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TRAINING WORKSHOP ON CROP GROWTH MODELING

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S. E. Taylor, Ph.D.

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CENTRAL ARID ZONE RESEARCH INSTITUTE
JODHPUR (INDIA)

LECTURE NOTES OF

S. E. TAYLOR

2104 AGRONOMY HALL
IOWA STATE UNIVERSITY
AMES, IOWA 50011 USA

(515) 294-1923

INTRODUCTION TO CROP GROWTH MODELING

S. Elwynn Taylor, Agricultural Meteorologist

Feb. 1990

--- A compilation of lecture material presented Feb. 17 - Mar. 1, 1990 at the Central Arid Zone Research Institute, Jodhpur, India. The lecture series is designed for students who have a variety of backgrounds in the areas of biology/agriculture, physics/meteorology, computer applications/programming. The class was comprised of 20 students with the Ph.D. degree in one of the disciplines, but none were trained (nor experienced) in all three areas, and few in even two areas. Accordingly, all subject matter is presented in its most elementary form in the realization that the math, biology and meteorology are each overly simplified. Students trained in all three areas will not benefit from the materials covered in this introductory treatment. --- E. Taylor

Chapter 1
Concepts of Modeling

Theophrastus (about 400 BC), I have been told, "commented on the importance of weather with respect to crop yield" (Kramer, 1987). DeDuillier, in 1699, discussed the modification of microclimate by the placement and orientation of inclined walls to improve fruit production. The work of leDuillier presents quantitative analysis of the primary elements of micro-climate modification and energy exchange and crop response. I know of no earlier physical model (this work is discussed in detail in Chapter 7). Stephen Hales, 1727 (reported by Kramer, 1987), "made important quantitative observations of rates of transpiration and water absorption .... He also observed that the rate of transpiration varied with time of day and temperature and that cold soil reduced water absorption. Hales apparently believed that water was pulled up by transpiring leaves...." I have not identified a candidate for the earliest mathematical model of weather and crop yield.

It was 1960 that I first became interested in modeling of plant production and water use in relation to atmospheric conditions. During the ensuing 30 years I have learned to appreciate the complexity of the physical world and of the utility for mathematical expression in comprehending the interaction of plants and animals with the environment.

My initial interest in modeling, and indeed in bio-physical relationships, began with doubts concerning the materials taught in a freshman level botany class. The professor likely did not think in terms of mathematical modeling when he stated: "Productivity of any plant is directly proportional to the water use." This, of course, I immediately questioned, both silently and in the form of several questions (asked after class). "If the humidity increases and the plant uses less water does, the plant produce less?" "If the humidity decreases and the plant uses more water, does the plant produce more?" "If the temperature increases and the plant uses more water, and because it is so hot the respiration of the plant is greater, will the productivity increase, if the plant is about to die from the heat?" "If it gets so cold that the plant freeze-dries, did it have any production at all as it lost all of the water?" The irritated professor explained that it was not really the transpiration that influenced the productivity but the aperture of the stomata, and that he had confused me by giving a generalization intended to avoid confusing students.

The statement that production is proportional to yield is in effect a MODEL. It is a model based on some observations, but not based on very much biology or physics. It is a holistic (based on a general concept) model and is purely STATISTICAL (based on correlation of a few observations or on only a sample of reality) and was assuredly not based on the population of all cases of reality in nature. Considering one special case and one extreme, it may be concluded that if there is no water, the plant is both dead and not transpiring and does not have any yield. Hence, we do have a zero point. A student of physics will, by training, look at the extremes or limits. Another extreme is that of infinite water available, in which case the plant will transpire freely and use water in amounts approximating the evaporation if the plant were entirely wet on the surface. If the only factor that varied in nature were the availability of water, the model may be a reasonable approximation of plant production (the linearity of the response must still, however, be questioned). The availability of water to the plant is a factor and if the model includes only this variable, it can be written: Yield = K * Water. Also a model could be written: Yield = K * Stomata. Or even Yield = K * ET where "ET" is the water loss by evaporation and transpiration.

The assumption that Yield = K * Stomata is the physically based model. It may be expressed more explicitly as:

$$\text{Yield} = K * (CO_2\text{air} - CO_2\text{leaf})/R \qquad (1)$$

where R is the resistance (primarily stomatal resistance) to the exchange of carbon dioxide and CO_2 is the concentration of carbon dioxide in the "air" and also within the "leaf."

The statistically based model stating that yield is proportional to transpiration may likewise be written more explicitly:

$$\text{Yield} = K * ET \qquad (2a)$$

$$ET = (H_2O\text{leaf} - H_2O\text{air})/Rw \qquad (2b)$$

Where H_2Oleaf is the concentration (or pressure) of water vapor in the leaf, H_2Oair is the concentration of water vapor in the air and Rw is the leaf resistance to the diffusion of water vapor.

This model may be expanded by extending the correlation to other biological and environmental parameters. If the ET is reduced because of leaf resistance to the loss of water (which also increases resistance to the exchange of carbon dioxide), the yield is decreased. However, if the atmospheric humidity increases, there will be less transpiration even though the leaf resistance is not changed. The equation is then commonly written as:

$$\text{Yield} = K * ET/PET \qquad (3)$$

where PET is the potential evapotranspiration (or the greatest amount possible for prevailing atmospheric conditions). Using equation 3, the yield can be very high even though the transpiration is near zero, provided that the low transpiration is because of atmospheric conditions and not because of resistance to water loss at the leaf.

The majority of crop yield models are based on one of these expressions. Some may be rather indirect, such as those that use only monthly rain and temperature as correlated with yield, but these are fundamentally water availability relationships and so can be rationalized by extended development of equation 3 (where ET is primarily controlled by the precipitation and PET by the temperature).

Biological and physical factors may be added to the fundamental models, above. If, for example, it is observed that yield increases as the atmospheric demand decreases, it may be that stomatal aperture was somewhat restricted when atmospheric demand was high; in this case, yield would be inversely proportional to transpiration and the model becomes somewhat confusing. If the basic model being used is developed from equation 2, the expected result is described by the line a-b in figure 1-1. When atmospheric conditions of water demand decrease and stomatal aperture becomes less restrictive, the yield response may be represented by a line b-d.

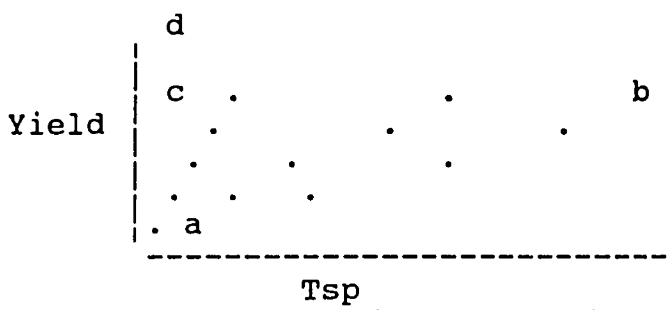


Figure 1-1 Hypothetical relationship which assumes (a-b) that crop yield is proportional to transpiration under constant atmospheric conditions. If atmospheric conditions are not constant (b-c), but crop parameters are constant, yield may be independent of transpiration. When atmospheric moisture demand decreases and stomatal resistance to diffusion of carbon dioxide and of water vapor decreases (b-d), the yield may increase as transpiration decreases.

In simple form, the line "a-b" in figure 1-1 may be described by a slope-intercept linear equation:

$$Yield = a + b*Tsp \quad (4)$$

where "a" represents some factor that may cause Yield to be different from zero at zero Tsp (if respiration is a factor, "a" may be some small negative number), and "b" represents the slope of the response line. If the equation is expressed as:

$$Yield = X + Y*Z \quad (5)$$

Where X represents respiration as a function of temperature, oxygen and/or other factors, Y represents environmental effects as a function of sun, temperature, wind, humidity, etc., and Z represents biological factors such as stomata resistance, photosynthetic capacity, and internal plant water status, etc. It will be seen that rather comprehensive models may be based on such basic concepts as these.

The second factor in my early interest in biological modeling also came from introductory lectures. Students were told that transpiration has no significant effect on leaf temperature. On these two, deceptively general concepts, I developed my interest in modeling, not because I was taught correct concepts, but because I questioned those that were being taught. One very successful scientist (E. A. Anderson) often stated that success in science is not "so much dependent upon our ability to learn as upon our ability to unlearn." If transpiration does not significantly influence the temperature as it controls photosynthesis and respiration, it can be demonstrated to serve as a valuable tool in evaluating leaf response to the environment. Also, modeling efforts will delineate the conditions under which transpiration influence on leaf temperature is significant.

References for Chapter 1:

Kramer, P. J. 1987, Plant Relative Water Content and Related Methods: Historical Perspectives and Current Concerns, in Proceedings of International Conference on Measurement of Soil and Plant Water Status, Vol 2-Plants, Utah State University, Logan, p. 311.

Chapter 2

THE LEAF AND MOVEMENT OF WATER VAPOR AND CARBON DIOXIDE

The supposition that growth or net photosynthesis is directly proportional to transpiration assumes that stomata are the only significant resistance to water loss from a leaf, and that there is no significant portion of the carbon dioxide uptake path that is not in common with the water vapor path. Naturally, the supposition also assumes that atmospheric conditions are not variable. If a yield model is to be used with confidence, the user must fully understand the full range of principles, concepts and assumptions associated with the expression of natural processes in a model. I am reminded of the story told concerning the World War II effort to produce the first atomic bomb: because of the secrecy that was kept, some problems arose. One group of engineers assigned to design and produce an important part, delivered a nonworkable prototype. When the prototype was returned by a project scientist, they again produced a nonworkable prototype. Frustrated, the lead scientist went to the laboratory to see what was wrong, and was told that the part had been redesigned because the original design was faulty and if followed could cause the device to explode! (Feynman, 1986). Scientists working with models that they do not fully understand are no less subject to the introduction of serious misinterpretations.

SATURATION OF WATER VAPOR

There is atmosphere inside a leaf. The internal structure of a leaf is one of loosely packed cells and some other biological materials. The integrity of the leaf is maintained by the epidermal covering. The epidermis is to some extent perforated with stomata (small "pores") that influence the exchange of water vapor and carbon dioxide (and any other gas) between the atmosphere outside and that inside the leaf. It is often assumed that the atmosphere inside the leaf is saturated with water vapor; this, of course, is not true as there is some potential associated with osmotic and matrix conditions of the leaf, and the stomata may not be the only resistance in the system. The deviation from saturation inside the leaf has been shown to significantly influence the energy and gas exchange of plants in arid portions of Australia (see comments on Jarvis and Slatyer, 1970, below).

If it is assumed that water vapor inside the leaf is saturated, the loss of water from the leaf may be expressed as a function of three factors: First, stomatal resistance to the diffusion of water vapor (and of any resistance of the air near the leaf surface to vapor diffusion); second, the vapor pressure of water in the external atmosphere; third, the saturation vapor pressure within the leaf as determined from leaf temperature.

Unless the atmosphere surrounding a leaf is very well stirred, there will be a moisture gradient (and a temperature gradient) between the leaf surface and the atmosphere at some distance from the leaf. This boundary layer can be significant in the exchange of heat and vapor at the leaf. Accordingly, the water loss may be described by an equation based on equation (3) (if R is considered to be the sum of all stomatal and external resistances to the diffusion of water vapor).

The deviation of the internal atmosphere from saturation is limited by the "leaf water potential" and by any resistance to the flow of water that exists in the leaf between the immediate water source and the internal air space. The effect of leaf water potential on the saturation condition within the leaf can be described by the Raoult formula of 1887 relating vapor pressure of a solution to the mole fraction of solvent (that is, to osmotic potential). A reasonable derivative of the relationship was expressed by Salisbury and Ross (1969, p37, p66) as:

$$\text{Potential} = 10.7 \times T \times \log(100/RH) \qquad (6)$$

where Potential is the water potential (in bars), T is temperature in degrees K, and RH is relative humidity.

Using equation (6), it can be seen that a leaf at air temperature (293 K) with a leaf water potential of -20 bars would have an internal RH of 98.54% and would take up moisture from the air when the atmosphere outside the leaf is saturated. Although leaves may gain water from the air under some conditions, normally it may be assumed that the water potential within the plant does not directly effect transpiration. The effect on stomatal resistance may, however, be very significant.

The influence of resistance is dependent upon both the resistance of the plant system between the soil-root and the intercellular air space. Because there may be some areas that have a water supply or reservoir, there may be some effect similar to "capacity" within the system. Resistances within the leaf may not need to be considered unless they are greater than the resistances from the evaporating surface to the free air. When the transpiration rate is high, it may be that resistance at the evaporating surface is great enough to limit the transpiration. Under these conditions, the humidity within the leaf would fall below saturation and the transpiration rate would be controlled by internal resistance (that is, by the number and characteristics of the internal evaporating surfaces). Well-watered plants subjected to atmospheric conditions that cause rapid water loss have been observed to exhibit apparent limitation to transpiration by internal leaf resistance (Jarvis and Slatyer, 1970). There were some earlier observations of morphology that were thought to influence internal resistance to transpiration (Turrell, 1944).

PATH OF WATER VAPOR AND CARBON DIOXIDE

WATER VAPOR Water transport throughout the plant is facilitated by the vascular structure. The vascular bundles found in most leaves provide a supply of water and to some extent structural support. Within the leaf water moves from the vascular system to individual epidermal, palisade, spongy parenchyma mesophyll, and to other cells by apparent diffusion. Evaporation from the surface of some cells may facilitate mass transport of water and accompanying solutes (but this implication will not be treated in this discussion).

Evaporation takes place near or within the cell wall and water vapor then migrates, primarily by diffusion, through the intercellular air spaces to the substomatal cavity, through the stomatal pore, and across the leaf boundary layer where it mixes with the "free" air of the environment external to the leaf. The nature of each of these steps is distinct and may vary from species to species and from leaf to leaf according to the physical condition and morphology of the leaf. Generally, it may be assumed that little water evaporates from the external surface of the epidermal cells, or at least from the epidermis of the leaf as it is, in most cases, covered with a waxy cuticle. Specialized cells that form the stomatal pore apparatus may be sites of evaporation that influence the mechanical function of the apparatus (Lange, et. al (1971) concluded that the stomatal action is directly sensitive to atmospheric moisture and may restrict the pore when the external atmosphere is very dry.) Evaporation is assumed to be unrestricted from palisade and mesophyll cell surfaces.

The path of the vapor has been expressed using an electrical analogue by numerous modelers. If the distance that vapor travels and the interaction with surfaces and viscosity, etc. are considered as the drag or the "resistance" to the flow or diffusion of vapor, then the law of diffusion expressed in 1855 as Fick's law is exactly analogous to Ohm's 1827 law of electrical current which in turn was derived from the flow of water through a pipe (Darcy's 1856 law of water movement in soil, Fick's 1855 law of diffusion, and Fourier's 1822 law of heat conduction expressed in a one-dimensional system are each similar to Ohm's law).

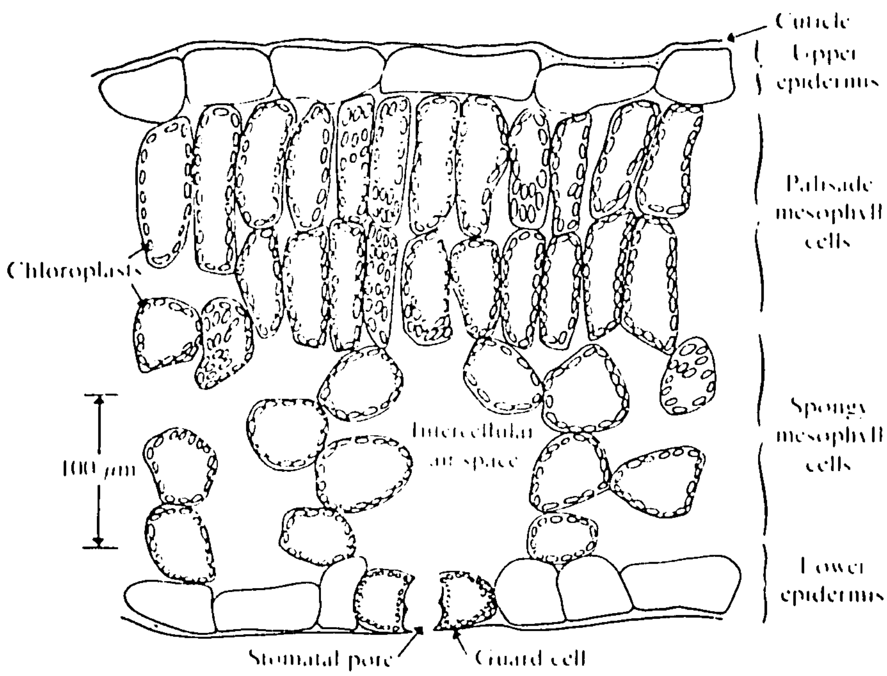
Using the electrical analogue, we may define a series of resistances to the flow of water vapor from the evaporation site to the free air. The resistance elements of the system may be defined as: the resistance at the site of evaporation identified as the internal resistance (Ri), the resistance from the evaporation site to the substomatal location as the mesophyll resistance (Rm), the resistance of the stomatal pore as Rs and the resistance to diffusion across the unstirred air layer adjacent to the leaf as the boundary layer resistance (Ra). Then, assuming that an excess of water is available at the site of evaporation and that any deviation from the energy status of pure water at the same temperature is negligible, the rate of water vapor loss from a one-dimensional model may be expressed as:

$$Tsp = (WVl - WVa)/(Ri+Rm+Rs+Ra) \qquad (7)$$

where Tsp is the transpired water vapor, WVl is the saturated density of water vapor in the leaf, and WVa is the density of water vapor in the free air in the vicinity of the leaf. With the exception of the cases described by Jarvis and Slatyer (1970) above, the internal resistances to loss of water vapor may be ignored (that is Ri=Rm=0).

A cross sectional diagram of a leaf, showing the principal elements influencing the loss of water vapor and the exchange of

Figure 2-1. Cross sectional diagram of a leaf. Water vapor is lost and carbon dioxide gained through stomata. Photosynthetically active cells in the palisade and spongy mesophyll, and epidermis are the sites of carbon dioxide absorption.



carbon dioxide is given in figure (2-1). Stomatal pores may be found only on the bottom of the leaf in some species, predominantly on the lower surface in numerous species and in approximately equal density top and bottom in relatively few plants. The size and proximity of cells within the leaf varies considerably from species to species and even from leaf to leaf on an individual plant. The epidermal layer is usually covered with a cuticle that essentially prevents water loss, but a wide range of surface characteristics does exist and may include tricomes (hairs) that may have marked effects on water loss.

The stomatal pores are the primary control of water vapor loss. The pores will, for most species, be open when water supplies are suitable, atmospheric conditions are not highly desiccating and insolation is above the photosynthetic compensation level (compensation level is that point where photosynthesis is sufficient to meet the instantaneous respiratory needs of the leaf). When plant response to the environment is modeled, the stomatal pores are assumed to restrict when plant water supplies are low and thereby reduce water loss and possible damage to the plant structure, this is an assumption and must be evaluated for each plant species (or perhaps cultivar) studied.

CARBON DIOXIDE Water vapor diffuses out through the stomatal pores of the leaf and carbon dioxide diffuses into the leaf through the same openings. The water molecule has lighter molecular weight (18) than does the carbon dioxide molecule (44). The diffusion rate for various gas molecules for a range of temperatures is given in the "International Critical Tables" found in most scientific and engineering libraries. Usually it is sufficient to consider that the diffusion of the water molecule is 1.57 to 1.6 times that of carbon dioxide. A pore that will admit carbon dioxide will accordingly admit water vapor. This concept has led some botanical philosophers to suggest that water loss is an unavoidable consequence of having a system that requires carbon dioxide. Some would suggest that it is an undesirable consequence and others may note that controlled water loss can have positive effects on leaf temperature and may enhance the mass translocation of solutes in the plant.

The stomatal pore and the leaf boundary layer are common elements in the path of carbon dioxide and water vapor. The substomatal cavity may also be considered as a common element. The mesophyll and cell wall elements may also be considered common, but are of much greater importance to the uptake of carbon dioxide than to the loss of water vapor. If water vapor is at or near saturation in the substomatal cavity, the path elements beyond the cavity do not contribute significantly to water loss. The mesophyll and the cell walls that absorb carbon dioxide are of primary importance in the assessment of the exchange of this molecule. A common diffusion path does exist but elements of the path have differential effect on the gas exchange of the leaf.

Although "normally" plants absorb carbon dioxide and it travels to the site of photosynthesis to be utilized in photosynthetic productivity, some plants have mechanisms that apparently overcome some of the effects of high water loss potential associated with carbon gain. Plants known as "C4" have been identified (they have a four carbon initial assimilatory product rather than a three carbon product found in the "normal" or C3 plant) and appear to have a rapid carbon fixation method. The rapid fixation of carbon would have the effect of reducing the resistance to carbon dioxide uptake (or give a greater equilibrium concentration difference between the free air and inside the leaf), thereby improving the ratio of photosynthetic uptake to water loss (the "Water Use Efficiency"). The C4 mechanism may allow the plant to rapidly and efficiently absorb carbon dioxide when environmental water demand is not too high and to restrict the pores at other times without a production loss. A third type of higher plant is known as Crassulacean Acid Metabolism (CAM) plant. CAM plants have a mechanism by which pores are open at night when water vapor loss will be small, nothing, or even allow the atmosphere to add water to the leaf. Carbon dioxide is fixed by a non-photo process for utilization in the day when the stomatal pores are closed and there is light present.

IMPLICATIONS OF LEAF THICKNESS There is an observed tendency for sun grown leaves to be thicker than leaves of the same plant from shaded localities. Although the increased thickness could be a consequence of environmental conditions rather than an adaptation, there is considerable evidence indicating that the tendency is adaptive. That portion of the diffusion path that affects carbon dioxide more than it affects water vapor exchange is directly impacted by leaf thickness. Thickened leaves may have more cells within the leaf and the total absorbing surface area within the leaf may be increased.

