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ON ENERGY AND AGRICULTURE

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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 well into the objectives of the Program.

The paper was prepared for and presented at the Conference on Science and Technology for Agriculture, Bari/Italy, October 27-29, 1978.

ABSTRACT

Energy analysis shows that, since the neolithic, agriculture has developed as a technology to reduce the amount of land necessary to support a given population. All technical discoveries and inventions were eventually bent to this final objective: intensification.

The ratio of food-energy output per energy input, on the other hand, did remain remarkably constant, around a value of 40, till agriculture operated on a bootstrap basis.

Basically, after World War II, the large-scale use of fossil fuels via machines and fertilizers drastically changed the trends, leading to an escalation in energy consumption per unit of product.

The trend appears reversible, and the proper processes to be supported in view of a judicious long-term energy management are indicated.

ON ENERGY AND AGRICULTURE

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 to 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 result of the last two innovations, and especially that of the last one, 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 spent 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 consequence 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 of splitting 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. Practically all of the biosphere finally depends on them for its energetic input, through a complex web of hierarchical parasitism.

When man differentiated from apes, he was well knitted into this web, as a hunter-picker. 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 a way or another, and occasionally poisonous. Animals developed counter-weapons, but these tend to be sophisticated and specialized, consequently restricting the range of edible material. Man's strike 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, improving and in many cases just making possible digestion of plant material and seeds in particular.

There are still populations living on the paleolithic, non-agricultural technology, and they fare not as bad as is usually imagined. A detailed study of the "work-leisure" distribution of time in a primitive tribe made by Eibl-Eibesfeldt [1] shows that these primitive men work the equivalent of two 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. Supposing our man supports an extended family of four, then the ratio of the energy he gets as food to the energy invested to procure it must be on the order of 50 [1, 2]. This ratio will be the common yardstick in the rest of this paper. It is defined as the energy ratio (E_r):

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

Agriculture conceptually 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 which still preserve neolithic characteristics will tell us what man really gained in the operation. Table 1 and Figure 1 show that the energy ratio

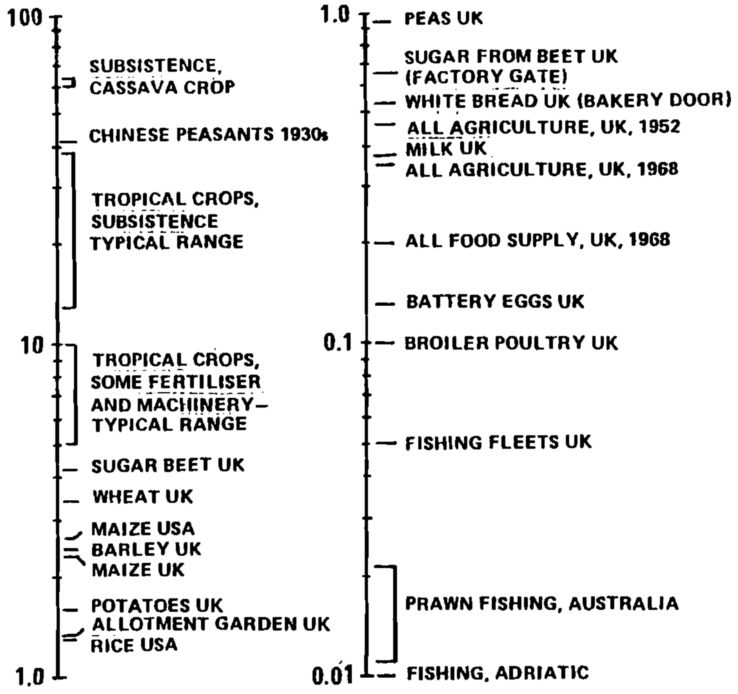

Figure 1. Energy ratios for various food sources (at farmgate or dockside). From G. Leach [2].

