Reading
Energy and Crop Production

Our industrialized society feeds greedily and insatiably on energy made available by burning fossil fuels—coal, petroleum, and natural gas. This stored energy was captured from the sun eons ago by plants whose remains became buried deep in the earth's crust. These fossil fuels are of course limited, and the efficiency with which we use them, which depends on our level of technology, will determine our standard of living for some time to come. Although we obtain some energy from water power and increasing amounts from nuclear reactors, the amounts obtained from these sources are still insignificant on a world basis. The world energy use is equivalent to the consumption of 4.8 billion metric tons of coal annually. Dividing this figure by the earth's estimated population of 4.6 billion gives an energy equivalent of 1.04 metric tons of coal per capita per year.

To compare the energy costs of today's technology with those required for primitive cultures is revealing (Fig. 1). In primitive agricultural societies, of which there are many in the world even

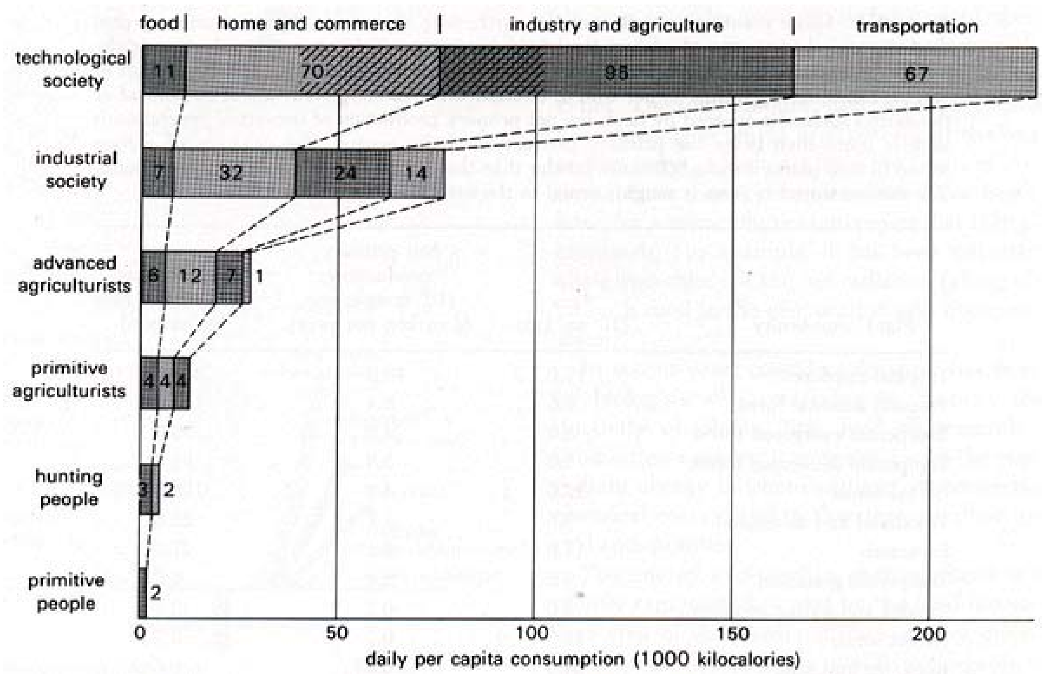


Fig. 1. Daily consumption of energy per capita was calculated for 6 stages in human development. Primitive people (East Africa about 1,000,000 years ago), without the use of fire, had only the energy of the food they ate. Hunting people Europe about 100,000 years ago) had more food and also burned wood for heat and cooking. Primitive agriculturists (Fertile Crescent in 5000 BCE) were growing crops and had gained energy by putting animals to work. Advanced agriculturists (northwestern Europe in AD 1400) had some coal for heating, some water power, wind power, and animal transport. Industrial people (in England in 1875) had the steam engine. Today technological people (in the United States) consume an average of 243 kilocalories per person per day, much of it in form of electricity (hatched area). Food is divided into plant foods (far left) and foods fed to animals. [After E. Cook, The Flow of Energy in an Industrial Society. Copyright © 1971 by Scientific American, Inc. All rights reserved.]

today, a total of 12 kilocalories of energy is required by each person per day. Compare this with the 243 kilocalories required per day by each member of a medium income family in the United States, and we find that our standard of living requires 20 times as much energy. Obviously, it is the affluent nations that are creating today's energy problems (and, Consequently, today's pollution problems as well).

Each day every human being consumes, on the average, the equivalent of 0.82 kilograms (1.8 pounds) of plant material containing 0.32 kilograms (0.7 pounds) of carbon. This is about 118 kilograms (260 pounds) of carbon per person annually, which amounts to a world total of about 0.5 billion metric tons. Most of this food is produced from cultivated land, but the oceans, other bodies of water, forests, and savannahs are important in developing countries. The primary production of the major plant communities of the world is listed in Table 1.

Table 1 Major plant communities of the earth, with their area, their net primary production, and the amount of carbon they hold in storage. Net primary production is the amount of carbon a plant community provides annually for harvesting or for the support of various consumer organisms, either wild or domesticated. Although only about 30% of the earth's surface is covered by land, the net primary production of terrestrial vegetation is slightly more than twice the primary production of the oceans. The quantity of carbon stored in land plants is some 500 times greater than the quantity stored in marine ecosystems. The carbon stored in trees is roughly equal to the carbon in the atmosphere.

Plant community	Area (106 km^2)	Net primary production (109 tonnes carbon / year)	Plant mass (109 tonnes carbon)
Tropical rainforest	17.0	16.8	344.0
Tropical seasonal forest	7.5	5.4	117.0
Temperate evergreen forest	5.0	2.9	79.0
Temperate deciduous forest	7.0	3.8	95.0
Boreal forest	12.0	4.3	108.0
Woodland and shrubland	8.5	2.7	22.0
Savannah	15.0	6.1	27.0
Temperate grassland	9.0	2.4	6.3
Tundra and alpine meadow	8.0	0.5	2.3
Desert scrub	18.0	0.7	5.9
Rock, ice and sand	24.0	0.03	0.2
Cultivated land	14.0	4.1	6.3
Swamp and marsh	2.0	2.7	13.5
Lake and stream	2.0	0.4	0.02
Total continental	149.0	52.8	826.5
Open ocean	332.0	18.7	0.45
Upwelling zones	0.4	0.1	0.004
Continental shelf	26.6	4.3	0.12
Algal bed and reef	0.6	0.7	0.54
Estuaries	1.4	1.0	0.63
Total marine	361.0	24.8	1.74
World total	510.0	77.6	828.0

Because of the inefficiencies involved, 4.1 billion metric tons of carbon must be produced each year to supply the amount actually consumed. The difference between the amount consumed and the amount produced is due to a number of factors. On the average only about 20% of the cultivated plant is eaten—for example, the grain constitutes only 28% of the dry weight of the wheat plant. Further, one-half of the plant material produced on cropland is consumed by animals, and only 3% of this stored energy ends up as human food. Losses to pests and diseases account for one-third of the total production. On the average only 1–2%, or less, of the total energy from the sun is utilized in fixing the carbon in plants, although some plants, such as corn and sugarcane, are somewhat more efficient. In the end, to produce the 0.36 billion tons of carbon per year needed at present to sustain the human population, 50 to 100 times as much energy is required as is used for all other human purposes.

Basically, agriculture is concerned with the conversion of solar energy to energy usable by people–for food, fiber, and fuel. Sadly, the average technology employed in the world's agriculture is insufficient to meet the immediate needs of our expanding populations. Fortunately, some cultures have developed intensive techniques so that a few people are able to produce the food required by hundreds of others. To increase agricultural production and efficiency, we need to be concerned with all phases of energy transformation–from the sun to the supper table.

CROP ENERGETICS

The problem of understanding and quantifying the total energy balance at the surface of the earth has been of concern to meteorologists for many years. They have become interested in how much of the sun's radiant energy is used for the evaporation of water, how much is reflected back to the sky, and how much is diverted into various other channels (Fig. 2). This accounting process is a matter of "balancing the energy budget" and is a bookkeeping procedure in every sense of the word, although much more complex than the business accountant's double-entry system. Precise and ingenious instrumentation has been devised to measure the energy flux at the surface of the earth and to determine how the total energy budget balances. This

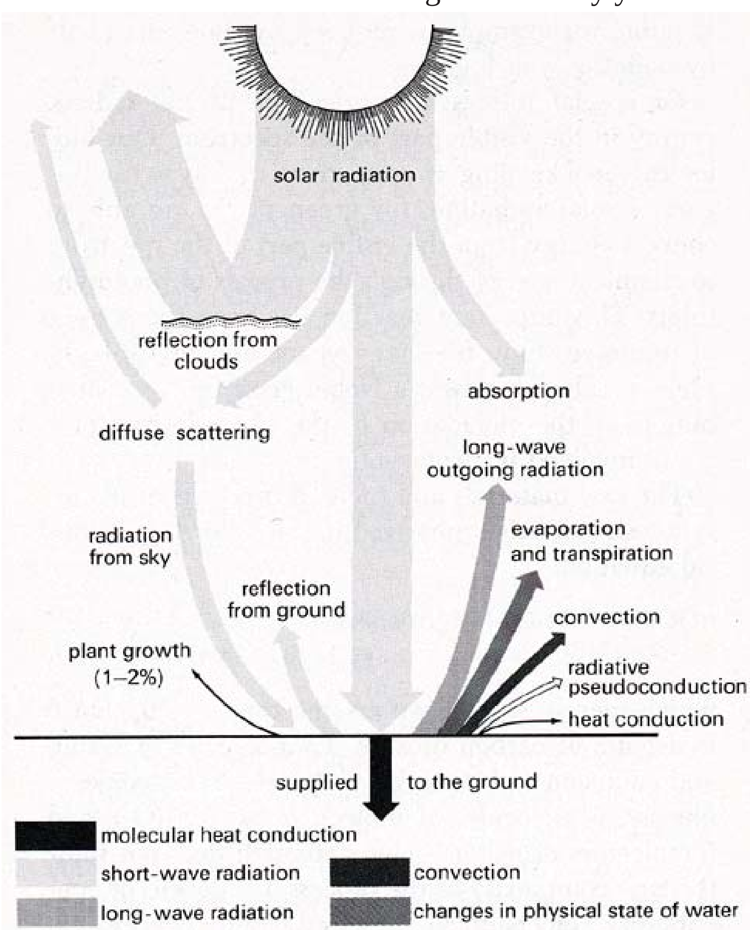


Fig. 2. Energy exchange at noon on a summer day. The width of the arrows indicates relative amounts of energy transferred. Note that plant growth accounts for a very small part of the total energy budget. [After R. Geiger, The Climate Near the Ground, Harvard University Press, 1950.]

objective of meteorology is of more than academic interest, for it relates directly to water availability for human needs. Unfortunately, the amount of energy captured by plants is so small that meteorologists seldom take it into account. The total amount used in photosynthesis usually amounts to only 1 or 2% of the total solar energy input, which is within the limits of computational error. Energy requirements have been calculated for various physical processes that take place in croplands. For example, it has been estimated that about two thirds of the net radiation falling on vegetation is used in the evaporation and transpiration of water.

