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Balancing Energy and Food Production, 1975–2000

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For hundreds of years a state of balance between energy and food production has controlled the world food supply. The balance has permitted a well-developed, but essentially solar energy–powered (1), traditional agriculture to produce 1100 kg of food grain per hectare.

This balance is currently being violated by two groups. One of these operates in the affluent nations, and during the past 100 years has developed a technology for mobilizing nonrenewable energy inputs from fossil fuel to increase yields and land use intensity. The other group in violation is the one whose numbers and food needs have, in the past few years, grown beyond the levels that can be sustained by yields of 1100 kg per hectare. The first group cannot continue indefinitely in its present patterns because its energy resources will run out. The second group is facing a more immediate prospect of frequent famine, economic depletion, or both.

In this article we take a worldwide view of various scenarios as population growth impacts with food production capabilities dependent on limited land and fossil energy resources (2).

Food and Energy Today in a World of Balance Violations

Population. World population is increasing at a rate of approximately 2 percent per year. Developing countries are, in general, experiencing rates higher than this world average figure, and Asia, a continent with many developing countries, has more than half of the world's population. Projections of world population indicate increases from 3.86 billion in mid-1973 to somewhere between 6.0 and 7.1 billion in 2000, depending on the assumptions and type of projection used (3).

Food. The world average per capita diet is expected to improve slightly between 1970 and 1985 and then to remain approximately stable between 1985 and 2000 (3). This improved per capita diet, multiplied by the intermediate population projection, indicates that the world requirement for food calories in 2000 will be 88 percent greater (nearly a doubling) than that in 1970.

Production of this 88 percent increase depends on the amount of additional land available for agriculture and on the intensity of use of all agricultural land. Despite the fact that the world's potentially arable land is approximately twice that currently in use, land use projections for 1985 show only a 10 percent increase over 1970 values, with most of the increase occurring in Latin America and Oceania (3).

Although developing countries have traditionally used only small amounts of fertilizer and have had low yields, the impact of Green Revolution technology (4) has been seen in world crop yields since 1967 (Fig. 1). These yield trends, as well as those in developed countries, were used in conjunction with crop land area projections to estimate world food production in 1985 (3). Food production estimates were then compared with both dietary food needs and projections of economic demand (5) for food (Fig. 2).

In 1985, world food calorie production is expected to almost equal economic demand, and the proportion that is actually consumed as food is expected to nearly equal dietary requirements. Protein production, however, is projected to be considerably in excess of dietary needs, even though less than economic demand. The main reason that food calorie production is expected to be more critical than protein production is that recent reevaluations of protein requirements for humans (6) have indicated lower average needs than previously believed necessary. However, certain groups (young children and pregnant and lactating women) were found to have higher protein requirements.

Although world food calorie production and needs may be in balance in 1985 on a world-average basis, geographic distribution of supplies and demands is expected to become more diverse than at present. Asia, which has 20 percent of the world's potentially arable land and 57 percent of the world's population, is expected to become progressively more food-deficient (Fig. 2). North America, in contrast, is expected to become a source of increased food surplus (Fig. 2). Consequently, intercontinental food shipments are expected to more than double between 1970 and 1985, in continuance of a trend evident since 1960 (7). Food imports are expected to supply 6 percent of the calories consumed in Asia in 1985 (3), which is a proportion sufficient to closely link food prices in Asia to those in the world market.

Energy. Not only is population increasing, but per capita energy consumption is increasing exponentially with time (Fig. 3). This is in contrast to per capita food requirements, which are expected to be static with time after 1985. Also, there is a wide diversity among world regions in both energy use levels and rates of increase in per capita consumption. Projections, therefore, show great increases in world energy use with time, as well as large increases for high-level users and small increases for low-level users.