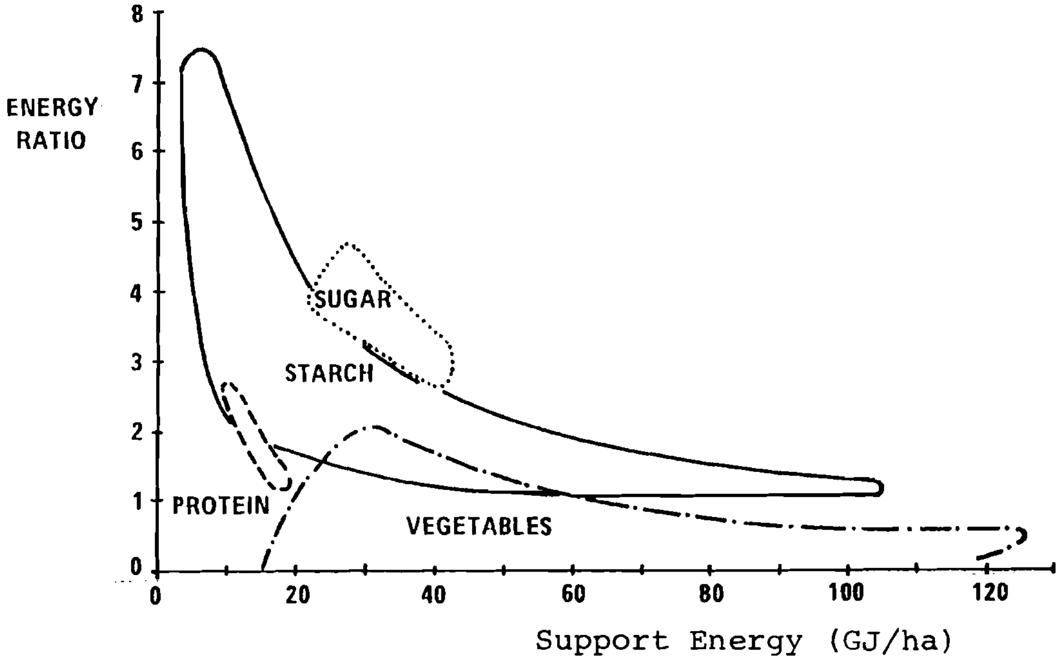

Figure 2. Energy ratio vs support energy intensity for various crops. The curves envelop about 50 points from a variety of agricultural systems. From R.M. Gifford [7].

E_r for primitive agriculture is still on the order of 50, showing no gains and no losses, in respect to the case of the hunter-plucker.

One may then ask what the driving force of the laborious development of agriculture was? Simply: 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.* All the development of agriculture up to now can be interpreted in this key.

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 leaving 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 roughages 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 of the few square kilometers necessary to support a hunter-plucker. A factor of more than 10^4 in intensification! And with a very honorable energy ratio of 40 [2].

The ecological system so created, however, although still very appealing aestetically, does not bear any resemblance to any natural ecosystem, at least because of its great structural simplification. As a consequence, equilibrium and resilience are lost, producing a system very unstable and difficult to manage. The wits and toil of most of the Chinese population are just employed to that. Chinese agriculture is the brilliant pinnacle of a monumental enterprise started about ten thousand 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. Like all food energy came from agriculture, this value for E_r was more or less necessary to give space to a certain level of social activities. In fact, with $E_r \approx 50$, about 20% 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 hunters, 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 is 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 the 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 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% perhaps 80% of the population could move from the land. Through the machine, with *its external energy input*, evolution branched away from the previous trend.

Being not constrained by tight energy balances, however, the machine also permitted an extension of the cultivatable land much in the direction of the previous trends. The effect of the use of chemicals, on the contrary, fits perfectly the original trend. Fertilizers are intensifiers. Their use has been practiced since ever, but only the external energy input from fossil fuels has permitted to produce them in significant quantity.

Significant is also the 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 [11]. Table 1 illustrates the situation by two typical examples.

The New Trends

As Figures 1 and 2 and Table 1 show, the consequene of these new trends has been a precipitous decrease in E_r, falling, in the mean, 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 >100 calories of fossil energy to produce 1 calorie of lettuce! Chasing for fish in the Adriatic, a food, but not agricultural operation reported for comparison, would certainly not have lured a neolithic fisherman, being very attentive to keeping E_r at the proper level in order to survive.

Table 1. Corn Production Energy Inputs-Outputs.

	Neolithic Agric. (Mexican Farmer)	Modern Agric. (American Farmer)
Labor	1150 hours	17 hours
Labor	115 Mcal	-
Machinery	15 Mcal (ax & hoe)	1500 Mcal
Seeds	36 Mcal (10 kg)	140 Mcal
Fuel	-	2100 Mcal
Nitrogen	-	2500 Mcal
P,K, Pesticides	-	500 Mcal
Irrigation	-	780 Mcal
Electr. & Drying	-	700 Mcal
Transportation	-	180 Mcal
Miscellaneous	-	200 Mcal
	167 Mcal	8600 Mcal
Corn Yield	2000 kg or 6700 Mcal	5400 kg or 18700 Mcal
$\boxed{E_r}$	$\boxed{40}$	$\boxed{2.16}$

Adapted from Pimentel [11].

The recent breakthrough of "external" energy inputs has made the intensification in agriculture develop much faster than the growth of population, particularly in the US. 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.