In recent years considerable work has been done by biologists who are trying to quantify the productivity of plants. This field of research, called **production ecology**, is concerned with the capture of radiant energy in photosynthesis, its conversion into chemical energy, and its flow through plant and animal communities.

The energy captured in photosynthesis is conveniently represented in part by the total biomass on a unit area of the earth's surface at any given time. **Biomass** merely refers to total living organic matter, usually on an oven-dry-weight basis, but for some purposes it may also include nonliving materials, such as bark, wood, cuticle, and resinous deposits. Even though a crude measure, biomass is useful for making comparisons of different crops and different land areas. The amount of organic matter present is only a partial measure of production, because respiration requires a high proportion of carbohydrates, which are part of the total or gross production.

Photosynthetic Efficiency

Every year, an average of 263,000 langleys* of solar energy is received at the outer edge of the earth's atmosphere. Of this, approximately 123,000 langleys of energy is either absorbed or reflected back into the atmosphere by molecules, water vapor, and dust, while the balance of 140,000 langleys actually reaches the surface of the earth. In terms of energy values one square meter of the earth's surface will intercept in one day the amount of energy required daily by an active person. This tremendous input of energy is potentially available for use by plants and animals. But solar radiation is not uniformly distributed over the surface of the earth. It varies with cloudiness, the amount of dust in the atmosphere, latitude, altitude, local topography, season, and time of day (Fig. 3).

It is interesting to compare the input of solar energy per unit area of land surface at various places on earth. In the United States the average amount of solar radiation received per day is 300 langleys and varies from about 100 to 800 langleys depending on season and region. At the University Experiment Station in Alaska, the total annual input of radiation is about 17,920 langleys during the course of a 64-day frost-free season. In Miami, Florida, where the growing season lasts about 10 months, more than 132,300 langleys of solar energy is available. The great difference in solar input between tropical and temperate regions is not indicative of the actual productivity, however, for many other factors must be taken into account. The effects of air pollution must not be overlooked in heavily populated or industrial areas. Total sunlight reaching the ground in and around London, for example, is reduced by more than half by pollution and fog.

Of special interest to agriculture is the radiant energy in the visible part of the spectrum. Our biological bookkeeping is concerned mainly with this part of solar radiation, for green plants are

*1 langley = 1 gram calorie per square centimeter. One gram calorie is the amount of heat energy necessary to raise the temperature of 1 gram of water by 1°C (specifically from 14.5 to 15.5°C); 1 kilocalorie = 1000 gram calories.

able to convert energy from the visible part of the spectrum to chemical energy through the process of photosynthesis. This important reaction has been the subject of intensive study for many years, and in 1961 Dr. Melvin Calvin received a Nobel Prize for his contributions to the elucidation of the physiological processes involved in photosynthesis.

The raw materials and the end products of photosynthesis can be summarized in the following chemical equation:

$nCO_2 + 2nH_2O$ + light energy — $(CH_2O)_n + nH_2O + nO_2$

which merely says, if we assume that $n = 6$, that 6 molecules of carbon dioxide, 12 molecules of water, and sufficient light energy will yield 1 molecule of glucose, 6 molecules of molecular oxygen (0_2), and 6 molecules of water.* This statement does not show the true complexity of the process, for dozens of contributory biochemical processes and energy exchanges take place during the photosynthetic process.

The 673 kilocalories of energy required by this reaction is released as heat when the molecule of glucose is burned by the plant to fuel its life processes (or by the animal that eats the plant). Because of the inefficiencies of the numerous reactions involved in photosynthesis more than 2 or 3 thousand kilocalories of energy is required for each molecule of glucose produced. Under special laboratory conditions experiments on the efficiency of the chlorophyll molecule in converting light into chemical energy have shown efficiencies as high as 75%, whereas estimates based on short term experiments with growing plants show efficiencies that range from 15 to 22%. (In diffuse light cultures of algae have reached efficiencies of 20-50%, but this range drops to 2–6% when large tanks are used). Under field conditions the overall efficiency of crops over extended time periods is only a few percent.

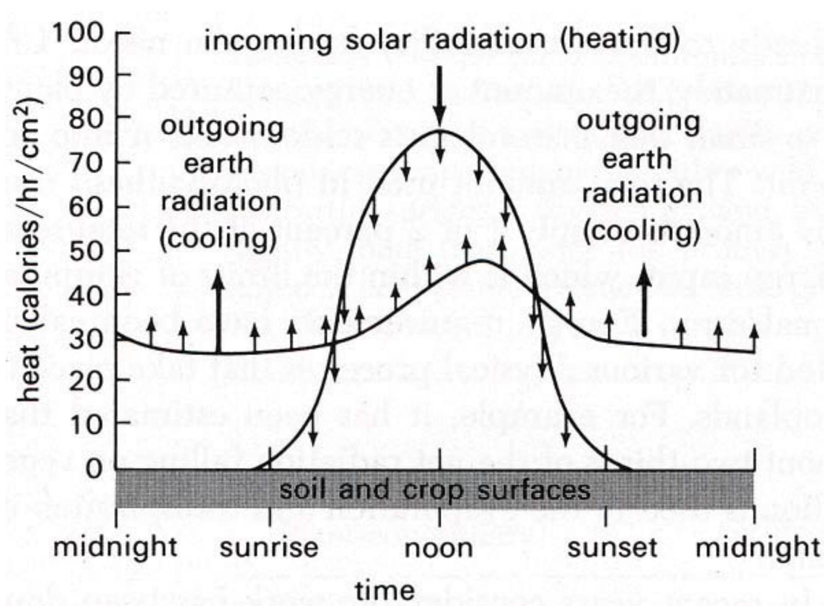


Fig. 3. Incoming energy is balanced by losses. Gains exceed losses during the day; the reverse is true at night. [After J.E. Newman and B.O. Blair, Crops and Soils Magazine, June-July 1964.]

*Although photosynthesis usually involves the reduction of carbon dioxide and the splitting of water to form sugars, some primitive organisms carry on variations of this process. Purple sulfur bacteria, for example, use H_2S rather than H_2O and produce elemental sulfur rather than oxygen. The equation for photosynthesis, therefore, can be generalized as follows:

$$nCO_2 + 2nH_2X + \text{light energy} — (CH_2O)_n + nH_2O + 2nX$$

Here H_2X is a compound that donates electrons; X may be either oxygen or sulfur. Light supplies the energy required to separate hydrogen from its donor.

The solar energy used by plants is derived only from wavelengths between 390 and 760 nanometers, the portion of the electromagnetic spectrum that we perceive as visible light. When captured by plants the energy is incorporated in the molecular bonds of many different kinds of compounds. Because all chemical bonds are not of equal strength, different compounds may possess different energy levels. Some, such as cellulose, are terminal structural products. Others, including starches and oils, function as intermediate storage compounds and may be converted to other forms, subject to demand by metabolic "messengers." Sugars are not only mobile transfer products, but are used almost immediately in respiration, the biological combustion of energy-rich carbon compounds. In a gross manner, respiration can be characterized as the reverse of the simplified photosynthetic equation. Of the energy released and made available by respiration, part is lost as heat and part is utilized in biosynthesis and chemical work. To a large extent the net amount of energy incorporated into organic matter represents the difference between photosynthesis and respiration. Transfers of energy from one compound to another within the plant are handled by special energy carriers such as adenosine triphosphate (ATP). This flow of energy is a specialized part of the energy concept, and is receiving much attention from biologists.

One important factor that determines the actual photosynthetic efficiency of a leaf is the manner in which the rate of photosynthesis changes with light intensity. The rate of photosynthesis changes with light intensity only up to a certain point. At this intensity it is convenient to say that the leaf is **light-saturated**.

Although photosynthesis increases with increasing light, it does so at a decreasing rate, and the efficiency of light capture consequently decreases. In fact, maximum efficiency can be obtained only under relatively low light intensities. When intensities are high, relatively more light passes through leaves and is reflected from them. At low intensities a high proportion of light may be absorbed and used. For short periods of time efficiencies of 7-10% are possible for some crop plants, but efficiencies of 2–3% are probably the most that can be expected over extended periods of time, even if temperature, carbon dioxide, water, and mineral elements are optimal.

Even though less efficient, total production is still greater at high intensities. Although photosynthesis in a single leaf may level off at about 3,000 foot-candles, the rate of photosynthesis in the whole plant may continue to increase up to 10,000 foot-candles because more light reaches the lower leaves, which are shaded.

Light may pass through only a few layers of leaves in low crops but may pass through as many as 15 or 20 layers in tropical forests, where 95% of the light may be absorbed before reaching the ground. Sugar beet leaves have a vertical distribution of about a foot, whereas in forests the distribution may extend more than 300 feet. In natural forest stands the amount of light reaching the lower leaves is below the **compensation point—**that light intensity required to maintain a rate of photosynthesis equal to the rate of respiration. Lower branches may actually persist at the partial expense of the upper ones, which supply them with some carbohydrates, and thus such lower branches have been called "negative branches."

Low crops, with leaves in a relatively narrow zone close to the ground, seem to be more efficient producers than forests, in which leaves are spread over a wide range of heights. This is probably because in low crops a smaller percentage of leaves is exposed to light below the compensation point. Moreover, trees have a more extensive transportation system through which the compounds move, and the construction and maintenance of the "plumbing system" and the movement of compounds through it requires much energy.

The growth of plants is a function of the efficiency with which they produce dry matter. This involves the efficiency with which they capture light energy and the efficiency with which they transform it into organic matter. The combined efficiency of these two processes in our most efficient cultivated crops–sugarcane, sugar beet, wheat, and rice–is between 2 and 3%. But since only a portion of the crop plant is edible (28% of the dry weight of cereals, 55% of the root of sugar beet), the net, or overall, efficiency is much lower. Furthermore, there are losses due to diseases, pests, and fires.

Measuring Productivity

The fundamental objective of agronomists, horticulturists, and foresters is to increase the efficiency with which solar energy is converted to useful products. Although the products are sold in arbitrary units (pounds of potatoes, bushels of corn, gallons of cider, or cords of wood), much better and more sophisticated units for measuring energy conversion are available. How much air space is there in a bushel of apples? How large is a head of lettuce? It is easy to see why bushels, pecks, and cords are not adequate for scientific use, and not even so for highly intensive agriculture. Furthermore, it is often desirable to measure rates of production of standing crops in the field. What are some of the possibilities for more precise measurement?