If the number of absorbing sites in a leaf increases, the apparent resistance to the uptake of carbon dioxide will decrease. There will be little effect on the loss of water vapor (so long as the assumption that water vapor is at saturation in the substomatal cavity is legitimate). The lowering of the resistance to carbon uptake while not influencing the resistance to water vapor movement increases the water use efficiency of a leaf. Although the thickened leaf has a longer diffusion path than that of a thin leaf, the increased path length resistance is small compared to the decreased resistance effect of having more absorbing surface.

Doubling leaf thickness was found to decrease the resistance to carbon dioxide uptake by about 40% for C3 plants (Charles-Edwards et al, 1986). A lesser effect was reported for C4 plants. Increased thickness resulted in an increased absorbing area inside of the leaf and, thereby lowered the total resistance to carbon dioxide diffusion according to Cooke and Rand (1980). The effect of internal surface area was modeled by Yun and Taylor (1985) in a study intended to delineate the ecological implications of thickening in sun leaves.

The thickening of leaves not only increases the internal surface area but the internal volume of a leaf. Increased volume may be related to an increased amount of photosynthetic machinery (Charles-Edwards, 1981) and hence have a significant effect on the internal concentration of carbon dioxide because of an increased "sink" capacity. The relative effect of the increased photosynthetic volume and the increased internal surface area was considered in the study reported by Yun and Taylor (198XXX).

If thicker leaves have greater water use efficiency, what is the limit to leaf thickness? The ultimate thickness for a leaf may be limited by genetics; however, environmental and physical conditions are more likely the factors in the general case. One may postulate that a leaf should be thick enough so that the "last" cell does not receive enough light to be profitable. This seems like a reasonable theory, but it is not borne out by observation; most leaves growing in full sun could be 4 to 6 times as thick before light extension became a factor (in Yun..------, 19XXX). A more likely explanation of the limit on thickness is simply a matter of the resistance ratio: As leaves thicken, the internal resistance decreases; but the stomatal and boundary layer resistances are not affected and become the predominant resistance in the pathway.

A simple mathematical exercise may be used to demonstrate the limitation of leaf thickness by resistance. Using some arbitrary values for resistance, photosynthesis and for respiration by leaf tissue, the nature of increasing thickness may be shown. Assuming an Rs of 10 and a carbon dioxide concentration difference between the air and the inside of the leaf of 100, and assuming that the photosynthesis of a leaf is then 100/Rt, where Rt is the total resistance of the diffusion path, the following relative values may be calculated.

a.	Rs=10	Ri=10	Rt=20	h=1	Ps=5	Rsp=2
b.	Rs=10	Ri= 5	Rt=15	h=2	Ps=6.7	Rsp=4
c.	Rs=10	Ri= 2.5	Rt=12.5	h=4	Ps=8	Rsp=8

where h is the thickness, Ps is the total calculated photosynthesis and Rsp is the respiration to support the leaf tissue (respiration doubles when leaf thickness doubles). This rough model shows that a fixed stomata resistance can only sustain a leaf to a certain finite thickness. There are several assumptions in this simple example such as the change in Rs that is observed in thicker leaves in nature, but the principle is not changed. The limit of thickness in this example is "4", but a leaf following "good economic theory" would stop thickening when the last increment of thickness failed to profit the leaf. This would likely be near step "b" above. Consider that at "a" the net photosynthesis is 3 (that is 5-2), and at "b" the net is 2.7, but the net increase for the second thickness layer is only 1.7, less the increased Rsp (2), hence the doubling of the thickness COST MORE THAN WAS GAINED! Accordingly, if a leaf has parameters proportional to the example, a "sun" leaf would be expected to be somewhat less than twice as thick as a "shade" leaf having the same stomatal resistance.

The capability of thickening continues beyond the period of leaf expansion in some, if not many, species. This capability is considered adaptive (Memar, 1990) to the extent that it provides a mechanism for leaves that become shaded to remain thin and for leaves that are exposed to continued high insolation to efficiently thicken. This adaptive characteristic may allow avoidance of partitioning of plant resources into areas where productivity would not be optimal. Modeling efforts to define optimal leaf thickness for specific microclimate conditions could be of value in the genetic engineering of more productive cultivars.

STOMATA Stomata are generally considered to be open when insolation is above compensation point and water stress is not a factor. Crop production models also assume that stomata close or at least restrict when water stress develops. Models may or may not account for stomatal response to atmospheric humidity. Taylor (1971) reported that increased atmospheric water demand resulted in lower stomatal resistance for leaves of a well-watered Redbud tree, and resulted in increased resistance when soil moisture was apparently limited.

The concentration of carbon dioxide within a leaf is partially controlled by stomatal resistance. When respiration is greater than photosynthesis the internal concentration of carbon dioxide exceeds the atmospheric concentration. The concentration within the leaf is thought to drop to a rather predictable if not almost constant value when insolation exceeds the compensation intensity. It is possible that some stomatal adjustment is made that influences the gas exchange sufficiently to maintain appropriate internal concentration of carbon dioxide while preventing the excessive loss of water vapor that could accompany minimal stomatal resistance. The observations of resistance decrease with increased atmospheric stress would support this concept in that an adaptation to prevent overheating may override the control of internal carbon dioxide when conditions become extreme.

YIELD AND TRANSPIRATION The correlation between yield and transpiration is logical because of the common path of water vapor loss and carbon dioxide uptake. However, the assumption that the correlation will yield a fixed or constant ratio of yield to water use is based upon many assumptions and there are many exceptions. Equations (2) and (3) are expressions of this correlation. Equation (2) assumes that the atmospheric condition is constant and that the only variable for the leaf is the stomatal resistance. Equation (3) allows the atmospheric conditions to vary but still the only biologic variable is the stomatal resistance. Although either expression would be better expressed as Yield = K * Rs, it is not always as practical to measure or estimate Rs as it is to estimate Tsp (transpiration).

There are numerous physical and chemical biologic variables that may enter into a productivity analysis. Plants may respond to weather conditions by leaf folding, rolling, stomatal adjustment, leaf orientation and even the shedding of leaves. Any of the biological adjustments will potentially influence the net photosynthesis and may influence the ratio of yield to transpiration. Roots may respond to conditions as well: Maize does not exhibit significant root growth after flowering but Soybean does (at least non-determinant cultivars). Shallow root systems may develop in very wet years and then be susceptible to dry periods later in the season. The reproductive stages of the plant may vary considerably with environmental conditions and adjust the partitioning of photosynthate considerably from normal. Established plants seldom die from water shortage in nature; as the water supply becomes limited the plant may conserve water by stomatal and leaf orientation etc. mechanisms. As shortage becomes more severe, leaves and other plant parts may be reduced in both mass and area; however, the plant will normally produce viable seed or complete some other survival mechanism before succumbing to desiccating conditions.

My house plants (especially weeping fig) tend to lose leaves when moved from window to window. The plants appear to develop new leaves that are more optimum to the "new" micro-climate. Flowers may be adjusted for optimal design and any change in climate (air temperature, relative humidity, etc.) may effect a response in the plant because the plant is not adapted to the new climate. Fruit may abort or develop at a modified rate or be of different size in response to climate variation.

In 1964 I was endeavoring to select a graduate school for my further training. I inquired of the best informed scientist I knew as to which schools would serve my needs, wants, and goals most appropriately. Six schools were suggested; one was Iowa State ... "Dr. Shaw has developed a crop-weather model that is the only one likely to be suitable for field application and will dominate the world's methods soon." Shaw's method, which indeed is the basis for many of the yield models since that time, is founded on the "AET/PET" (actual evapotranspiration divided by potential evapotranspiration) assumption that when the actual evaporation does not equal the potential, the plant will, to some extent, suffer from stress and will sustain some yield reduction. Some of the prominent weather and yield models that are based on the constant WUE assumption include: Montieth, Hanks, Shaw, and Ramano Rao.

When the transpiration ratio was first presented to me, I questioned it strongly, but data seemed to verify that within a localized area the assumption was suitably accurate. When the ratio given in equation (3) is correct, it may be concluded that the water use efficiency (WUE) of the crop at that location is constant. Realizing that many factors influence leaf temperature and photosynthetic rates, it is almost surprising to find that the WUE is essentially constant, at least for well adapted crops. Midway in graduate studies, I found that a physical formulation of water use (Energy Budget) and photosynthesis (Gas Exchange) model that accommodated all of the principal environmental and biological factors would explain the apparent constant nature of WUE for principal crops. The answer to the consistency of the WUE has at least two parts: First the lowest WUE efficiency at which the plant performs is likely to be near the average WUE even if in actuality the efficiency varies considerably. Consider a plant at WUE = 0.5 for 2 hours and at WUE = 1.3 for an additional two hours. It may be erroneously concluded that the average WUE = (0.5 + 1.3)/2 = 0.9. However, if we consider that during the first two hours the net photosynthesis was 6 units, the transpiration must have been 12 (as WUE = 0.5) and in the second two hours if the stomatal restriction decreased the net photosynthesis to 1 unit, the transpiration must be 0.77. The total photosynthesis for the two periods is 6 + 1 = 7 and the transpiration is 12 + 0.77 = 12.77 for an average WUE of 0.55 [it must be remembered that the average WUE cannot be obtained from averaging the hourly WUE values, but is obtained from the total production and total water use]. The ecological aspect of the constant WUE problem may be analyzed by energy budget and physiological methods.

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Chapter 3
ENERGY BUDGET and CONSERVATION

Energy budget modeling can be useful in the evaluation of water balance and statistical models. Energy budget analysis is of value in its own right and can be used as the basis for either a water balance model or for physiological models of crop growth and development. An energy budget model is based on the "continuity equation" (or the law of conservation of energy) and must always consider the primary environmental conditions of the locality. Temperature (plar and air), wind, humidity, insolation and soil temperature are generally included in the parameters evaluated.

[Note: Carnot introduced the cyclic heat engine concept in 1824 (English translation by R. H. Thurston, 1890). The Carnot cycle has persisted as a fundamental introduction to thermal physics and as a persistent gremlin to physics students. The cycle was not fully understood by Carnot, who believed that heat is not lost or gained from boiler to cooler. The engine concept appears to have been the catalyst that, over the next 30 years, prompted the dramatic development of the concepts of thermodynamics. In 1842, Robert Mayer published "On the Forces of Inorganic Nature," where he stated that the energy of the world is constant. Mayer's papers apparently were not well accepted and one or possibly several were published at the physician's personal expense. Mayer's conclusions were sharply criticized by Jolly who stated that if Mayer was correct a "container of water could be warmed by shaking." It is reported that Mayer quietly left the room without reply but returned some weeks later loudly proclaiming, "it is so." Mayer measured the rise in temperature of paper pulp in a large cauldron stirred by a horse walking around a circle and published the results in 1849 but accomplished little more as he was soon thereafter committed to an insane asylum and was there treated harshly. James Prescott Joule was publishing (with some resistance by publishers) a series of papers concerning the mechanical equivalent of heat between 1845 and 1878 (the present equivalent relationship was published in 1879 by Henry A. Rowland). Fick's 1855 first law of diffusion was combined with law of conservation of matter (continuity equation) to give Fick's second law which has been little recognized as contributing to the development of physics but had great impact on the development of biophysical process understanding. Lord Kelvin, W. J. M. Rankine and R. Clausius, somewhat independently, began the definitive expressions of the laws of thermodynamics in the period 1850-1852 (Rankine was apparently the first to use the expression "conservation of energy" according to F. Cajori in "A History of Physics by Dover, 1962).

ENERGY BUDGET The concept of energy budget in describing soil, plant, atmospheric relationships is basically an expression of the laws of conservation of energy. However, there was at least one very insightful expression of the principles well before the concepts of conservation of matter and energy were well developed: deDuillier in 1699, gave mathematical description of the energy factors influencing the temperature of a garden. This reference is discussed below in "Aspect and Slope, chapter 7XXX. In 1814

William Charles Wells published "Essay on Dew," where in Cajori (p 214) reports he said, "In a clear, quiet night, the grass radiates heat into free space, whence no heat returns. Being a poor conductor, the lower parts of the grass receive little heat from the earth. The grass cools and vapor condenses upon it. Good conductors, like metals, receive heat from surrounding bodies, and, therefore, are not covered with dew. A cloudy sky hinders the formation of dew by returning the radiated heat. Winds are unfavorable, because they carry heat to the cooling objects...."

Wells' concept of the energy budget cannot be faulted, although his concept of the source of the moisture condensing as dew did not withstand later investigations. The contemporary crop yield modeling, although not universally oriented to energy budget analysis, must be to some extent rationalized by the principles of energy budge or face severe reviews.

The concepts of radiation developed rapidly between 1860 and 1912. During this fifty year period, the fundamental laws of radiation were formulated, instrumentation for measurement of radiation was developed and the quantum theorem postulated. The solar constant was defined by Abott and Angstrom who developed instrumentation that was not replaced until 1975 as the pyrheleometric standard.

Balfour Steward, in 1858, published the law of absorption and emission of heat. Little attention was paid except by Kirchhoff, who considered himself "not one to initiate, but one to complete." In December 1859, Kirchhoff published what became know as Kirchhoff's Law of radiation: "for radiation of the same wave length at the same temperature, the ratio of the emission and the absorption powers is the same for all bodies" (in Cajori, 1962. pp 169, 186-7).

Quantitative radiation measurements followed the description of the "bolometer", an instrument suitably delicate for the measurement of solar radiation, published by Samuel Pierpont Langley in 1881. The bolometer used a fine iron wire (later platinum) sensor and a Wheatstone bridge to detect resistance change with temperature. Using this instrument, it was determined that the maximum solar energy was in the orange, not in the infrared as Herschel claimed (either conclusion is legitimate as can be seen from wave length and wave number plots of the solar curve). Langley in 1890, found the radiation of the moon to have two peaks (short and long wave), this gave conclusive data that the noon did not itself generate light. He also measured the light from a firefly (Lampyridae family) and found there was no thermal peak, showing that light could be produced without heat. His instrument was used to dispel the concept that the atmosphere of the Earth acted exactly the part of glass in a hot-bed, keeping the planet warm by absorbing the infrared rays radiated by the earth. His experiments on Mt. Whitney, showed that the atmosphere is selective, but infrared radiation passes with comparative ease (news reporters and the general public today, may need to have this re-explained as the term "green house effect" is commonly misunderstood). (Cajori, p 188-9).

Measurements and theory developed rapidly following the invention of the bolometer. Kirchhoff made extensive studies of the spectrum emitted by the sun. A story is told that his banker, scoffed at Kirchhoff's efforts to evaluate the contribution of gold in the sun because "why study gold that you can't fetch." He was somewhat chagrined when Kirchhoff one day deposited the prize for his studies awarded by the Queen in gold, with the comment "Look here, I have succeeded at last in fetching some gold from the sun." (Cajori, p. 169). Wilhelm Wien in 1893 published Wien's displacement law which was verified experimental by Pringsheim and by Kurlbanm. The law states that the product of temperature and the optimal wave length is a constant. It is often expressed as:

$$\text{Max} = 2897/T \quad (8)$$

or

$$\text{frequency} = 5099/T \quad (9)$$

or

$$\text{Midpoint} = 4100/T \quad (10)$$

where Max is the wavelength in micrometers of the maximum emission, Midpoint is the midpoint of energy emitted and T is degrees Kelvin. Wein's law was the primary basis of the quanta theory of Max Planck in 1900 and the 1916 derivation (by Einstein, for which he received the Nobel Prize), now known as Planck's Law.

The first generally usable energy budget equation describing plant-atmosphere interactions was published by Dr. Brown and Mr. Escombe in 1905 and by Dr. Brown and Mr. Wilson in the same issue of the Proceedings of the Royal Society, Series B Vol. 76, 29-111, 122-137. These articles followed the 1900 article on diffusion of gas in the Philosophical Transactions of the Royal Society B. Vol. 193, 223-291. The development of fully functional physical models required considerable development of theory and measurement technology in all aspects of heat exchange. This includes the principal areas of radiation, temperature, convection, conduction and evaporation. Additionally, considerable biological information concerning the exchange of gas and energy by plants was needed to produce meaningful biophysical models.

TEMPERATURE MEASUREMENT

The earliest temperature scale appears to be that of Gabriel Fahrenheit (1724) where body temperature was set at 100 (he may have had a fever?) and zero as the water ice mixture that seemed to be the coldest temperature obtainable in the laboratory (this explains why salt on frozen roads is not effective when temperatures in nature fall below zero). By 1740 there were 13 temperature scales mentioned in the literature. In 1742, Anders Celsius proposed zero as the boiling point of water and 100 degrees as the melting point of ice. Christin of Lyon, apparently independently, proposed in 1743 a scale with the melting point of ice as zero and the boiling of water as 100, this scale is now known as the centigrade scale and has, for some reason been termed the "Celsius Scale" by some international agreements. By 1779 there were 19 temperature scales in use. The concept of an absolute temperature scale was proposed by Lord Kelvin in 1848, based on the analysis of the Carnot heat engine, however, Amontons had suggested absolute zero as -239.5C in 1702 and Lambert (1779) as -270.3C (the accepted value is -273.135C).

Galileo's thermometer (1592) was likely the first instrument for directly measuring the temperature of the air. A modern type mercury in glass thermometer was introduced at the Academia Lincei in Italy in 1640. A rain gauge (Castelli) was invented in 1639, and meteorological records were kept at Florence beginning at this time; however, the record was not continuous after 1681. The earliest modern rain gauge and measurement network appeared to in the 1400s in Korea and some instruments may be seen on display in the lobby of the Korea National Weather Service Office headquarters in Seoul.

The first major step toward measurement of absolute temperature is credited to Guillaume Amontons in 1702, a mercury column in a U-shaped tube, sealed at one end with an air space. The height of a mercury column required to maintain constant air volume gave indication of temperature, the effects of atmospheric pressure were apparently not recognized.

The liquid in glass thermometer has remained the standard instrument for measurement of the temperature of a fluid (liquid or gas) in which it is immersed. The types of instruments used to measure temperature has expanded to almost anything that is predictably temperature dependent: the electrical conductivity of metals, the thermal expansion of metals and of other substances, melting points, and radiated heat may each be utilized in the modern measurement of temperature. Thermocouples and thermistors have found some application in the measurement of temperature where automatic electronic logging of data is desirable. The measurement of crop temperature is usually accomplished with a bolometer based thermal emission sensor.

RADIATION MEASUREMENT

Radiation is often the primary component of the energy budget of terrestrial objects. Direct radiation from the sun (insolation) may or may not be a significant factor, but thermal (or infrared radiation) is always a factor unless the object is immersed in a fluid that is thermally opaque, such as water. Often the insolation (or short wave) contribution to radiation exchange is measured separately from the long wave (thermal or Infrared) radiation.

SOLAR RADIATION

Solar radiation may be measured in terms of minuets of sunshine, or as percent of possible minuets, or in terms of actual energy received. Often the solar radiation (insolation) is measured on a horizontal, flat plate with uniform absorbing characteristics regardless of the angle of incidence of the energy (such a surface, known as a Lambert Surface, does not exist, but may be approximated by measuring instruments).

The standard instrument for the measurement of solar energy is a bolometer constructed so that one of the two thermally sensitive elements is shielded and the other exposed to insolation. The difference in temperature that results from insolation is matched by heating the shielded element. The energy required for the heating is equal to the energy absorbed by the instrument. Such an instrument is known as an active cavity radiometer.

Passive bolometers are commonly used for the observation of solar radiation. A typical radiometer uses multiple thermal junctions located in either a blackened or a whitened medium. The output of the instrument is proportional to the temperature differences observed. Black and white sensors are often configured as flat plate radiometers, often called global radiometers. These insturments ideally have cosine response to ratiation incitent upon its surface.

A global radiometer may, with certain precautions, be inverted to measure solar radiation reflected from a field or other surface. The difference between the up-looking and the down-looking instruments is known as the energy absorbed or the "net radiation." The down-looking instrument should be positioned at a height sufficient to overcome errors introduced by irregularities in the measured surface. However, the height should not be so high as to have a significant view of surfaces beyond the limits of the field being studied.

The view factor is important in the placement of instruments to measure both solar and thermal radiation. An flat plate radiometer will be influenced by radiation from any location in the hemisphere associated with the sensor. If the sensor is a diffuse surface, the detected radiation will obey the cosine law in that the amount of radiation received, from a constant source, will be proportional to the the cos of the angle of illumination. Accordingly a radiating object directly below a down-looking instrument will have a greater effect than one some distance to the side of the sensor. If a sensor is placed 10 m above the ground, 50% of the detected effect will be seen from a area of 20 m diameter. Should the sensor be intended to detect the reflected solar radiation of an expirmental plot, up to half of the effect measured may be comming from beyond the 20 m diameter. It is important to place a sensor far enough from a surface to insure that a irrigularities on the surface are "averaged out" and close enouth to the surface to limit the view factor to the intended sample area. For the sensor 10 m above a surface, 90% of the view is within a diameter of 60 m, and 95% within a diameter of 90 m. A detailed development of the view factor concept is given by Reifnyder and Lull (1965), an extract of which may be found in appendix B.

THERMAL RADIATION All objects at a temperature exceeding absolute zero, emitt thermal radiation. The German physicist Josef

Stefan (1835-1893) discovered that the total amount of energy emitted by a hot body is proportional to the fourth power of its absolute temperature. This discovery was derived theoretically by Ludwig Boltzmann and is now known as the Stefan-Boltzmann law of radiation. The law, integrated across all wavelengths may be expressed as the fourth power of the absolute surface temperature of an object times the emissivity (0-1) of the object times the Stefan-Boltzmann constant.

The thermal emissivity of an object is a number that expresses the ratiation from an object as compared to a perfect (black body) radiator. Water and most biological substances are very nearly black body radiators. Metals that are not oxidized may have very low emissivity and accordingly are not good radiators. Information concerning thermal radiation and emissivity as it influences energy exchange in the soil, plant, atmospher system is given in the materials presented in appenticies C, D and especially E.