A breakdown of the 8.16×10^6 kcal

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used to provide food for an average U.S. resident in 1963 (*8, 9*) indicated that 10 percent of this amount was embodied in farm inputs and an additional 7.9 percent was used directly on the farm. This energy to produce products leaving the farm gate (1.46×10^6 kcal per person per year) was approximately equal to the food energy derived from these products (1.27×10^6 kcal per person per year). If all the world had the same per capita energy bill for the entire food chain (about four times the total per capita energy use in Asia), a quantity equal to two-thirds of the 1970 world commercial energy use would have been consumed for this purpose.

In North American style agriculture, energy for fertilizer production and for irrigation (where used) are the major items on the energy bill. California has a predominantly irrigated agriculture and of the energy used there for crop production and transport in 1972 (excluding processing and energy embodied in production facilities) 22 percent was used for fertilizer production and 44 percent was used for irrigation (this includes energy rejected in generating the electricity used in irrigation) (*10*). In the production of unirrigated grain and corn (maize) in Canada, energy use for fertilizer manufacture constituted 46 and 57 percent, respectively, of the energy consumed to get these products to the farm gate (*11*).

Because of the large proportion of energy requirements needed for fertilizer production, and because world consumption of fertilizers is expected to increase, attention to energy use for food must first be focused on energy use for fertilizer production. Production of nitrogen fertilizer requires several times as much energy per unit of plant nutrient than does production of P_2O_5, the next most energy-intensive primary nutrient. Since nitrogen makes up nearly half of the fertilizer nutrients produced, energy requirements for nitrogen fertilizer production are of primary concern.

The major and most convenient energy source for nitrogen fertilizer production is natural gas. Approximately 2 percent of the U.S. natural gas consumption is used for this purpose, and about 5 percent of world consumption is so used (*3*).

World energy supplies. Of the three main fossil fuels, natural gas is the one in shortest supply. Furthermore, of these three fuels, natural gas has the highest rate of expansion of use (4.7 percent per year) (*3*). The U.S. natural gas situation is such that if use is decreased as exhaustion of the total supply is approached, half of the U.S. supply will be depleted

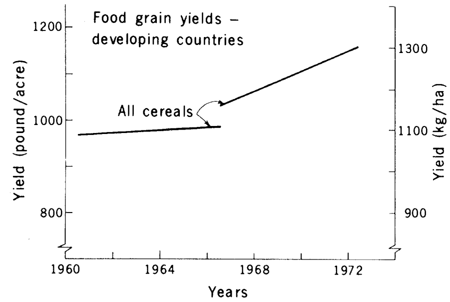


Fig. 1. Linear regressions of cereal yields against time for developing countries for the periods 1960–1966 and 1967–1972. The increase slope shown between 1967 and 1972 is due to the increase in use of Green Revolution technology. [Data from (*24*)]

by 1980 (*12*). If use continues to increase exponentially, near-total depletion will occur only a few years after that. It is therefore expected that the price-supply interaction for natural gas will have a major impact on nitrogen fertilizer price and availability within 10 years.

World petroleum resources are only slightly less critical relative to demands than is the case for natural gas (*12*). Naphtha from petroleum refining is the second most common energy source for nitrogen fertilizer production.

Of the three main fossil fuels coal has the most ample world supply; however, half of the coal resources may be consumed within the next 150 years (*12*).

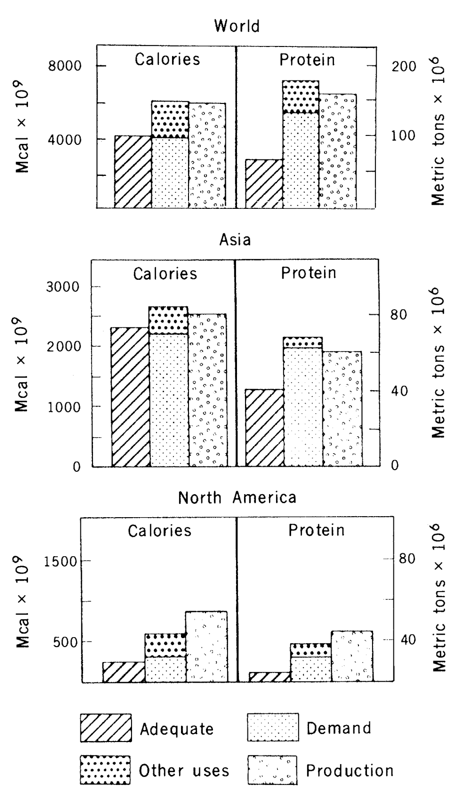


Fig. 2. Projected food balances for 1985. "Other uses" include seed, waste, and nonfood industrial use. [Adapted from (*3*)]