Plant productivity can be precisely estimated by measuring either the oxygen released or the carbon dioxide used in photosynthesis. Since the amount of carbon in CO_2 is directly proportional to the amount of carbon fixed in sugars during photosynthesis (Fig. 4), productivity can be estimated by the rate of disappearance of CO_2 from its environment. This is a straightforward task in a small growth chamber, but it is difficult in the field, where the apparatus for collecting and measuring gases must be disturbingly complex.

It is also possible to estimate production by determining the amount of chlorophyll present in a given amount of vegetation on a given area of land. To do this a sample of leaves of known weight is collected, and the chlorophyll extracted in boiling alcohol. By knowing (1) the total weight of leaves from which the chlorophyll was extracted and (2) the efficiency of chlorophyll in photosynthesis, the total photosynthetic efficiency of

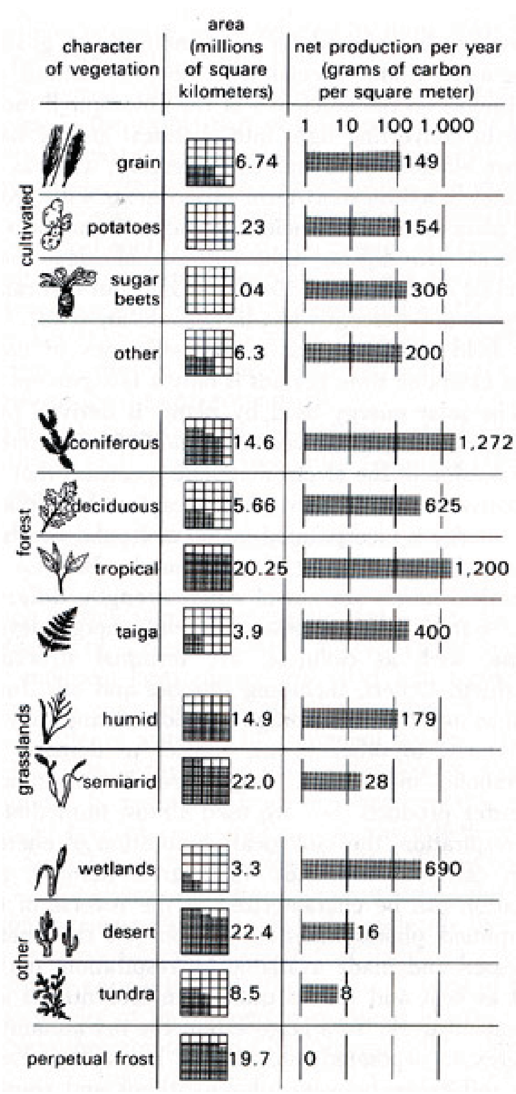


Fig. 4. The amount of carbon incorporated in organic compounds is a measure of the amount of organic matter produced. Within any given area, cultivated vegetation is less efficient than forest vegetation, but more efficient than for grassland vegetation. Increasing the productivity of the vast areas of desert on the surface of the globe may be our greatest scientific challenge. [From E.S. Deevey, The Human Population. Copyright © 1970 by Scientific American, Inc. All rights reserved.]

vegetation can be estimated. This technique is sometimes used for forest vegetation.

The use of energy to measure productivity gives a degree of precision not heretofore possible. It offers a single unit, the calorie, which is equally useful from the time that light energy is captured by plants until it is incorporated into consumer products. For example, a fairly active man requires approximately 3000 kilocalories of energy each day, a yearly requirement of about 1,100,000 kilocalories. This energy theoretically could be supplied by about 2 metric tons of potatoes (fresh weight) or 340 kilograms (750 pounds) of wheat–a filling if incomplete and uninspiring menu (Table 2). The energy unit of measurement is also useful for expressing the production of fiber crops such as wood. Paper mills are already buying wood on a weight basis. Even though few foresters regard boards or sticks of pulpwood as bundles of energy, this is precisely what they are. The specific energy content of a woodpile or a bale of cotton depends largely upon the total amount of cellulose present. Energy levels of crops can be used precisely as expressions of quantity regardless of volume or specific gravity.

The process of estimating energy values in terms of caloric equivalents is a fairly complicated process, and must be done by statistically controlled sampling of the biomass. The energy values of organic materials are determined by burning known quantities of materials under carefully controlled conditions and determining how much heat is given off.

It may well be that many agricultural products that we enjoy today will not be produced on the farm, but will be manufactured chemically from component parts. If people could become conditioned to each and enjoy reconstituted foods and make other such substitutions, agricultural production could be channeled into crops that offer maximum productivity of one or more of the basic requirements of the human diet. For example, certain crops would be grown primarily for their high caloric content, whereas others would be grown for their content of particular organic compounds, such as amino acids. The basic materials, after being synthesized by plants, could be subsequently elaborated into foods with a wide variety of flavors, tastes, and textures, thus satisfying the psychological need for a varied diet.

Programming Crop Production

We have stressed the capture of light energy by plants. Using the energy concept does not alter the objectives of crop producers, nor would many practices necessarily be changed if the concept were universally adopted, for we have learned through experience to manipulate our crops to make good use of available energy. We will, however, be able to control crop production with much greater precision than is now possible.

Table 2. Yield per acre per year and equivalent caloric values from selected crops produced from 1974 to 1979.

Crop	Average yearly yield (lb/acre)	Kilocalories/lb	Millions of kilocalories/acre	Day equivalents of energy/person/acre[1]
Potato	5622[2]	1270	7.1	2380
Rice	3819	1460	5.6	1858
Corn	5413	1450	7.9	2616
Soybean	1798	1600	2.9	958
Wheat	1898	1470	2.8	930

[1]At rate of 3000 kilocalorics per day per person.

[2]Dry weight (22%).

Business uses computers to "plan" the most economical and profitable succession of events for particular purposes. One of the important mathematical decision-making devices employed is called linear programming. It has been accepted by American industry and become a routine management tool. But it is only usable because all of the different kinds of materials and efforts involved have a common denominator: Time, materials, and manpower can be expressed in terms of dollars and cents.

By convention, biologists describe the ecological environments of organisms in terms of rainfall, temperature, soil moisture, wind, sunlight, available nutrients, soil conditions, composition of the atmosphere, pollutants, and living organisms. Although these are adequate parameters, they must be used correctly and expressed in comparable terms if they are truly to be understood. The most suitable common denominator for crop production may be energy. Measurements of input and of output can be compared by making use of caloric equivalents. Thus the energy concept will allow more precise analysis, computerized if necessary, in crop production.

In order to maximize the capture and storage of energy, the specialty of crop energetics must take into account not only the standard cultural practices, but many factors that have received little attention in the past, such as plant density and distribution, leaf coloration, and height of individual plants.

Scientists are quantifying the chemistry and physics of plants in terms of their metabolic requirements. The water relations of plants and soils are especially easy to quantify, and much is being done to explain and describe the movement of water in the environment on the basis of energy gradients, using mathematical expressions. Sooner than we realize, most of the biological aspects of crop production will yield to mathematical quantification.

THE ENERGY-FLOW CONCEPT

The function of agriculture is to direct and maximize the capture and concentration of solar energy by plants and to optimize the flow of this energy through the various manufacturing and distribution processes in a manner that provides the greatest possible benefits to society. This point of view gives a common denominator, energy, by which crop production can be measured, and provides an absolute standard for equating the effects of different cultural treatments and practices. Considering crops as traps that can be manipulated to capture, transfer, and store energy, provides insight into the means by which we can improve and increase agricultural efficiency and productivity.

Energy Capture

There have been many proposals to broaden the base of energy capture. Most of the photosynthesis on the surface of the earth takes place in water, mainly in oceans and seas (see Table 1). Only an insignificantly small fraction of this production is used by people for food. By systematic fertilization and management, it might be possible to "farm" certain areas of the seas and oceans to raise their levels of productivity even higher. Can we produce fiber as well as food in this manner?

In some places extending agricultural production to deserts and other areas with unfavorable climates may be feasible. Many desert soils are extremely fertile and only need carefully controlled irrigation to become highly productive.

One obvious method of increasing energy capture is to increase the length of the growing season. Artificially extending the growing season by using greenhouses makes it possible to produce crops where the growing season is very short. But this technique has limited application in today's economy because of the high cost of building and maintaining greenhouses, and it has generally been restricted to the production of flowers and such high-value food crops as tomatoes and grapes. In the future though, solar heating may be used more extensively, even to the point of making possible the production of relatively low value carbohydrate sources throughout the year.

These proposals require extremely high inputs of technology and capital. The process of energy capture in present agricultural areas offer opportunities for improvement. For example, in many situations of intensive production the factor that limits energy capture is the availability of carbon dioxide. Producers of greenhouse crops can increase yields by releasing CO_2 gas from storage cylinders to "fertilize" the air.

Air movements affect photosynthesis by influencing CO_2 exchange between leaves and the surrounding atmosphere (Fig. 5). Thus the orientation of rows with respect to prevailing winds may influence productivity. Where the prevailing winds are negligible to moderate, corn yields can be increased if the rows are oriented at right angles to the wind. The tops are blown back and forth and there is greater turbulence and mixing of air.

Plant morphology also has a relation to energy capture. Such characters as plant type, leaf shape, and branch angle influence light absorption. Redesigning crop plants to increase the capture and use of energy will be the future course of the technology of plant improvement.

The energy-flow concept is particularly applicable in forestry. The present production of lumber and pulpwood may well give way to a forest economy based on two commodities: alpha cellulose for structural purposes and degradation products of lignin for stock feed. The primary need, however, will be for molecules of cellulose. Such a change in the objectives of production seems logical. In the form of dissolving pulp, a product of alpha cellulose, wood can be exploded, foamed, extruded, molded, shaped, and combined with other materials to form products that are dimensionally stable, resistant to fire, insects, decay, and rot, and highly adaptable to many uses. Unwoven fabrics are already finding a good market, and it may not be too long before fiberless paper is in use.