HUMIDITY MEASUREMENT Topic ommitted in workshop.

CONVECTION MEASUREMENT See appendix C and D for an introduction to the convection term of the energy budget equation. Also, information concerning the nature of the plant boundary layer and the characteristic dimension of leaves is presented.

EVAPORATION The formulation of evaporative loss of mass and energy from a plant is described in appendix C.

COMPLETE ENERGY BUDGET The accounting of all sources and sinks of energy in a biological system is termed "Energy Budget" and accounts for all significant interactions of a plant with physical environment. Because photosynthesis is normally less than 3% of the total energy exchange, but is of primary importance, it is usually formulated seperately from the evaporative, convective and radiative elements of the energy budget. The energy budget formulation given in Appendix C is normally considered sufficiently detailed to describe all elements required in models of weather affects on crop development and yield.

References for chapter 3

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Thurston. 1890. (See Cajori.)

Chapter 4

YIELD MODELS

I STATISTICAL All models are statistical in that they involve only a sample of all existing conditions and individuals. Yield models developed from data correlating yield with weather conditions are commonly termed "statistical models." Crop yields over a period of years may show a trend and extrapolation of the trend may be considered as a model; however, if there is no physical or logical reason why a trend may be expected to continue, it is not desirable to extrapolate. Imagine a home on a south California hill; observations indicate that the home has settled 2 inches each year over the past 24 years. Since the hill is 100 feet high, and has settled only 4 feet, it may be assumed that it will continue to "slide" at a rate of 2 inches per year. This assumption has proved reasonable in many cases but, as pointed out by news headlines, there are significant exceptions where the remaining 96 feet are traversed in a matter of seconds.

An excellent example of statistical yield models is given by Thompson. Models by Thompson (1986) are based on growing season monthly average temperature, preseason precipitation and monthly total precipitation during the growing season. The temperature and precipitation parameters are modified by a coefficient peculiar to the locality, crop and month (Appendix E).

II WATER BALANCE Water balance models assume that photosynthesis is directly related to transpiration. When water stress is noted, it is assumed that the leaf or plant is not operating under optimal photosynthetic conditions. In arid and semi-arid localities, water may be the most limiting factor influencing productivity. In more humid localities, the resource that limits may be light. If mineral resource (soil fertility, etc.), genetic components, and agronomic practice remain relatively constant from year to year (or is changing slowly and predictably), variability of crop yield from season to season may be attributed to light or to moisture.

Crop dry matter production was related to water use by Briggs and Shantz (1912). The concept of "water use efficiency" appears in the 1960s (perhaps Viets (1962) was the first to mention the term). Water use efficiency is influenced by biological properties of the plant and by environmental conditions. The environmental conditions involve both the supply of water to the crop (soil moisture, soil aeration, etc.) and the supply of energy to evaporate the water (humidity, insolation, wind, temperature). It is assumed that when light and temperature are near normal for a locality, that any reduction in the potential yield is related to a limited supply of water for a given plant with normal nutrient availability. It is important, however, to evaluate the evaporative potential of the locality before the water availability impact may be assessed. The evaporative potential may be considered as a constant or may be computed from energy budget, as discussed later.

WATER IN SOIL The soil environment consists of solids, water with various solutes and air. The relative mass of these constituents depends, in large measure, upon the nature of the solids. The specific gravity (numerically equal to the density) of soil solids is about 2.7 times that of water. Organic matter lowers the density. The ratio of the mass of solid to total soil volume (solids and pores) is termed the BULK DENSITY. The bulk density may approach, but never reach the soil density as there is always some space between particles. A loose soil of a loamy nature may have a bulk density of 1.1 (grams per cubic centimeter) and sandy soil may be as high as 1.6. When soil is moist, there will be a certain swelling and the wet bulk density may vary from the dry bulk density by more than the quantity indicated by the mass of water in the system.

The physical characteristics of the soil particles together with the bulk density (and some other soil properties) determine the water retention characteristics of a soil. Because the water molecule exhibits considerable hydrogen bondin,g a significant amount of water will bond to the soil particles and to other water molecules. Capillary action will influence the amount and distribution of water in the soil. Water distributes in the soil according to capillary action, diffusion, bulk flow, vapor movement and some other mechanisms. There are numerous lengthy studies of the physics of water and water movement in the soil. The student should review any text of soil water for detailed explanations of the nature of the status of moisture in soils. For introductory purposes, it is sufficient to assume that there is a significant amount of moisture that is not available to plants, and that moisture movement in the soil is very little influenced by gravity until the soils are at or near the water holding capacity. As a general rule, it may be assumed that soil moisture in excess of water-holding capacity will drain unless the water table is within the limits of the profile, that evaporation from the soil surface has only a small influence on subsoil moisture and finally that only vegetation can reduce the moisture in the subsoil after excessive water has drained away.

SOIL MOISTURE MODELING A soil moisture model would normally be better termed a plant available water model. When the yield as related to the water use is the desired outcome of the model, the important elements may be clearly identified as:

$$ET = \text{Water In} - \text{Run off} - \text{Drainage} + \text{Storage} \qquad (11)$$

where ET is the total water withdrawn from the soil by plants or by direct evaporation, Water In is the precipitation or other source of water, Run off is the amount that does not enter the soil profile, Drainage is the amount that exits the bottom of the profile by drainage or percolation and Storage is the amount of moisture added to or subtracted from the soil reservoir of plant available moisture. This expression assumes that the soil does not ever dry beyond the amount of moisture that is available for withdrawal by root systems (surface drying by the sun, etc. is ignored for now).

Drainage is assumed to remove all moisture in excess of the water-holding capacity of the soil after a period of time. When excess moisture has been removed, the drainage becomes zero. It is not technically proper to assume that any water entering the soil in excess of the water-holding capacity is immediately discharged by drainage; however, this treatment is normally satisfactory for water balance models. Models dealing with aeration or drainage characteristics must model the time course of the movement of excessive water. As a rule of thumb: whenever drainage tiles are flowing, there is excessive water in at least that portion of the subsoil where the drain tiles are located.

In like manner to the drainage assumption, it is often assumed that water entering the top foot of the profile in excess of the capacity of that foot immediately enters the second foot. The profile need not be broken into one foot increments, the increments may be of any thickness desired. It seems appropriate to have the increment within the range of 15 to 30 cm. Whatever the increment, the assumption that water beyond the capacity of the increment will immediately enter the next lower increment is generally made.

Precipitation and Run Off are not normally considered to be time dependent. The daily precipitation and daily Run Off are assumed to be instant during the day the precipitation is recorded. This is an area that is often the subject of considerable debate as a gentle rain over a 24-hour period will enter the soil more effectively than the same amount of rain falling over a brief span of time, especially if soils are sloping.

In an operational soil moisture model only the precipitation is measured. The storage term may be occasionally measured to initialize or to verify predictions by the model. Run Off is considered to be a percent of the daily precipitation. This percent may vary with season and crop or soil condition. In operation, the ET is calculated and the Storage term is computed as the unknown of the expression. If no plants are established in the soil, the ET is considered to be only the water that evaporates from the soil surface. When the surface is wet, the amount will be substantial; but as the surface moisture is reduced, the evaporation will diminish. Because the surface evaporation is difficult to evaluate in field conditions, a model may be selected which neglects the evaporation or sets it at a fix d low value from the subsoil. The top few cm are considered top soil and the condition of the upper layer is not evaluated in models of "subsoil" moisture.

The transpiration portion of the ET term depends upon the density of vegetation and the rooting depth and activity (density) at the various levels of the profile and upon the amount of plant available water in the soil. When the plants are full sized, having full population count, and roots are at maximum density throughout the profile, the transpiration will reach the potential ET for the day if the profile was initially at or near the field capacity. If the profile was void of plant available water, the ET for the day is zero. If the soil moisture level is at 50% of the plant available water-holding capacity, the ET will be near the potential on a cool, cloudy, humid day. However, on a sunny, warm, dry and windy day, the ET may be only 75% of the potential. Curves of ET under various atmospheric conditions for some soil types, according to percent available subsoil moisture, were given by Denmead and Shaw (1962). Shaw chose to express the atmospheric condition in terms of the amount of water evaporated from a U. S. Weather Service, Class A Pan. Less than 0.20 inch of daily evaporation was considered as low, from 0.20-0.30 inch as medium, and more than 0.30 inch as high.

Most soil water budget models include a potential ET term. The potential depends upon the conditions of the atmosphere and of the vegetation. An evaporation pan is a good measure of the evaporative power of the atmosphere. If pan evaporation data are not available, a mathematical model of the evaporating power of the atmosphere may be applied. The more complex terms of some soil moisture models are those intended to compute the evaporative power of the atmosphere. Because the temperature of the evaporating surface is often the most significant parameter contributing to the potential ET, many models include elaborate methods for estimation of the surface temperature (these were important before surface temperature measurement instruments were readily available). The potential ET is the product of the evaporative power of the atmosphere and the ability of a crop to withdraw and evaporate water. Shaw found that Maize will potentially evaporate 82% of the measured open pan evaporation during the several weeks around the time of pollination (fig. 4-1). When the crop has not yet reached full leaf area, the potential water use by the crop is reduced as it is when leaves are becoming senescent.

When the potential evaporation has been evaluated, the actual ET is estimated according to the water retention relationship discussed above (fig 4-2). If there is no plant available water in the root zone, the actual ET will be zero. The percent of the potential transpiration from each soil layer depends upon the atmospheric demand, the root development in the layer and upon the leaf area development of the crop.

Figure 4-1 Ratio of ET to open-pan according to date ....The total potential water use depends upon the leaf area and the root zone exploitation according to calendar date.

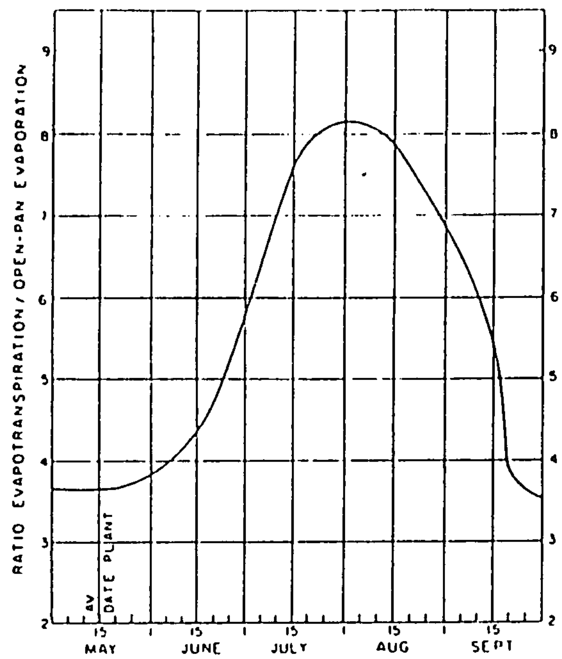
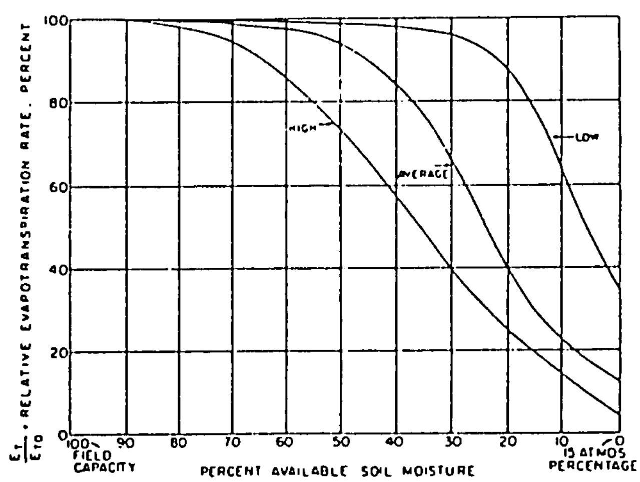


Figure 4-2 The amount of water that may be removed according to atmospheric demand and soil water content in the root zone.



III PHYSIOLOGICAL Models based on physical or chemical processes. Often the models require some serious assumptions such as concentration of carbon dioxide in the leaf internal air spaces holding constant over a wide range of photosynthetic conditions. The constant internal concentration assumption makes it valid to assume that the leaf resistance to carbon dioxide uptake is a function of resistance to the transfer of water vapor.

GAS EXCHANGE MODELS The modern gas exchange model is, in almost all cases, a refinement of the model of Brown and Escombe (1900). There was debate concerning the function of stomata and the exchange of carbon dioxide. Experimental demonstration had not been conclusive, and many experiments had be interpreted as indicating that the cuticle and epidermis play an important role in the gaseous exchange. In 1895, Blackman (cited in Brown and Escombe, 1900) conducted an experiment measuring the carbon dioxide evolved on each side of a leaf that had unequal stomata distribution. Brown and Escombe applied the principles of diffusion known from physics to mathematically demonstrate that the stomata could fully account for the observed exchange of gas. They calculated a resistance for the stomatal pore and, using a diffusion expression, equated the range of possible gas exchange rates. Fick's 1855 results for diffusion of soluble substances in liquid were used in the analysis.

A basic physiological model of photosynthesis may begin with the well-known Michaelis-Menten expression of the kinetics of enzyme catalyzed reactions. A description of the fundamental assumptions may be found in most plant physiology texts. The equation is often expressed:

$$P = Pmax/(1+(Km/Ci)) \qquad (12)$$

where P is the rate of photosynthesis (in this case), Ci is the concentration of carbon dioxide within the leaf (or more properly at the site of photosynthesis), Km is the kinetic constant (that is not likely to be a constant in the general case), and Km is the maximum possible photosynthetic rate at a given temperature, pressure, and light level, etc.

An operational photosynthesis model requires that the Pm term be evaluated (or modeled) according to temperature, light, etc. conditions that may be encountered by the plant. Also, the Ci term which cannot (at this time) be measured must be evaluated. During the 1980s, there was considerable discussion among physiological model developers concerning the use of an assumption that Ci is constant throughout the bulk of the photosynthetic period. Several well-known crop development and yield models incorporate the constant internal concentration assumption. If the constant concentration assumption is rejected, the modeler must compute the value from inferred or physically known relationships.

The fundamental diffusion equation states that the rate of gas exchange is proportional to the concentration difference across a resistance. The equation may be expressed as:

$$P = (Co - Ci)/r \qquad (13)$$

where P is the rate of photosynthesis, Co is the concentration of carbon dioxide outside of the leaf (beyond the boundary layer), Ci is the concentration within the leaf, and r is the resistance of the system to the diffusion of carbon dioxide. The concentration of carbon dioxide may be expressed as density for simplification of mathematical treatment. The concentration (normally near 0.0003, but rising with time in most locations of the Earth) is multiplied by the density of pure carbon dioxide at a given temperature. When the air temperature is 30C and the carbon dioxide concentration is 0.0003, the carbon dioxide density is 5.322 E-7 (the pure carbon dioxide density used was 1.774 E-3 (g/cc)). Table 4-1 gives some density values taken from a Handbook of Physics and Chemistry.

Table 4-1
Carbon dioxide density at 760 mm Hg for various temperatures:

Temp C	E-3 g/cc
0	1.967
10	1.897
20	1.835
30	1.774
40	1.721
50	1.664
100	1.439

Because plants are observed to respond to increased carbon dioxide in the environment, it is apparent that the constant internal concentration assumption is not valid under conditions of changing external concentrations, and the assumption may not be valid under any field conditions. The Michaelis-Menten expression may be combined with the diffusion equation to yield:

$$P = Pm/(1+K/(Co-Pxr)) \quad (14)$$

where the diffusion equation, solved for Ci is substituted for that term in the Michaelis-Menten expression. Because it is possible to evaluate the resistance to the diffusion of water vapor for a leaf system, the assumption of constant internal concentration need not be made so long as the assumptions relating the resistance to the movement of water vapor to the resistance to the uptake of carbon dioxide are reasonably correct.

The leaf resistance to the diffusion of water vapor may be determined in any of several ways. If the actual water expended is known and the elements of energy exchange are measured, the resistance may be computed from the Ohm's law analog. The resistance to the diffusion of carbon dioxide is assumed to be 1.54 of the resistance to the diffusion of water vapor (this value is slightly temperature dependent). Detailed development of the resistance to the loss of water vapor is given in numerous text books (e.g., D. M. Gates, 1980). There are two papers by Taylor included in the appendix (C and D) that also provide further information. The mesophyll resistance to the diffusion of carbon dioxide is not included in the path of the water vapor for the purpose of analysis. Several authors have reported values ranging from 2 to 12 s/cm for the mesophyll resistance to carbon dioxide diffusion.

The photosynthesis expression (14) has "P" appearing twice. The expression may be evaluated by the quadratic formula. The form of the equation is given in appendix C.

The value of the Michaelis-Menten rate constant is difficult to determine for plants in a natural condition. The value used by Taylor and Sexton (1972) is 1.3 E-7 g CO2 per cc. The actual value of K may not be a constant over the full range of natural conditions. The value for K must normally be determined by experiment for the specific cultivars being studied. The value used above was consistent with data for several species calculated by Hesketh (1963).

Temperature and light factors limit the maximum rate of photosynthesis. Additionally there may be biological factors that set the maximum possible rate of photosynthesis for any particular plant. If, however, the photosynthesis rate is measured for a plant at different carbon dioxide levels for a range of light and temperature conditions, the maximum photosynthetic rate (Pm) is approached as carbon dioxide concentration approaches system saturation. This assumes, of course, that the optimum temperature is included in the study and the light is sufficient to reach saturation at the upper limit. This method was used by Taylor (appendix C) to estimate the effect of light on Pm. The temperature function was an empirical approximation of reported temperature effects on photosynthetic rates for an exhaustive assemblage of reported data. A generalized expression was developed that may be adapted to a wide range of plants by adjusting the compensation (or zero net photosynthesis) temperature and the optimal temperature. When the temperature function is evaluated (giving a relative reduction in photosynthate according to variance from optimum temperature) and the light function is determined (giving an maximum potential amount of photosynthate produced) the Pm is found as the product of the functions:

Pm = T function for Pm X Light function for Pm (15)

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Chapter 5

CURVE FITTING

Polynomial
Logistic Curve
Hurrell function

Most statistical analysis programs include capabilities for fitting polynomial expressions to data and include reliability of fit analysis. The polynomial fit has become very popular, perhaps because of the ease of application. However, the polynomial is not without pitfalls. By using a polynomial of an order approaching the number of data points in a sample, a polynomial expression can be forced to fit every point; but the behavior of the expression between points is unreliable. As a rule-of-thumb: the number of points must exceed the order of the polynomial by at least a factor of 5 to avoid alias effects in curve fitting.

If the nature of a biological or physical relationship clearly fits a specific type of curve as determined by theory or by observations, it is desirable to use the specific curve. For example, many growth patterns may be described by a logistic curve, and fitting a logistic expression to a data set may be considerably more accurate than a polynomial expression, as points that deviate because of measurement error will not impact the final curve form radically.

The remainder of the section on curve fitting was not presented at the workshop because of time limitations.

Chapter 6

LEAF ORIENTATION

(Omitted from the workshop because of lack of time.)

Chapter 7

LEAF DIMENSION AND ENVIRONMENT

CLIMATE ZONES Raunkier (1934) studied a wide assortment of herbarium specimens and showed that leaves of an elliptic shape tended to have leaf area governed by climate. He defined a leaf classification based on leaf area that was functional for leaves of the basic elliptic shape but was not effective for lobed or irregular leaf shapes. He defined 3 size classes in each of 6 groups: Leptophyll, Nanophyll, Microphyll, Mesophyll, Macrophyll and Megaphyll. Some authors have added an additional class, but it is only satisfactory to do so if the major classes given by Raunkier are not divided into 3 parts each as Raunkier defined them.

Using energy exchange modeling, Taylor (1974) (appendix D) was successful in defining a Dimension Class for leaves based on Raunkier's concept. The Dimension Class was created by calculating the dimension of a rectangular flat plate that would have the identical convective heat transfer characteristics as a leaf. The equivalent rectangular plate dimension is known as the characteristic dimension of a leaf. The characteristic dimension of a leaf of any shape may be determined and like characteristic dimensions are found to correlate with the climate where the leaf developed. This method allows leaves of any configuration to be compared and is an important method in the determination of plant adaption to microclimate.

ASPECT AND SLOPE Nicolas Satio deDuillier published in 1699 an insightful and quantitative analysis of the effect of aspect and slope at various latitudes. His work, intended to modify the climate of an orchard or vineyard, showed good understanding of energy exchange factors in an area that apparently became smoggy, hazy or cloudy in the afternoons. He commented on solar energy, dew, air temperature and wind. I noticed no recognition of thermal radiation. He did seem to appreciate the cyclic nature of plant (possibly stomatal) activity. The following, rather long passage is included for its colorful presentation as well as the historical contribution to agricultural climatology:

"FRUIT-WALLS IMPROVED, By Inclining them TO THE HORIZON: OR, A WAY TO BUILD WALLS FOR FRUIT-TREES; Whereby they may receive more Sun Shine, and Heat, than ordinary. By a Member of the Royal Society. LONDON: Printed by R. Everingham; and are to be Sold by John Taylor, at the Sign of the Ship, in St. Paul's Church-Yard. MDCXCIX.
AUGUST 31. 1698.
PAGE 1- After all the Application of so many Men in all Times and Countries to Agriculture, one would scarce have thought there was yet left so notable and so very obvious an Improvement of it as that I am a going to propose. It consists in building Walls for Fruits, Grapes &c, not in a perpendicular Situation, as is commonly done, but so sloping, tho otherwise straight and plane, as to receive the Beams of the Sun, not only for a longer time, but also

with a much fuller and better Exposition. ...