Elements of the Dynamics Linking Food and Energy

Today's status of food and energy balances is, in a number of respects, the result of dynamic factors operating over the past years. These and similar factors will influence changes in the coming 25 years, which may, or may not, lead to improved food and energy balances.

Population. Population growth rates have been increasing during the past 50 years because the world death rate has been decreasing notably, due to improved public health and medical measures, whereas the world birth rate has declined only slightly (Fig. 4). It thus appears that world population control depends on reducing birth rates. Factors linked to economic living levels seem to influence birth rates (Fig. 5).

An encompassing statement on the dynamics of world population was provided by Roger Revelle (*13*). He explained that the poorest 60 percent of the world's population generates most of its population increase; to slow population growth, conditions for these people must be improved. Raising the status of women, reducing unemployment, improving health care, especially for children, raising the level of human capital that a family invests in a child, equalizing income and land distribution—all these reforms are likely to make the birth rate drop. It seems that fertility decreases as people gain more control over their own lives.

Structural transformation. Structural transformation is the phenomenon in which each production unit specializes in the efficient production of a limited number of products. These products are then shared among all users at prices reflecting the efficiency of their production.

Structural transformation is thus in contrast with the type of subsistence agriculture in which each farm family makes and does all things required for its existence. Structural transformation of U.S. agriculture has permitted a three- to fourfold increase in the efficiency of food production. This gain in efficiency in producing the most resource-consuming of human necessities has released a great amount of surplus productive capacity for use in other pursuits.

One of the main contributors to the great efficiency increases brought by structural transformation is the formation of institutions that channel surplus productive capacity into the mobilization of both material and energy resources to enhance fundamental human productivity. This enhanced productivity leads to even greater surpluses, and consequently to accelerated use of material and energy resources. As a result of this mutually amplifying circuit connecting energy use and productivity, nations having high per capita levels of one necessarily have high per capita levels of the other (Fig. 6).

The use of natural material resources and the natural sinks to which they are disbursed is linked to productivity levels by the same system that joins energy use and productivity. Similarly, use of material resources (especially at their costs of extraction rather than at costs of reconcentration from natural sinks) enhances apparent productivity. Thus, structural transformation, with its surpluses of productive capacity and its mobilization of energy resources, has permitted exponential acceleration of the use of finite natural material resources. One projection (*14*) in which current exponential rates of use are extended until five times known world reserves are consumed, gives the values shown in Table 1 for the number of years (after 1975) until total resource depletion.

Energy resources, on the other hand, can be used to reconcentrate materials from natural sinks for reuse. The most common natural systems of this type are the hydrologic cycle (using about 23 percent of the solar energy received by the earth) for recycling water, and photosynthesis for recycling carbon and oxygen. An important man-made system of this type is the one that recycles about 20 percent of the nitrogen used by crop plants worldwide (about 40 percent in the United States). Unfortunately, the energy resources used in this system are of the nonrenewable type.

Substitution of energy for land. The use of fertilizers, particularly nitrogen fertilizer, permits crop quantities to be harvested from 1 hectare that might require several hectares if these fertilizers were not used (Fig. 7). Although nitrogen fertilizer use is very extensive in developed countries, Green Revolution technology has provided genetic strains of crop plants which, in developing countries, respond with the same large yield increases when fertilizers are applied and water management is improved.

One irrigated hectare can also produce the yield of several hectares with inadequate moisture. Furthermore, irrigation can increase multiple cropping and bring unused land into production.