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; and
(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 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

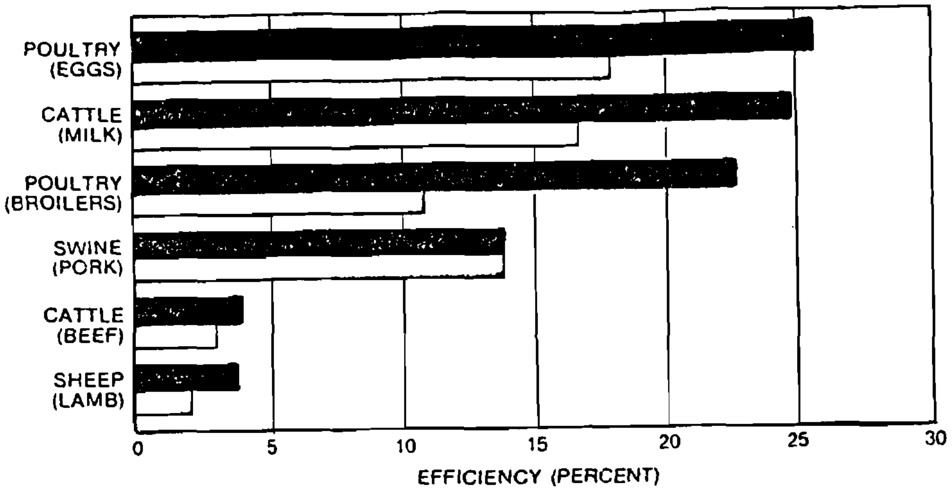

Figure 3. Efficiency in conversion by transforming animals. ■ Protein. □ Energy. From C.H. Noller [10].

a factor of four to five (Fig. 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, however, precipitates to levels well below unity. For feed-lot beef it is in the range of $\sim .1$, meaning that one needs an input of more than 10 calories of fossil fuels to get one calorie of beef. For proteins only, the ratio is 100 [12]! 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, and Figure 5 shows how energy expenditure increases with intensification of agriculture, here expressed in terms of hectare/ man to be supported. Four nations are located on the abscissae to indicate were 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, where 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 ballpark of $R_r \simeq .1$, with present technology [12]; a possible asymptotic value of .5 has been considered.

Microorganisms have a long history of domestication by man, providing chemical transformations which improve 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.

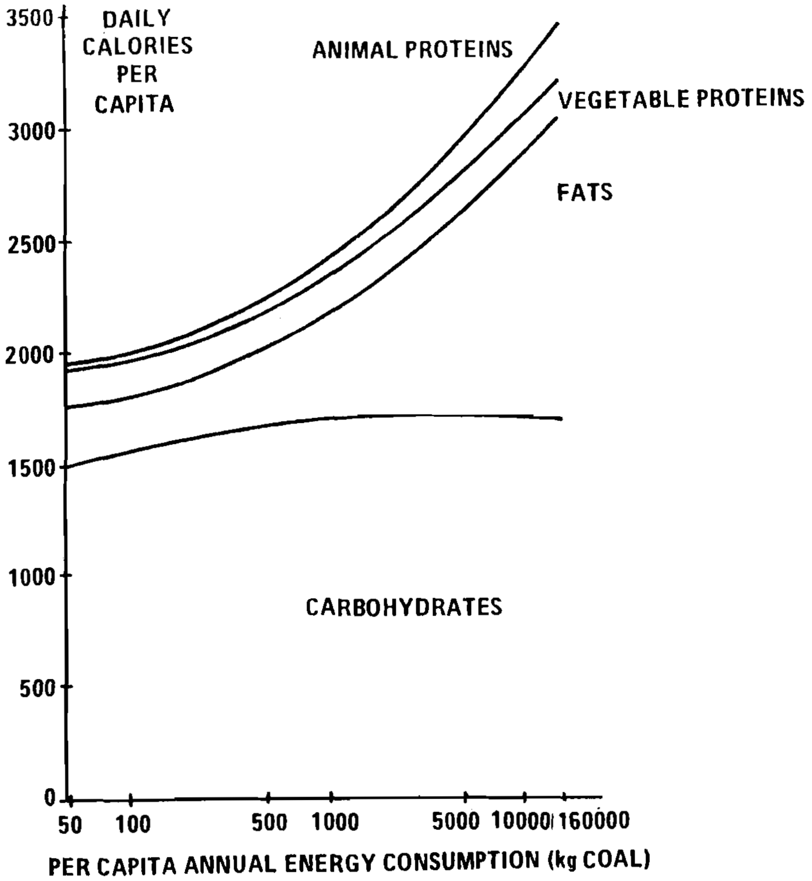

Figure 4. Caloric input versus per capita energy consumption (kg coal equivalent) taken as an index of health. From L.A. Sagan and A.A. Afifi [16].