Since straight tree trunks and a high degree of structural ability are not important to cellulose production *per se*, tree form would be of no consequence. The form and structure of the forest stand would receive primary consideration. Forests would be designed to make energy capture and storage most efficient. It is probably

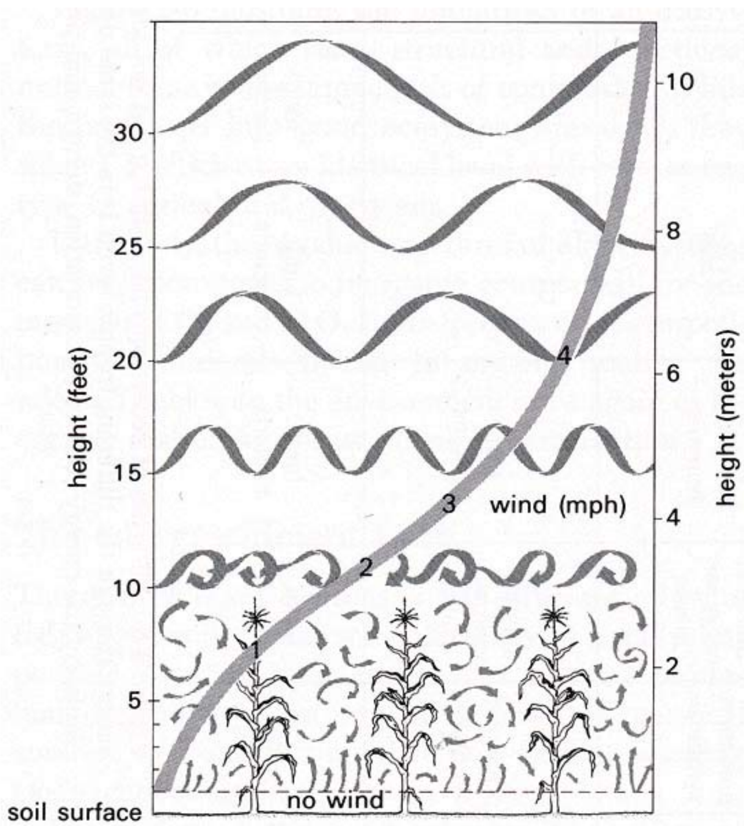


Fig. 5. The turbulence of wind increases with distance above the soil surface. Crop spacing can increase turbulence at lower elevations, thereby increasing the exchange of carbon dioxide between leaves and the atmosphere. [After J.E. Newman and B.0. Blair, Crops and Soils Magazine, June–July 1964.]

safe to assume that harvesting and processing techniques would keep pace with forest management and wood utilization, so that even the shrubs, saplings, and suppressed trees of multilayered forests would be used profitably. Under such conditions as these, there might well be a change to a more naturalistic silviculture (tree culture) based on the hypothesis that vegetation types with many layers are photosynthetically more efficient than those with only a single layer.

Structure and Function of Agricultural Ecosystems

All ecosystems have structure and function. *Structure* refers to the relations among producers, users, and decomposers. Strictly speaking, only green plants are producers. However, some ecologists refer to transfers in food form also as a secondary sort of production. For example, animals that eat plants produce animal flesh.

The structure of an ecosystem may be very complex, such as that of a forest or ocean ecosystem, or it may be fairly simple, as are those of most agricultural ecosystems. In untrammeled nature we seldom find simple systems but are confronted with highly complex ones. To maximize productivity, we try to keep agricultural ecosystems as simple as possible, and the food chains in it as short as possible, thereby decreasing energy losses.

Function refers to the role that each member of the ecosystem plays in its maintenance and development. The primary function of a corn plant in a cornfield is to produce corn. But if the corn is infested with pests, then it also assumes the function of supplying food for the pests, which use it as an energy source. Thus the corn plant may have primary, secondary, tertiary, and even further functions. When one of its functions is undesirable we attempt to block it by using pesticides or some other cultural practice.

Figure 6 illustrates the similarities of all ecosystems, all of which share structural and functional units at some of the same levels of complexity. While the producers in a pond ecosystem are algae, they share a position at an identical level with corn in one type of agricultural ecosystem.

Ultimately, the organic structures of all ecosystems can be decomposed to inorganic compounds, for the most part CO_2 and H_2O. In the process of decomposition the minerals bound in organic matter are released back into the environment once again as inorganic matter, a process called **mineralization**.

The Energy-Efficient Farm

The goal of many persons is self-sufficiency, but in today's economy total self-sufficiency is usually impossible. Also, we have learned that a degree of mutual dependency can provide a level of personal comfort and satisfaction that one person, working alone, cannot attain.

The crop-production unit, whether it be a farm or a giant cooperative, is one place in which the energy subsidy from outside sources can be reduced, though few farms can probably ever reach total self-sufficiency. There are waste products at nearly every step in the process of crop production. In years past the disposal of wastes has been a problem, contributing to pollution and to the expense of crop production. But today waste is recognized as a potential asset, convertible to energy and to the nutrition of crops.

Figure 7 illustrates some, but not all, of the potential for recycling minerals and energy that would have been wasted in years past. At practically every stage of crop production there are waste organic materials that can be used to generate methane gas, which can be stored in a compact form and used at a later date. Such materials as sawdust and corn cobs can be stored for later use as fuel, but they are bulkier and not so versatile.

Figure 8 illustrates the value of auxiliary energy in increasing the percentage of the population available to do work other than that directly connected with food production. People not needed in the agricultural work force can apply their talents, time and energy to writing, music, art, teaching, and other occupations that contribute to the completeness of human society.

INCREASING CROP PRODUCTION

One of the present-day anomalies is that some areas of the world are blessed (?) by agricultural surpluses while others are plagued by persistent and agonizing shortages. There is, of course, a marked difference in the intensity and efficiency of crop production practices used throughout the world. Consequently, appropriate methods for increasing production will depend on the existing level of technology.

In developing areas the productivity of land can be increased by many agricultural techniques that are now routine in the developed countries. In an area saturated with plants, some environmental factor soon becomes scarce. Light, soil moisture, and nutrients are the factors most often in short supply. These are some of the well-known growth-limiting factors with which agriculturists

structural unit	function	functional unit	ecosystem type						energy pathways for all ecosystems	organism types common to all ecosystems
			pond	forest	grassland	corn	wheat	orchard crops		
producers	production	green plants	algae, phytoplankton	trees, shrubs	grasses, forbs	corn	wheat	apples, peaches, nuts, etc.	x heat	green plants
						transportation, storage, and processing				
X_1 users	herbivore, symbiosis	animals, nongreen plants	fish (bluegill), snails, zooplankton, bloodworms, water fleas	small rodents, deer, humans, vegetarian birds	rodents, sheep, bison, cattle, prairie dogs	insects, fungi, humans, bacteria, cattle	humans	humans, vegetarian birds, deer, squirrels	x heat	arthropods, disease organisms, symbionts, insects, herbivores
						transportation, storage, and processing				
X_2 users	predation, symbiosis	animals, nongreen plants	fish (bass), humans, snakes, bloodworms	birds of prey, snakes, weasels, humans, mountain lions	hawks, humans, wolves, vultures, snakes	bacteria, fungi (fermentation products), humans, pets		humans, birds of prey	x heat	carnivores, disease organisms, carrion eaters, insects, predators, symbionts, insectivores
						transportation, storage, and processing				
X_3 users	predation, symbiosis	animals, nongreen plants	fish (bass), humans	foxes		humans			x heat	carnivores, disease organisms, insects, predators, symbionts, insectivores
X_4 users	predation, symbiosis	animals, nongreen plants	fish, humans						x heat	carnivores, disease organisms, insects, predators, symbionts, insectivores
decomposers	decay	fungi, bacteria	fungi, bacteria	fungi, bacteria	fungi, bacteria	fungi, bacteria	fungi, bacteria	fungi, bacteria	fungi, bacteria heat	fungi, bacteria

Fig. 6. All types of ecosystems have similar but not identical structural and functional units. The flow of energy through the different tropic levels is in the same direction, but is complicated, in the care of crop plants, by the energy costs of transportation, storage, and processing.

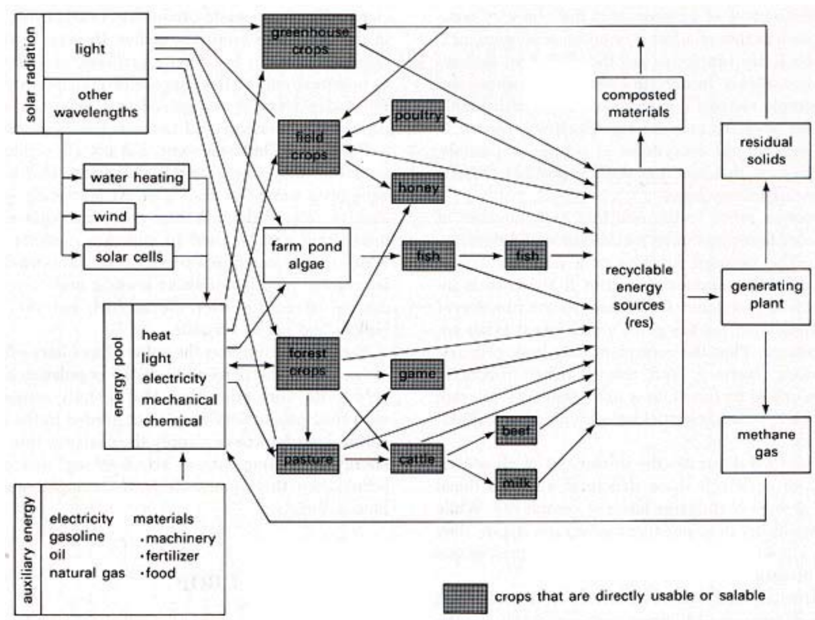


Fig. 7. Radiant energy from the sun is harnessed to produce plants of many kinds. These primary producers, in turn, provide energy and structural materials for the animals of lower trophic levels. Such a system must receive subsidies from outside the farm, such as fertilizer, to replace the materials that are lost when such a product as poultry, beef, or hay is sold and moved to another location. These subsidies can be reduced, however, if efficient use is made of farm wastes by recycling them to produce fuel and soil amendments.

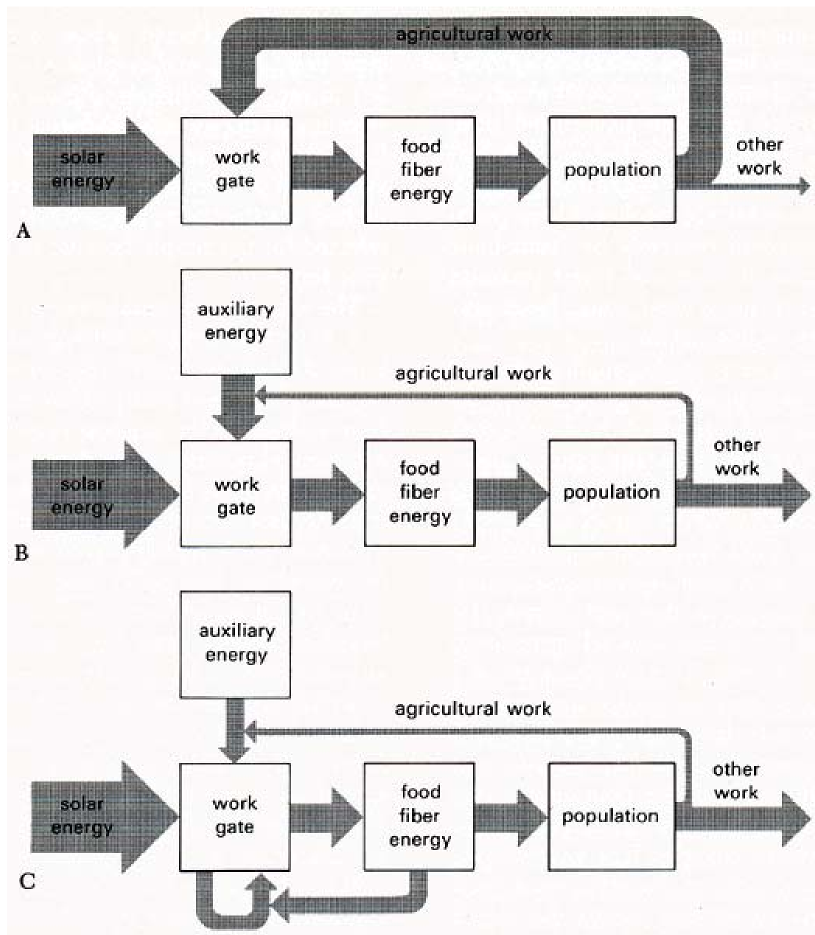


Fig. 8. The role of auxiliary energy in determining the economic will-being of a society is illustrated by these diagrams.