South-Walls are commonly reckoned to be the best for Fruits. But in these Climates, and much more in hotter Countries, when the Days are something long, and the Heat of the Summer is in its greatest strength, it is late before the Sun shines upon them, and the Sun leaves them as early in the Afternoon. When it is about Mid-day the Sun is so high, that it shines but faintly and very sloping upon them; which makes the Heat to be much the less; both because a small quantity of Rays falls then upon these Walls; and because that very quantity acts with a kind of glancing; and not with full force...

In the North part of France East Walls are looked upon as almost of the same goodness for Fruit as South-walls: which proceeds more from the Defect I have noted in South-walls, than from any particular Excellency in those facing the East. And accordingly South-walls are here, and in all other cold Climates, much the best of the two. West-walls in France, as well as here, are but indifferent, tho they have the like Exposition to the Sun as East-walls. I take the reason of this difference between East-walls and West-walls to be partly because in the Morning the Air is purer, and that the Sun shines oftener and stronger than in the Afternoon; and meets with the Dew while it is yet fresh upon Plants, whose motion it revives after a long rest, and as it were a refreshing Sleep. But the chief cause of it must be attributed to the coldness of the Air in the Morning, that checks the Vegetation, till the presence of the Sun revives it; which it dos much sooner and much more effectually on the East-wall than on the Westerly. In the Afternoon the Heat of the Air is great every where; and Heat alone, without any Sun-shine, is able to make Plants vegetate, tho not so perfectly.... I said that the Sun shines stronger in the Morning than in the Afternoon, tho it be hotter in the Afternoon than in the Morning. But this is not because the Sun in the Afternoon shines with more force; but because it continues to act upon a Air already warmed with the impression of the Morning Sun."

A number of models of the insolation on a sloping surface have been published. All are based on the geometry of the solar path and all are precision models. Models of the effect of the slope and aspect on vegetation are not governed by such well known laws of physics. However, an energy exchange model configured to identify the effect of leaf dimension on leaf suitability to a specific environment may be used to delineate the leaf dimension most ideally suited to a specific slope. A study of oak leaves around a hill in California showed dimensional segregation from large Nanophylls to medium Microphylls (Benson et al., 1967). The results are presented in Appendix D, along with a description of the method for determining leaf dimension.

In a study in Panama, Taylor (appendix D) found good clustering of leaf dimension about the "ideal". Taylor defined ideal as a leaf dimension small enough that the leaf would not suffer thermal damage when transpiration was reduced by limited water availability and large enough to have close to optimal net photosynthesis during favorable water conditions. In several cases, it was found that this dimension resulted in a "constant" water use efficiency for the climate zone where the plants were growing. This, for the first time, as far as I can determine, provided a theoretical basis for the observation that water use efficiency is a constant and therefore production may be computed as water use times a constant (equations 2 and 3).

Exercise- The student should use appendix D and compute the characteristic dimension of the leaf outlines given in figure 5.2 of the appendix using equations 1 and 2 of the appendix.

References for chapter 7

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Chapter 8

PRACTICAL MODELS

These models are presented on computer disk and will be operated in the laboratory session following the completion of computer basics provided in Appendix A.

CERES

RESCAP

RISK

SHAW

SPAW

APPENDIX A

APPENDIX A: USING THE MS-DOS PERSONAL COMPUTER

This information has been used with first-time users of microcomputers. This material is presented by an instructor in a series of 5 or 6 sessions of 2 hours each. Students should be using a computer and should master each command presented. When there are two, or at most three, users per computer, each user will both perform the exercise(s) and guide other users. The concepts are elementary but when mastered are an effective introduction which enables the student to communicate effectively with the professional programmer (an important skill for a laboratory or research director). Additionally, the new user will develop the confidence to personally operate programs and be prepared to develop additional skills by self-study as needs arise.

The user is introduced to the concept of computer logical operations and to three important computer "languages": DOS, BASIC, and LOTUS 1-2-3.

THE ELECTRONIC DIGITAL COMPUTER

The history of digital computational aids is at least as old as the tying of knots in a string, carrying of sticks of various lengths and colors, or of making marks on a wall. Some computational aids, such as the "Abacus" in any of many forms, prove to be very useful; and contemporary applications indicate that they will continue to have a place in human culture. The line between calculation aids, calculators, and computers is by no means clear. When a device can carry out a computation without human interaction, it may be classified as a computer. However, as complex as it is for a person to compute the square root of a number without aids, an electronic aid with a square root key to press (which instantly yields the square root of any number which happened to be on the screen) would not in itself be considered a computer.

By 1940, the electronic digital computer was an idea whose time had come. Accounting machines, weaving machines, enciphering devices, and calculation aids (mechanical and electronic) provided the concepts needed for the emergence of the electronic digital computer. If the pattern generated by a loom could be controlled by a sequence of cards with holes coded into them, advancing after each weaving cycle as completed, a card could also contain a number or an instruction of what to do with a number. Holes in cards to specify the status of an electronic switch and the automatic comparison of electronic switch configurations was a natural step. This step was accomplished by a graduate student and his professor at Iowa State University in the late 1930s. The resulting computer was meager by today's standards, but it provided the basis for the development of the first large commercial electronic computers. John Vincent Atanasoff and student Clifford Berry constructed the "ABC" computer in the basement of the Iowa State University Physics Building (a 32-bit 54-word, and later 108-word device). It was operational in 1942, but for only a short time as the war took the inventor to other efforts. However, the concept had taken root with John Mauchly who had visited and reviewed the project, and together with J. P. Echert constructed ENIAC, the first commercial computer memory.

The concept of using switch positions to represent numbers is not at all difficult to visualize. If a switch is closed, it may represent a value. Normally "Yes/No" or binary numbering systems are comprised of an array of switches with each representing a specific value. The first of a series may represent the number 1, the second the number 2, the third the number 4, etc. To represent the number 7, all three switches would be closed; the number 5 would be represented by the closing of switches 1 and 3. Although the concept is simple, not all people are quick to recognize such a system and a simple parlor amusement may be constructed using this binary principle to aid understanding: A person is asked to secretly choose a number between 1 and 63. The person is then shown a page with 6 blocks of numbers (Table A-1). The person is asked whether the chosen number is in the first block, the second, etc. and then is amazed when the selected number is announced from the six "Yes/No" responses. Of course, the blocks represent binary divisions and the knowledgeable host is simply adding the values in the upper left position of each block that contains the selected number.

Table A-1. Binary Component Blocks

1	3	5	7	9	11	13	15
17	19	21	23	25	27	29	31
33	35	37	39	41	43	45	47
49	51	53	55	57	59	61	63

8	9	10	11	12	13	14	15
24	25	26	27	28	29	30	31
40	41	42	43	44	45	46	47
56	57	58	59	60	61	62	63

2	3	6	7	10	11	14	15
18	19	22	23	26	27	30	31
34	35	38	39	42	43	46	47
50	51	54	55	58	59	62	63

16	17	18	19	20	21	22	23
24	25	26	27	28	29	30	31
48	49	50	51	52	53	54	55
56	57	58	59	60	61	62	63

4	5	6	7	12	13	14	15
20	21	22	23	28	29	30	31
36	37	38	39	44	45	46	47
52	53	54	55	60	61	62	63

32	33	34	35	36	37	38	39
40	41	42	43	44	45	46	47
48	49	50	51	52	53	54	55
56	57	58	59	60	61	62	63

The blocks in Table A-1 are constructed such that all numbers that require the "first switch" to be closed are contained in the block having the number "1" in the upper left corner. Likewise, all numbers that require the third switch to be closed are contained in the block beginning with the number "4". Hence, the number "5" appears in the first and third blocks only, as switch one and switch three are the components. Table A-2 provides a binary representation of switch values. Any binary code of 1's and 0's can be interpreted by adding the values given at the top of the table for each column that contains a 1. For example, the binary expression "0 0 1 0 0 1" is seen to be the sum of "8" and "1" or "9".

Table A-2 A Binary Coding Table

Value	8	4	2	1
0	0	0	0	0
1	0	0	0	1
2	0	0	1	0
3	0	0	1	1
4	0	1	0	0
5	0	1	0	1
6	0	1	1	0
7	0	1	1	1
8	1	0	0	0
9	1	0	0	1
10	1	0	1	0
11	1	0	1	1
12	1	1	0	0
13	1	1	0	1
14	1	1	1	0
15	1	1	1	1

As numbers may be represented by this simple method, they may also be manipulated. Addition and subtraction may be conducted as with any other numbering system. For example, "1001" + "0010" is "1011" (or 9+2=11) and "1001" + "0101" = "1110" [note that adding 1+1 cannot be 2 in the binary system, so you place a 0 and carry a 1 or 01+01=10]. Computers, therefore, can add, subtract, and compare values. To multiply numbers, multiple addition is performed; for example, 5 times 4 may be better enunciated as "5 taken 4 times" or 5+5+5+5. Computers can divide by subtracting repetitively in a like manner. When a simple algorithm was devised to convert any number to a log expression, computers could multiply and divide by simple addition and subtraction. As complex as computers have become, basically they only add, subtract, and compare.

LANGUAGE OF COMPUTERS

If deep in the machine computers can only understand 1s and 0s, at the user level this is far from the language the programmer need use. As late as 1974, I used a computer that programmed in 1's and 0's only, but such computers have been totally replaced by machines that have logic devives to accept symbols more familiar and natural to people. The devices do the work of translating higher level expressions to codes that the computer can manipulate.

Common computer languages used in personal computers include DOS, UNIX, BASIC, LOTUS, FORTRAN, PASCAL, COBOL, etc. (some may debate the classification of these in one group as languages, but each does represent some symbolic instruction level for user interaction with the computer).

DOS (just enough to get started)

Most personal computers have a set of operating instructions (or an "operating system") that the computer automatically ingests when power is applied. Computers that are in the IBM family or related machines are often DOS oriented. The DOS may have some name variation such as MS-DOS. If only the operating system instructions are installed in the computer, the user will observe a prompt of some sort on the screen. Often the prompt is in the form of a letter that specifies the disk drive to which the computer is presently positioned. If the prompt is the letter "C" with trailing notations that may include ":\>" etc., the computer is positioned to the "C" drive. The C drive is normally the fixed hard disk devise. The "A" prompt normally refers to the primary floppy drive included with the original computer. If the computer has only one floppy drive, it will serve as both the "A" and the "B" drive.

When power is applied to the computer, it will normally spend some seconds completing internal evaluations and then will attempt to read operating information from the disk drive(s). Often computers are configured to read any disk in the "A" drive initially and then check the "C" drive. When an operating system is located and activated, the computer is said to be "BOOTED" and it is ready to proceed with further instructions.

A "booted" computer may continue, apparently of its own volition, to perform operations beyond that of booting. This automatic procedure is controlled by an automatically executing batch file named "AUTOEXEC.BAT" that may be user generated and implemented on the system. Batch files are in essence programs written in DOS instructions (or language).

DOS instructions may be executed from the keyboard or included in batch files to execute sequentially as a program. Batch files are very useful for accomplishing tasks related to the configuration of the computer and the calling of application programs. It is important that the computer user have at least a fundamental understanding of the DOS instruction set. Only a few instructions are required to operate the computer, the batch files and a number of special instructions provided for automated and specialized operations. It is important that the user understand the fundamental "file" operations instructions.

DATE When the computer has booted, and in the absence of a batch file, the date will be displayed and the user prompted to enter a new date. If, as the user, you are satisfied with the date displayed, simply tap the "ENTER" key (on some keyboards labeled "RETURN" because of the similar function to the typewriter return key). It is important that the date display be meaningful because the date is "stamped" on any files that you save during the course of your session.

Computers may or may not have a battery-operated clock installed. If there is a clock, the date on the clock will be displayed when the computer is booted. If there is no battery-operated clock, the display will likely be the date of manufacture of the computer electronics. You should set the date, if needed, following the format as displayed.

TIME The computer may display a time and user prompt to enter a new time. The time function is under the same constraints as the date function.

PROMPT After booting and the possible display of the date and time, the computer will likely display the "DOS prompt" in a form that has been selected by the user or in the native form: C:\>. In the native case, the "C" indicates that the computer is positioned to the "C" disk drive, which is normally the fixed or internal disk drive. The initial prompt may indicate the "A" drive or some other drive. Following is a series of important file operation DOS instructions and some explanation of their functioning:

C:\> [The native DOS prompt indicating that the computer is positioned to the C drive.]

C:\> DIR/P [The user has asked to see the directory of files on the C drive, displayed one page (screen full) at a time.]

C:\> CD LOTUS [The user has given the "current directory" instruction which in this case specifies that the computer should be positioned to a specific directory with the name LOTUS. The disk drives may be visualized as a filing cabinet with drawers labeled A, B, C, etc. You are looking in the "C" drawer and have just opened a folder labeled LOTUS. Within this virtual "folder", there may be many items and even other "sub" folders or "sub-directories" to which you may also position the computer.]

C:\> CD [The computer is instructed to annunciate the directory to which it is currently positioned.]

C:\> DIR [The computer is instructed to display the contents of the current directory.]

C:\> CD\ [The computer is instructed to reposition itself to the ROOT directory. This may be visualized as replacing any folders in the file drawer but keeping the drawer labeled C open.]

C:\> A: [The computer is instructed to position itself to the "A" drive. This may be visualized as the closing of file drawer "C" and the opening of file drawer "A."]

A:\> C: [The computer is instructed to position itself to the "C" drive.]

C:\> MD SOIL [The computer is instructed to create a directory named "SOIL" on the "C" disk. The "make directory" (MD) instruction may be visualized as adding a folder to the file drawer.]

C:\> CD SOIL [The computer is instructed to position itself to the directory named SOIL.]

C:\> COPY A:NITROGEN.DAT [The computer is instructed to copy from drive "A" a file with the prefix NITROGEN and the suffix DAT to the current directory of the "C" drive. The name will be the same when copied to the "C" drive.]

C:\> COPY A:*.* [The computer is instructed to copy all materials from the current directory of the "A" drive to the current directory of the "C" drive. This instruction may be vocalized as: Working in the "C" drive, COPY from "A" all files regardless of prefix (first name) and suffix (last name).]

C:\> COPY GOOD.DAT A: [The computer is instructed to copy the file "GOOD.DAT" from the "C" drive to the "A" drive. This may be vocalized as: Working in the "C" drive, COPY a file named GOOD.DAT to the "A" drive.]

WARNING---- PLACE A NEW (BLANK) DISK IN DRIVE "A" BEFORE THIS NEXT STEP!!!!

C:\> FORMAT A: [The computer is instructed to format the disk in drive "A". The computer must have the format program installed in the "C" drive to accomplish this instruction (perhaps you will have to position to the DOS or to the BIN directory to find the program). All disks must be formatted before the computer can utilize them as a storage medium.]

C:\> GREAT [The computer is instructed to execute a program with the prefix GREAT. Such an application must be located in the current directory and the suffix must be BAT, EXE, or COM.]

These DOS instructions are only to get a user started. A book of DOS instructions is normally provided with a computer. The book will typically exceed 300 pages. Needless to say, the instructions above do not make you a DOS master.

BASIC

Programming of a computer is best left to programmers, just as writing is best left to writers. We spend more time reading than writing, but still need to know how to write. A scientist should, likewise, be computer literate. Programming skills at least to the level typical of a 9-year-old child are appropriate for any scientist who uses a computer regularly (this does not imply the skill of programming achieved by an extraordinary 9 year old, just the average American child not having any special training). There are volumes written on programming, even volumes regarding programming in the BASIC language; the following is but an introduction.

BASIC was, originally, the 13 basic FORTRAN statements and served as a learning language. Using these few statements, the beginning programmer could create simple programs to learn and experience programming methods. The personal computer brought a demand for a simple computer language and soon many companies published BASIC with "added" instructions. Eventually, there were many BASIC versions with a great deal of variation between them. Some improvement was noted in the 1980s, but still there is some variation between versions of the language. BASIC also became a very powerful language as it grew, but is not necessarily the "best" language for operating a computer.

Computers will often have a program called "BASICA.EXE" or having some name that is not too different. A program with this name can be initiated by simply typing "BASICA" at the DOS prompt. When the BASIC system is loaded, the user will see a BASIC prompt, usually a %. A few very simple programs will demonstrate the principles of BASIC.

BASIC programs are written with each statement numbered. Type the following on the computer screen:

```
10 CLS

20 PRINT "EXCEPT FOR THAT, MRS. LINCOLN,"

30 PRINT "   HOW DID YOU ENJOY THE PLAY?"

RUN
```

This program demonstrates:

```
CLS        [Clear the screen]
PRINT      [Print anything enclosed in "   " on the screen]
RUN        [Instruction to execute the program instructions]
```

Now, we will teach the computer to repeat itself, type:

```
40 PRINT: PRINT

50 FOR I = 1 TO 5

60 PRINT "MY NAME IS JOE"

70 NEXT I

RUN
```

The program followed any instructions in steps 0 - 30 and then placed two blank lines on the screen as a result of the isolated PRINT commands in line 40. It then executed a conditional loop.

FOR I=1 TO 5 [The computer will execute the subsequent program steps down to the NEXT I instruction and then return to the FOR statement until this has been done 5 times. The computer would then continue down the program steps, if there were any.

This program may be saved (recorded on disk) by typing the keyboard instruction, SAVE, followed by a quotation mark and a name by which the program should be known in the directory of the disk.

SAVE "XX [This will save the program to the active directory on disk and give it the name XX.]

LIST [This instruction will cause the computer to list the program steps on the screen.]

CTRL BREAK [Holding the CTRL key down while punching the BREAK key results in the termination of a computer program.]

NEW [This instruction will remove the program steps from the active memory of the computer. The file saved to disk is not affected.]

SYSTEM [This instruction will cause the computer to exit the BASIC language program and return to DOS. The user should then see the DOS prompt (e.g., C:\>) rather than the BASIC prompt (%).]

RUN "XX [This instruction will recall a program (in this case, named XX), from disk and cause it to be executed.]

The following are three short programs to demonstrate a few additional instructions and how they may be used in a simple program. When a program is entered, you may wish to save it on disk as practice or perhaps as a program for later reference.

BASIC demonstration of a simple program to save data:

```
10  CLS
20  PRINT:PRINT:PRINT "This Program Will Create a Data File for
Temperature and Precip."
30  PRINT: PRINT "      Enter DAY=99 to END"
40  PRINT: PRINT
50  OPEN "DATA" FOR APPEND AS #1
60  INPUT :DAY";A
70  IF A=99 THEN CLOSE #1:CLS:PRINT:PRINT "Finished, data are in a
file named 'DATA'":END.
80  INPUT "TMAX";MX
90  INPUT "TMIN";MN
100 INPUT "PREC";RN
110 PRINT,"DAY ";A;"   TMAX=";MX;"   TMIN=";MN;"    PRECIP.=;RN
120 PRINT #1,A;MX;MN;RN
130 GOTO 50
```

Save this program and then RUN it until you have entered several days of data. Then type NEW and punch in the program that will recall the data saved to disk.

```
10 CLS
20 PRINT:PRINT:PRINT  "This Program Will Read and Display a File
Named 'DATA'"
30 PRINT:PRINT:PRINT
40 OPEN "DATA" FOR INPUT AS #1
50 PRINT "DATE    TMAX    TMIN    PRECIP"
60 INPUT #1,A,MX,MN,RN
70 PRINT " ";A;"   ";MX;"   ";MN;"    ;RN
80 GOTO 60
```

When all data are read, an "out of data" error will be indicated (this is not a problem in this simple program) and the program will stop, leaving your data displayed on a portion of the screen. Both of these programs are very simple and are intended only for an introduction to BASIC and as a demonstration of file creation and handling.

```
  1 REM   This is a 'REM' statement, it is just a comment to the
  2 REM   programmer, it does nothing in the program.  Use a lot
  3 REM   of these to document what you are doing.
  4 REM
  5 REM   THIS PROGRAM ALLOWS YOU TO READ THE FILE CALLED 'DATA'
 10 CLS
 20 PRINT " THIS READS THE 'DATA' FILE"
 30 PRINT:PRINT
 40 OPEN "DATA" FOR INPUT AS #1
 50 INPUT "HOW MANY DAYS TO READ";Y
 60 DIM A(Y),MX(Y),MN(Y),RN(Y)
 70 FOR I = 1 TO Y
 80 INPUT #1,A(I),MX(I),MN(I),RN(I)
 90 NEXT I
100 INPUT "WHICH DAY'S DATA DO YOU WISH:;X
110 PRINT, A(X),MX(X),MN(X),RN(X)
105 PRINT
110 GOTO 100
120 REM As this program never ends, press CTRL BREAK to stop
130 REM Look in your manual for PRINT USING to format printouts
```

```
  10 REM This program demonstrates the GOSUB.  It is well to use a
  20 REM lot of subroutines in a complex program.
  30 REM The program calculates a simple linear regression
  40 CLS:DIM X(200),Y(200)
  60 INPUT "ENTER THE NO. OF XY PAIRS OF READINGS";N
  70 FOR I=1 TO N
  80 INPUT "ENTER X,Y PAIR ";X(I),Y(I):NEXT I
  90 GOSUB 4000
 100 REM THE PROGRAM WILL FOLLOW ALL INSTRUCTIONS AT LINE 4000
 110 REM AND THEN RETURN TO THE LINE FOLLOWING THE GOSUB AND
 120 REM CONTINUE DOWN THE PROGRAM.
 130 PRINT:PRINT "    THAT'S ALL FOLKS ! !"
 140 END
4000 S1=0:S2=0:S3=0:S4=0:S5=0
4010 FOR I=1 TO N
4020 S1=S1+X(I): S2=S2+(YI): S3=S3+X(I)^2
4030 S4=S4+Y(I)^2: S5=S5+X(I)*Y(I)
4040 NEXT I
4050 M=(N*S5-S2*S1)/(N*S3-S1^2)
4060 C=(S2-M*S1)/N
4070 R=(M*(S5-S1*S2/N))/(S4-S2^2/N)
4080 PRINT:PRINT "Y=M*X+C":PRINT "M=";M:PRINT "C=";C:PRINT
4090 PRINT "REGRESSION COEFF.=";SQU(R):RETURN
```

```
10 REM THIS PROGRAM DEMONSTRATES STRINGS ($) AND "IF"
20 INPUT "WHAT IS YOUR FIRST NAME";A$
30 PRINT "HOW OLD ARE YOU?";A$
```

```
 40 INPUT AGE
 50 IF AGE >40 THEN GOTO 100
 60 PRINT "I LIKE YOUNGER PEOPLE"
 70 END
100 PRINT "YOU ARE OLDER THAN MY SON"
110 END
```

SPREAD SHEET COMPUTING

The spread sheet is not strictly a language, but it does allow the user to give the computer instructions that will automatically execute when data are entered and so a method of programming and for our use may be considered as "spread sheet language." The spread sheet is the most successful computer program ever written (to date). The program appears on the user screen as a ledger sheet with numerous columns and rows. The user may program the spread sheet to add columns, display totals, subtract one column total from another and display the balance, etc., etc. The following instructions are intended as an introduction for users who have the spread sheet program "LOTUS 1-2-4", or a compatible, running in their computer.

