- MICROMETEOROLOGICAL METHODS AS TOOLS FOR INCREASING CROP PRODUCTION AND WATER-USE EFFICIENCY[1]

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ABSTRACT

The application of micrometeorological methods to problems of agronomic importance has greatly increased the understanding of the physical processes controlling the natural environment of plants. The methods and the basic information gained from studies utilizing these methods are presented to illustrate the importance of microclimatic factors and to indicate the applicability of the methods to problems of practical importance. The results of micrometeorological studies have increased our understanding of such things as partitioning of energy at the earth's surface, factors controlling the rate of evaporation of water from the earth's surface, and the effects of management practices upon the microclimate of a plant community. A deeper understanding of these basic factors increases the possibility of obtaining more efficient use of water, and greater and more economical crop production through improved irrigation management practices, the modification of the natural microclimate of a crop, and the development of improved crop types which will maximize the beneficial factors of the microclimate.

INTRODUCTION

The science of micrometeorology, which deals with atmospheric processes near the earth's surface, is providing increased knowledge of the mechanisms controlling our environment. Micrometeorological methods have only recently been applied to agronomic problems. Such application has increased our understanding of the response of crop plants to their physical environment, thereby permitting us to develop improved agronomic practices aimed at achieving more efficient use of water with increased and more economical production of crops.

This discussion summarizes some of the key factors in the application of the meteorological methods to agronomic problems. The application of the methods to the problems of increasing water-use efficiency and crop production will be emphasized rather than the details of the methods. This will include a review of some of the basic physical factors controlling the microclimate at any point on the earth's surface and the application of the meteorological approach in studying this microclimate.

The meteorological method has a twofold application to agronomic problems. First, it serves as a useful research tool, permitting the study of basic physical processes within the microclimate. Second, it has the potential for direct application to farm management practices, such as measurement of the evaporative loss of water and determination of when to irrigate. The expenditure of considerable time, effort and money in the development of

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these methods is fully justified because only by gaining an increased understanding of the natural physical environment of soils and plants and their response to this environment can we hope to understand and predict plant responses to microclimatic conditions. The resulting information will permit us to develop methods of altering the natural environment to increase crop production and water-use efficiency.

METEOROLOGICAL METHODS AND THE PLANT MICROCLIMATE

The Plant Microclimate

The physical processes of the atmosphere, called meteorological processes, establish the existing climate or microclimate. Although it does not act alone, climate, in turn, determines the regime of soils and plants at a given location. Wind, precipitation, sunshine, temperature, humidity, and soil moisture are the primary factors involved. The profitable production of crops and efficient use of water require a microclimate suitable for plant growth. What makes the microclimate suitable? The meteorological methods are helping us answer this question. Recent studies of the nature of the microclimate have yielded a wealth of information on the interaction of the physical processes of the environment and the response of plants to these processes. A brief review of the results from these studies will be presented here. (Those interested in pursuing the subject further will find Geiger (2), Slatyer and McIlroy (6), Waggoner (9), Munn (5), Evans (1) and Lettau and Davidson (4) very helpful.)

The meteorological processes are dynamic, each reacting to the changes in the others. The dynamic balance involves a continual exchange of mass and energy. Of particular importance to us are the exchanges of molecular heat energy, radiant energy, momentum, water vapor, carbon dioxide, and oxygen between the plant or soil surface and the atmosphere. We refer to this exchange as the vertical flux of the respective quantities. The meteorological method currently offers one of the best approaches to the study of these fluxes. It also permits an evaluation of the rates of the associated plant physiological processes such as photosynthesis and transpiration under natural field conditions.

The energy exchange processes are basic to the rest of the dynamic system. We can evaluate these by an energy balance approach. The sun provides the source of radiant energy called solar radiation. Of the total solar energy reaching the outer edge of the earth's atmosphere, about, 65% is available at the earth's surface for processes requiring an energy input. The other 35% is reflected by the atmosphere and the earth's surface. The solar energy absorbed by the earth causes it to be warmed. The heated surface emits thermal radiation back into space, resulting in a loss of energy and a cooling of the surface. We refer to the portion of the radiant energy absorbed at the surface and remaining after the emitted thermal radiation portion is subtracted as the net radiation component. This is the important component so far as the energy-utilizing processes at the earth's surface are concerned because it is partitioned among the various physical and physiological processes existing here.

A small portion of the net radiant energy is utilized in the photochemical processes of photosynthesis. A larger portion goes into the heating of the soil, plants, and air. A fairly large portion provides latent heat for the evaporation of water. Expressing this in terms of an energy balance, we can say that the net radiation is equal to the total incoming solar radiation minus that which is reflected and that which is lost by reradiation from the surface. We can further say that the net radiation is partitioned among the components: (1) sensible heat, utilized in the heating of the air; (2) latent heat, utilized in the evaporation of water; (3) stored heat in the soil and plant materials; and (4) the photochemical energy, utilized in photosynthesis.

