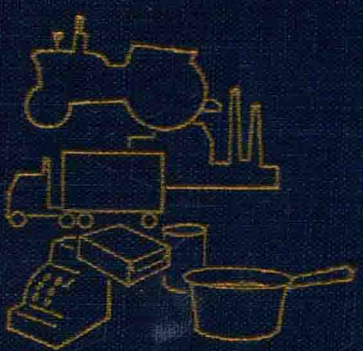

AGRICULTURAL ENERGETICS

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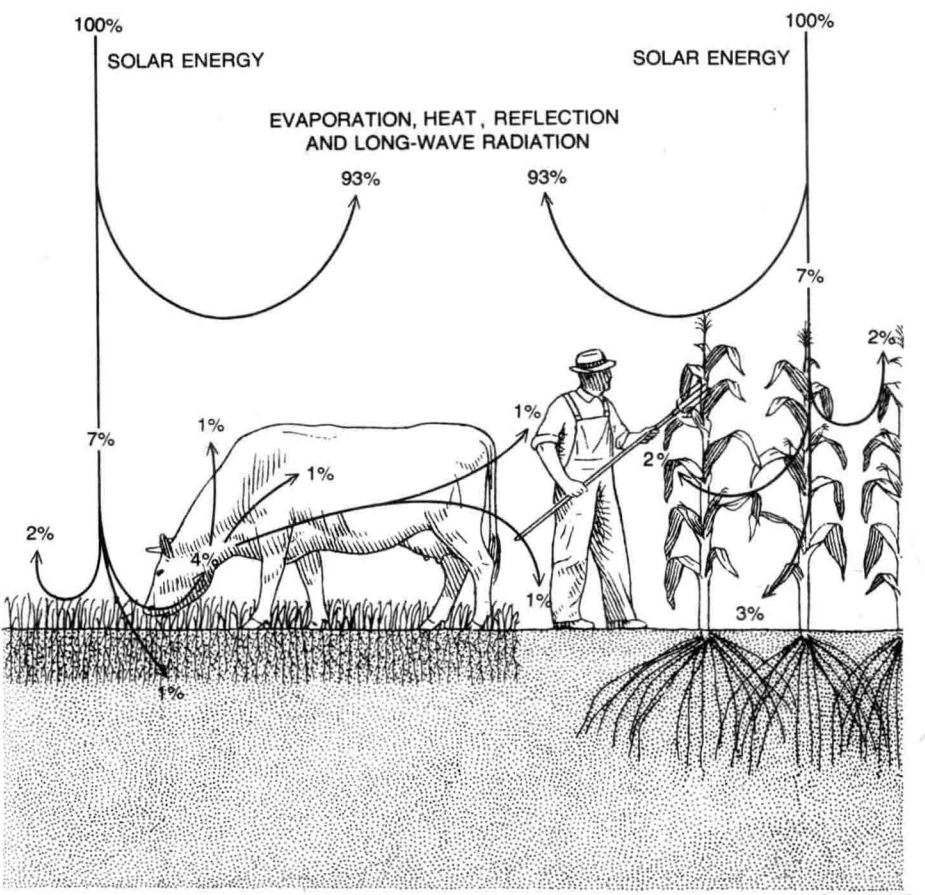

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Preface

Energy's importance to agriculture and to the food chain is universally accepted. Yet there is much confusion and misunderstanding over the functioning of energy in agricultural systems and much controversy over how agricultural systems should be modified in response to limited supplies of higher priced energy. Some of this confusion results from the fact that agriculture is one of only a few industries which directly utilizes solar energy, or from the fact that agricultural products have caloric energy.

Agricultural Energetics describes our conception of how energy causes agricultural and food systems to function. The various flows of energy are identified and quantified, enabling one to make accurate and useful energy analyses of agricultural systems.

We believe this book will serve usefully as a textbook for courses on agricultural energetics or for courses including agricultural energetics as a portion of the subject matter. This book should also prove highly useful as a reference for scientists of various agricultural disciplines, policy makers, planners, energy analysts and energy extension service personnel.

Our thanks are directed toward Ernie Smerdon who in 1973 encouraged us to develop and teach a course on energy and food production. The resultant interaction with enthusiastic students from many disciplines has contributed signficantly to the breadth and depth of the subject matter. *Agricultural Energetics* draws heavily from the class notes we developed over the five years we have taught the course. To write this book was an opportunity to further organize and sharpen our concepts, which we greatly appreciate.