A In an economicallly less developed country, the bulk of the population must be devoted to agriculture in order to support itself at a subsistence level.

B In an economically more developed and industrial country, auxiliary energy sources "open the gate" to the more efficient utilization of the sun's energy, and the entire population can maintain a higher standard of living.

C In the future, agriculture must be much less dependent on auxiliary energy, a feat that can be accomplished by making use of products formerly regarded as waste.

concern themselves. The technology necessary to identify and overcome these limiting factors and to control such crop hazards as pests, disease, and fire is the subject of a large part of this book. This is the direction that agricultural improvement in developing areas must take.

As limiting factors are recognized and corrected it becomes increasingly difficult to obtain further gain. Nevertheless, there is much room for improvement in the developing areas of the world. Fertilization is one of the most powerful tools for increasing crop production, yet in many developing agricultural areas little or no fertilizer is applied. Large increases in efficiency can be obtained with crop improvement through genetics and breeding. The ruinous losses to pests and diseases in developing areas can be prevented with better control methods.

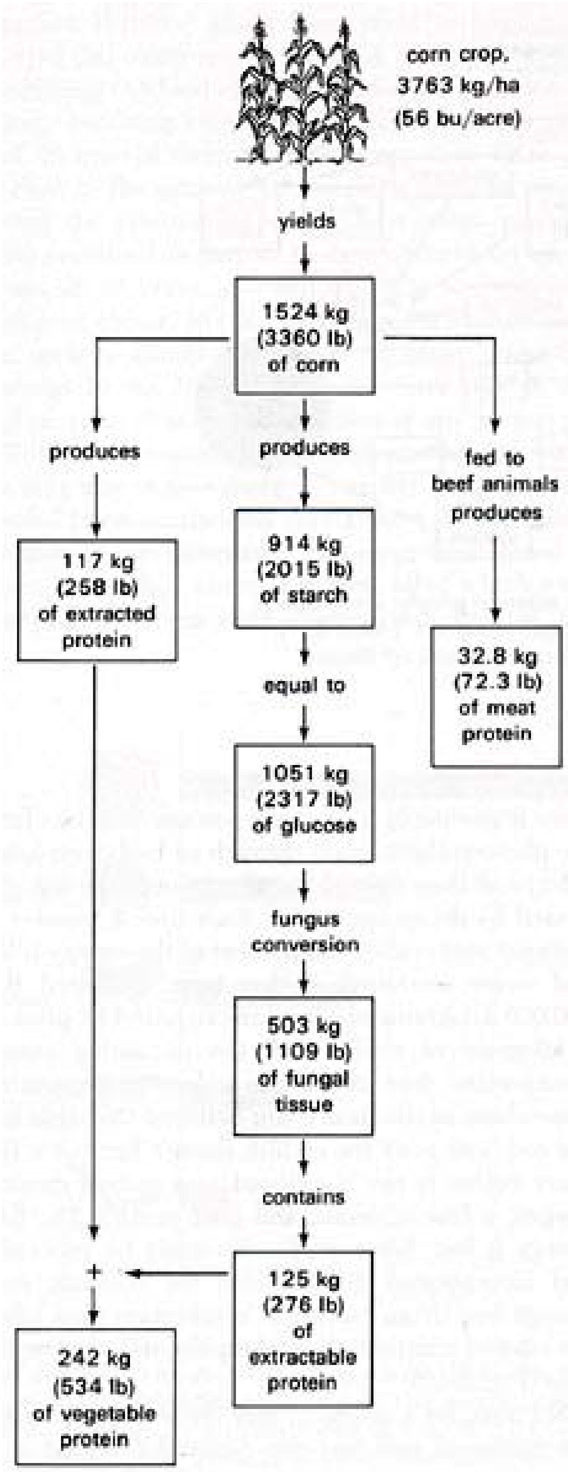
In the developed agricultural areas the immediate, practical problems of production—the amount of fertilizer and the method of applying it, the control of crop pests, the optimum depth to which plowshares should be set, the length of the rotation period, the choice of weed killers—have received much attention. These types of problems have often been solved on an experience and expediency basis, but they have also been tackled by organized research groups using experimental approaches. Many problems can be now handled routinely by "cook-book solutions." The surplus of farm and forest products produced each year in the United States bears witness to the efficiency of this system.

In the United States most of the small, inefficient farmers and timber growers are being forced, by economic pressures, either to leave their land or to seek supplemental employment in nearby cities. Consequently, the production of farm and forest products has increasingly become the privilege of a relatively few large producers. Even though small applied research projects have been useful in years past in providing immediate answers to many problems, this approach no longer works in advanced agricultural economies. Most of the remaining problems are of a basic nature. To solve them we need a hard core of biological and economic facts. Crop production is taking on a new personality. It is big business, and has become more nearly a science than an art. It is only prudent to assume, in the face of increasing national and world populations, that local overproduction will cease to be a problem. Should international crop sharing become a complete reality, the day of underproduction in the United States is likely to face us sooner than we realize. To prepare for this almost certain eventuality, it is essential that we learn to improve the efficiency of each phase of the energy-flow system of agriculture.

Residue Utilization

The first approach to increasing agricultural efficiency should be to use a greater part of current production. This is partly a simple matter of thrift. In some countries straw, cobs, husks, shells, and manure are carefully collected and used either for feed or for fuel. But in other, more prosperous countries they are usually discarded or, at best, composted. In the forests of Europe, even the smallest branches and twigs are carefully collected, while in the United States, tops, bark, slabs, and sawdust are usually burned or left to rot. The cellulose in these discarded parts of trees is potentially as good as that in the wood of the finest firs and pines, and the bark has many unusual and useful properties that have infrequently been exploited. Furthermore, many forest species are totally rejected for use simply because of their small size or poor form.

The extraction of usable fibers from plant residues is a field that holds much promise. Of the many kinds of residues, grain straw, corn stalks, sugarcane bagasse, cottonseed hulls, cotton stems and pods have been utilized to the greatest extent. Strawboard is a commercial product; ground walnut and pecan shells are used as fillers in plastic molding powders; sugarcane bagasse pith is useful as a filler in low-density dynamite. Fine quality papers of the kinds required for cigarettes, fine books, and stationery are made from the fibers of hemp and flax. Sawdust is collected at saw-mill sites for manufacture into pulp, an operation that has greatly increased the utilization of wood. Sawdust does not make paper equal to that made from wood chips, but nonetheless it has a number of excellent applications. Someday, a widespread commercial use may be found for the enormous quantities of lignin that are usually dissolved and discarded in the manufacture of paper.



Many industries based on the utilization of discarded plant products could be established. Tops of plants produced mainly for their starchy roots and tubers may be used as sources of protein. Proteins from leaves are now used for animal feed and may someday be extracted for human consumption. Under any circumstances, a comparison of the efficiency of protein production of corn by two different methods is revealing (Fig. 9). If 1524 kilograms of corn (3360 pounds, or about 56 bushels) is fed to beef cattle, the end product will be only 32.8 kilograms (72.3 pounds) of meat protein. However, if all of the vegetable protein were extracted from the same 1524 kilograms of corn, the yield would be 117 kilograms (258 pounds). By using the residual starch in the corn to produce a crop of fungi, we can produce another 125 kilograms (276 pounds) of extractable protein. The 242 kilograms (534 pounds) of vegetable protein thus produced might not be as tasty as that of the beef, but future generations will undoubtedly consume it in increasing quantities, prepared as a meat substitute. Even today vegetable protein is used to supplement ground meat and reduce its price.

Food processing is an area in which tremendous strides can be made in decreasing waste. Potatoes, which are produced in greater abundance in the United States than any other vegetable, provide a good example. Many potato-processing plants handle more than 450,000 kilograms (nearly a million pounds) of potatoes per day, with the resulting

Fig. 9. More than seven times as much protein can be produced by the extraction and fungal conversion of corn as by feeding the corn to animals to produce meat protein. However, the technology of producing vegetable protein is complicated, and we have not yet learned how to make vegetable protein as palatable as beefsteak, lamb, and pork roast.

organic pollution equal to that of a city of 300,000 people. Potatoes were once commonly peeled by dipping them in a vat of 16–20% lye solution to loosen the skin, and then spraying them with a high pressure water jet to remove it. In a new process, they are dipped in a 12% lye solution, held for 3–5 minutes, heated for 1 minute by infrared lamps, and peeled by rotating rolls with half-inch rubber studs. The waste thus produced is mixed with other organic wastes and fed to steers as 80% of their dry ration, practically eliminating potato skins as a source of pollution.

Utilization Efficiency

One of the most troublesome problems, to those concerned with supplying the necessities of life to our expanding population, is the inefficiency with which consumers use food and other plant products. Plants usually function with an average efficiency of no more than a few percent in storing the energy that arrives from the sun. Animals and other organisms that feed on the green plants are equally inefficient. And so it goes, with each successive consumer utilizing only a part of the food it consumes. Consumption is, of course, a means of transferring energy and building materials from one organism to another. Such a transfer of materials takes place through a **food chain** or **food web**, depending upon the linearity of transfer, to different kinds of organisms (Fig. 10). Eventually, all of the original energy produced by plants, and not dissipated by fire, is depleted by respiration (Fig. 11). We are primarily concerned with the food chain from plants to ourselves. Food webs, however, may be extremely complex, and may involve various degrees of predation among lower forms.

It is easy to see that the **ecological efficiency** of the various organisms in the food chain is of the utmost importance. Ecological efficiency may be either a measure of the effectiveness with which (1) solar radiation is captured or (2) the biomass of one organism, either plant or animal, is converted to the biomass of another. Respiration and the production of such indigestible materials as hair, hide, and bone all detract from the efficiency of conversion.

