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Energy at the Surface of the Earth

An Introduction to the Energetics of Ecosystems

David H. Miller

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Student Edition

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To the memory of F. A. Brooks, radiation and engineering meteorologist, innovative micrometeorologist at the University of California at Davis, and to C. F. Brooks, meteorologist and climatologist at Harvard University, founder of the American Meteorological Society

PREFACE

This book presents one way of looking at the manner in which the biological, physical, and cultural systems that mantle the landmasses of our planet receive, transform, and give off energy, which is an essential condition of existence that takes many forms. Energy conversions establish the climate in which these systems operate.

The principal forms of energy that are converted at the ecosystem scale include radiant, latent, mechanical, chemical and fossil, and thermal. We begin with radiant energy absorbed by ecosystems, a phenomenon that is independent of their surface temperature and that can be looked on as a burden or a gift, depending on circumstances. An increase in such absorption raises surface temperature, as described in the fulcrum chapter of the book, Chapter VIII. This increase in turn sets into action outflows of energy that by the first law of thermodynamics are equal in energy units, although not necessarily equal in quality to the inflows. While the second law comments that quality is likely to suffer in such a transaction, our principal tool of analysis is the first-law equivalence, which can be stated as a simple accounting in watts per square meter of ecosystem area. These temperature-dependent fluxes of energy are discussed in the chapters following Chapter VIII; the final chapters deal with vertical stratification and areal contrasts in energy budgets, the augmented energy budget of the city, and the responses that serve to keep the budget balanced.

Anyone who looks at the landscape perceptively, whether in wildlands, cultivated areas, or the city, can see energy in movement or transformation everywhere; awareness of the environment as a functioning entity is enhanced, I believe, by recognizing the manifestations of energy in it. I first encountered this way of analyzing nature when studying snowmelt floods that had occurred and that conceivably might occur in the Sevier River in Utah; subsequently I applied energetics to another system—the clothing that protects a soldier from a hostile thermal environment. In both cases, seemingly so far apart, much the same energy fluxes are important, and it appeared that an organizing concept that could make sense out of such different situations had much to commend it as a means of studying a set of objects in which I had long had interest, the ecosystems that comprise the variegated surface of the earth. It is true that energy budgets are routinely cast for thermodynamic systems in such artifacts as engines and houses, others for atmospheric motion systems, others within leaf cells, others encompassing an entire planet or star; but here we select for energetic analysis only those systems that are located at the outer active surface of the lands, confronting sun and atmosphere and functioning at the scale of ecosystems. Smaller systems (e.g., leaves) are considered in passing, and the scale is enlarged only slightly to take in cities, those fascinating interminglings of human and natural systems, still *terrae incognitae* to science and yet whose working and very survival are basically expressed in their energetics. The uncertain future of fossil energy poses questions for wildland and agricultural ecosystems too, but nowhere more than for the vulnerable modern city.

My aim is not to tell everything about any one energy flux or any ecosystem, but to try to develop a proportioned and numerically illustrated treatment that will help the reader see each flux in its true setting and observe ecosystems coupled into their environments. Because real measurements carry more conviction, I have preferred observed data, many of them from sites I have visited or worked in, over modeled or assumed or asserted quantities or mere symbols divorced from numerical content. Similarly, I have not repeated oversimple formulas for the fluxes, but prefer that the reader who finds it necessary to estimate should refer to the original articles, where qualifications and cautions were set out by the field worker.

Study of the energetics of systems at the surface of the earth draws upon the content of several disciplines, each of which has its own objects of study and its own way of viewing the rest of creation. No single discipline—not meteorology, not hydrology, not ecology, not geography—and no practitioner field—forestry, agronomy, architecture, city planning, or engineering—can encompass the subject essayed in this book. Although these fields make use of energetics as a mode of investigation, they do so only in an auxiliary role. Accordingly, I make no attempt to summarize the principles or content of any discipline, but rather select what it can contribute toward interface energetics. Contributions to the resulting synthesis, if such it is, have come from many disciplines of science and practice and I hope the synthesis will give back to each field as much as it takes; for example, the climate of the soil and the structure of the atmosphere are governed by energy fluxes at the interface between these adjoining media.

Spatial contrasts in energy reflect contrasts in geology, soil conditions, hydrology, topography, solar input, and atmospheric coupling, as well as in cultural practices, and at the same time heighten contrasts in the landscape. Energetics analysis helps us to perceive the true variety of the world, and beyond these hoped-for contributions to individual disciplines I hope that ecosystem energetics may contribute in a small way to the riddles of food production and overpeopling of the earth, energy and water resources, urbanization, and the imperiled environments of life.

Different forms of energy have different kinds of utility and are the provinces of different disciplines, but there exists behind this diversity of appearance a unity of essence. The energy problems besetting the world are not likely to yield to single disciplines, each regarding its own form of energy as if it had little to do with other forms and generating its own specialized data. In the service of a broader integration I have tried to use data from these disciplines to make sense of it all. How well the resulting picture captures nature is for the reader to say.

