with a lower consumption of meat and well-balanced vegetable protein diets, may establish itself as a healthy custom and then lead the European curve in Figure 5 to approach the Chinese one, thus making possible a further gain of perhaps a factor of 5 in energy expenditure.

A last point, which is beginning to receive some attention, is the use of farm waste (and finally forests) as a source of food. Cooking, as I said, extended the range of edible resources, and biochemical processing, the clever way, may extend it further. Ruminants have done a lot in this direction, but microbiologists can certainly do better. And forests may constitute an almost inexhaustible resource if a clever way can be found. With total world food production amounting to less than 1 billion tons of coal equivalent per year, farm waste amounts to about 3 billion, and biomass production in forests to about 50 billion.

These two sources are so large that fermenting part of the farm waste or forest biomass to biogas or alcohol, to be used to run tractors, for example, may be a good intermediate objective to increase the resiliency of the agricultural system by decoupling it from the world energy system.

To conclude, my analysis of the trends as seen through the optics of energy consumption patterns does not induce pessimism or optimism. It shows a challenge that is within the technical capacity of man, and it shows a fast-changing pattern that will tax the *ingenuity* of engineers in the field of agriculture.

To summarize my view about the best path to the solutions, I shall say: *More bits and less kilowatts.*

REFERENCES

Brill, W. (1977) Biological nitrogen fixation. Scientific American 236(3): 68–81.

Eibl-Eibesfeldt, I. (1976) Liebe und Hass. Piper, Munich.

Gifford, R.M. (1976) Energy in agriculture. Search 7: 411.

Hardy, R.W.F., and U.D. Hawelka (1975) Nitrogen fixation research: A key to world food? Science 188: 633.

Hollaender, A., ed. (1977) Genetic Engineering for Nitrogen Fixation. Plenum Publishing Corp., New York and London.

Janick, J., C.H. Noller, and C.L. Rhykerd (1976) The cycles of plant and animal nutrition. Scientific American 235(3): 74–86.

Leach, G. (1976) Energy and Food Production. IPC Science and Technology Press, Guildford, England.

Marchetti, C. (1973) Hydrogen and energy. Chemical Economy and Engineering Review 5: 7–25.

Pimentel, D. (1977) Energy use in cereal grain production, in Proceedings of the International Conference on Energy Use Management. Pergamon Press, Oxford.

Pimentel, D., W. Dritschilo, J. Krummel, and J. Kutzman (1975) Energy and land constraints in food protein production. Science 190(4216): 754–761.

Sagan, L.A., and A.A. Afifi (1978) Health and Economic Development I: Infant Mortality. RM-78-41, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Sahal, D. (1975) A generalized logistic model for technological forecasting. Technological Forecasting and Social Change 7(1): 81–97.

Schlegel, H.G., and R.M. Lafferty (1971) Novel energy and carbon sources, A. The production of biomass from hydrogen and carbon dioxide. Advances in Biochemical Engineering 1: 143–168.

Slesser, M., C. Lewis, and W. Edwardson (1977) Energy systems analysis for food production. Food Policy 2(2): 123–129.

Triplett, G.B., and D.M. Van Doren (1977) Agriculture without tillage. Scientific American 236: 28.

Von Foerster, H., P. Mora, and L. Amiot (1960) Doomsday: Friday 13 November AD 2026. Science 132: 1,291–1,295.

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