The flow of energy through food chains and food webs is essentially a one way process. It

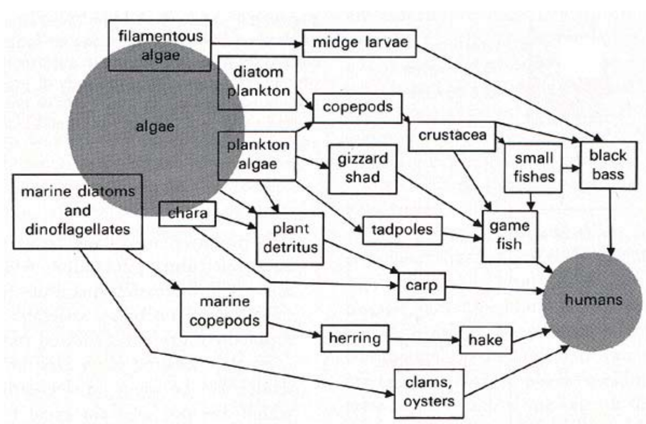


Fig. 10. An aquatic food web from algae to people. Each time a transfer of energy is made, a 90-95% loss occurs. [After E.N. Transeau, H.C. Sampson, and L.H, Tiffany, Textbook of Botany, Harper & Row, 1940.]

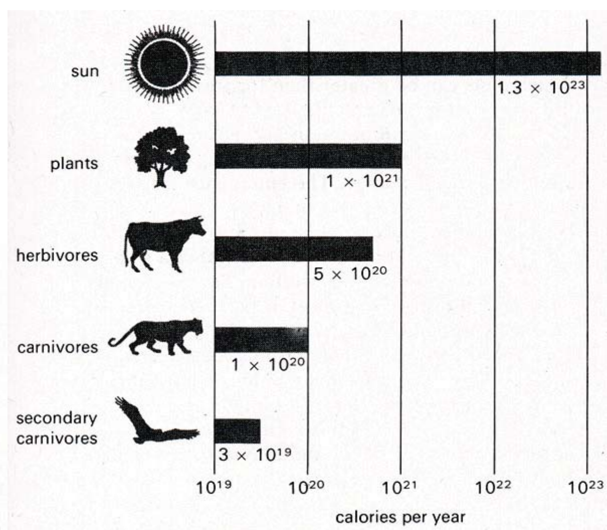


Fig. 11. The efficiency with which solar energy is used decreases with each step along a food chain. Plants use only a small fraction of the energy that reaches them; herbivores indirectly use only a part of this energy, and carnivores still less. [From L.C. Cole, *The Ecosphere*.]

moves from the photosynthetic plant through an herbivore (plant eater) and then through carnivores until the last of it is used by decay organisms. Each time a transfer of material occurs about 90% of the energy is lost and never recovered. It has been estimated that 100,000 kilograms of algae are required to produce 1 kilogram of codfish! All the remaining energy incorporated into the algae is lost in respiration, somewhere in the food chain between the algae and the cod, and even the codfish doesn't last but a few years before it too is reduced into carbon dioxide, oxygen, a few minerals, and heat energy. The heat energy is lost, however, for it cannot be recovered and incorporated directly into the biomass, even though heat from biological combustion does affect the rates of reactions that take place in living organisms (Fig. 12).

Suppose, for a moment, that the world population has increased and that the demand for food is so great that every possible means at hand must be applied to avoid starvation. When we eat animals we lengthen the food chain from plant to human; to shorten this chain means less steak and more starch. Shortening the food chain precludes the great loss of energy resulting from each conversion to the next link. In time of shortage the strategy must be to get as close to the primary producers as possible, eliminating the intermediaries. We have eaten primary plant producers in part, or in their entirety, for many thousands of years, and will continue to do so as a matter of choice. In the Orient the diet of most people consists almost exclusively of plant materials, whereas in the United States we have one of the highest rates of meat consumption of any nation.

But the improvement of biological efficiency is not the only way to save energy. In earlier cultures, crops needed to be transported only a short distance from the field to the homestead. The crops were stored in caves, root cellars, rooms, and bins, all of which were close to the preparation center–the stove or the loom. But today, transporting the crop to the consumer in the city must take place in a number of stages, each of which contributes to its marketability and availability (Fig. 13). In addition to processing, there must be some provision for storing both the raw materials and their products until they are needed. The energy costs of transportation and storage add to the cost of the end product. Because of the longer chain of events in the preparation of meat

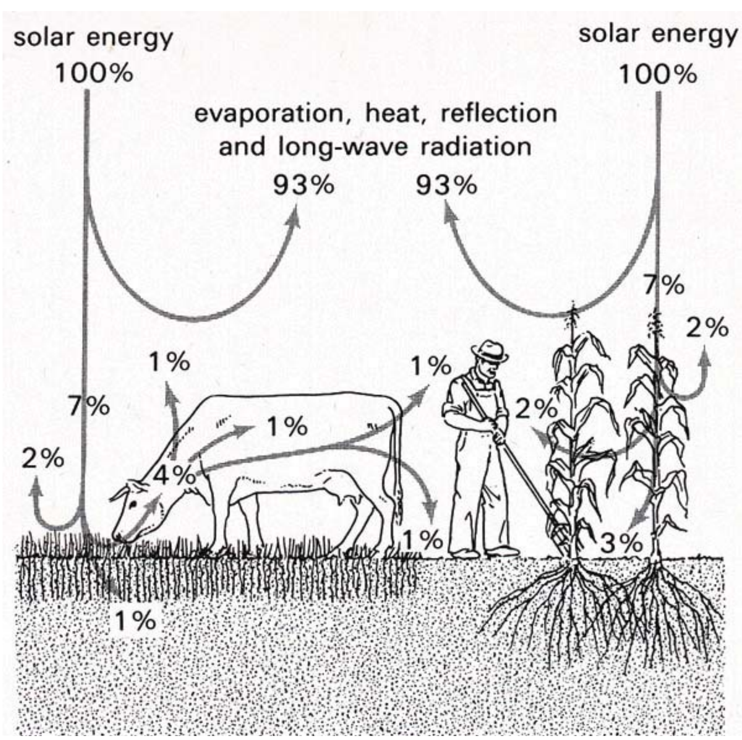


Fig. 12. Of the solar energy that reaches the earth, about 93% returns to the atmosphere. With nutrients and water abundant and with a full cover of leaves, about 7% of that solar energy can be converted in photosynthesis by corn; 2% goes into respiration, which is required for the growth and maintenance of the crop, and 5% goes into the dry matter of the crop. In corn, 3 percent goes into roots, stems, and leaves, which constitute a crop residue that is recycled to the soil or fed to animals, and 2% emerges as grain that can be eaten by people. For grass, as much as 4% may be consumed by a cow. [From R.S. Loomis, Agricultural Systems.]

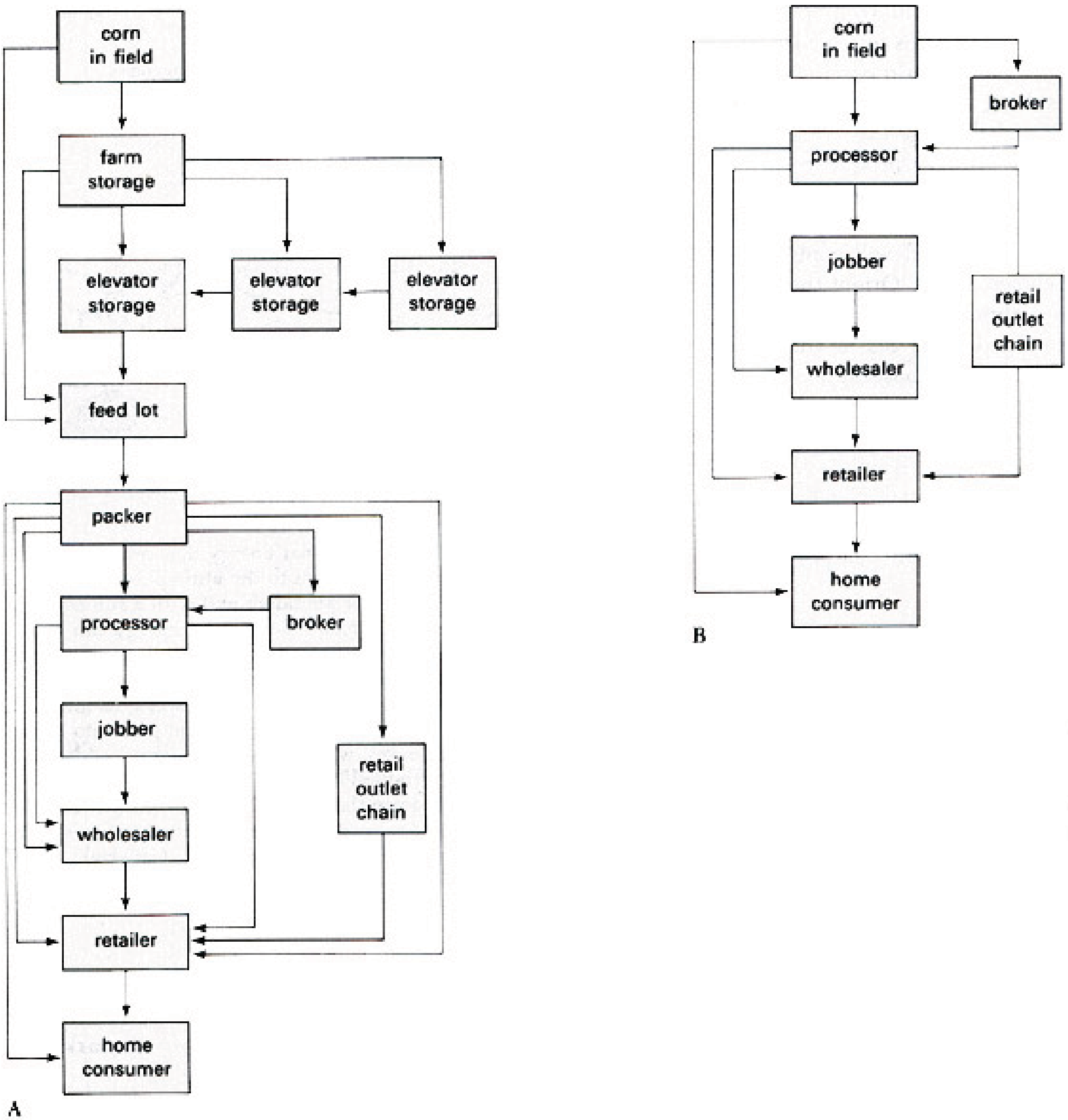


Fig. 13. The energy costs of transportation and storage are great. If corn is consumed in the form of meat, such costs can be greater than for fresh or canned corn by several orders of magnitude.

A Movement of corn to the home for consumption in the form of beef can be tremendously complicated, involving many stages of transportation and storage. The emergence of large retail outlet chains has further complicated the system and has contributed to the decline of the traditional role of the jobber. The packer, which can be either a small family operation or a giant corporation, has the task of slaughtering and distributing meat as box beef, carcasses, or primal cuts through several outlets.

