The Energy Budget Approach to the Study of Microenvironment

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ALTHOUGH THERE exists a widely published reference system for the study and description of climatic environments, very few instances of its use by biologists are apparent to the authors. It is the purpose of this paper to describe the system and to point out some of its potentialities for use in the study of microenvironment, and particularly in the classification and study of plant communities.

The Energy Budget

Perhaps the description of the energy budget most likely to be familiar to biologists is the one in Geiger's famous book on microclimate (1950). His discussion of the interrelationships of the various elements that figure in the distribution of the sun's energy may be summarized in equation form:

$$R_n = E + B + L$$

which we will refer to as the energy budget equation. In this equation the symbols are as follows:

R_n = the net amount of radiant energy of all wave lengths arriving at the earth's surface,

E = the net amount of energy used at the surface in the processes of evaporation, condensation, freezing, and melting,

B = the net amount of energy transferred from the surface into the soil and other material below the surface,

L = the net amount of energy released by the surface to the air by convection.

When considered as a system of debits and credits, this concept of climatic environment takes on the nature of an accounting or budget system, hence the term "Energy Budget."

Published Biological Applications of the Energy Budget

A detailed study by Pasquill (1949) of the climatic environment in a pasture was primarily for the edification of meteorologists, and only incidentally of interest to agronomists. The energy budget was the foundation of a study by Miller (1956) of the role of vegetation in the nature of the climatic environment of the Sierra Nevada. In this case, too, the author did not have the biological factors present as his primary interest. In fact, a study by Wang and Suomi (1957) of the growing season is the only publication of which the authors are aware in which the energy budget approach has been applied in the study of a bioenvironmental problem.

The Energy Budget as an Ecological Tool

Before adopting the energy budget approach to the study of microenvironment, ecologists should satisfy themselves about the answers to several basic questions:

1. Do the energy budget components give a true picture of effective environment? If the quantitative components of the energy budget equation are no more clearly related to observed differences between plant communities and plant growth requirements than the customary measurements of temperature, wind, etc., then the concept is unlikely to be of greater usefulness than those presently employed.

2. What are some of the reference points of the energy budget with respect to community ecology? Assuming that question "1" is answered in the affirmative, one would want to know whether or not variations in the energy budget system might be greater within one community type than would be found between several community types. As a partial answer to this question, Table 1 presents a summary of energy budget data for several distinct types of natural environment as compiled by Sutton (1953, p. 200).

3. What is the reliability of energy budget measurements in depicting small differences in environment? It is likely that the sensitivity is a function primarily of the precision of instrumentation and secondarily of the manner of interpretation of the results. The general framework of the energy budget approach allows for all processes of energy distribution in the environment, including those of respiration, transpiration, and photosynthesis in the plant.

Several major advantages are offered by the energy budget concept if satisfactory answers are found to the above questions:

1. The system is capable of describing in concise form the entire climatic environment during short periods of time. Table 2 is based on the paper by Billings (1952), in which he analyzes the various factors of the environment. An attempt is made in this table to show that most of the factors not involved in geomorphological processes can be re-evaluated under the four components of the energy budget.

2. The system involves the use of only one unit of measure: e.g., gram-calories/cm^2/minute.

3. The system provides a basis for effective duplication of field environments where interpretation of phenomena is required at the growth chamber level.

4. The system is a basis for investigations of internal responses within plant communities because it permits a realistic assignment of cause. For example, a temperature change at a point may be caused by radiation, by air drainage (advection), by changes of air mass (also advection), by changes of wind behavior (convection), or by a combination of these. Where proper assignment of the causal relation is important, the energy budget should be a distinct aid.

5. The system provides an aid to the description, classification, and delineation of plant communities in various stages of succession.

6. The system provides a basis for comparison of environments by means of a simple, objective, and quantitative scheme.

An additional consideration in the usefulness of the energy budget is that the system may be used with various planes or surfaces of reference. As outlined above, the energy budget is most frequently referred to the plane of the earth's surface. Miller (1956), however, uses a plane of reference located at the height of treetops protruding through a deep snow cover. Other primary surfaces, such as the tops of broadleaf shrubs, may be used in the energy budget approach.

Instrumentation

It is likely that the precision of the energy budget method is a function primarily of instrumentation. Fine examples of elaborate instrumentation designed especially for gathering data to be analyzed according to the energy budget concept are the works of Pasquill (1949) and the Johns Hopkins Laboratory of Climatology (1954). If precision is not a prime requisite of the study, however, there are adquate systems of instrumentation that are relatively inexpensive. One such system, which is described below together with some tentative results (Table 3), has been used in the field by Lowry and can be recommended as a starting point for investigations such as are proposed here.

Description of the system is broken down by energy budget components.

Net radiation, R_n: the net radiation component of the system is measured by means of the instrument described by Lowry (1957). This instrument employs primarily two mercury-in-glass thermometers and operates on the principle that the temperature difference between two sides of a blackened plate is a function of the net amount of energy passing perpendicular to the plane of that plate.