Mechanical power can be substituted for cropland used to feed draft animals, and can permit development for agriculture of some land that would otherwise be unusable.

In all these ways, energy, in the form of nitrogen fertilizer, power-driven pumps, and engine-powered traction, can be substituted for the additional land otherwise required to produce increased amounts of food each year. A quantitative estimate of the effect of implementing this substitution is as follows.

For a traditional agriculture producing 1100 kg of food grain per hectare the amount of energy required for fertilizer manufacture and irrigation pumping to achieve an increase in on-farm production equivalent to one additional crop per hectare per year is approximately 1.74×10^6 kcal (*15*), while about 0.453×10^6 kcal would be required to produce enough food for one additional person at the average Asian diet of 0.952×10^6 kcal per person per year. This figure represents about a two-to-one return of food energy for nonfood energy. At this rate, on-farm production of a year's supply of food for three people can be obtained from the energy in 1 barrel of crude oil—all without increasing cropland area.

The case of developing country X. To illustrate the dynamic interaction linking food, energy, and money, the case of a hypothetical developing country of typical circumstances may be investigated. It might be assumed that in country X 20 percent of the food requirements are being met by farmers using Green Revolution technology, there is available only limited foreign exchange, and half of the fertilizer supply is imported.

If a 100 percent increase in fertilizer prices occurs, the following sequence of events may take place.

1) Because of limited foreign exchange, fertilizer purchases must be halved, reducing total fertilizer supply to 75 percent of the original level.

2) Farmers using Green Revolution technology bid up the price of fertilizer, discouraging other farmers from trying this practice.

3) The total food grain supply drops 2½ percent, but since farm families consume half the country's food, the shortfall in marketable surplus is 5 percent.

4) Persons anticipating the shortage enter the market trying to buy advance food supplies, consequently driving food prices up to perhaps double their original level.

5) Persons with low incomes who must buy food are forced to starvation-level diets.

6) The government, in order to prevent starvation, buys grain on the world market and sells it internally at low prices.

7) Grain purchases consume the limited foreign exchange reserves being accumulated for energy resource development and fertilizer plant construction.

Food prices in such developing countries become linked to international energy, fertilizer, or food prices irrespective of the productive capacity of the people. With energy prices dependent on what the market will bear, affluent economies,

Table 1. Number of years until total resource depletion based on current exponential rates of use (*14*).

Material	Years to depletion	Material	Years to depletion
Aluminum	52	Molybdenum	62
Chromium	151	Natural gas	46
Coal	147	Nickel	93
Cobalt	145	Petroleum	47
Copper	45	Platinum (group)	82
Gold	26		
Iron	170	Silver	39
Lead	61	Tin	58
Manganese	91	Tungsten	69
Mercury	38	Zinc	47

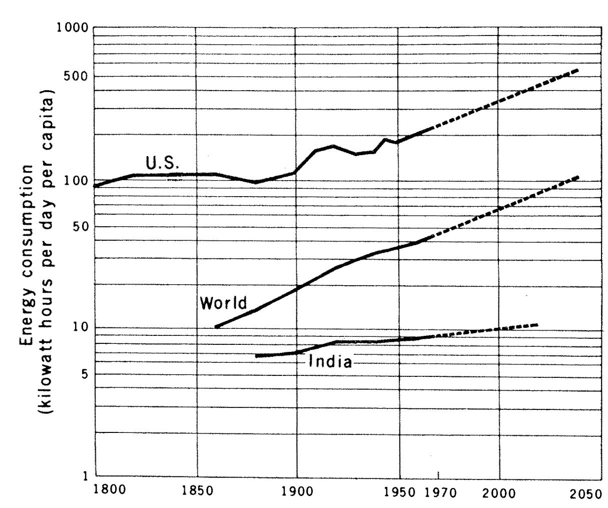


Fig. 3. Trends in per capita energy consumption in the United States, India, and the world. Note the exponential upward trend (on this semilogarithmic plot) in all cases and the lower slope for India. [Adapted from (*25*)]

Table 2. World land use and annual potential photosynthetic product. Values for 1966 are from (*20*).