If the computer is positioned to the directory containing the program LOTUS and/or the program "1-2-3", you may initiate operation by typing 123 at the DOS prompt. You should then see a screen that looks something like Table A-3.

Table A-3 Representation of the general appearance of the LOTUS 1-2-3 screen when the 1-2-3 program is initiated.

	A	B	C	D	E
1	[ ]				
2					
3					
4					
5					
6					
7					
8					

The spreadsheet screen is composed of columns labeled A, B, etc. and of rows labeled 1, 2, etc. The user may enter numbers, words, or instructions into any "cell" at the location indicated by the cursor, [], which is displayed within some column and row, usually at "A1" initially. The cursor may be moved around with the arrow keys on the user key board.

Information is entered at the cursor location. If the first key pressed is a letter, all information entered in the cell will be alpha-numeric, that is text only. If the first key pressed is a number, the cell will contain only numbers. If the first key pressed is an operator, +, -, @, (, the cell will contain a formula and the value computed will be displayed in the cell (the formula will be displayed at the top of the screen when the cursor is positioned to the cell).

The user may program a conversion from degrees C to degrees F by placing the cursor at A1 and entering a value such as 20. Move the cursor to A2 and type: +A1*9/5+32. When the Enter key is pressed the computer will display the value "68" in the A2 cell and the formula will still be displayed at the top of the screen. The user may move the cursor to A1 and enter another value, the conversion will be displayed in A2 as soon as the Enter key is pressed.

If the "/" key is pressed while entering a formula, the computer will interpret it to mean "divide." However, if the "/" key is pressed as the initial key of a sequence, the computer will enter the instruction mode and will display a list of instructions at the top of the screen. The cursor will be positioned on the first of the line of instructional words. As the cursor is positioned to various words along the line, a second row of instructions is displayed appropriate to the particular word selected with the cursor. If the user desires to clear the worksheet, preparatory to beginning a new effort, the sequence of keys used to accomplish the refreshing of the sheet are: / W E Y

If the user wishes to abandon the instruction set menu, the "Esc" is the method of choice. Often a user will inadvertently enter the instruction mode or will make a "wrong turn" in the use of the instruction set. A series of taps on the escape key "Esc" is the sure way to bring the computer back to a position where the user can gain control of almost any situation.

The spread sheet program is very useful for tabular data. A sample program to accept daily temperature data is given in Table A-4. The sample demonstrates the computation of daily and monthly averages. The user should place the labels in rows 1,2,33 and 34 and type the numbers for the days (from 1 to 31) in column A. Formulas are placed in line 34 and in column D.

Table A-4 Spread sheet programmed to accept entries of temperature (Max. and Min.). The daily average is calculated (column D) and the monthly averages are calculated (row 35).

Column D contains the average of the Max. and the Min. for each day. That is, it contains the average of the daily value in B and in C. The cursor should be placed in D3 and the expression (+B3+C3)/2 entered. The cell at D4 contains the expression (+B4+C4)/2. Rather than key in 31 of these similar formulas, the user need only key the one at D3 and then copy the formula using the instruction sequence: / C Enter D 4 . . D 33 Enter. Column D will fill with replications of the relative formula. You may inspect the formula of any cell by placing the cursor in the cell and observing the formula on the top line of the display.

The monthly averages have a slightly more complex formula as they require that the temperatures in a column be summed for the month and then divided by the number of observations (which may vary from 28 to 31). The computer does have an instruction to sum the numbers in a column and also has an instruction to determine the number of entries in a column. These two instructions will be used in the calculations appearing on row 35 in columns B, C, and D. Place the cursor in B35 and enter: @SUM(B3..B33)/(@COUNT(B3..B33)).

	A	B	C	D	E
1	Day	Max.	Min.	Ave.	
2	----------	----------	----------	----------	----------
3	1	20	10	15	
4	2	22	10	16	
5	3	30	16	23	
6	4				
7	5				
.					
.					
.					
33	31				
34	----------	----------	----------	----------	----------
35	Average:	24	12	18	
36					

When data are entered in the data columns (B and C), the calculated values in column D and in row 35 are automatically generated. If an incorrect entry is made, simply return to the cell and type in the correct values. If an entry is made in day 31 during a month with only 30 days, remove the incorrect data by typing: / R E Enter.

Printing of the results is important. If a printer has been save the file, then refresh the screen with the instruction: / W E Y. The saved file may then be retrieved with the instruction: / F R (note that the computer lists the files that exist on your directory, set the cursor on the desired file and press Enter). Should you wish to exit the language, type: / Q Y.

Graphic display of data is often very useful. The 1-2-3 spread sheet program provides simple graphic capability. The program can display dots, lines, pie diagrams, and bar graphs. The graphs can display several variables at one time (i.e., both Max. and Min. temperature with respect to date).

Prepare a 1-2-3 screen with the data shown in Table A-5. The data in column A may represent days and B and C represent values of Max. and Min. temperature. Place the cursor in cell A1 and enter the graphics mode with the instructions: / G. You are presented with choices including "Type" which allows the selection of type of graph (line is fine to begin), X, A, B, etc. Select "X" and key: A1..A6, which specifies the days column of data as the "X-axis" of your graph. Select "A", the first data range and identify B1..B6 as the range. Select "B", the second data range and identify C1..C6 as the range. Press "V" to view your data as a graph. Strike any key to return to the data display. Strike "O" (Options) to create titles, legend, etc. The data may be displayed as a "bar" graph by selecting "Type" (you may have to "Quit" the options menu). Try several graph types and options.

Table A-5 Data displayed on the spread sheet may be displayed in graphic form using the "Graph" instruction in the 1-2-3 program.

	A	B	C
1	1	20	10
2	2	22	10
3	3	24	12
4	4	22	14
5	5	20	15
6	6	19	15

APPENDIX B

Radiant Energy in Relation to Forests

BY
WILLIAM E. REIFSNYDER, Professor of Forest Meteorology, Yale University School of Forestry, New Haven, Conn.
AND
HOWARD W. LULL, Northeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture, Upper Darby, Pa.

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If the clouds are warmer than the ground, the surface temperature may even increase as a result of the exchange. Conversely, a clear night sky may radiate downward much less than the ground is radiating upward, and the ground will sustain a net loss of energy and consequently cool rapidly, possibly with formation of dew or frost. On the so-called "radiation nights," incoming radiation is much less than outgoing radiation, and cooling at the surface is rapid.

Although the radiation from the sky is complex, and occurs only in certain wavelengths as a result of selective emission by water vapor and carbon dioxide, it can be considered as coming from a black body at the temperature appropriate to the amount of radiation emitted. This temperature (the *effective temperature*, as previously defined) is sometimes known as the *equivalent sky temperature* (Brooks 1959). By comparing the equivalent night sky temperature with the temperature of the ground surface, we can immediately know whether the ground will cool off or warm up as a result of the radiation exchange.

Most of the downcoming radiation from the clear night sky comes from water vapor in the lowest few hundred feet. Therefore, the moisture content of the surface air layers can be used as a good estimator of nocturnal sky radiation. Goss and Brooks (1956) give the equation:

$$R = (0.660 + 0.039\sqrt{e})\sigma T^4 \qquad (16)$$

where

R is the sky radiation in ly./min.;

e is the 2 p.m. weather-shelter vapor pressure in millibars, and T is the weather-shelter air temperature, °K.

This empirical relationship assumes that the 2 p.m. vapor pressure is a good estimate of moisture content of the lowest thousand feet or so of the atmosphere.

The values given are for total hemisphere radiation, i.e., from the entire vault of sky. However, because the atmosphere is thinnest directly overhead, and thus contains less mass of water vapor than any other path, radiation from the zenith is usually a minimum. Thicker layers of the atmosphere contribute to the incoming radiation at angles approaching the horizon, and the incoming radiation from these angles is correspondingly greater than that from overhead.

Long-wave sky radiation is somewhat greater during the day than at night because the radiating substances in the atmosphere are heated by the sun. Sauberer and Dirmhirn (1958), measuring downcoming long-wave radiation at Vienna in midsummer, found daytime rates of about 30 ly./hr. and nocturnal rates of 28 ly./hr.

View Factor

As already stated, in addition to direct-beam solar radiation, any object on the earth's surface receives diffuse and reflected solar radiation, and long-wave radiation emitted by various components of the atmosphere and by terrestrial objects. It is often important to know how much each portion of the "view" of the object contributes to the total radiation received by the object. For example, a small spot on the ground in a forest opening receives on a clear night radiation from the sky that may have a much lower effective temperature than the surrounding trees which are also radiating to the spot. Since the spot radiates outward at a rate that is dependent only on its own temperature, the radiation balance on the spot is determined largely by the relative amounts of radiation it receives from "cold" sky and "warm" tree canopy.

The geometric concept that expresses this proportion is the view factor, or shape factor. It is defined as the fraction of the radiation leaving a surface in all directions that is intercepted by another surface. Consider a small area, dA_1 (fig. 14) radiating to the hemisphere above it. A portion of the radiant energy is intercepted by area dA_2. Because of Lambert's cosine law, the amount leaving dA_1 in the direction of dA_2 is proportional to $dA_1 \cos \beta_1$. The amount received by dA_2 is proportional to $\cos \beta_2$ (cosine law of illumination) and inversely proportional to the square of the distance, r. If I_1 is the intensity of radiation from dA_1 (in the direction of the normal to the surface), then the rate of radiation from dA_1 to dA_2 is given by (McAdams 1954):

$$dW_{1\rightarrow 2}=\frac{I_1 dA_1 \cos \beta_1 dA_2 \cos \beta_2}{r^2} \tag{17}$$

The total radiation leaving dA_1 can be found by integrating equation 17 over the entire hemisphere above dA_1. Similarly, the radiation received by any portion of the hemisphere can be found by a suitable integration. The ratio of the received portion to that radiated to the entire hemisphere is the view factor, $F_{1\rightarrow 2}$. It follows that the view factors for the various portions that make up the entire hemisphere must add up to one. Because the relationship is reciprocal, the view factor of the first area relative to the second is the same as that of the second relative to the first.

In the example cited, the view factor of the sky relative to the spot on the ground together with the equivalent temperature of the sky permits calculation of the amount of energy received by the spot from the sky. Similar calculations for other portions of the view permit calculation of the total radiation received by the spot.

The usefulness of the view factor concept can be illustrated. A spot in the middle of a forest opening radiates to the entire hemisphere above it. However, it receives radiation partly from the sky and partly from the trees surrounding the opening. The proportion of the upper hemisphere occupied by the sky is a function of the diameter of the opening and the height of the surrounding trees. In terms of diameter, d, of the opening, and the height, h, of the trees, the fraction of the radiation received by that portion of upper hemisphere occupied by the sky is

$$F=\sin^2\left(\arctan \frac{d}{2h}\right) \tag{18}$$

F, then, is the view factor of the open sky relative to the spot; and by reciprocity, the view factor of the spot relative to the open sky.[8] If the effective sky temperature and the temperature of the surrounding trees are known, the incoming radiation to the spot can be calculated by the Stefan-Boltzmann law. The function, F, for this simple case is presented in figure 15.

[8] Complete derivation is given in app. C.

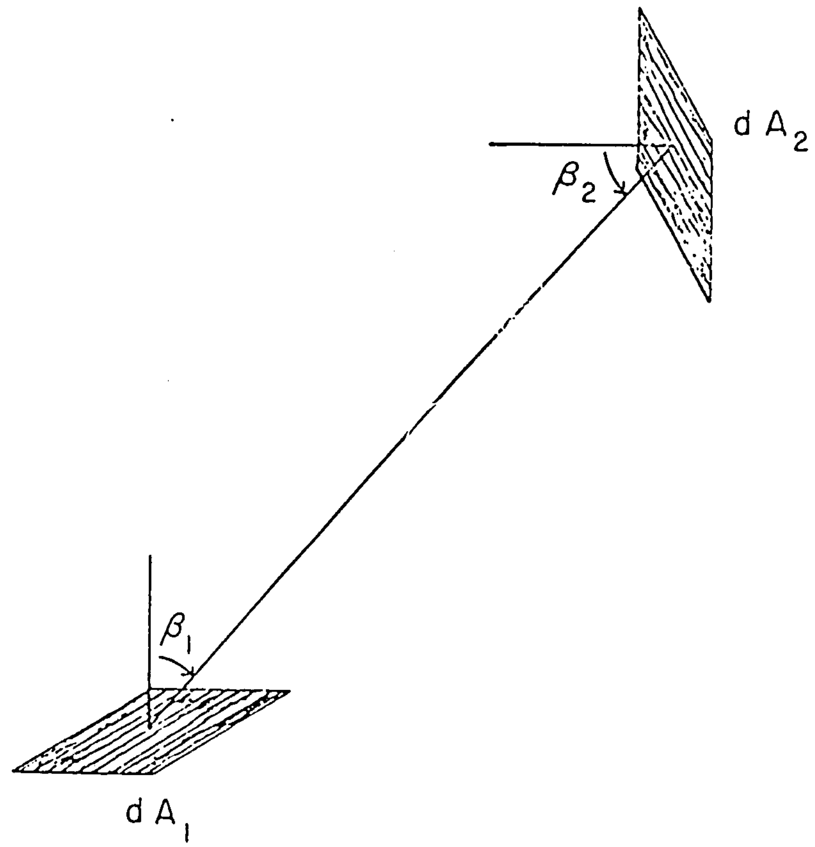

FIGURE 14.—Radiation exchange between two elemental areas.

The view factor depends only on the ratio of the tree height to opening diameter. Therefore, where the net outward radiation to a clear, cold sky is the consideration, a large opening in a tall forest acts similarly to a small opening in a young forest with the same diameter-height ratio.

View factors for a number of interesting and useful cases are contained in standard heat-transfer texts, such as McAdams (1954). The case for a free-standing tree in an incomplete forest canopy is treated by Waggoner and Reifsnyder (1961).

Radiation Balance

Radiant energy streams to and from the surface of a leaf, the bark of a tree, or the ground surface itself. The magnitude of these streams, their direction, their spectral composition, and their distribution through time control the energy that is available for heating the surfaces, evaporating water, supporting photosynthesis, and, in general, for making life on earth possible. The sum of these streams

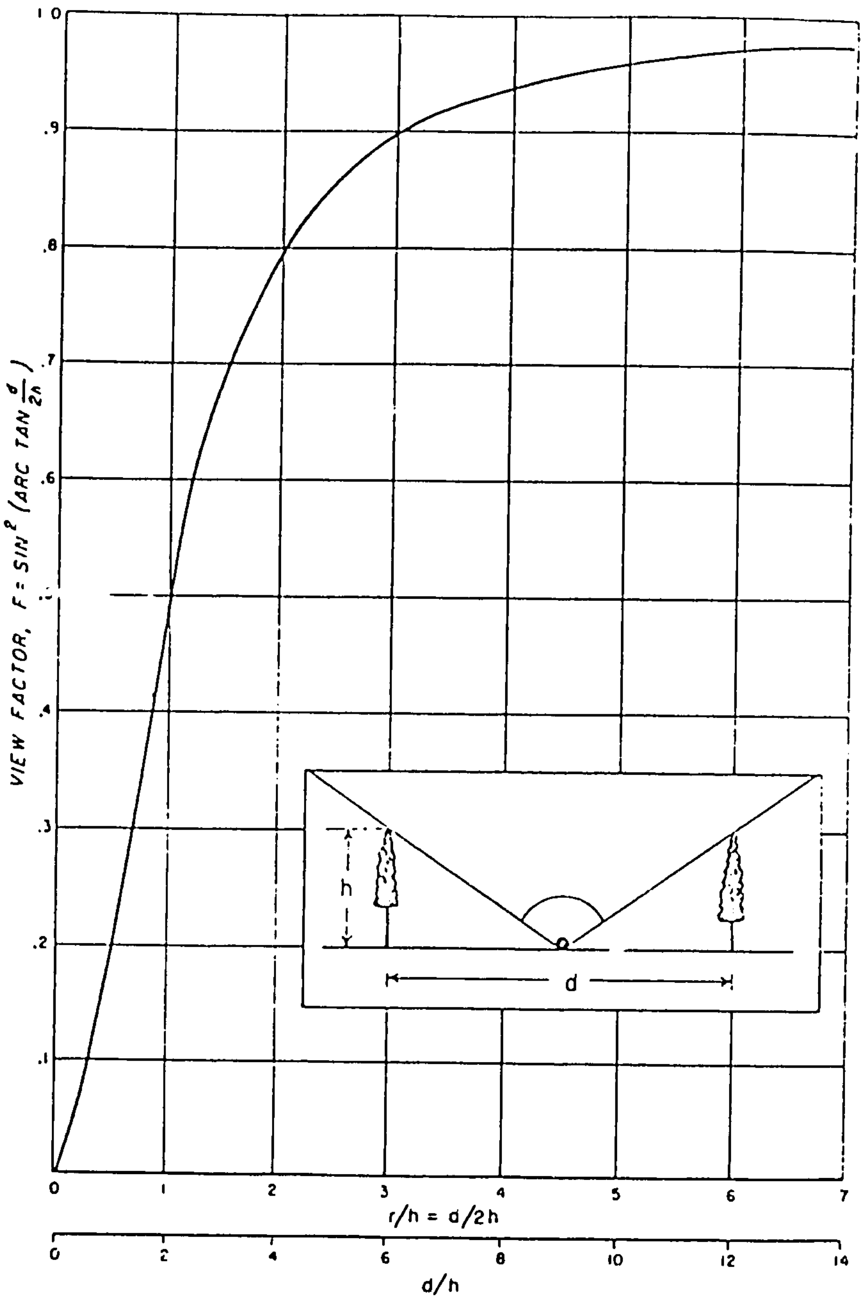

FIGURE 15.—View factor of differential area at center of forest opening to sky above.

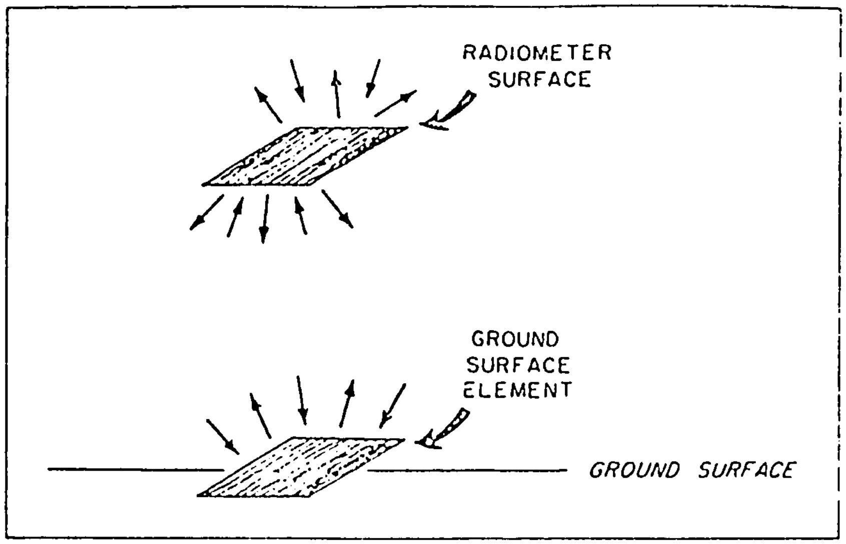

FIGURE 17.—Radiation fluxes on the radiometer surface compared with those on the ground surface element.

If the measurements cannot be made on the surface, where should they be made? Most radiometers have a receptor that is exposed to an entire hemisphere; others have a conical view of various dimensions. For heat-balance measurements, flat-plate receptors open to a hemisphere are commonly used. The farther the receptor is from an area source of radiant energy, the larger the area from which the bulk of the energy incident on the receptor is coming; i.e., for a given percentage of the hemispherical view of the radiometer, the farther the radiometer is from the surface the larger the area making up the fixed percentage. These relationships can be calculated from tabulations of the view factor of a circular disk relative to an elemental area perpendicular to and distant from the center of the disk. Figure 18 gives these relationships in terms of height of the radiometer as a function of diameter of seen area encompassing various percentages of the visible hemisphere. For example, nine-tenths of the "view" of a horizontal flat-plate radiometer 10 feet above the ground will be a circular area of 60 feet in diameter directly beneath the plate.

Such measurements integrate radiation values over an area; this is advantageous if there is much space variation in the energy leaving the surface (for example, reflected sunlight from a dappled forest floor). On the other hand, if the radiation from a plot of restricted size is being measured, the radiometer must be placed close enough to the plot so that most of the measured radiation is coming from the plot and not from the ground outside the plot. But if it is too close, it will "see" its own shadow and be in error. Generally this is not important. A radiometer 1 foot above the center of its own 1-foot-diameter shadow will have only about 10 percent of its view occupied by the shadow. If it is 3½ feet above the ground, the view factor of the shadow will be only 0.01.