The authors would also like to express their thanks to Dr. D.K. Tressler, Dr. N. W. Desrosier and Ms. Lisa E. Melilli of the AVI Publishing Company for encouragement and assistance in bringing this book into being.

No book is ever finished according to the authors' perception of its needs for further additions and refinement. This one is no exception. However, we are well aware that the areas of energy analysis in general and agricultural energetics in particular are rapidly advancing. Therefore, this being the First Edition, we would greatly appreciate communications from readers for suggestions or recommendations on how to improve it and also to call to our attention errors which may be corrected in the next printing.

RICHARD C. FLUCK
C. DIRELLE BAIRD

July, 1979

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1

Fundamentals of Energy and Agriculture

Energy is both the fuel and the feedstock for agriculture. Primary energy is the fuel; solar energy is the feedstock material. Both are essential in industrialized agriculture.

Concern for the efficient and proper use of energy in industrialized agriculture is evidenced from many quarters, including many nonagricultural sources. Widely differing proposals have been made for changes in agricultural policy in response to these energy-related concerns. Controversy exists over the correctness and feasibility of many of these proposals. It is of extreme importance, therefore, that the energetic relationships of agricultural systems be known and understood. We must be able to correctly identify and measure the flows of energy in the systems comprising crop and livestock production, food processing, distribution and preparation. We call such activities agricultural energetics.

It is painfully evident that energy costs have risen sharply since 1973. The spector of future energy shortages dwarfs the long and slow-moving service station lines of the winter of 1973–74. Energy's increasing costs and decreasing availability affects agriculture, which in turn affects everyone. Though trite, it is seemingly forgotten by some that food is a basic necessity for life. Many of our other activities are not so important as those of our food system.

The emphasis here is on the consumption and depletion of nonrenewable energy resources. The ultimate bottom line the authors attempt to reach is the amount of primary energy required for the

production of an agricultural product. The required primary energy is conventionally measured as output of the energy producing sectors of the economy, i.e., coal mining, crude oil and natural gas production, and their equivalents in hydroelectric and nuclear power.

The authors attempt to be exact and precise in use of terms associated with energy analysis. Many terms have, however, come into common usage without proper definitions. And, as with any infant discipline, there is confusion and conflict over definitions and usage. The authors have provided a list of definitions and sources in Appendix A.1.

Many different energy units are in common usage around the world. This book uses the metric (SI) system, and its energy unit, the Joule. Most energy quantities are expressed in the more convenient quantity megaJoule (MJ) or 10^6 Joules (J). Appendix Table A.2. gives conversions among various energy units.

ENERGY FUNDAMENTALS

Several definitions are basic to an understanding of the nature of energy:

(1) *Force* (push or pull): A vector quantity (a quantity having both magnitude and direction) tending to produce change in the motion of objects. Measured in units such as pound force, kilogram force, dyne and Newton.
(2) *Work:* Product of force and distance. Measured in units such as foot-pound and Newton-meter (Joule).
(3) *Energy:* Capacity to perform work and is equivalent to work. Forms of energy include heat or thermal, chemical, electrical, radiant and nuclear energy, etc. Measured in units such as British thermal unit (Btu), kilocalorie (kcal), Joule (J), kilowatt-hour (kWh), footpound (ft lb) and horsepower-hour (hp · h).
(4) *Power:* Time rate at which work is done or energy is expended or generated. Measured in units such as watt ($J \cdot s^{-1}$) and horsepower (550 ft lb $\cdot s^{-1}$), where s = second.

The two laws which govern energy conversions are the first and second laws of thermodynamics which are:

(1) *Conservation of energy:* Energy cannot be created or destroyed, but it can be changed from one form to another.
(2) *Entropy law, irreversibility of all natural processes:* It is impossible to construct an engine that, operating in a cycle, will produce no effect other than the extraction of heat from a reservoir and the performance of an equivalent amount of work. In other words, some heat must be rejected to another (lower temperature)

reservoir. Another statement of the second law is that heat flows by itself only from the hotter to the colder body or reservoir, never in reverse. Entropy is a quantity closely associated with the second law; change in entropy is defined as the quotient of the energy discarded during a process and the lowest temperature available for heat rejection. Entropy remains constant for a reversible (ideal, and, so far as is known, nonexistent) process and increases for every irreversible process. The total entropy of the universe is relentlessly increasing, although the entropy of individual objects, organisms and systems may be caused to decrease.