As an example of information gained from studies of the microclimate on the interaction of the radiation energy exchanges and the other processes existing within the microclimate, let us consider what happens within a growing crop on a clear summer day. Beginning at sunrise, the soil and plant surfaces are rapidly heated by the absorption of radiant solar energy. Because the air is nearly transparent to shortwave radiation, it does not absorb as much of the radiant energy as do the surfaces. Therefore, the surfaces are much warmer than the air and there is a resulting flow of heat from the surfaces to the air, referred to as sensible heat flux. Because of this, a strong temperature gradient develops very near the surface and the rising of the warmer air parcels causes the air to become unstable. This greatly increases the mixing motion or turbulence of the airstream, which serves to cool the surface and warm the air at even faster rates.

In addition, the solar energy absorbed provides energy for the evaporation of water from the surface. The increased turbulence of the unstable air increases the rate of transfer of water vapor away from the surface, so that there is a rapid drying of soil surfaces and wilting of plants if moisture is limiting.

During photosynthesis, photochemical energy is used by the crop leaves to synthesize organic matter using carbon dioxide from the air. This results in a net transfer of carbon dioxide from the air to the leaves of the plant. Turbulent air motion enhances this transfer rate.

The net result is that the surface gains energy from the sun, then loses energy in heating the air, in the evaporation of water and in the flow of heat to the deeper soil layers. This is accompanied by a flow of water vapor away from, and a flow of carbon dioxide to, the surface.

After sunset, the situation quickly reverses. The surface radiates heat away rapidly and cools to a temperature below that of the air. There is then a flow of heat from the deeper soil layers and from the air to the cooling surface. A strong temperature gradient develops between the air and the soil or plant surface opposite in direction to that existing during the daytime. This condition, called temperature inversion, results in the air mass becoming more stable, with decreased turbulent mixing. Evaporation rapidly decreases, and photosynthesis ceases so there is then an uptake of oxygen and a release of carbon dioxide associated with respiration.

The plant and soil surfaces thus act as sources and sinks for the various energy and molecular entities throughout the day. There is a flux of energy and molecular quantities either away from or toward the surface at almost all times, the direction depending upon the daytime conditions. The microclimatic conditions determine the flux rates, but the plant can modify these by stomatal closure, shading the ground, and increasing the surface roughness. Our desire is to be able to quantitatively measure these flux rates on a continuous basis. The meteorological approach serves as a useful tool in enabling us to do this. A complete study of the microclimate involves the measurement of net radiation, total incoming incident radiation, windspeed, air temperature, air humidity, soil temperature, the flow of heat into the soil, the soil moisture content, and the various properties of the surface or plant community itself.

The Meteorological Approach

The meteorological approach to determining the vertical flux of energy and mass from a crop surface requires the measurement of the respective gradients, with height, of the energy and molecular entities and the determination of a transfer coefficient. The plant and soil surfaces acting as sources and sinks for the various entities establish the concentration or energy differences, which we call gradients, along which the respective entities are transferred. The transfer rate, or flux, of the particular entity is related to its gradient by a transfer coefficient. This coefficient, which is similar to a diffusion coefficient, characterizes more than any other single parameter the effectiveness of the exchange process.

Of particular interest to the agronomist is the flux of carbon dioxide and water vapor associated with photosynthesis and evapotranspiration. The evaporation rate can be calculated under natural field conditions without altering the crop or soil system from measurements of the water vapor gradient and the transfer coefficient. Short period results so necessary in the evaluation of the important aspects of the highly transient system are possible. The meteorological approach also lends itself to mobility. It does, however, require careful application, considerable instrumentation, and involved analysis procedures. Recent advances in instrumentation, electronic technology, and computer developments have enabled use of this approach in spite of its complexity.

It is not possible to present here all of the variations in the meteorological methods that have been, and are now being, used. (These are adequately discussed in many places and have been the topics of several recent symposiums.) However, an example of one of the meteorological methods is presented to show how they can be applied to problems of crop production and water-use efficiency.

The energy balance approach is a suitable example because of its basic nature and its prominence in studies of evapotranspiration. This approach involves determination of the partitioning of energy among the various physical processes contributing to the microclimate, and can be used to measure daily evaporation with little more effort than that required to measure weekly evaporation by soil moisture sampling methods. It has been applied to the determination of evapotranspiration from crops only within the past few years (7, 4).

The Energy Balance Method

A brief theory of the energy balance is presented here to illustrate what is involved in using such a method. A simplified energy balance equation for a crop community, neglecting the relatively small photosynthetic energy component and assuming horizontal uniformity, can be written as:

$$R_n = H + LE + S \qquad 1$$

where R_n = net radiation, cal cm^{-2} sec^{-1}

H = sensible heat flux, cal cm^{-2} sec^{-1}

LE = latent heat flux, cal cm^{-2} sec^{-1}

S = sensible heat storage, cal cm^{-2} sec^{-1}.