B Movement of fresh or canned corn to the home is less complicated. Because sweet corn has a freshness value, it must move to the consumer or the processor as rapidly as possible. Transportation and storage must be minimized. The broker serves only as an agent and may actually be a nonprofit farmers' cooperative.

for the consumer, the costs of meat production are significantly higher. It is fair to say that meat production is ecologically less efficient not only in the biological production of protein but also in its processing and marketing.

Let us ignore, for the moment, all matters of dietary custom and consider the most efficient methods of providing a hungry world with food. It has been demonstrated, in a laboratory, that algae can produce a biomass, on a dry-weight basis, of 90 metric tons per hectare (about 40 tons per acre) per year. Of this production, 45 metric tons would be protein, 7 metric tons would be fat, and 38 metric tons would be carbohydrates. No present crop produces organic matter so efficiently.

The culture of algae as a crop is possible with a one-celled species called *Chlorella*. Much is known about its physiology and reproductive habits, and it would be a simple matter to get it into production should economic factors become favorable. Perhaps few readers would find soup made from algae as desirable as sirloin, but it is at least as rich in some vitamins and amino acids. One group of people ate such a soup for an extended time and found it to be palatable and nutritious. Powdered algae could probably be incorporated into many of our foods with little apparent change in quality or flavor. If it is not acceptable as human food, the Chlorella might be rendered into feed for animals, thereby allowing people to maintain a more conventional diet. Many other kinds of algae are eaten by people all over the world (Fig. 14).

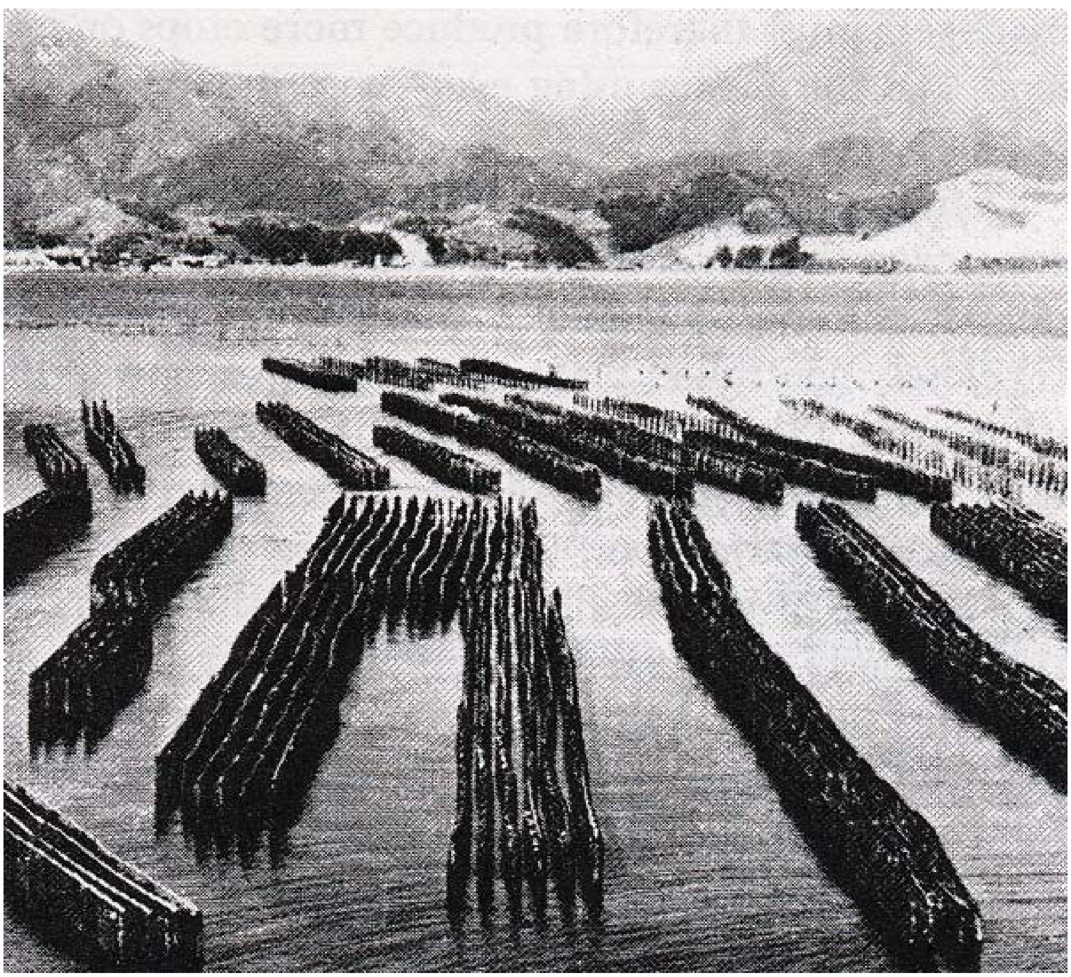


Fig. 14. Intensive agriculture can be conducted even in the oceans. Posts and nets support a crop of edible seaweed, Porphyra, in the Inland Sea of Japan. [Courtesy J.H. Ryther.]

In a food crisis even wood can be made edible. By treating wood with a strong acid, molasses can be made that is easily purified for human consumption. How many years would a giant redwood sustain human life if converted into food? Cultivating yeast on wood molasses could produce a complete, well balanced food. In Germany, during World War II, edible fats were manufactured from coal. This, however, is a complicated process that can be used only when expense is no object.

Woods that cannot be used as structural materials or food could be used for the production of gaseous and liquid hydrocarbons. Even though the costs of conversion are high, some countries do find these techniques economically feasible.

Brazil, a country that must import all of its petroleum, has explored the possibility of using biochemically produced alcohol to extend its gasoline supply. They have found that as much as 10% of wood alcohol can be added to gasoline with no special engine adjustment. While the energy content of alcohol is not as great as that of gasoline, burning alcohol is virtually nonpolluting, which is important in many of our smog bound cities. At present, this mixture, gasohol, is in use throughout the country. The alcohol component is made largely from sugarcane.

In the United States, gasohol is sold in some states but is likely to be more of a novelty than a competitive product for several years. Whether farmers can grow corn for producing fuel alcohol is still in doubt, but as the price of crude oil increases, the economics improve. In years past, crop producers have been charged with the responsibility for producing “food and fiber.” In the future this slogan may change to “food, fiber, and fuel.”

Intensive Agriculture and Energy Conservation

There have been many pleas from environmentalists that farmers use less fertilizer, which is a prime pollutant of water. This can be done, these environmentalists maintain, by the use of more extensive farming practices—using more land to produce crops so that better use is made of natural fertility. Unfortunately, land suitable for crop production is becoming scarcer, because productive land is being usurped by urban sprawl, superhighways, and shopping centers. It seems inevitable that such losses of farmland will increase at an even greater rate in the future. Farm managers must therefore produce more crops on less land, and this means using even more intensive agricultural practices.

Defining “intensive agriculture” precisely is not easy, even though some of its characteristics may be quickly listed. It includes, but is not limited to:

- Closely controlled plant spacing
- Precise fertility control
- Mechanization of field cultural practices
- Insect control
- Disease control
- Weed control
- Irrigation
- Drainage
- Burning
- The use of genetically improved plant materials
- Properly timed seeding and harvesting practices
- Decreased distances of crop transport.

The relative importance of each of these factors is subject to local conditions and constraints.

For example, insects may be a first order problem in some areas for some crops, but not important for the same crops in other areas. Intensive agriculture might best be defined, rather generally, as the application of the optimal balance of farming practices to produce crops with the largest possible net yield of value.

There are many benefits of intensive crop production. For example, fertilizers can be used more effectively if individual crop plants are close together. This, of course, calls for good placement and timing. Chemical weed control can be minimized, because with close spacing crops are better able to compete with weeds. Because of the smaller areas of tilled land, soil losses by wind and water can be minimized by stubble cropping and by alternating crops with strips of grasses or other permanent soil covers. Also, there should be less use of land that is poorly adapted for tillage and difficult to manage.

If less land is used, the energy subsidies of transportation and cultivation can be smaller. There can be less unused residue, because collection will be made easier. Further, irrigation and drainage can be more efficient when land is used intensively, which in turn requires less of the materials and technology of these practices.

In the United States, agriculture is intermediate in intensity. The high degree of reliance on machinery would seem to indicate highly intensive agriculture, but machinery is not the only indicator of intensity. Machinery can produce a better seedbed and a more timely harvest, but yields may be lowered when wide spacings are used to accommodate machines, and the machines may compact the soil and thereby decrease productivity. What a machine oriented agriculture represents is an optimization of labor.

The most intensive agriculture is practiced in countries that have a small land base, such as Japan. There, the use of sunlight is maximized by the use of large quantities of fertilizer and by the intensive use of human labor. Japan and other land poor countries serve to show us how close the level of productivity can come to the potential provided by soil, climate, crop selection, and genetic improvement,

The least intensive agriculture can be found in those parts of the world in which some environmental factor is in short supply or in which the people are too poor to pay for such practices as irrigation or fertilization. If the length of time for which some of these agricultural systems have been operating is any measure of success, then some of them are among the most successful in the world. However, their productivity is usually low, and it must be sustained with great care, patience, and planning.

In the end, intensive agriculture may free some land for other uses. The demands of hunters, realtors, engineers, backpackers, campers, conservationists, city planners, and many other special interest groups will play an important part in shaping agricultural practices of the future, because each group is eager to have more land for its own purposes. Unfortunately, the amount of prime agricultural land available for crop production is more limited now than it ever has been in history.

ENERGY FARMS AND FORESTS

In Europe during the Middle Ages, kings and barons frequently owned vast estates of land, most of it forested. While timber cutting, hunting, and even trespassing were forbidden, they gave their serfs–and others, for a fee–permission to pick up fallen branches to use for firewood, the main fuel for cooking and heating. As a result, the forest floor was nearly always devoid of branches, dead trees, cones, and other detritus. Even though the feudal system broke down, the practice of branch collecting continued until after World War II, when Europe became heavily industrialized. At that time, because of industrial employment, it became economically feasible for most people to buy oil for fuel instead of searching the forest for branches.

In the past, people have used plant agriculture mainly to produce food and fiber. People have always burned plants and plant parts to provide heat for cooking and warmth, but plants have only rarely been grown for this specific purpose. Fallen branches, bagasse, crop residues, and surplus or undesirable trees, as well as otherwise useful trees cut specifically for firewood, have been used for fuel through the ages. Until recent years there has been an abundance of such materials in nearly all parts of the world.

Today we are entering an age of energy awareness, brought on by increasing fuel shortages and rising prices. We are on the threshold of economic feasibility for growing plants to be used as energy sources rather than for food and fiber. With plants as bioconverters of radiant energy to chemical energy, it is increasingly probable that *energy farms*, or *energy forests*, will be used to produce plant biomass as a source of energy (Table 3).