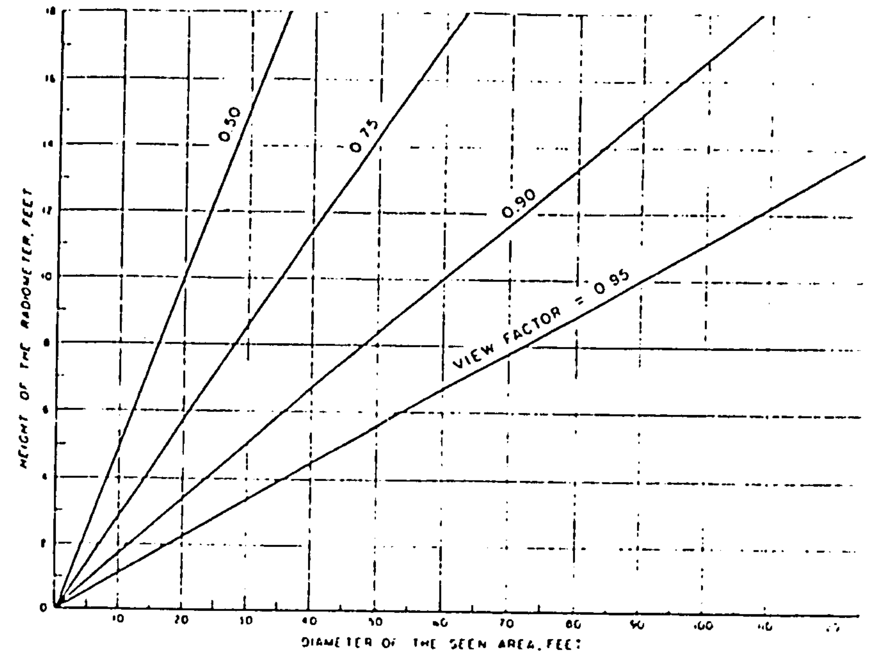

FIGURE 18.—View factor of a radiometer in relation to height.

Area-source radiation from the upper hemisphere measured from within a plant stand (for example, under a forest canopy) will generally be different at different heights above the ground; i.e., the radiometer's view of the three-dimensional plant canopy will change as the radiometer is moved upward from the ground. For example, the angular diameter of an opening in the canopy will increase as it is approached from below. Also, as the proportion of the plant stand below the instrument increases, the more solar and sky radiation will be received (see fig. 16).

Measurements of sunlight or solar radiation under plant canopies are especially difficult when complicated patterns of light and shadow are present. Little is known about the variation, or of suitable methods of sampling. Here again one must first determine the data required: A daily mean, noon value, seasonal total, or other values. Atkins (1957) reported that for a well-stocked 80-year-old red pine stand with a basal area of approximately 200 square feet, reducing the number of photocell readings in half-acre plots from 255 taken at 10-foot spacing to as few as 20 at 40-foot intervals caused little variation in mean values. Some increased variation was noted in sparser stands with a basal area of about 100 square feet.

In a study of illumination under a hazel and dogwood understory that remained after an 80-year-old upland oak stand in Iowa was clear cut, Gatherum (1961) found that a given number of spot measurements gave a more reliable estimate of the mean in stands in which the understory had also been heavily cut than in stands in which the understory was left standing. He calculated that he would need

C.—Derivation of View Factor for Forest Opening

Consider a circular opening in the forest with a diameter, d, with surrounding trees of height, h (fig. 25). The sky above a small area, dA_1, in the center of the opening subtends a solid angle corresponding to the angle, arc tan $(d/2h)$. A ray from dA_1 to the partial hemisphere of sky makes an angle, β_1, with the normal to dA_1. This ray meets the hemisphere at an angle, β_2, which is, of course, 90°. By equation (17), the amount of radiation leaving dA_1 in the direction β_1 and intercepted by the surrounding hemisphere is:

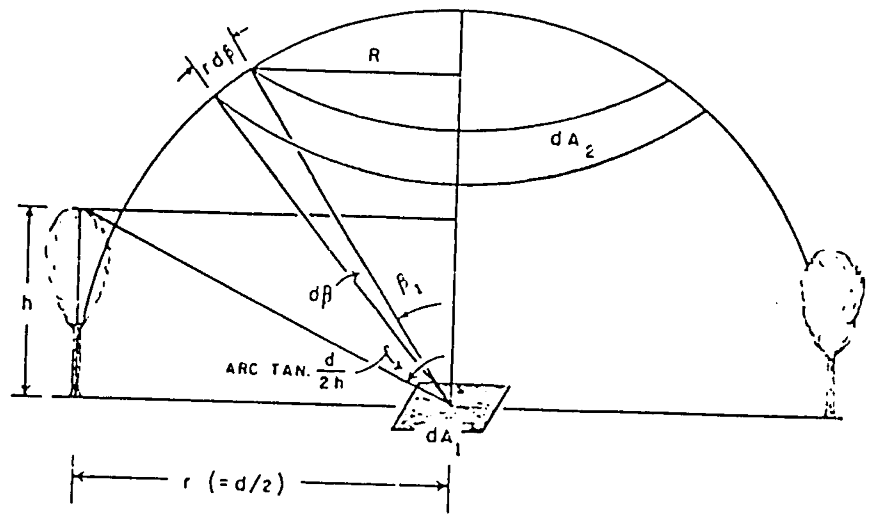

FIGURE 25.— *View factor of circular forest opening.*

$$dW_{1\to 2}(\text{sky}) = \frac{I_1 dA_1 \cos \beta_1 dA_2 \cos \beta_2}{r^2} \qquad \text{(C1)}$$

the differential ring, dA_2, is,

$$dA_2 = 2\pi R r d\beta$$

Since $\cos \beta_2 = 1$, equation (C1) becomes,

$$dW_{1\to 2}(\text{sky}) = \frac{I_1 dA_1 \cos \beta_1 2\pi R r d\beta}{r^2} \qquad \text{(C2)}$$

Since $R/r = \sin \beta_1$, substituting and rearranging,

$$dW_{1\to 2}(\text{sky}) = 2\pi I_1 dA_1 \sin \beta_1 \cos \beta_1 d\beta \qquad \text{(C3)}$$

Integrating from $\beta_1 = 0$ to $\beta_1 = \text{arc tan}\ (d/2h)$,

$$W_{1\to 2}(\text{sky}) = 2\pi I_1 dA_1 \int_0^{\text{arc tan}\ (d/2h)} \sin \beta_1 \cos \beta_1 d\beta \qquad \text{(C4)}$$

$$= 2\pi I_1 dA_1 \Big\{\sin^2 \beta_1\Big]_0^{\text{arc tan}\ (d/2h)}$$

$$= 2\pi I_1 dA_1 \sin^2 [\text{arc tan}\ (d/2h)] \qquad \text{(C5)}$$

Similarly for the entire hemisphere above dA_1,

$$W'_{1\rightarrow 2}(\text{total}) = 2\pi I_1 dA_1 \int_0^{\pi/2} \sin\beta_1 \cos\beta_1 d\beta \tag{C6}$$

$$= 2\pi I_1 dA_1 \left[\sin^2\beta_1\right]_0^{\pi/2}$$

$$= 2\pi I_1 dA_1 \tag{C7}$$

The view factor, $F_{1\rightarrow 2}$ of the sky relative to the spot, dA_1, is defined as the portion of the total radiation leaving the spot that is directed toward the sky,

$$F_{1\rightarrow 2} = \frac{W'_{1\rightarrow 2}(\text{sky})}{W'_{1\rightarrow 2}(\text{total})} \tag{C8}$$

$$= \frac{2\pi I_1 dA_1 \sin^2[\text{arc tan } (d/2h)]}{2\pi I_1 dA_1} \tag{C9}$$

Therefore,

$$F_{1\rightarrow 2} = \sin^2[\text{arc tan } (d/2h)] \tag{C10}$$

The same view factor applies if we are considering radiation from the spot to the sky or from the sky to the spot.

APPENDIX C

ECOLOGY

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SOME IMPLICATIONS OF LEAF TEARING IN MUSACEAE[1]

S. ELWYNN TAYLOR[2]
Missouri Botanical Garden, St. Louis, Missouri

AND

OWEN J. SEXTON
Department of Biology and Center for the Biology of Natural Systems
Washington University, St. Louis, Missouri

Abstract. Leaf temperatures associated with torn and untorn leaves of Musaceae were taken in both dry and wet seasons at Barro Colorado Island, Canal Zone. Transpiration rates and leaf resistance to water-vapor diffusion were determined. Energy-budget analysis is used to describe the relationship of leaf dimension and leaf resistance to thermal survival and water usage. Gas-exchange theory is applied to predict the photosynthetic implications of leaf tearing. The analyses showed that leaves less than 10 cm wide are not subject to critical heat stress, have lower water loss, and higher ratios of photosynthesis to water expended than do leaves of widths greater than 10 cm. In wet season, leaves have lower resistance to the diffusion of water vapor and accordingly are less subject to excessive heating.

INTRODUCTION

Leaf tearing among members of the Musaceae occurs commonly. The tearing is most extensive for plants growing in exposed sites. No permanent leaf damage is apparent as a result of leaf tearing, although temporary damage (a short period of excessive water loss) does occur. Brun (1961), working with *Musa acuminata* L. var. Hort. Gras. Michel, has reported that in the laboratory a fresh tear 10 cm long loses approximately as much water as is transpired by a 10-cm^2 area of leaf. He found that the period of excessive water loss was of short duration.

Prevalent leaf size decreases from the humid darkness of the tropical forest to the sunny, exposed forest edges, or vertically to the upper canopy level. The banana relatives found in exposed sites, such as old fields and clearings, are certainly an exception to the small "prevalent" leaf size; however, the segments of a torn banana leaf are more in keeping with the observed "prevalent" leaf width of other exposed species.

Raschke (1956) suggests that in an environment exposed to insolation the small leaf should transpire less and be at a lower temperature than a large leaf. He further states that to determine whether a decrease in leaf size is advantageous, we must investigate the physical relationships of energy exchange between the leaf and the environment. Subsequent refinement of energy-exchange equations and methods (e.g., Gates, Alderfer, and Taylor 1968) has produced a useful tool for evaluating the advantage or disadvantage of leaf characteristics, such as size, for any given environment.

Idle (1970) used energy-budget techniques to evaluate the relationship of leaf width and resistance to transpiration and thermal survival. He found that there is a width for *Rubus chamemorus* L. below which the leaf is in no thermal danger for "extreme natural" conditions.

FIELD OBSERVATIONS AND DATA ANALYSIS

Leaf-temperature readings were taken for several species that occur commonly in a man-made clearing on a north-facing slope of Barro Colorado Island, Canal Zone.[3] An infrared thermometer (Model PRT-10, Barnes Engineering Co.) was used to determine leaf-surface temperature. This instrument and its use are described by Gates (1968). Leaf temperatures were determined in early April 1969 during the "dry season" when the soil surface was dry and cracked. "Wet season" data were obtained in October 1969, when the soil surface was moist at all times. Air temperature and relative humidity were determined from sling psychrometer observations; air speed was measured with a heated-thermocouple air meter (Hastings Model RB-1); insolation was sensed with a pyranometer (Eppley Model 8-48) using a portable millivolt potentiometer (West model 9B).

The ranges of environmental parameters and temperatures for torn and untorn leaves of *Heliconia latispatha* Berth. are summarized in Table 1. Temperatures were measured in the wet season on the same individual plants and in two cases the same leaves studied in the dry season. Leaf temperatures were determined for six non-Musaceae species. These "other" plants are included only as an indication of typical leaf temperatures. Observations were made at intervals of 5–10 min throughout the periods. The torn *H. latispatha* leaf was never less than

[1] Received April 20, 1970; accepted June 16, 1970.

[2] Present address: Department of Biology, New Mexico State University, Las Cruces, N. Mex. 88001.

[3] Barro Colorado Island research facility is sponsored by the Smithsonian Institution, Washington, D.C., as a part of the Smithsonian Tropical Research Station.

TABLE 1. Environmental parameters and leaf temperatures of *Heliconia latispatha* Berth. and other species in a man-made clearing on Barro Colorado Island, Canal Zone (observations were made every 5–10 min; all readings were within the ranges specified in table)

Characteristic	Exposed environment April 8, 1969 Dry season (0945–1200 hr)	Exposed environment Oct. 8, 1969 Wet season (800–1200 hr)	Shaded environment April 8, 1969 Dry season (0945–1200 hr)
Air temperature (°C)	31–33.5	30–32	30–33
Relative humidity (%)	72–70	78–70	85–70
Wind (cm sec^{-1})	67–90	22–60	10–70
Insolation (0.32–4.2 μ erg cm^{-2} sec^{-1})	8.5-9.1x10^5	8.2-8.6x10^5	Low[a]
Soil surface temperature (°C)	46–50	44–48	28
Sky temperature[b] (°C)	7–8	10–13	28
Intact leaf temperature (°C)	44–48	37–43	28.8–29.2
Divided leaf temperature (°C)	39–44	34–39	29.3–29.8
Leaf temperature (other species)[c] (°C)	38–44	32–40	—

[a]Could not be measured with instrument utilized in study.
[b]Measured with the infrared thermometer on partly overcast day.
[c]Leaf temperatures were measured for six of the non-Musaceae species in the study area.

2°C cooler than the intact leaf, and the temperature difference was as great as 5°C for exposed leaves in both seasons. The parameters are expressed as ranges because simultaneous readings of all instruments is not possible for a lone observer; hence, the air speed at the precise time of leaf-temperature determination, for example, is not known. However, all parameters were undoubtedly within the ranges specified in Table 1 in all cases. Leaf-temperature measurements are expressed as one representative temperature for the divided and one for the untorn side of the leaf. The representative temperature was considered to approximate the mean leaf temperature.

Transpiration rates were determined by a technique that applies energy-budget analysis to the basic quick weighing method as described by Taylor and Gates (1970). The technique requires that a leaf be cut, weighed, and quickly returned to the natural environment, where it is oriented identically with another leaf of the plant with nearly identical characteristics. The temperatures of the intact leaf and the cut leaf are measured, and at intervals the cut leaf is weighed. A difference of temperature between the undisturbed and the cut leaf indicates unequal transpiration rates. This method makes it possible to calculate the transpiration rates of the undisturbed leaves. Laboratory testing of this method (using the weight loss of potted plants as an absolute measure of transpiration) showed that this method will consistently predict transpiration rates within ± 9% of the actual measured transpiration (Taylor and Gates 1970).

Small leaves are close to air temperature since their narrow width allows increased interaction of the air with the leaf surface; i.e., the magnitude of the boundary layer is related to the characteristic dimension of a leaf. The energy-budget equation describes the dimension effects explicitly. The form of the energy-budget equation presented by Gates et al. (1968) is

$$Q_{abs} = \sigma\epsilon T_L^4 + k_1(V/D)^{1/2}(T_L - T_a) + L\frac{{}_s\rho_L(T_L) - r.h.\ {}_s\rho_a(T_a)}{r_i + k_2\dfrac{W^{0.2}D^{0.35}}{V^{0.55}}}, \qquad (1)$$

where Q_{abs} is the total absorbed radiation (erg cm^{-2} sec^{-1}), T_L is leaf temperature (°K), T_a is air temperature (°K), V is air velocity (cm sec^{-1}), σ is the Stefan-Boltzmann constant (5.67×10^{-5} erg cm^{-2} sec^{-1} $°K^{-4}$, ϵ is leaf emissivity (0.94–1.0) (as determined by Idso et al. 1969), $r.h.$ is relative humidity (0–1.0), L is the latent heat of evaporation of water (erg g^{-1}), r_i is the resistance of the leaf to diffusion of water vapor (sec cm^{-1}), D is the characteristic leaf dimension (cm) (as described by Taylor and Gates 1970), W is the width perpendicular to D (cm), ${}_s\rho_L(T_L)$ is saturation density of water vapor at leaf temperature (g cm^{-3}), ${}_s\rho_a(T_a)$ is saturation density of water vapor at air temperature (g cm^{-3}), k_1 is 1.13×10^4 when W is 5 cm or less and 6.98×10^3 when greater than 5 cm, and k_2 is 1.56 for W of 5 cm or less and 2.10 when W is greater than 5 cm.

The temperature of the leaf is determined by the simultaneous interaction of energy absorbed, air temperature, wind, leaf size, and leaf diffusion resistance. With environmental parameters similar to those in Table 1 (air temperature 30°C, relative humidity 80%, wind 10 cm sec^{-1}, radiation absorbed 8.38 $\times 10^5$ erg cm^{-2} sec^{-1}), the energy budget was solved to show leaf temperatures as affected by leaf size (D) and leaf resistance to water vapor diffusion (r_i) (Fig. 1). The torn parts of the leaves are effectively independent leaflets; and from an energy-exchange standpoint, each segment was treated as an individual

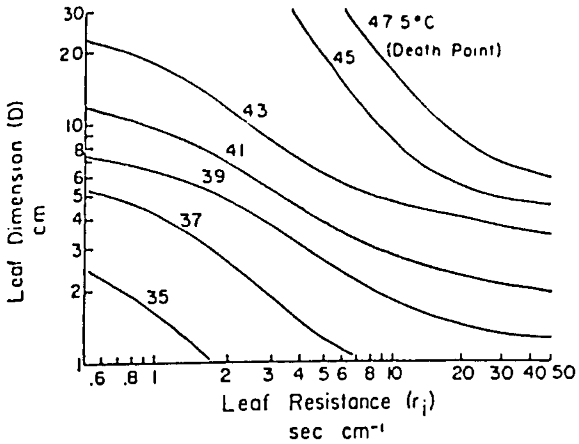

FIG. 1. Leaf-surface temperature as a function of leaf width (D) and the leaf resistance to diffusion of water vapor (r_i) for hot, humid, calm conditions (air temperature 30°C, relative humidity 80%, wind 10 cm sec^{-1}, solar radiation absorbed by the leaf 8.38×10^5 erg cm^{-2} sec^{-1}). The 47.5°C isoline represents the thermal death point for *Strelitzia nicolai*. Canal Zone plants in dry season were found to have leaf resistances (r_i) near 30 sec cm^{-1}, but during the wet season resistances were near 6 sec cm^{-1}. During dry season leaves wider than 10 cm attain temperatures in excess of 47.5°C, but during wet season, when r_i is low, this leaf temperature is not attained.

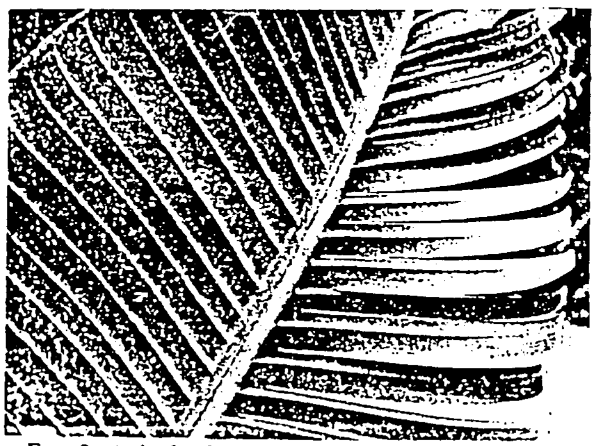

FIG. 2. A leaf of *S. nicolai* has been purposely torn on one side to resemble natural tearing in the Musaceae. The small characteristic dimension of the torn portions allows increased convection, which results in cooling of the leaf as well as reduction of the boundary-layer resistance to diffusion of water vapor and carbon dioxide.

leaf. The lethal leaf temperature varies for different species and according to the history of the individual plant; 47.5°C was considered to be the thermal danger point based on observations made on greenhouse-grown leaves at the Missouri Botanical Garden.

The temperature of a *Strelitzia nicolai* leaf (Fig. 2) was monitored for nearly 60 min. The natural insolation was supplemented with incandescent illumination sufficient to approximate extreme natural conditions (about 1.1×10^6 erg cm^{-2} sec^{-1} incident solar radiation). The highest temperature sustained

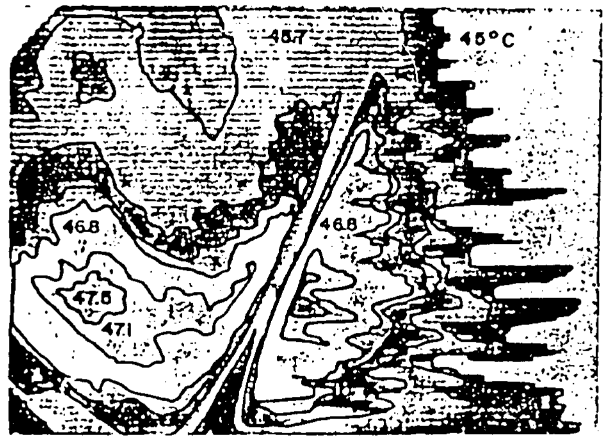

FIG. 3. Thermogram of the portion of *S. nicolai* leaf shown in Fig. 2. The temperature distribution on the leaf is indicated by the isothermal lines; each division represents a temperature change of 0.36°C. The temperatures range from 45° to 47.5°C. Thermal damage occurred in the 47.5°C regions but nowhere else. Note that the midrib is cooler than adjacent tissue. The cool area to the upper left is a result of non-uniform illumination. (Thermogram courtesy of Barnes Engineering Co.).

by the leaf was 47.5°C, which was maintained for 10 min. A prototype scanning infrared camera from Barnes Engineering Co. was used to produce a color thermogram of the leaf (Fig. 3). Each color change (change of tone or texture in the black and white reproduction) represents a temperature change of 0.36°C. A few days after the thermogram was produced, the leaf had two dead spots precisely within the two 47.5°C isolines seen in Fig. 3.

Leaf temperatures in excess of 47.5°C are considered dangerous to members of the Musaceae. However, it is expected that the actual thermal death point does vary with the individual leaf and its history, as has been reported for other plants by Yarwood (1961) and Lange (1965, 1967).