Use	Land use				Potential photosynthetic product	
	Percentage		Hectares ($\times 10^8$)			
	1966	Future	1966	Future	$\times 10^7$ kcal/ha	$\times 10^{15}$ kcal
Tilled land	10.6	15.0	14.3	20.2	17.7*	358.3
Pasture	21.3	19.0	28.5	25.5	1.77	45.4
Forest	29.9	27.8	40.2	37.3	3.55	132.0
Other	38.2	38.2	51.2	51.2		
Total	100	100	134.2	134.2		535.7†

*The source (*21*) includes all aboveground combustible plant parts (half of the weight of which can provide edible food energy). This value may be compared with the world annual insolation of 1682×10^7 kcal/ha. †This amount divided among 8 billion persons is 67×10^6 kcal per person per year.

which are already dependent on high energy use and stand to incur great losses if energy flow is cut, can afford to bid energy prices up to very high levels. One recent economic model of California agriculture shows shadow prices (profit reduction per unit constraining resource withdrawn from the system) of diesel fuel of around $550 per barrel (*16*). The impact of all this is basically to prevent countries such as X from using or expanding the use of Green Revolution technology.

When starvation is imminent, food aid or food sales on concessional terms is a humanitarian necessity. However, these programs, which may become politically and economically popular in developing countries, frequently tend to hold food prices within the country at low levels. This tends to have the effect of discouraging local farmers from increasing their production at times when additional marketable surplus is critically needed.

The tenuous situation associated with food shortages, the need for concessional financing, food supply chains thousands of miles long, food prices dependent on energy markets in distant countries, and need for imminent starvation before food relief can begin, just do not contribute to people feeling that they have more control over their own lives—an apparent prerequisite for fertility rate decline.

Is There Any Possibility for Food and Energy Balance?

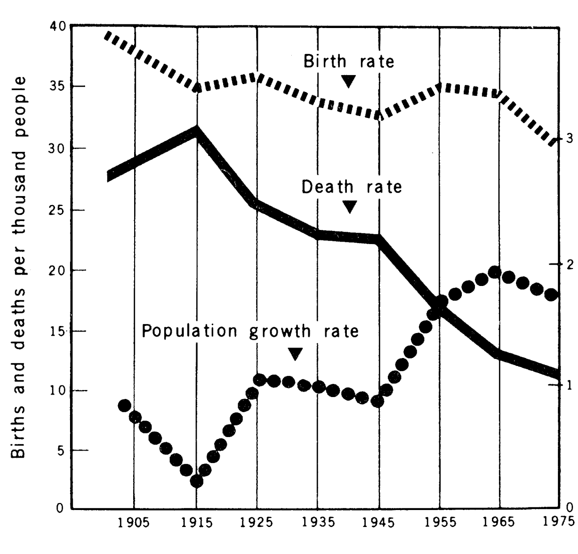
There are three favorable signs indicating the possibility of achieving key elements required for balance.

1) Zero population growth. Recently, in the United States, the total fertility (average number of children born per woman) has dropped from 3.77 in 1957 to 1.86 in 1974 (*17*). (A similar drop has occurred in a number of other developed countries.) If a ratio of 2.11 (or less) can be maintained, population growth in these countries will finally cease in the future. The fact that this ratio can be achieved on a mass national basis is a source of encouragement.

2) Limited per capita resource consumption. Although consumption of material resources seems to be growing at exponential rates, studies of key material resources in economically developed countries (*14*) indicate that there may be a limit to the amount of a particular material resource that a person can or will consume—irrespective of the amount of productivity or income he has available for it (*18*). This, in combination with zero population growth, presents at least the possibility that the world rate of material resource use will someday reach a stationary level.