Energy in one form may be converted to another form. For instance, steam may be converted to electrical power by a generator. No single conversion will result in all the input energy being converted to the desired form of output energy. Efficiency measures the ratio of output to input and, in doing so, quantifies the amount lost, usually as waste heat.

$$\text{Efficiency} = \frac{\text{Useful Work}}{\text{Input Energy}} = \frac{\text{Input Energy-Waste Heat}}{\text{Input Energy}}$$

Conversions of chemical energy to mechanical work or electrical power are typically 20–40% efficient. Conversions of chemical energy to heat are typically 60–80% efficient. Conversions of electric power to mechanical are usually 60–90% efficient. Conversions of chemical to mechanical by animals are typically 3–10% efficient.

Conservation denotes the efficient use of energy, i.e., in conversions of high efficiency and elimination of waste energy. Fluorescent lamps produce the same amount of light for less electric power than incandescent lamps; therefore, fluorescent lamps are more efficient and conserve more energy than incandescent lamps.

Energy exists in many forms. One useful energy classification scheme is renewable and nonrenewable.

Nonrenewable	*Renewable*
Fossil Fuels	Solar
Natural gas	Sunlight
Oil	Wind
Coal	Hydroelectric
Peat	Photosynthesis
Nuclear	Tidal
	Geothermal

Nonrenewable fuels are often termed *stock* and renewable fuels *flow*.

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2

Energy in Nonindustrial Food and Production Systems

Energy is necessary for food production. Solar energy is the source of energy for food in natural ecosystems. It is supplemented by energy from other sources—primarily fossil fuels, such as crude oil, natural gas and coal—in some agricultural systems. Fossil fuels are the predominant forms of energy in most industrialized agricultural systems and are the predominant energy sources in subsequent portions of the food system in industrialized societies.

Food contains energy which is partially released to the consumer. Nonfood agricultural products, fibers such as cotton and wool and ornamentals such as foliage and flowers, also contain energy but ordinarily this is not an important characteristic of such products.

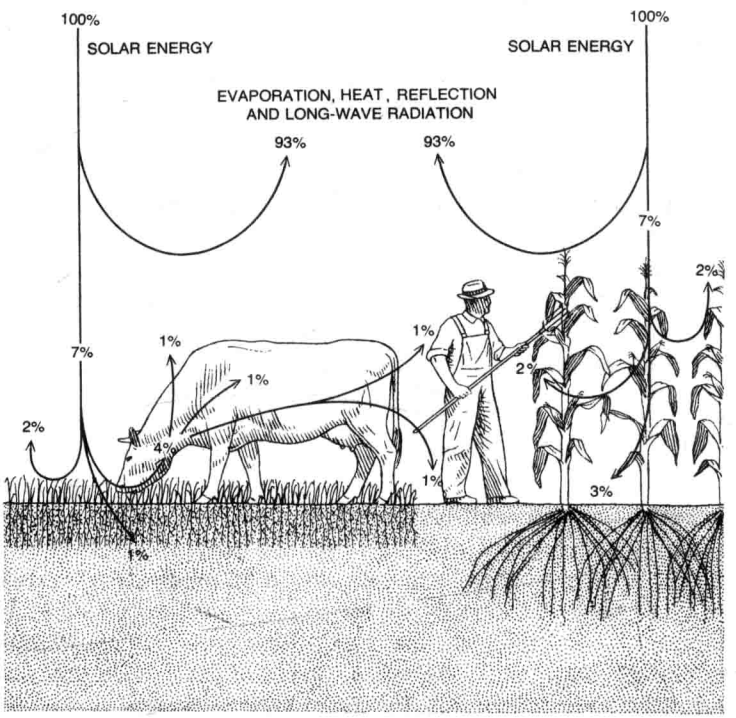
NATURAL ECOSYSTEMS

Natural ecosystems run on energy in a self-regulating manner, solar energy being the fuel for such systems. Photosynthesis is the chemical conversion of solar energy by plants into food products or carbohydrate forms. Plant parts, serving as energy sources, are eaten by herbivores or decomposed by microorganisms. Carnivores consume other animal life for their energy sources. Therefore, all forms of life in a natural ecosystem depend ultimately on the sun for the energy necessary to sustain life.