Leaves of *H. latispatha* were found (from eq. (1)) to have an r_i near 30 sec cm^{-1} during the dry season. The undivided leaf has dimension greater than 15 cm and is subject to dangerously high leaf temperatures, whereas the divided leaf has dimensions from 2–5 cm and is in no danger of overheating (Fig. 1). Except for the Musaceae, no leaves with characteristic dimension greater than 10 cm were found in the exposed environment during the dry season. In times of severe soil-water stress, when the plant must maintain high r_i to prevent dehydration, and when the environmental parameters are similar to those specified in Fig. 1, leaves of D less than 6 cm are in no danger of overheating. When the soil is wet and the leaf resistance (r_i) is near 2 sec cm^{-1}, a leaf could be as large as $D = 60$ cm without entering the thermal danger zone.

A successful plant species must be able to withstand the extremes of the environment as well as be

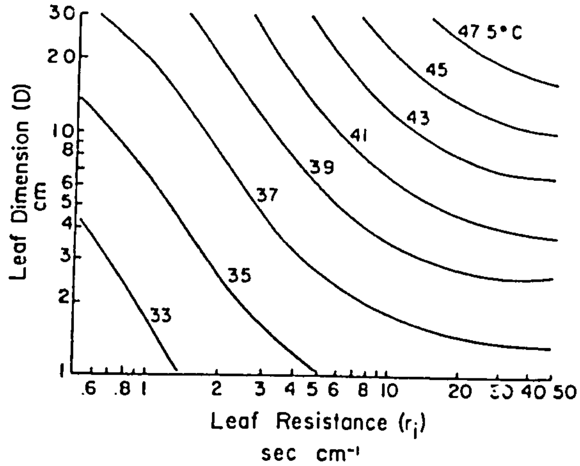

FIG. 4. Leaf-surface temperature as a function of leaf width (D) and the leaf resistance to diffusion of water vapor (r_i) for hot, humid, low wind conditions (environmental conditions are the same as in Fig. 3 except wind is increased to 50 cm sec^{-1}). Leaf temperature is nearer air temperature at the increased wind.

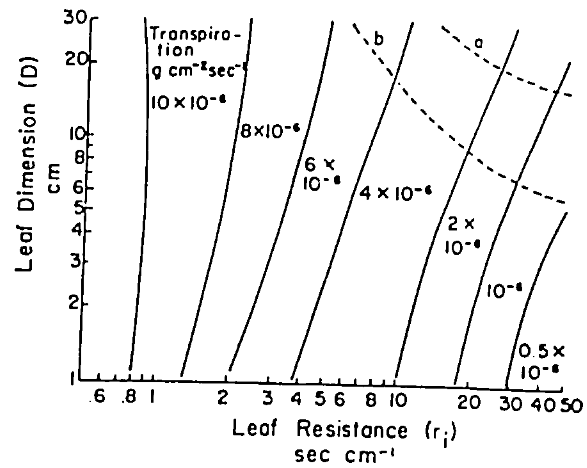

FIG. 5. Transpiration rate as a function of leaf dimension (D) and leaf resistance (r_i). Transpiration rate is controlled more by resistance of the leaf than by leaf size, but the size of the leaf has influence on water use indirectly because it affects the external diffusion resistance (boundary-layer resistance) and the leaf temperature (and hence vapor pressure). Environmental conditions are identical to those in Fig. 4. The broken lines show the thermal danger zone; "a" is taken from Fig. 4 and "b" is taken from Fig. 3.

competitively productive under more or less normal environmental conditions. It is no simple task to determine the significant extreme conditions. Dry air and soil together with warm air and high insolation are stressful, but if these conditions persist for only a short time or occur infrequently, they may not be highly significant. The conditions reported here affected all unshaded leaves, and the environmental parameters were within the ranges reported in Table 1 for a portion of the day, 6 days out of 10 during the study.

Although the conditions of low wind used for Fig. 1 occur regularly in clearings surrounded by forest, the mean air speed is generally considerably greater (see Table 1). A leaf of 20-cm dimension with resistance of 30 sec cm^{-1} at the conditions specified for Fig. 1 would sustain thermal damage in a short period of time; however, the water loss and net photosynthesis during this short period may not be significant to the survival of the leaf. The water-loss and photosynthesis rates are more significant to species survival at winds near 50 cm sec^{-1} because the higher air speed predominates. Figure 4 was produced for conditions identical to those in Fig. 1 except the wind was increased to 50 cm sec^{-1}. Notice that the temperature for a leaf of any given dimension and resistance is lower than in Fig. 1 due to the increased convection.

Transpiration rate as a function of dimension (D) and leaf resistance (r_i) was calculated from the energy-budget equation and is shown in Fig. 5. Figures 4 and 5 were produced from eq. (1) with identical environmental conditions for each. The transpiration rate of *H. latispatha* was determined to be more than twice as great per unit surface for the undivided leaf as for the torn leaf in the dry season. The transpiration rate for the torn leaf was 0.55×10^{-6} g cm^{-2} sec^{-1}.

PHOTOSYNTHETIC IMPLICATIONS

Thermal survival of the leaf and water expenditure as influenced by leaf form are two important aspects of species success. An additional aspect that should be considered is the photosynthetic rate as affected by leaf form. Theoretical models of photosynthesis that are compatible with the energy-exchange treatment of the single leaf are yet in their infancy. The use of available models as they now exist can, however, provide some further insight on the significance of leaf form. The use of these models should not be neglected even though further refinement will be expected to alter and improve the absolute results.

A crude analysis of the effect of D and r_i on productivity was made using a formulation combining the Michaelis-Menton equation for enzyme-catalyzed chemical reactions with Fick's diffusion law. According to Gates et al. (1969), this photosynthesis equation may be expressed in quadratic form as:

$$P = \frac{(r'P_m + K + \rho'_a) - [(r'P_m + K + \rho'_a)^2 - 4r'\rho'_a P_m]^{1/2}}{2r'}, \quad (2)$$

where P is the rate of CO_2 exchange between the air and the leaf (g CO_2 cm^{-2} sec^{-1}), ρ'_a is the atmospheric density of carbon dioxide, r' is the resistance to diffusion of carbon dioxide from the atmosphere to the chloroplast, K is the Michaelis rate constant for the reaction, and P_m is the maximum carbon dioxide exchange rate possible for given light and temperature conditions (g CO_2 cm^{-2} sec^{-1}).

The effect of illumination is not included for these calculations because only one leaf is involved, and the torn and untorn portions are assumed to be exposed to equal insolation and to have identical photosynthetic response to any given illumination, other factors such as leaf temperature notwithstanding. A temperature difference between the torn and untorn sections does exist, so the influence of leaf temperature on the value of P_m must be considered. Gates et al. (1969) presented curves describing the temperature effect on P_m. Equation (3) is an empirical approximation of the temperature-P_m relationship:

$$P_m = \frac{-(T+A)^4 + 2(T+A)^2(T_m+A)^2}{(T_m+A)^4}, \quad (3)$$

where T is the temperature of the leaf (°C), T_m is the optimum photosynthetic temperature for the leaf (°C), and A is a constant such that the formula will predict zero net photosynthesis at a particular temperature. For example, if net photosynthesis is zero for a particular species at +5°C, then

$$A = -1 \times 5 = -5.$$

The r' term in eq. (2) is determined from eq. (1), assuming that where the path for water and CO_2 is identical, the resistance to water-vapor diffusion times 1.54 gives the resistance to diffusion of CO_2 (at temperatures near 40°C (Washburn 1929)). Some water is lost by cuticular transpiration, but it is assumed that negligible CO_2 is taken up by the cuticular path (Holmgren, Jarvis, and Jarvis 1965); hence, cuticular resistance must be considered for transpiration calculations, but can be neglected in calculations of carbon dioxide exchange. A cuticular resistance to water loss of 300 sec cm^{-1} was calculated from data by Brun (1961) for young *Musa acuminata* L. The development of wax on mature leaves probably makes cuticular resistance even higher (Mueller, Carr, and Loomis 1954). The cuticular resistance of banana is so high that it can be ignored without introducing significant error in the determination of the CO_2 resistance.

Mesophyll resistance to water-vapor diffusion is generally considered negligible and so was not considered in this treatment. Recent work indicates, however, that this assumption may not be strictly legitimate (Jarvis and Slatyer 1970).

The common pathway for CO_2 and H_2O diffusion is considered to be the sum of the stomate resistance and the boundary-layer resistance (the total value of the denominator of the final term of eq. (1)). Therefore, the total resistance to diffusion of CO_2 (r') is 1.54 times the stomate plus boundary-layer resistance plus the mesophyll resistance to CO_2 diffusion:

$$r' = 1.54\,(r_i + r_a) + r'_m, \quad (4)$$

where r'_m is the mesophyll resistance to CO_2 diffusion and r_a is the boundary-layer resistance to diffusion of water vapor:

$$r_a = K_2 \frac{D^{0.35} W^{0.20}}{V^{0.55}}. \quad (5)$$

The final term in eq. (4) (r'_m) was assigned a constant value of 2.4 sec cm^{-1}, which is in the range of values reported for soybeans by Dornhoff and Shibles (1970), turnips (Gaastra 1959), and cotton (Bierhuizen and Slatyer 1964). The value of K in eq. (2) was set at 1.2×10^{-7} g CO_2 cm^{-3}. The values given K and r'_m were consistent with unpublished laboratory results of D. M. Gates and associates and are of the magnitude for K and r'_m of other species calculated from data by Hesketh (1963). Atmospheric CO_2 density at 300 ppm is 5.32×10^{-7} g CO_2 cm^{-3} (at 30°C and 1 atm).

The Michaelis rate constant (K) must be considered as the rate constant at the metabolic site, since it was not determined whether photorespiration does or does not occur in *H. latispatha*. The optimum temperature for photosynthesis in eq. (3) was arbitrarily set at 35°C and net photosynthesis zero at 46°C to be consistent with values given for some tropical grasses by Hesketh and Baker (1969).

Equation (2) was solved to show net photosynthesis as affected by leaf dimension and resistance to water-vapor diffusion (Fig. 6). All biological characteristics were considered constant except D and r_i.

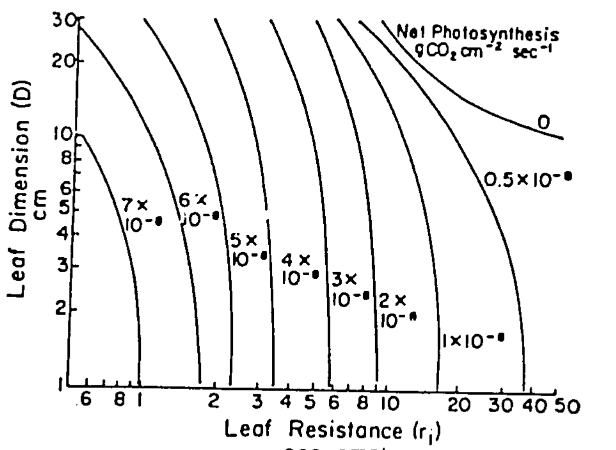

FIG. 6. Net photosynthesis as a function of leaf dimension and resistance for *H. latispatha* at the conditions specified in Fig. 4. Photosynthetic rates at constant illumination are dependent on leaf temperature (a function of dimension and resistance) and the resistance to carbon dioxide uptake. Resistance to carbon dioxide exchange is a function of leaf resistance (r_i) as described in the text.

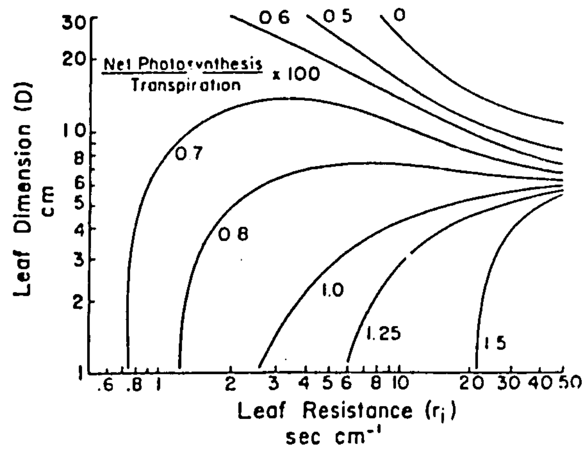

FIG. 7. The ratio of net photosynthesis to water expended is dependent on leaf resistance and dimension; however, a dimension (7–10 cm) exists for these environmental conditions (as described in Fig. 4) such that the ratio is nearly independent of leaf dimension; the small exposed leaf with high resistance has the most favorable photosynthesis-to-transpiration ratio.

The environmental parameters for Fig. 6 and 7 are the same as for Fig. 4 and 5.

The relative photosynthetic efficiency with respect to water expended is shown in Fig. 7. When the characteristic leaf dimension (D) is near 8 cm, changes in r_i have little effect on the ratio of photosynthesis to water expended. This indicates that a leaf of 8-cm dimension would maintain approximately the same efficiency in both the dry season when leaf resistance (r_i) is high and under moist conditions, when resistance is lower. There are many implications to the constant efficiency ratio, but discussion should be withheld until the phenomenon has been further investigated.

The results presented in Fig. 6 and 7 are, due to the estimation of certain biological parameters, more or less relative and are perhaps most useful to demonstrate relationships and photosynthetic trends. Further research to define more explicitly the photosynthetic rate constant, optimum temperature, and mesophyll resistance to diffusion of carbon dioxide can improve the absolute values of the calculations.

Example calculations for *H. latispatha* are presented in Table 2, which includes results for shaded leaves also. The dimension effect was not as marked in the shade as in the sun.

Leaf tearing in the Musaceae can insure that the leaves are no more liable to sustain excessively high temperatures than are the exposed leaves of other plants. Leaf division can result in 50% reduction of transpiration rate during the stressful time of the day, and the small size leaf segment is in an apparently more favorable regime for net photosynthesis during times of environmental stress. Thermal survival in the dry season and increased productivity when soil water is plentiful appear to be significant beneficial effects of leaf tearing.

The thermal danger zone shown in Fig. 4 does exist during both the dry and wet seasons, and exposed leaves greater than a certain characteristic dimension will sustain dangerously high leaf temperatures unless the leaf resistance to water loss is low enough to provide significant evaporative cooling. The broad banana leaf is definitely in thermal danger during the dry season when leaf resistance is high. The tearing of the banana leaf can be considered to be a factor for reduction of the thermal danger to the leaf.

TABLE 2. Sample results for *H. latispatha* for exposed sites during dry and wet seasons and for shade leaves during dry season[a] which demonstrate the effects of leaf tearing on water loss and photosynthetic rate

	Leaf temperature[b] (T_L) (°C)	Leaf diffusion resistance[c] (r_i) (sec cm^{-1})	Transpiration[c] (Tsp) (g cm^{-2} sec^{-1})	New photosynthesis[d] (P) (g CO_2 cm^{-2} sec^{-1})	$P \times 10$ / Tsp
		Exposed leaf			
Dry season					
Intact	46	24	18.8 x 10^{-7}	−0.160 x 10^{-7}	−0.85
Divided	40	29	5.5 x 10^{-7}	0.097 x 10^{-7}	1.76
Wet season					
Intact	42	5.6	52 x 10^{-7}	0.322 x 10^{-7}	0.619
Divided	38	5.9	38 x 10^{-7}	0.365 x 10^{-7}	0.961
		Shaded leaf			
Dry season					
Intact	29.0	30	2.4 x 10^{-7}	0.070 x 10^{-7}	2.91
Divided	29.5	30	2.7 x 10^{-7}	0.072 x 10^{-7}	2.65

[a]Air temperature 30°C, relative humidity 70%, wind 50 cm sec^{-1}, radiation absorbed 8.38 x 10^5 ergcm^{-2} sec^{-1} (exposed leaves), radiation absorbed 4.68 x 10^5 ergcm^{-2} sec^{-1} (shaded leaves).
[b]Measured with infrared thermometer.
[c]Calculated from eq. (1).
[d]Calculated from eq. (2).

Discussion

The model presented in this paper indicates that in the exposed Canal Zone environment the smaller the leaf, the better; it does not explain the clustering of characteristic dimensions that can be observed for the clearing vegetation as a whole (the mean dimension (*D*) is near 5 cm). The model indicates that leaves should have characteristic dimension less than 10 cm to avoid excessive dry season leaf temperatures and that the exposed leaf with characteristic dimension near 8 cm is in a regime where the ratio of net photosynthetic rate to water expended is nearly independent of the amount of water expended. The question can be asked, however, Why are the leaves not smaller? Further, solving eq. (1) for deep shade conditions predicts that large leaves will transpire less than small leaves and as leaf dimension increases, the photosynthesis-to-transpiration ratio also will increase. Environmental conditions exist, at least theoretically, such that leaf dimension (*D*) has no effect on transpiration or photosynthesis. In this regime the size of the leaf is determined by the genetic history of the species or is a result of other factors such as economics or shading competition or other factors not considered in this model.

Contemplated additions to the model to account for the economics of producing many small units (leaves) opposed to a few large leaves and calculations to show the effectiveness of large versus small leaves for shading competition may be useful to describe the lower limit to leaf size in the exposed environment as well as the upper limit to leaf size in a sheltered or shaded environment.

Acknowledgments

We are grateful to Dr. D. M. Gates of the Missouri Botanical Garden and the members of his research group, especially Drs. Hyrum Johnson and Paul Lommen, for the development and testing of the photosynthesis model that is used in this paper in a simplified and elementary form.

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APPENDIX D

REPRINT FROM

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5 OPTIMAL LEAF FORM

S. Elwynn Taylor

Environmental Study Service Center
National Oceanic and Atmospheric Administration
National Weather Service, U.S. Department of Commerce

Auburn University, Auburn, Alabama 36830

5

Optimal Leaf Form

S. ELWYNN TAYLOR

Introduction

The size of leaves typical for specific climates has been studied for many years, and several investigators have considered the "leaf size class" as an indicator of climatic conditions (Raunkiaer, 1934). Bailey and Sinnott (1916) concluded that the form and size of leaves were more a result of environment than of genetic history, although the latter was certainly an influence. Benson *et al.* (1967) reported ecotypic differentiation of leaf form with respect to slope exposure for a hybrid population of *Quercus douglassii* × *Q. turbinella*. They suggested that hybrid variability may permit the rapid evolutionary selection of characters best suited for the particular microclimate. They reported that individuals found on the northeast slope had leaves of significantly larger dimension than did those growing on the more arid southwest slope (Fig. 5.1). It is generally considered that the reduction of leaf size in arid areas has the effect of conserving water, but quantitative evidence of the effects of leaf size has been available only recently.

The effects of leaf size are inseparably coupled with other characteristics of the leaf and the environment. Proper evaluation of the significance of any characteristic must consider all environmental and biological factors. The analysis must include the primary meteorological and edaphic parameters: solar and thermal radiation, air temperature, atmospheric vapor pressure, air speed, atmospheric gas concentrations (CO_2, O_2), and availability of soil moisture. Biological parameters include absorptivity to radiation; stomatal and mesophyll resistance to uptake or loss of carbon dioxide, oxygen, water vapor, and other gases; size, shape, and orientation of the organism; and the temperature range critical to survival. When the biological and environmental parameters are known, one can properly evaluate the biological responses to the environment and thereby determine the significance of variations in the individual characteristics or parameters. The biological responses considered in this paper are leaf temperature, transpiration rate, net photosynthesis, and the ratio of photosynthesis to transpiration.

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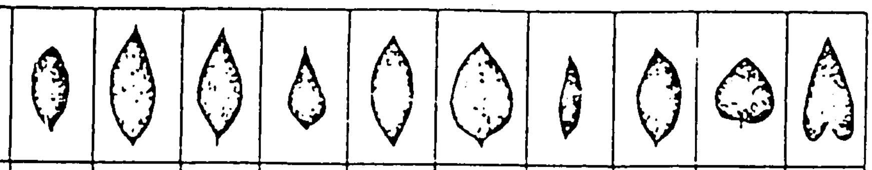
Table 5.1 Dimension Constants for Leaves Collected in the Canal Zone*



R_D	0.791	0.772	0.700	0.807	0.784	0.699	0.766	0.762	0.769	0.661
R_W	0.648	0.668	0.585	0.640	0.647	0.575	0.833	0.664	0.721	0.664

* The characteristic leaf dimension is found by multiplying the maximum width by R_D. The characteristic length is found by multiplying the maximum length by R_W.

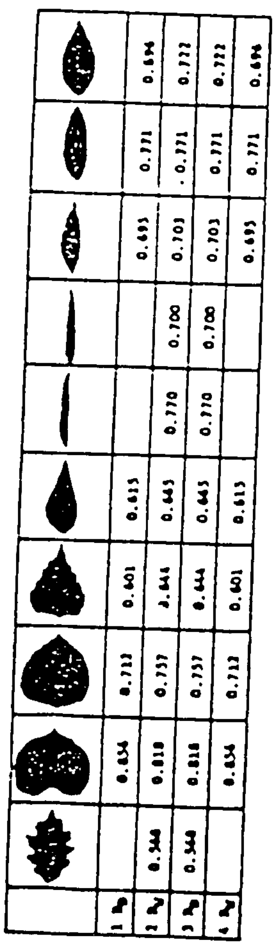
Leaf size is often classified, according to Raunkiaer (1934), on the basis of surface area. However, for energy-exchange evaluations, leaves should be classified according to "characteristic dimension." Some have found it desirable to express the characteristic dimension using Raunkiaer's classifications as a basis (Brunig, 1970). A dimension classification scheme compatible with the Raunkiaer size classification was formulated according to Eq. (2) for leaves of the basic "elliptic" shape given by Raunkiaer. The characteristic dimension for leaves of each size suggested by Raunkiaer is given in Table 5.2.

Raunkiaer considered the leaflets of compound leaves as individual leaves. Further, deeply lobed leaves were not considered in the size class distribution with entire leaves; i.e., a size class distribution for entire leaves, one for lobed leaves, and one for compound leaves is made for the vegetation of a region by the investigator. All three groups are considered together by use of the "dimension class." Hence only one leaf class distribution is given, rather than three.