3) Zero energy growth. Despite the fact that U.S. energy use is high and exponentially increasing, a recent study (*19*) has considered a policy scenario for the United States that would lead to zero energy growth by approximately 1990. Detailed examination of this possibility indicated that concerted economic, social, and physical programs would be required, but that such a goal was achievable. Furthermore, this scenario would not lead to economic depression, but would entail future levels of the gross national product (GNP) and employment similar to those anticipated with higher levels of energy use and expansion.

A possible state of balance. It is proposed to investigate here the possibility of a new state of balance between food and energy—a balance at a higher standard of living than is afforded by 1100 kg of grain per hectare, and to be achieved



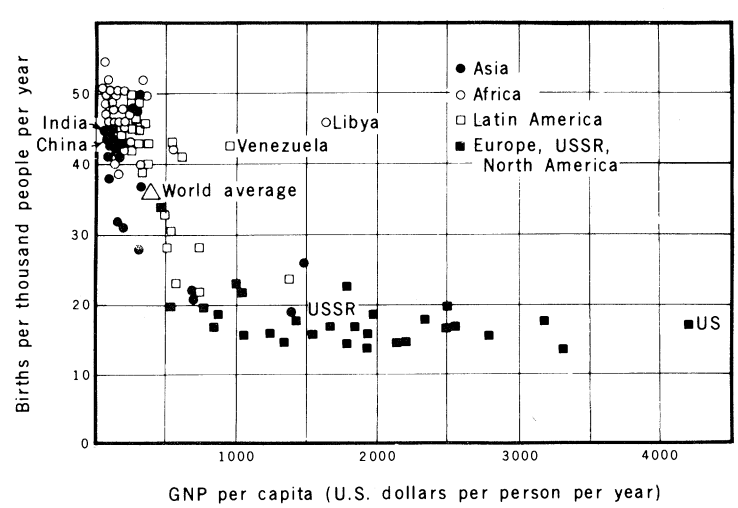


Fig. 4 (left). World trends of birth rate, death rate, and the difference between the two, which is the rate of population growth. Current high levels of population growth are mainly due to a sharp trend toward reduction of death rates in the past 40 years, whereas birth rates have declined only slightly. [Adapted from (*13*)] Fig. 5 (right). Correlation of figures from various nations for per capita GNP and birth rate. Most countries having per capita GNP values above $800 per year tend to have low birth rates. [Adapted from (*14*)] sometime between 2050 and 2200. The two key elements of the potentially balanced system are:

1) Cessation of population growth by the time there are about 8 billion people on the earth (approximately 2050).

2) Provision of all energy by our only renewable source—the sun.

There is adequate potential for deriving all energy needs from the sun. In 1970, the annual human use of commercial energy was 52.9×10^{15} kcal, whereas the annual solar energy incident at the earth's surface was $876{,}960 \times 10^{15}$ kcal. Global photosynthesis was able to convert 605×10^{15} kcal of this solar energy annually (*20*).

Table 2 shows a possible arrangement for harvestable photosynthetic product based on (i) the distribution of solar energy on the earth's land areas during months that have mean temperatures of more than 10°C (*21*), (ii) the application to all land areas of a future land use breakdown based on modification of the 1966 status (*20*), and (iii) photosynthetic capture efficiencies of approximately 1 percent for tilled lands (*21*), 0.2 percent for forests (*22*), and 0.1 percent for pasture lands.

If only the mechanism of photosynthesis were used to capture solar energy for human use, there might be available 535.7×10^{15} kcal annually—about ten times the 1970 level. If the energy were divided equally among 8 billion people, the amount available per capita would be 67×10^{6} kcal annually—slightly less than the 1970 U.S. per capita consumption level, but more than four times the 1970 world average per capita consumption.

If half of this energy were to be used for recycling material resources from natural sinks for reuse, the energy remaining for discretionary use would be 33.5×10^{6} kcal per person per year. This amount correlates historically with annual per capita GNP levels of approximately $2150 (see Fig. 6).