As the following table shows, the energy values of plants are not as rich as those of coal.

Energy source	Btu per lb
Bituminous coal	15,000
Slash pine	7,000
Sugarcane	6,500
Alfalfa	6,500
Sycamore	5,800

Despite the fact that their energy values are low, there are many good reasons for using plants and plant products for energy production:

- They have high location value because of short distance transportation.
- They are relatively abundant at many locations.
- They are renewable resources.
- They are largely materials that would otherwise be wasted.
- They are otherwise materials of relatively low value.
- They can be used in many combinations or mixes.
- Their sulfur content is very low.
- Land unsuitable for other purposes can be used to produce them.
- The land itself is not disrupted (forests).
- Their residues are often useful as soil amendments.

Because of the bulkiness of such materials, it seems unlikely that they will be shipped in quantity to central locations for energy production. Rather, it would seem most feasible to produce and use the conversion products locally. However, the conversion products themselves, having a higher energy value, might profitably be transported for use elsewhere.

There are many possibilities for using plants as sources of energy, Nobel laureate Melvin Calvin has proposed the mass production of hydrocarbons very much like gasoline from plants of the genus *Euphorbia*. Plants in this genus produce a milky sap, called latex, which contains hydrocarbons of low molecular weight that are similar to those in petroleum. Grown in arid regions not suitable for growing food plants, they might be capable of producing from 25 to 125 barrels of oil per hectare per year. The plants would be harvested by cutting close to the soil, run through a crushing mill to extract the sap, and processed in a refinery very similar to those used for crude oil.

Since the plants sprout prolifically from stumps, replanting would be necessary only after about 20 years. Oil produced in this manner would be practically free of sulfur.

Methane is an example of an energy source that can be produced from a variety of farm and forest waste products. The use of small waste digesters for the production of methane for heating and lighting in rural, single family situations has proved feasible in India, Europe, and the United

Table 3. Bioconversion technologies for producing selected energy products from wood.

Product	Technology	Remarks
Electricity	Combustion by spreader	Developed and in use for capacities up to 55 MW equivalent
	Stokers in boiler	
	Furnaces	
	Fluid-bed combustion	Limited use for steam generation with wood-yard waste as fuel
	Charcoal/oil slurry firing	Under development by ERDA
Substitute natural gas	Gasification/methanation	Under intense development for coal. New development activity required for gasification of wood. Current experience at atmospheric pressure using municipal solid waste.
	Anaerobic bacterial digestion	Well-known technology for municipal sewage treatment. Lignin may inhibit bacterial activity.
Medium-Btu fuel gas	Gasification	Same as for substitute natural gas. Product can be a raw material (synthesis gas) for manufacturing methanol and ammonia.
Fuel oil	Pyrolysis	Flash-pyrolysis pilot plant using municipal solid waste to produce fuel oil now in early stages of operation. Moving-bed pyrolysis developed on significant scale by Georgia Institute of Technology. Low-grade oil may require aftertreatment.
Charcoal	Pyrolysis	Coproduct of processing or fuel-oil production. Multiple-hearth furnace process now standard practice for charcoal production
Ammonia	Gasification/hydrogen production/ammonia synthesis	Gasification same as for substitute natural gas. Carbon monoxide shift to hydrogen and ammonia synthesis widely used and well-developed technology
Methanol	Gasification /methanol synthesis	Gasification same as for substitute natural gas. Methanol synthesis widely-used, and well-developed technology
Ethanol	Cellulose hydrolysis and fermentation	Fermentation step widely used, and well-developed. Industrial experience significant for dilute sulfuric acid as the hydrolytic agent

States. Methane from such digesters is rapidly replacing dried cow dung as the main fuel for heating and cooking in rural India today. In Europe, small digesters were constructed during World War II to produce methane gas as a replacement for fossil fuels, which were in very short supply. The use of such digesters has continued in Europe, particularly in rural, isolated areas of France and Germany, the methane serving as an important supplement to fossil fuels. Simple digesters applicable to single family use, which can be constructed from used oil drums and plumbing materials for a cost of less than fifty dollars, can produce approximately 0.5 cubic meter (15 20 cubic feet) of methane gas per day, enough to cook 3 meals a day for 2 people.

Digesters of the single-family type (Fig. 15) and the types used on intensive livestock-production operations, have the potential to produce far more methane per kilogram of digested material than do large municipal-type digesters. This is true because it is possible to monitor closely, and relatively simple to control, environmental conditions within a small digester.

Total dependence on conventional fuels, especially in rural areas, is likely to become a serious handicap in years to come as reserve shortages and increasing recovery costs continue to push energy prices upward. However, by producing energy from local resources, farmers can be partially freed from dependence on remote sources of increasingly expensive fuel supplies.

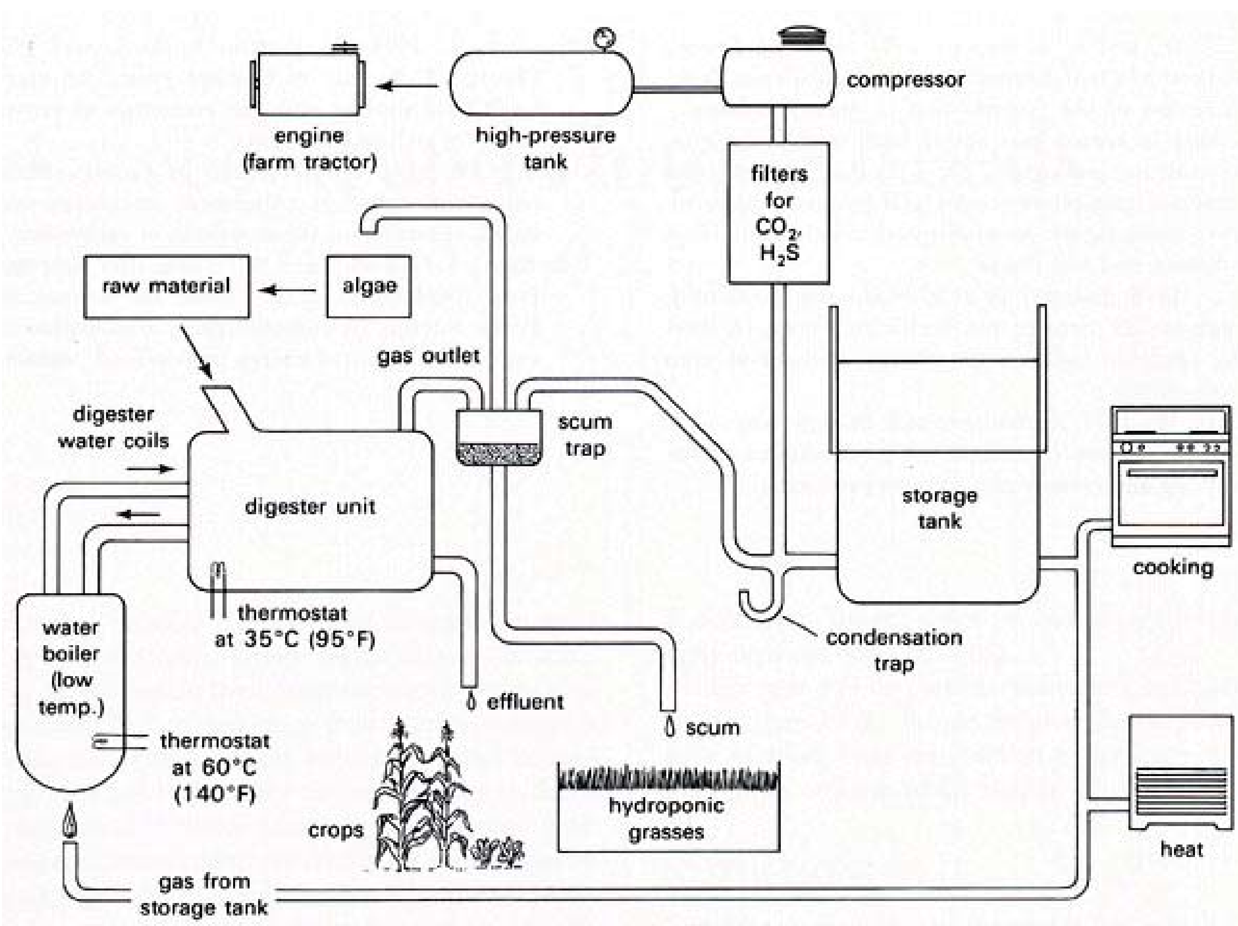


Fig. 15. An organic digester, using 50 gallon drums for digestion units, can produce significant amounts of gas from waste materials. In India, such units are commonplace, and the gas they produce is used principally for home heating and cooking.

Selected References

Asimov, I. 1960. *Life and Energy*. New York: Doubleday. (A broad, popularized treatment of fundamental concepts of energy relations.)

Brown, H., J. Bonner, and J. Weir. 1957. *The Next Hundred Years*. New York: Viking Press. (An exciting and stimulating discussion of the earth's natural resources in relation to human society and technology.)

Buttel, F.H. 1977. *Energy and Agriculture: A Bibliography of Social Science Literature*. Monticello, Ill.: Council of Planning Librarians. (A list of references on the sociological aspects of energy use for crop production.)

Cox, G.W., and M.D. Atkins. 1979. *Agricultural Ecology: An Analysis of World Food Production Systems*. San Francisco: W.H. Freeman and Company.

Fritsch, A.J., L.W. Dujack, and D.A. Jimerson. 1975. *Energy and Food*. Washington, D.C.: Center for Science in the Public Interest. (An analysis of the amounts of energy used for food production and preparation.)

Gates, D.M., and L.E. Papian. 1971. *Atlas of Energy Budgets of Plant Leaves*. New York: Academic Press. (A review of the factors–that is, energy balance–needed to keep a leaf viable, and therefore a crop growing and productive. The book discusses leaf temperatures, transpiration rates, and the like as they relate to such factors as wind speed, relative humidity, radiation, and leaf shape.

Leach, G. 1976. *Energy and Food Production*. Guildford, England: IPC Science and Technology Press. (A short and readable book on the energy analyses of crop production.)

Lockeretz, W. 1977. *Agriculture and Energy*. New York: Academic Press. (A comprehensive treatment of energy use and conservation in crop production.)

Margaleff, R. 1968. *Perspectives in Ecological Theory*. Chicago: University of Chicago Press. (An excellent small book dealing with the energetics of ecosystem structure and management.)

Odum, E.P. 1971. *Fundamentals of Ecology*. Philadelphia: W.B. Saunders. (A textbook on ecology with an excellent section on the energetics of ecosystems.)

Peirotti, A., A.G. Keeler, and A. Fritsch. 1977. *Energy and Food*. Washington, D.C.: Center for Science in the Public Interest. (A comprehensive examination of the sources and inputs of energy used in food production.)