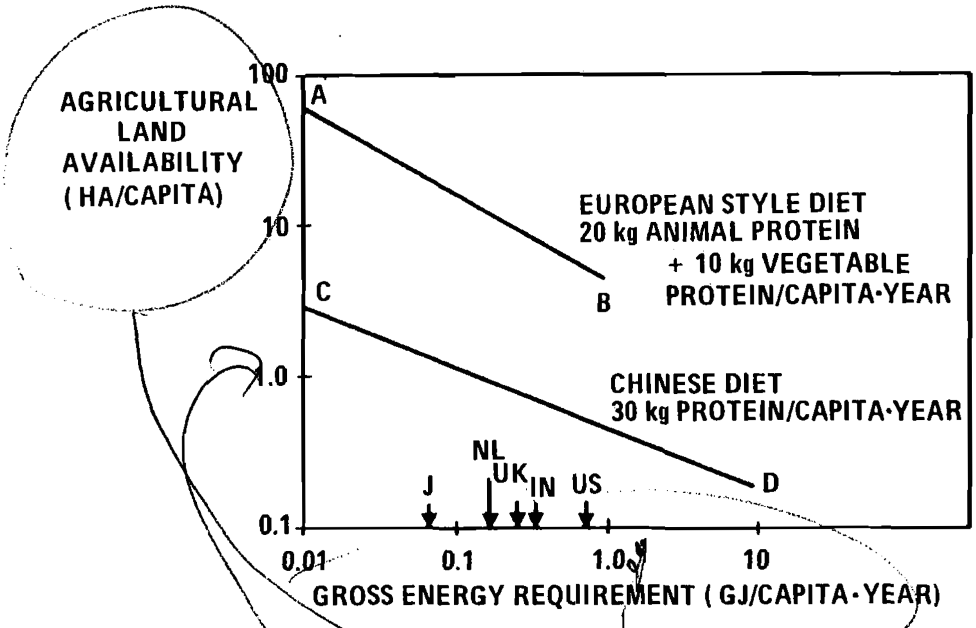

Figure 5. Fossil energy inputs versus agricultural intensification. Four countries' positions are reported. About 150 case points have been used to construct the curves. From M. Slesser [12].

Microorganisms are top geniuses in handling biochemical problems, and the next question--whether one can feed them fossil energetic products--has been solved without a hitch. Plants, as I said, 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 is no more required?

Proposals in that sense have been made [3] with nuclear reactors to be used as primary energy sources, and hydrogen produced by water decomposition as a feed. The proper microorganisms able "to do the rest" are under intensive development [14].

Conclusions

The menace for agriculture, if not of very short term, is quite visible, and agricultural practices start reacting I think in the proper direction, to retard, if not to avoid, the defeat. The increase in human population, expected to reach 6 billions in the year 2000, and a roof of perhaps 20 billions in 2050, spells in fact a final defeat [13]. Not only will these people ask for a better nutrition than available now, 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 U.S., and will be in the near future in other countries like Australia, low intensity is exported where high intensity is already the rule. The U.S. export of grains and soy-beans to Japan can be interpreted in that way. The energy cost of transportation from the U.S. to Japan is lower than the energy cost of intensification of agriculture in Japan to get the same result.

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

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 mechanics and chemistry. In mechanics, most of the work goes into tillage, whose main objective is to kill weeds. Here we have to say first that tractors did not really improve over the last 30 years [5], except perhaps for their power to weight ratio. As their efficiency at the axle may be perhaps 15%, there is good room for improvement there.

Low tillage techniques are under development and their application is spreading, especially in the U.S. Tillage 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 [15].

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 on the other hand mostly goes to grains. Consequently the other line of attack that promises to minimize energy expenditure lies in the development, by genetic engineering [4], of grains capable directly or more probably through symbiosis with bacteria to fix 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) spends to reduce this nitrogen is almost exactly the same a legume (e.g. soybeans) spends to extract it from the atmosphere [8, 9]. From a purely chemical angle this is very plausible, but one tends to think that all the work to make ammonia would be finally saved to the plant.

Back of the envelope calculations show that improved tractors, low tilling, targeted herbicides and pesticides, 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" feeding habits, with a lower consumption of meat and well balanced vegetable protein diets, may approach the European curve in Figure 5 to the Chinese one, thus making possible a further gain of perhaps a factor of five in energy expenditure.

A last point, which is beginning to receive some attention is to look at the farm waste (and finally at the 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 the clever way can be found. With total world food production amounting to less than one million tons of coal equivalent per year, farm waste amounts to about three million, and biomass production in forests to about 50 billion TCE.

To conclude, my analysis of the trends as seen through the optics of energy consumption patterns does not induce pessimism nor optimism. It shows a challenge that is inside 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 resume my view about the best path to the solutions, I shall say: *More bits and less kilowatts.*

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