If a world average annual per capita GNP of $2150 is considered relative to the historical relationship between birth rate and GNP (see Fig. 5), it would be likely that the average world birth rate might be much lower than the current rate. Of critical importance here is the distribution of energy use and productivity (GNP) among the people of the world. Even with a world average annual per capita energy use of 33.5×10^{6} kcal and a GNP of $2150, if a sizable proportion of the world's population were to fall below 40 percent of these average levels (13.4×10^{6} kcal and $860 per capita annually), it would be unlikely that it would be possible to have a stabilized world population (see Fig. 5 at a GNP of $860). In 1970, about 63 percent of the world's population lived in countries or regions for which the annual per capita levels of energy use (*3*) and GNP (*23*) were less than 40 percent of the world average. Thus, if a balance is to be achieved there must be major reductions in disproportionate levels of energy use and productivity achieved throughout the world.

Once population growth can be halted, the time remaining to adequately mobilize for a fully solar energy–powered world will be a function of the ability of people, particularly in the affluent countries, to reduce rates of increase of energy and material resource consumption. Energy supplies from coal may be adequate for this transition period, or at least until a nuclear energy technology with fewer physical-social interaction problems can be developed to complete the transition period.

The timing of steps to implement action toward the achievement of a balanced state is critical. An extensive project modeling the world situation (*14*) first examined prospects based on cur-

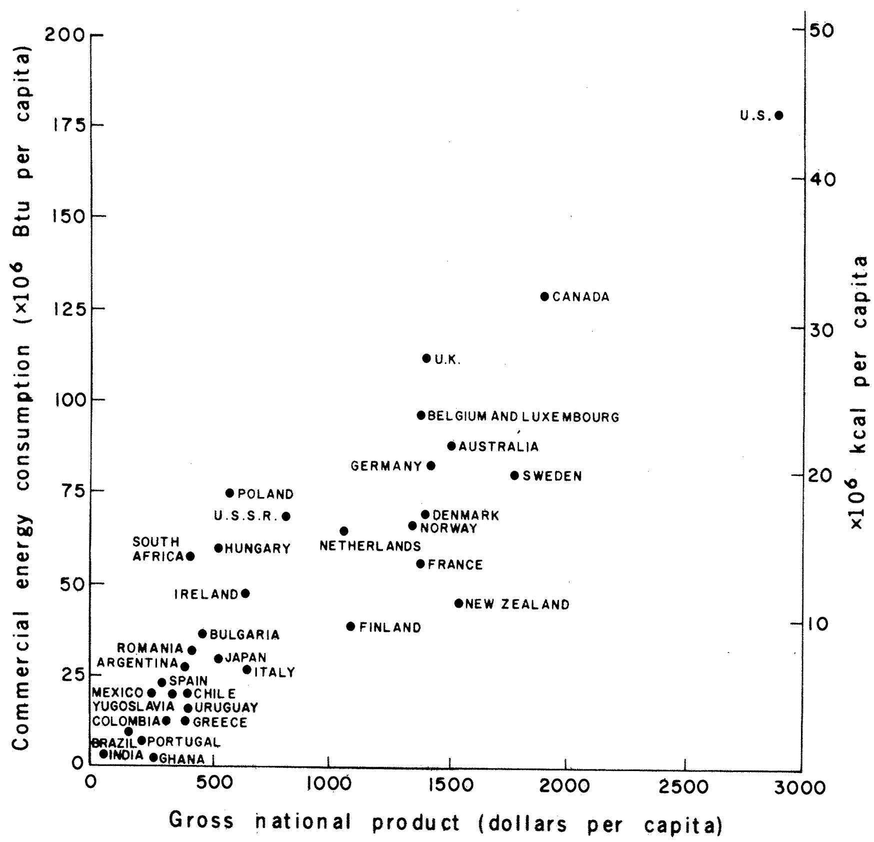


Fig. 6. Correlation of annual per capita figures from various nations for GNP and commercial energy consumption. Note that most points fall close to a common line of correlation. [Adapted from (*26*)]