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Chapter I

INTRODUCTION

THE ENERGY BUDGET

Energy, a basic quantity in the universe, is present at the surface of the earth in many forms, so diverse that recognition of its continuity was a major intellectual feat of 19th century scientists. Familiar changes in its form are the absorption of solar energy by plant leaves, emission of longwave radiation by all surfaces, formation of chemical energy from radiant, its release in decomposition of organic material, and energy going into latent form when water evaporates or snow melts.

Transformations imply inputs and outputs of energy. Inputs include the delivery of energy as sunshine to an ecosystem, the sensible heat it extracts from warmer air, and the return of heat in winter from warmer layers of an aquatic system to its cold surface. Outputs from ecosystems include energy that is radiated away or carried off in the atmosphere or carried off in the harvest.

Budget accounting of inputs and outputs shows that when all forms of energy flow are considered, the inputs balance the outputs. This statement of continuity is the first law of thermodynamics, that energy is not created or destroyed. It says nothing about the quality of energy of different forms; that is a matter of the second law, which indicates the ability of a particular form of energy to do useful work. Solar and chemical energy have higher quality than thermal energy at ecosystem temperatures or longwave radiation (Moore and Moore, 1976, p. 73; Lönnroth *et al.*, 1980). These considerations suggest direction of transformation, but our concern here is primarily with first-law accounting. Determining an energy budget for a surface is a matter of striking an account of all the inputs and outputs, and the necessity for them to be in balance provides a quantitative check on the measurements. The concept is straightforward. Problems arise in applying the budget over time and space.

Variability over Time and Space

The budget by definition is never out of balance; if any input increases, one or several outputs increase to the identical amount. While the balance remains, the mix of its constituents changes. Some variations are regular, like summer and winter, and seasonal budgets show how an ecosystem responds to a change in energy loading. Sudden changes, like the arrival of a cold wave, show in a different way how the system responds. Variability is generated both by extraterrestrial changes, which are relatively regular, and by systems in the earth's atmosphere since the clouds and wind of a passing storm cause fluctuations in energy budgets at the underlying ecosystems.

Spatial differences in the energy budget occur at many scales, among which we will be primarily concerned with those of ecosystems and secondarily with differences within ecosystems and contrasts among them. Energy fluxes differ from place to place and thereby depict in a physical way the variety we see in the world around us.

Components

Let us list the basic energy fluxes that are found in ecosystems:

(1) Solar (or shortwave) radiation absorbed by an ecosystem;
(2) Longwave radiation from the atmosphere absorbed by an ecosystem;
(3) Photosynthetic conversion of solar energy;
(4) Energy released by decomposition and from fossil sources;
(5) Emitted longwave (thermal) radiation from leaves;
(6) Heat converted in evaporation and in melting snow;
(7) Heat taken into the ground at certain times and released at others;
(8) Sensible-heat flux from the surface into the air;
(9) Conversions of kinetic and potential energy, such as wind energy.

Sum: All of the above total to zero if we assign a positive value to inputs and a negative value to outgoes.

Our emphasis is on the rates of transformations and flows—the dynamics of energy. The watt appears more often than the joule, and the watt per square meter still more often (see Table I).

TABLE I

Approximate Conversions to Older Metric and Traditional Units

1 joule (J) = 0.24 gram-calorie (cal) = 0.28×10^{-3} watt-hours (W h) = 0.95×10^{-3} Btu
1 MJ m^{-2} = 24 gram-cal cm^{-2} = 24 langley (ly) = 88 Btu ft^{-2}
1 watt (W) = 1 J sec^{-1} = 0.24 cal sec^{-1} = 3.4 Btu hr^{-1}
1 W m^{-2} = $\frac{1}{698}$ ly min^{-1} = 0.086 ly hr^{-1} = 2.06 ly day^{-1} = 0.32 Btu ft^{-2} hr^{-1}

THE LOCUS OF ENERGY TRANSFORMATION

Energy transactions are studied in many kinds of systems, initially in steam engines, later in natural systems. In any thermodynamics investigation it is first necessary to delimit a system as an object of study. We can then distinguish its internal processes from the energy inputs and outflows that express its relations with the rest of the world.

In studying energy transactions at the surface of the earth, the most convenient system to define is the ecosystem. This is a biological concept that expresses the structure of the earth's green mantle and can be expanded to include aquatic systems, desert surfaces where plants are sparse, winter snow cover, and urban systems. Ecosystems are as convenient for energy studies as for water studies because they are reasonably homogeneous pieces of the earth's surface. Many of them are stratified in the vertical, but are effectively uniform in the horizontal and delimited by sharp edges (Fig. 1). A person flying over Wisconsin sees a mosaic of contrasting ecosystems—woodlots, corn, alfalfa, and oat fields; each unit is uniform horizontally. In wildlands too ecosystems of reasonable homogeneity make up the whole landscape. Rocky ridges, meadows, pine stands, and brush fields: each is internally uniform.

For reasons that are not entirely clear, the spatial scales of ecosystems in human landscapes are of about the same size, i.e., a horizontal extent of a hundred to a few hundred meters (Miller, 1978). In agricultural lowlands sizes are related to cultivation practices and the size of the total farm or unit of land management. In uplands ecosystem sizes are related to dissection of the surface, which produces slope facets of differing exposure to sun and wind; the different inputs of water and energy support different kinds of ecosystems. These entities can be compared on a unit-area basis by use of data expressed as energy flux density (watts per square meter).