The rate of incoming solar energy at the outer limits of the earth's atmosphere is indicated by the solar constant, 1.395×10^{-3} MJ $\cdot$ m$^{-2} \cdot$ s^{-1}. After depletion by hours of darkness, atmospheric absorption, cloudi-

ness, etc., the solar energy (insolation) on the earth varies from an average of 0.09×10^{-3} MJ $\cdot$ m^{-2} $\cdot$ s^{-1} at polar regions to 0.29×10^{-3} MJ $\cdot$ m^{-2} $\cdot$ s^{-1} in desert areas. In the summer, a typical United States location will receive a total of 20 to 30 MJ $\cdot$ m^{-2} in the course of a day. The earth, during an average day of the year, receives about 1.49×10^{16} MJ $\cdot$ d^{-1}, where d = day.

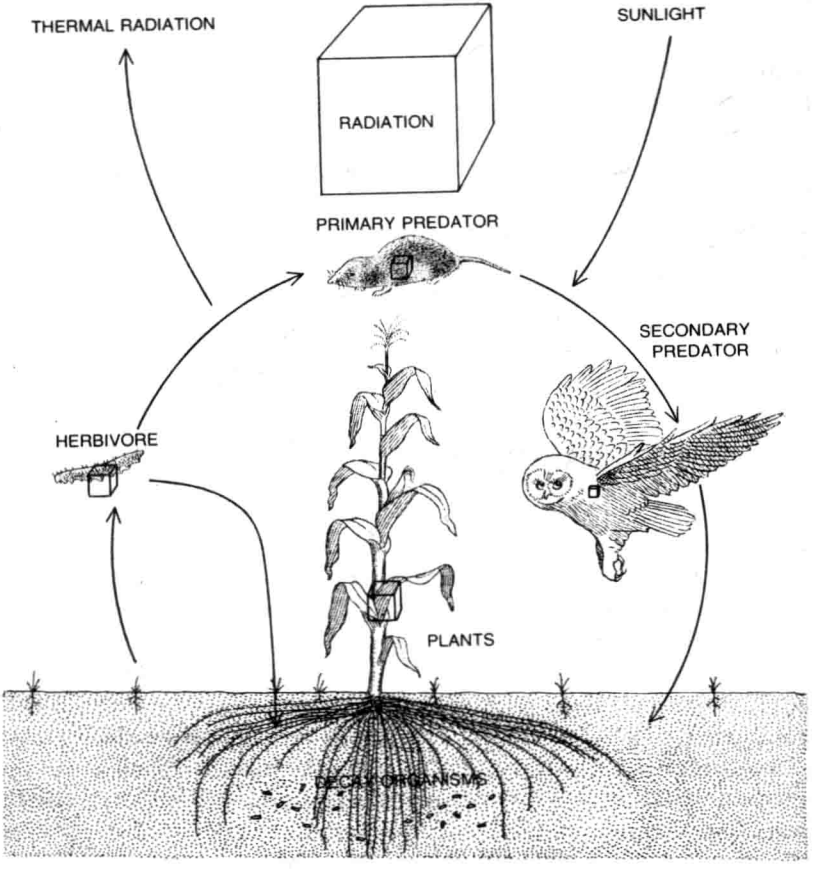
What happens to the solar energy coming into the earth's atmosphere? About 30% is directly reflected as short wavelength radiation. Another 47% is converted to heat by the atmosphere or by the earth and reradiated to outer space as long wavelength radiation. Another 23% evaporates water and thus drives the earth's hydrologic cycle. Only 0.2% drives the earth's weather system through wind and waves. Only 0.02% or about 3.5×10^{12} MJ $\cdot$ d^{-1} is used in photosynthesis by plants.



From Loomis (1976) with permission of Scientific American

FIG. 2.1. PARTITIONING OF ENERGY INVOLVED IN PRODUCING CROPS SUCH AS CORN AND GRASS

Photosynthesis is the fundamental photochemical reaction of life. As photosynthesis occurs in plants, CO_2, H_2O and radiant energy are combined to form O_2 and carbohydrates. Only wavelengths of light centering on blue and red, which consist of about 25% of the incoming solar radiation, are utilized in photosynthesis. Solar energy converted by photosynthesis is contained and stored in the carbohydrates formed. It may subsequently be released by respiratory metabolic processes by the producing plant or by other organisms in the food chain. Animals use this source of energy when they perform muscular work. Energy from the sun cascades through plant and animal communities as it passes from one organism to another, supplying life-supporting energy for all.