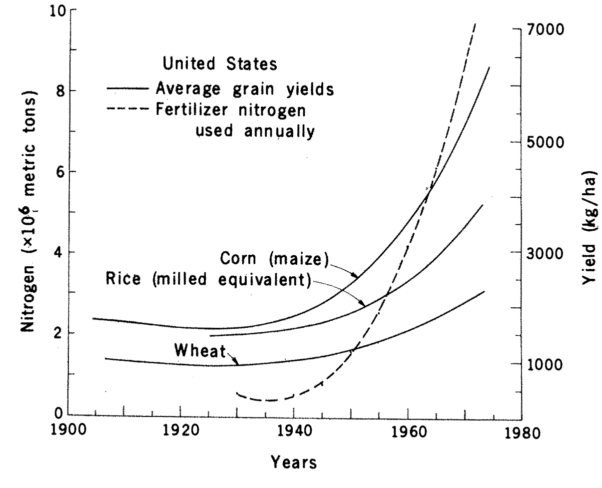


Fig. 7. Polynomial regressions of grain crop yields and fertilizer nitrogen use (metric tons) against time. In the late 1930's, U.S. food grain yields were about the same as those of any other traditional agriculture—1100 kg/ha. The increase in yields since that time is linked to nitrogen fertilizer use. [Data from (*27*)]

rent exponential trends of population and resource consumption growth. The results showed a rapid depletion of resources and an increase of pollution leading to severe depression of living conditions in the 21st century.

When the model was modified to incorporate in the year 1975 the following changes: (i) zero population growth fertility rates (two children per family), (ii) capital investment set equal to depreciation, (iii) a 75 percent reduction in pollution, and (iv) high capital investment in an agriculture in which there was extensive recycling of materials, a reasonable stability was achieved at high levels of food and industrial output per capita.

However, when these same four changes were instituted in the model in the year 2000 instead of 1975, the equilibrium state was no longer sustainable, and resource depletion caused per capita food and industrial production to decrease rapidly from a high level, starting in about 2050. The drop in population due to impoverishment was projected to begin about 50 years later.

It can thus be concluded that the key to the system of balance is stopping population growth, and the necessary goal must be a solar-powered world. The time to use this key and set out toward this goal must be now—otherwise there may be no such thing as a calamity-free balance between energy and food.

References and Notes

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Surface Modulation in Cell Recognition and Cell Growth

Some new hypotheses on phenotypic alteration and transmembranous control of cell surface receptors.

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Developmental biologists have long recognized that the evolution of metazoan organisms required the development of special mechanisms to coordinate cell division, cell movement, and cell-cell interactions. Although the precursors of these mechanisms undoubtedly existed in unicellular organisms, the particularly stringent requirements for stable specialized functions within the tissues of multicellular organisms demand much stricter regulation of cellular social behavior and conformity. Nowhere is this more evident than in the patterns of embryonic development of higher organisms (*1*). Even after their removal from mature organisms, cells growing in tissue culture show contact inhibition of movement and density-dependent regulation of growth (*2*). These phenomena reflect the presence of intrinsic phenotypic mechanisms of control that can be genetically altered by transformation of normal cells to tumor cells. The products of such a transformation must affect the various regulatory mechanisms concerned with both cell interaction and cell growth.

All these phenomenological observations point up a problem in the phenotypic behavior of cells that is not simply resolved by such notions as sequential gene programming during development (*3*). This problem is to determine the nature of those cellular structures that regulate division, movement, and cell-cell recognition in such a fashion as to give rise to tissues and organs. It is possible that this complex problem does not have a simple solution despite the evidence suggesting that the cell surface is a major component in the regulatory events (*1*). For example, cell division, movement, and interaction may be under separate regulation by unrelated structures which, like parallel processors in a computer, are coordinated with each other by separate mechanisms at key points in their cycles.

It is my purpose here to propose, on the contrary, that while cell recognition

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