The terms for sensible heat and latent heat can also be represented by diffusion-type equations:

$$H = -C_p \rho_a K_H (\partial T/\partial z) \qquad 2$$

$$LE = -\frac{\epsilon}{P} L \rho_a K_E (\partial e/\partial z) \qquad 3$$

where C_p = heat capacity of air, cal g^{-1}

ρ_a = density of air, g cm^{-3}

T = temperature, deg

z = height above ground, cm

ϵ = mole weight ratio of water vapor and dry air

P = atmospheric pressure, mb

e = water vapor pressure, mb

K_H = heat transfer coefficient, cm^2 sec^{-1}

K_E = water vapor transfer coefficient, cm^2 sec^{-1}

Turbulent transfer is a bulk transfer, so the transfer coefficients K_H and K_E are nearly equal because they are not as much a function of molecular properties as are molecular diffusion coefficients. Substitution of Equations 2 and 3 for the sensible and latent heat terms of Equation 1 and solving for the latent heat term gives:

$$LE = \frac{-(R_n + S)}{1 + \frac{C_p P}{L \epsilon} \frac{(\partial T/\partial z)}{(\partial e/\partial z)}} \qquad 4$$

Therefore, if we measure the net radiation, soil heat storage, and the air temperature and humidity gradients -- all of which we are presently able to do -- we can calculate the latent heat flux and from it the water vapor flux which gives us the evaporation rate.

The Application of Meteorological Methods

The energy balance method has much potential in the study of rate of evaporative loss of water from cropped surfaces because of its fundamental nature and because it can be employed in various other forms. It lends itself to estimating evapotranspiration by approximation procedures when complete data are not available. Such approaches have been suggested and successfuly used by Jensen and Haise (3), for example.

The meteorological methods serve as tools for increasing crop production and water-use efficiency by providing a means of obtaining fundamental information about the controlling physical processes involved in the microclimate. The economic use of water, for example, requires a knowledge of the water evaporated by various vegetated or treated surfaces. It requires an understanding of the effects of stage of growth, plant characteristics, and various management practices on water use and crop production. An understanding of plant response to the microclimate in the evaporation of water is necessary for predicting the amount of water that will be evaporated under given conditions and for controlling evaporation.

Furthermore, the meteorological method has a potential for more direct application to these problems. It was suggested several years ago that the careful determination of evaportranspiration by such a method could be used to determine the time to irrigate (8). This has been tested on an experimental basis and found to be a usable technique. With more information about crop factors and their relationship to water use, the utility of this approach will be increased.

As a further development along this line, the scheduling of irrigation of several crops on farms in this area is now being cooperatively carried out on a trial basis. The scheduling is based on meteorological parameters and previously obtained information about the response of crops to certain conditions. This procedure offers an alternative to present methods of determining when to irrigate. The method most commonly used is that of judging irrigation needs by the plant or soil appearance, which often results either in irrigation after the plant has already suffered from lack of water or in the waste of water by irrigating before it is required. Another method is that of using soil moisture measuring instrumentation or sampling procedures to monitor the water content of the soil. These methods can be used satisfactorily on a research basis or on large-scale operations where individuals highly skilled in the interpretation of these instruments are available. However, it is not likely that these instruments will ever be used extensively on the small farming scale. It is highly probable that within the near future the meteorological approach will find widespread application and that with further developments it may be possible to forecast irrigation requirements from crop data, meteorological data, and predicted weather patterns.

Meteorological methods may also be used to study the effects of irrigation on the microclimate and the plant response to these effects. Irrigation decreases air and soil temperatures and increases the humidity of the atmosphere near the surface. It, therefore, exerts a profound influence upon the disposition of energy at the surface and upon the climate near the ground. Such side effects of irrigation may have great importance in the management of suitable microclimates.

Another interesting application is that of studying the modification of the microclimate by such management practices as planting of windbreaks. Studies at several locations in the Great Plains have indicated that the production of some crops can be increased by altering the microclimate with snow fences or with occasional rows of corn planted among low-growing crops such as soy beans.

In another application, the meteorological approach has been used to gain valuable information about the distribution of photosynthesis within a crop throughout the day (10, 11). Still other studies are aimed at gaining more information about the effects of row orientation and plant populations on the microclimate. Information gained from these studies could lead to the development of an ideal model of a plant so far as leaf arrangement, leaf characteristics and other plant morphological characteristics are concerned. This might help plant breeders in the development of improved plants.

CONCLUDING STATEMENT

Water-use efficiency and crop production go hand in hand. Thus, we probably will achieve our greatest efficiency of water use when we achieve our highest production. In the past, crop production has increased greatly through use of improved fertilization practices, improved crop varieties, and advances in farming technology. However, as we approach the upper limits of the benefits to be derived from these improved practices, the response of plants to their microclimate will become of ever-increasing importance in our quest to further increase production and water-use efficiency. The micrometeological method of studying the microclimate and all its important physical processes is serving as a useful tool for gaining information about these processes. With this information, we will be better able to predict the response of plants as we alter the natural environmental conditions in an attempt to provide an ideal environment for plant growth. Also, the micrometeorological methods may in the near future serve as the basic tool by which we manage our crops and decide when to irrigate our agricultural lands.

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