From Janick et al. (1976) with permission of Scientific American

FIG. 2.2. ENERGY CYCLE OF THE BIOSPHERE

Only a very small portion of the total solar energy incident upon a plant leaf is converted to chemical energy by photosynthesis. One estimate of the maximum potential net (photosynthesis minus respiration) plant production is 1.11 MJ · m^{-2} · d^{-1} (71 g · m^{-2} · d^{-1}) or 5.3% of the total incident solar radiation (Gates 1971). This is 12% of the visible portion of the solar spectrum. Actual production and conversion rates are considerably less, up to about 1% of total incident solar radiation. Gorz *et al.* (1978) found that 0.8% of the annual solar radiation was fixed in plants by photosynthesis in a New Hampshire forest; net production was about 0.4%.

Energy stored in plants and in animals consumed by other animals is used by the consumer. Only a small portion usually contributes to an increase in weight of the consumer, typically in the order of 10% (Gates 1971; Odum 1971). Janick *et al.* (1976) gave a range of from 2 to 18%. The remainder supports ongoing body functions, such as maintenance, movement and reproduction.

There are two ways of interpreting the energy flow as it proceeds from plants to higher forms of animal life. One is that the energy is concentrated and collected as it flows to a relatively few higher organisms. One might imagine a funnel pouring the net productivity of many organisms in an ecosystem into these few organisms. An alternative interpretation is that most of the energy is consumed along the way and that only a small portion of the energy, but of higher quality, reaches these organisms.

HUNTING AND GATHERING SOCIETIES

Energy is required to produce food and food contains energy. In order to gain an appreciation for the forms and quantities of energy flows which result in food, we shall examine several examples of food production which man has utilized in the past or now utilizes.

Man requires about 10–15 MJ · d^{-1} of food energy, the amount varying with sex, age and size, physical activity, etc. Passmore and Durnin (1955) presented a comprehensive review of food energy needs. However, due to the inefficiencies of conversion of energy from one form to another, more than 10–15 MJ · d^{-1} is ultimately required to provide food for a person. The ultimate requirement may consist of nonrenewable sources, renewable sources, or a combination of the two.

Prior to the development of agriculture (cultivation of crops and raising of livestock useful to man) food was obtained by hunting, fishing

and gathering. Few examples of hunting-gathering societies yet exist, and those which do are likely atypical because they are the few which have been left or pushed to the least desirable geographic areas. Hunting-gathering societies are characterized by a total energy consumption not much greater than the nutritive energy of the food they consume.

Lawton (1973) analyzed and gave guidelines for the energetics of food gathering. For an animal to survive, the energy in the gathered food must be at least equal to the energy expended during its collection. To allow energy for other functions, Lawton wrote that the ratio of the two energies should be at least two. He found, for several species, that the ratio of energy gained to energy expended ranged from slightly greater than one for damselfly larva to 70 for a tropical hummingbird. He further cited a human society on a Pacific atoll having a ratio of 18.4.

Lee and DeVore (1968) edited a book in which descriptions of various hunting-gathering societies are presented. It includes a description by Lee of the !Kung Bushmen of the Kalahari desert of Botswana, who are able to provide their food needs by about 60% of their population spending approximately 12 to 19 hours per week hunting and gathering food; or, in other words, an average of 6% of the total time per 24-hour day is required in getting food. The remainder is used for resting and in providing their housing and clothing requirements, and in leisure and socializing. (For additional information *see* Lee 1969.)

A tribe of modern-day Indians of eastern Nicaragua was studied by Nietschmann (1972). They hunt, fish and farm. He found the energy of their catch per hour of activity averaged 5.32 MJ $\cdot$ h^{-1} for hunting and 4.03 MJ $\cdot$ h^{-1} for turtle fishing.

The Batak, a group of Philippine forest hunter-gatherers, were found to obtain 2.02 and 7.28 MJ $\cdot$ h^{-1} from digging two species of wild yams (Eden 1978). Gathering mollusks yielded 1.32 MJ $\cdot$ h^{-1} and jigging for eels yielded 2.27 MJ $\cdot$ h^{-1}.

Kemp (1971) provided a description of a modern Eskimo society. This group is quite interesting given their ability to survive in a hostile environment. However, it has been sharply influenced and is greatly energy subsidized by the outside world (ammunition, fuel, food, snowmobiles, outboard motors, etc.). Total energy consumption is approximately 78 MJ $\cdot$ $caput^{-1}$ $\cdot$ d^{-1}.

Cottrell (1955) briefly described the American plains Indian and suggested that food gathering-hunting societies lived a rather precarious existence.

Clark and Haswell (1970) gave a more detailed description of several such societies, pointing out land requirements and also the beginnings of agriculture.

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