Evaporation, E: the evaporation, or change of state, component may be estimated by means of the method described by Lowry (1956) and by Selleck and Schuppert (1957). This method employs records of the weight of soil samples cut from their surroundings, placed in perforated sample cans, and returned to their original surroundings. Refinements are in progress, and the authors invite inquiries as to these more recent results.

Soil heat storage, B: the soil term can be approximated by means of records obtained from any of the available temperature probe indicators or recorders. Subsurface soil temperatures are used in conjunction with the following equation:

$$Q = \frac{\rho c \ (\Delta T) \ (\Delta X)}{\Delta t}$$

where Q = the heat stored in a layer of soil Δx (centimeters) thick during the time Δt (minutes).

ΔT = the temperature change during Δt at a point midway in thickness of the layer: i.e., Δx/2 (centimeters) from the top of the layer.

ρ = the density of the soil in the layer ($grams/cm^3$), and

c = the specific heat of the soil in the layer (calories/degree/gram) that may be determined with a thermos bottle calorimeter.

Then the soil term B is equal to the sum of the separate values of Q computed for as many layers as there are levels of temperature record in the soil. During periods of a few days, it is seldom necessary to evaluate Q for layers below about 30 centimeters because of the very small changes in temperature at that level over short periods.

Convection exchange, L: the nature of turbulence and convective exchange do not lend themselves to simple or convenient theoretical description; therefore, computation of the convective exchange component using direct measurements is a matter unresolved among specialists. However, it is common practice to consider the convective term as a residual of the other three (see note at bottom of Table1):

$$L = R_n - E - B$$

This measurement scheme is admittedly crude and approximate, but its ruggedness and low cost have considerable merit in many investigations of the energy budget as related to microenvironment.

TABLE 1

Description of Environment	Hour for Which Means Are Presented	R_n	B	E	L
			Mean Values in gm-cal/cm^2/min		
English pasture, spring	1030 - 1930	——	.014	.079	.058
Finnish meadow, August	0550 - 1770	.540	.070	.350	.130
Finnish meadow, September	0550 - 1630	.480	.050	.220	.190
Finnish meadow, October	0730 - 1500	.310	.030	.080	.200
Gobi desert, date not known	0600 - 1800	.344	.107	.057	.194
Finnish sand heath, August	0550 - 1770	.540	.130	.120	.290
Finnish sand heath, September	0550 - 1630	.480	.110	.180	.190
Finnish sand heath, October	0730 - 1500	.310	.120	.060	.130
Rock surface, Finland, August	0550 - 1770	.540	.300	0	.240
Rock surface, Finland, September	0550 - 1630	.480	.230	0	.240
Rock surface, Finland, October	0550 - 1500	.310	.180	0	.130

Note: Some idea of the accuracy of considering $L = R_n - E - B$ may be gained from this table in which the values of L are almost certainly computed directly from observations rather than by using the residual method. In every case L is equal or very nearly equal to $R_n - E - B$.

TABLE 2

Component of the Environment after Billings (1952) for Which Measurements Are Made		Component of Energy Budget in Whose Computation Environmental Measurements Are Used Directly (Depending upon Instrumentation) B=Biological Processes P=Physical Processes				Geomorphological Processes	"Purely" Biological	Remarks
		R_n	E	L	B			
Radiation	solar	PB						
	cosmic	PB						
	terrestrial	PB						
Temperature	air	PB	PB	PB				
	soil	PB	PB	PB	PB			
	rock	PB	PB	PB	PB			mosses, geothermal gradient
Water	water vapor	PB	PB	PB	PB			
	cloud, fog	PB						
	precipitation				P			
	soil water		PB		PB			
Gases	composition	PB	P	P	B			air density
	pressure		PB	PB				
	wind		PB	PB				
Soil	parent material			P	PB			
Soil	physical	P	P	P	PB			
	chemical	PB			PB			
	biotic		B	PB	PB			
Gravity	runoff			PB	PB			
translocation, seed dispersal, etc.							B	
Landslides, vulcanism, erosion, diastrophism, fire, etc.						PB		
Competition, dependence, etc.							B	

TABLE 3

The entries in this table are three-hour mean values in gram-calories/cm²/minutes

Site and Weather	Time											
	0800-1100				1100-1400				1400-1700			
	R_n	E	B	L	R_n	E	B	L	R_n	E	B	L
Station A open, cut-over, with scattered bracken and vine maple, sunny and clear with afternoon sea breeze, elevation 2600′, south-facing at 25°	.91	.08	.61	.22	1.59	.16	.72	.71	1.03	.17	.06	.80
Same as above, low overcast all day	.31	.02	—.03	.32	.36	.02	.30	.04	.36	.07	—.14	.42
Station B open, recently logged, little vegetation but heavy concentrations of slash on bare, clayey soil, elevation 2450′, north-facing at 20°, same sunny day as above	.74	.05	.18	.51	.87	.05	.32	.50	.69	.04	—.02	.67
Same Station B on same overcast day as above	.21	.01	.07	.13	.26	.01	.08	.17	.15	.01	0	.14

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