It should be noted, however, that the classifying of leaf dimensions should be broken down according to the energy environment typical for the leaves; i.e., leaves considered together should come from similar energy environments, such as deep shade, semishade, exposed to full sun, terrain slope and aspect, and time of solar exposure. Also, moisture regimes should be separated, for example, dry hillside from moist valley environments.

The leaf dimension classification system utilizes the basic nomenclature of Raunkiaer to describe the dimension grouping of leaves. Each group is divided into three subgroups, as suggested by Raunkiaer (1934). The classes are referred to as small–medium–big and are more satisfactory to the author's needs than the addition of another major class, as has been suggested by several investigators (Cooper, 1922; Webb, 1959).

The foliar physiognomy can have a considerable influence on the "leaf dimension," so that a leaf with an entire margin may be larger in dimension than a deeply lobed leaf that has considerably greater surface area (Fig. 5.2). Deep lobing or foliar pinnation can reduce the leaf dimension without changing the leaf size appreciably. Taylor and Sexton (1972) demonstrated that tattering of the leaves in Musaceae effectively reduced the dimension to one better suited for their climate (Fig. 5.3). It must be noted, however, that very fine pinnation may not be effective



1 R_D		0.834	0.722	0.601	0.615			0.695	0.771	0.694
2 R_W	0.548	0.818	0.757	0.644	0.645	0.770	0.700	0.703	0.771	0.722
3 R_D	0.548	0.818	0.757	0.644	0.645	0.770	0.700	0.703	0.771	0.722
4 R_W		0.834	0.722	0.601	0.615			0.695	0.771	0.694

FIG. 1. — Dimension coefficients for actual leaves when air flow is laminar and in the plane of the leaf blade. The effective leaf dimension is the product of the actual maximum leaf dimension and the appropriate coefficient. When air flow is parallel to the midvein, the coefficients are taken from rows 1 and 2. For flow perpendicular to the midvein, values are taken from rows 3 and 4. R_D is the coefficient for the dimension parallel to air flow and R_W is the coefficient for the dimension measured at right angles to the air flow.
Adapted from PARKHURST et al. (1968).

Table 5.2 Raunkiaer Leaf-Size Class and Leaf-Dimension Class[a]

Size Class[b]	Leaf Area One Side (cm^2)	Characteristic Dimension Width × 0.742 = D^c (cm)	Dimension Class
Leptophyll	0–0.25	0–0.33	*D*-leptophyll
S	0–0.056	0–0.16	D–Le–S
M	0.056–0.12	0.16–0.24	D–Le–M
B	0.12–0.25	0.24–0.33	D–Le–B
Nanophyll	0.25–2.25	0.33–0.93	*D*-nanophyll
S	0.25–0.52	0.33–0.47	D–N–S
M	0.52–1.08	0.47–0.68	D–N–M
B	1.08–2.25	0.68–0.93	D–N–B
Microphyll	2.25–20.25	0.93–2.75	*D*-microphyll
S	2.25–4.68	0.93–1.32	D–Mi–S
M	4.68–9.74	1.32–1.80	D–Mi–M
B	9.74–20.25	1.80–2.75	D–Mi–B
Mesophyll	20.25–182.25	2.75–7.38	*D*-mesophyll
S	20.25–42.09	2.75–3.8	D–Ms–S
M	42.09–87.68	3.8–5.3	D–Ms–M
B	87.68–182.25	5.3–7.38	D–Ms–B
Macrophyll	182.25–1640.25	7.38–22.26	*D*-macrophyll
S	182.25–378.82	7.38–10.8	D–Ma–S
M	378.82–789.13	10.8–15.2	D–Ma–M
B	789.13–1640.25	15.2–22.26	D–Ma–B
Megaphyll	1640.25–*x*	22.26–*x*	*D*-megaphyll
S	1640.25–3409.31	22.26–31.5	D–Mg–S
M	3409.31–7102.11	31.5–43	D–Mg–M
B	7102.11–*x*	43–*x*	D–Mg–B

[a] Leaf-dimension classification is directly derived from the leaf-size classification by Raunkiaer (1934) for elliptic leaf form. The elliptic form does not constitute an ellipse which has D = width × 0.87, but the dimension is found as D = width × 0.742. Each class is divided into three groups: small, medium, and big, as suggested by Raunkiaer, with the areas for each division chosen by the author as consistent with the original class size divisions.

[b] S, M, B (small, medium, big) are class divisions suggested by Raunkiaer (1934) but divided (values chosen) by me.

[c] The characteristic dimension for Raunkiaer's leaf outlines is width × 0.7420, after Parkhurst *et al.* (1968).

in reducing dimension since the elements might share a common boundary layer (Parkhurst and Loucks, 1972).

A study of bracken fern (*Pteridium aquilinum*) conducted by the author with Hyrum Johnson at The University of Michigan's Biological Station in August 1968 showed that, for air speeds of 10–300 cm s^{-1}, the final or third pinnation did indeed have a boundary layer in common with the second pinnation. Utilizing the energy-exchange equations (Gates *et al.*, 1968) [see Eq. (3)] to solve for dimension, we found that the first pinnation was the fundamental unit of energy exchange. Calculations of energy exchange based on the second pinnation caused an error of +83 percent in the calculated amount of energy released by convection. Calculations utilizing the final pinnation produced errors of +210 percent. All measure-

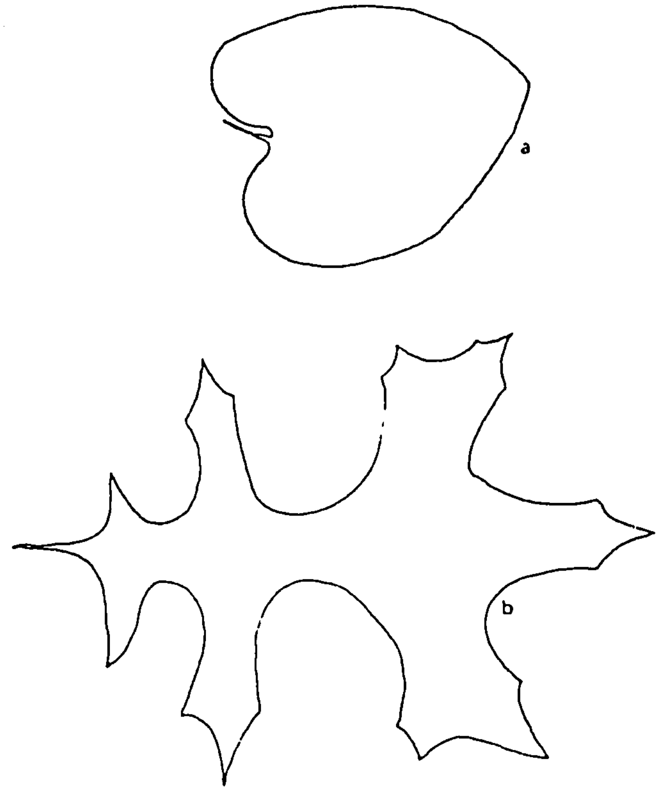


Fig. 5.2. The leaf of *Aristolochia durior* (a) is smaller in area (small mesophyll) than the *Quercus palustris* leaf (mesophyll); (b) yet, because of the leaf shape, the former has the larger characteristic dimension. The *Q. palustris* is a medium microphyll in dimension, whereas *A. durior* has the dimension of small mesophyll.

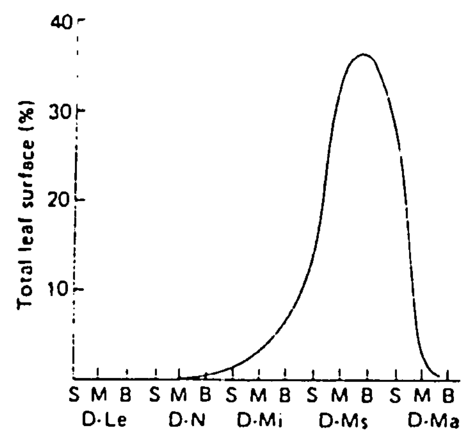


Fig. 5.3. Leaves from the exposed portion of the Barro Colorado Island Forest canopy, Canal Zone. Approximately 80 percent of the total leaf surface has dimensions in the range 4–11 cm, including the banana relatives, whose very large leaves are reduced in dimension by tearing.

ments were made for the natural sunlit environment using potometer-mounted fronds.

The leaf form typical for geographical regions is best expressed as a dimension class distribution, especially in cases where leaf size is limited by the physical environment. For example, Taylor and Sexton (1972) calculated that no leaves larger than a "big-dimension-mesophyll" (7.4 cm) would be anticipated in exposed areas during the dry season at Barro Colorado Island, Canal Zone, unless a continuous water supply were available. The leaves of several Musaceae species have dimension greater than this, but as mentioned above, leaf tearing had the effect of reducing the dimension to within the specified class. A frequency distribution of leaf size and dimension was made for exposed leaves on B.C.I. during December 1970 as the wet season was nearing an end (Fig. 5.3). The analysis included all exposed leaves of randomly chosen plots (9 m^2) in an old clearing on the north side of the island. The mean dimension and the upper limit to dimension for leaves in the specified climate were predicted by the energy-budget and gas-exchange analysis. Commonly, leaves of greatly different surface areas taken from similar environments have similar characteristic dimension. Such leaves are of equi alent dimension insofar as energy-exchange parameters are considered.

Climate Classification

Classification of leaf climates becomes a necessity if finite observations of leaf form and environment are desired. Gates (1968) defined leaf climates for purposes of convenience and discussion. He included air temperature, humidity, wind, and solar radiation in the classification. Taylor (1971) utilized a clima e classification based on that of Gates but defined somewhat finer divisions. The classification (Table 5.3) included the solar and thermal energy absorbed by the leaf and also qualitative observations of soil-moisture availability and canopy condition. No range of values was assigned the latter two parameters because of insufficient quantitative observations. Values for realistic natural ranges should be defined as understanding permits.

The climate for an individual leaf is almost a unique condition for that leaf. It can be expected that one would need several climates to describe the environment of a tree or forest canopy.

The proposed "plant climate classification," together with the leaf form classification presented herein, provide a reasonable matrix for the analysis of plant–climate relationships.

Environmental Limitations to Leaf Form

The environmental conditions together with the biological characteristics of the leaf interact to determine, among other parameters, the leaf temperature. Small leaves are close to air temperature since their narrow width allows increased

Table 5.3 Leaf-Climate Classification[a]

Parameter	Designation	Range	Designation	Range	Designation	Range
Air temperature (T_a)	Hot	50–30°C	Warm	29–15°C	Cool	14–0°C
Humidity (rh)	Dry	0–40%	Moist	41–70%	Wet	71–100%
Sunlight (Epp)[b]	Bright	1.26–0.83 $\times 10^6$ ergs $cm^{-2}\,s^{-1}$	Hazey	0.83–0.56 $\times 10^6$ ergs $cm^{-2}\,s^{-1}$	Cloudy	0.56–0.28 $\times 10^6$ ergs $cm^{-2}\,s^{-1}$
Wind (V)	Windy	> 100 $cm\,s^{-1}$	Moderate	100–10 $cm\,s^{-1}$	Still	< 10 $cm\,s^{-1}$
Absorbed radiation (Q_{abs})	High	1.12–0.70 $\times 10^6$ ergs $cm^{-2}\,s^{-1}$	Moderate	0.70–0.49 $\times 10^6$ ergs $cm^{-2}\,s^{-1}$	Low	0.49–0.21 $\times 10^6$ ergs $cm^{-2}\,s^{-1}$
Soil	Dry		Moist		Wet	
Canopy (during observations)	Open		Partial shade		Closed	

[a] The factors of the environment utilized in energy- and gas-exchange analysis are placed in categories that can be used to designate the immediate climate for an organism. A few other factors, considered significant, are included for convenience.
[b] When the solar insolation is less than 0.28 $\times 10^6$ ergs $cm^{-2}\,s^{-1}$, the designation "dark" is used.

interaction of the air with the leaf surface; i.e., the magnitude of the boundary layer is related to the characteristic dimension of a leaf. The energy-budget equation describes the dimension effects explicitly. The form of the energy-budget equation presented by Gates *et al.* (1968) is

$$Q_{abs} = \sigma\epsilon T_L^4 + k_1(V/D)^{1/2}(T_L - T_a) + L\,\frac{{}_s\rho_L(T_L) - (\mathrm{rh})\,{}_s\rho_a(T_a)}{r_l + k_2(W^{0.2}D^{0.35}/V^{0.55})} \qquad (3)$$

where Q_{abs} = total absorbed radiation (ergs $cm^{-2}\,s^{-1}$)
T_L = leaf temperature (°K)
T_a = air temperature (°K)
V = air velocity (cm s^{-1})
σ = Stefan-Boltzmann constant (5.67 $\times 10^{-5}$ ergs $cm^{-2}\,s^{-1}\,°K^{-4}$)
ϵ = leaf emissivity (0.94 – 1.0) (as determined by Idso *et al.*, 1969)
rh = relative humidity (0 – 1.0)
L = latent heat of evaporation of water (ergs g^{-1})
r_l = resistance of the leaf to diffusion of water vapor (s cm^{-1})
D = characteristic leaf dimension (cm)
W = width perpendicular to D (cm)
${}_s\rho_L(T_L)$ = saturation density of water vapor at leaf temperature (g cm^{-3})
${}_s\rho_a(T_a)$ = saturation density of water vapor at air temperature (g cm^{-3})
k_1 = 1.13 $\times 10^4$ when W is 5 cm or less and 6.98 $\times 10^3$ when greater than 5 cm
k_2 = 1.56 for W of 5 cm or less and 2.10 when W is greater than 5 cm

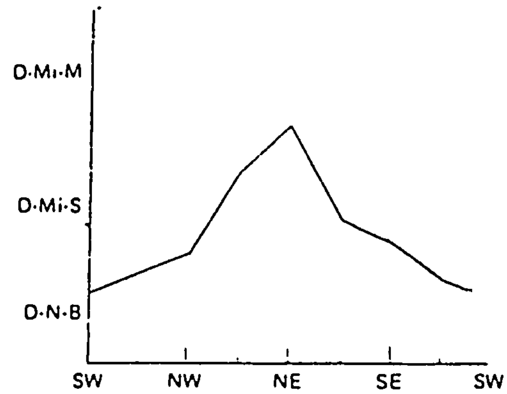


Fig. 5.1. Leaf-dimension class for hybrid *Quercus douglassi* × *Q. turbinella* with slope direction. (Adapted from Benson *et al.*, 1967.)

Leaf Size and Dimension Classification

Leaf dimension directly affects the energy exchange at the leaf because the thickness of the boundary layer, which limits exchange of heat and diffusion of water vapor, depends on air speed and leaf size. The leaf size is best expressed as "characteristic dimension" or "effective leaf width" (Parkhurst *et al.*, 1968; Taylor and Gates, 1970). The effective leaf width is the downwind leaf width that has convective heat transfer equal to a flat rectangular plate having actual dimensions equal to the effective or characteristic dimensions. For any specified leaf shape, a constant can be determined such that maximum leaf width times that constant yields characteristic dimension. The constant is calculated according to the expression

$$R_D = \frac{D}{D_{max}} \tag{1}$$

where D_{max} is the maximum leaf width, R_D is the constant for the leaf form, and D is the characteristic dimension defined as

$$D = \left(\frac{\sum_{i=0}^{W} D_i \, \Delta W_i}{\sum_{i=0}^{W} \sqrt{D_i} \, \Delta W_i} \right)^2 \tag{2}$$

where D_i is the length of an increment in the direction of air flow and W is the length of the leaf perpendicular to air flow. The leaf is divided into i increments in the W direction.

Constants for several leaf shapes are presented in Table 5.1 for wind flow across the leaf at right angles to the midvein. Evaluation of leaf dimension to air flow along the vein can be made in a similar manner. Constants for other leaf shapes were given by Taylor and Gates (1970), as adapted from Parkhurst *et al.* (1968).

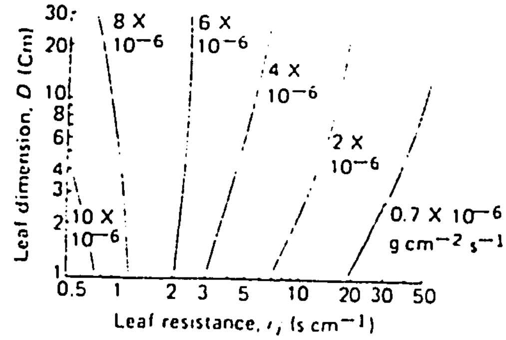


Fig. 5.5. Influence of leaf dimension and resistance on transpiration rate for environmental conditions identical to Fig. 5.4.

the free air. The relative balance of increased vapor pressure at the leaf and additional boundary-layer resistance to the transfer of water vapor results in the limited effect of dimension on transpiration. The transpiration rate may be increased, decreased, or unaffected by leaf dimension depending on the interaction of other energy-exchange parameters. The energy-budget equation is effective as a predictive model to describe biological response to various environmental conditions.

Dimension of the leaf has almost no effect on transpiration for a leaf resistance of 2 s cm^{-1} under the environmental conditions specified for Fig. 5.5. The transpiration rate increases with increased dimension at higher resistance values, and the rate is decreased by increased leaf dimension for low resistances.

Leaf temperature and transpiration rate nomograms may be produced for any environment and can serve as a guide to the limitations on leaf form imposed by the environment. The temperature nomogram is used to determine potential zones of thermal danger to the leaf. The transpiration nomogram delimits the conditions, resulting in excessive transpiration (I have observed that maximum transpiration rates are normally less than 8×10^{-6} g H_2O cm^{-2} s^{-1}).

Photosynthesis and Water-Use Efficiency

Leaf temperature and transpiration as influenced by leaf characters are important aspects of species success. Additionally, the effects of leaf form on photosynthesis and water-use efficiency may profitably be considered. The photosynthesis model developed by D. M. Gates and associates was used to describe effects of leaf tattering on production and water-use efficiency (Taylor and Sexton, 1972).

According to Gates *et al.* (1969), the photosynthesis equation may be expressed in quadratic form as

$$P = \frac{(r'P_m + K + \rho_a') - [(r'P_m + K + \rho_a')^2 - 4r'\rho_a'P_m]^{1/2}}{2r'} \qquad (4)$$

where P = rate of CO_2 exchange between the air and the leaf (g CO_2 cm^{-2} s^{-1})
ρ_a' = atmospheric density of carbon dioxide
r' = resistance to diffusion of carbon dioxide from the atmosphere to the chloroplast
K = Michaelis rate constant for the reaction
P_m = maximum carbon dioxide exchange rate possible for given light and temperature conditions (g CO_2 cm^{-2} s^{-1})

The effects of light intensity, leaf temperature, and mesophyll thickness on net photosynthesis must be known individually. Trends of photosynthesis can be described from general approximations of the above biochemically related parameters. Examples of parameter approximation for the temperature and light dependence of photosynthesis and for leaf thickness are developed elsewhere (Taylor 1971; Taylor and Sexton, 1972).

A photosynthesis nomogram was generated for leaves with optimum photosynthesis near 30°C (Fig. 5.6). The environmental conditions were identical to those used in the above nomograms. Large dimension and low resistance affect the greatest net photosynthesis.

Water-use efficiency or the ratio of carbon dioxide fixation to transpiration is of importance to modern plant management, although I do not consider it the most significant factor of natural leaf adaptation. Cohen (1970) theorized that the most successful species is one that photosynthesizes at the maximum rate when water is available with no specific measures toward water economy that would limit photosynthesis, and is capable of surviving dry periods, although not necessarily being productive. I have found that natural plant communities tend to exist between the extremes of maximum water economy and maximum net photosynthesis (as discussed below).

The water-use-efficiency nomogram (Fig. 5.7) is produced from Figs. 5.5 and 5.6. Small leaves with moderate resistances exhibit greatest water-use efficiency. The zone of maximum efficiency, however, has only one-sixth the potential for net

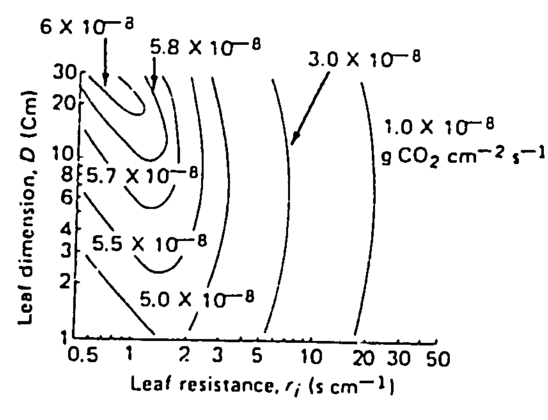


Fig. 5.6. Net photosynthesis is maximum for large leaves with low resistance (see the text for biochemical description) in the environment specified for Figs. 5.4 through 5.8.

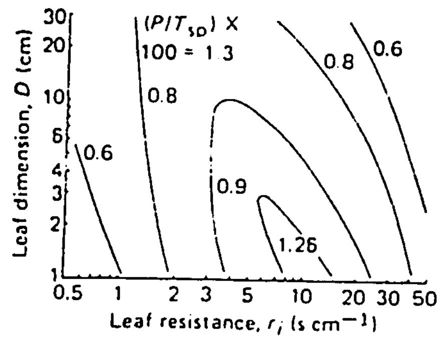


Fig. 5.7. Water-use efficiency expressed as the net weight of carbon dioxide fixed per weight of water expended times 10^2. Small leaves with moderately high resistance have greatest efficiency.

photosynthesis. Unless a plant were free from competition by other vegetation, this low productivity would not be expected to be competitive for space or available water. The possibility exists that a leaf might have such high water-use efficiency that it has little or no productivity since carbon dioxide uptake is reduced, together with decreased water loss.

Natural Communities

A composite nomogram of Figs. 5.5 through 5.7 depicts the zones of maximum photosynthesis and greatest water-use efficiency, together with transpiration values (Fig. 5.8). Actual leaf data taken from Taylor (1971) are plotted on the nomogram. The data represent the dominant vegetation of the study area and show a trend of

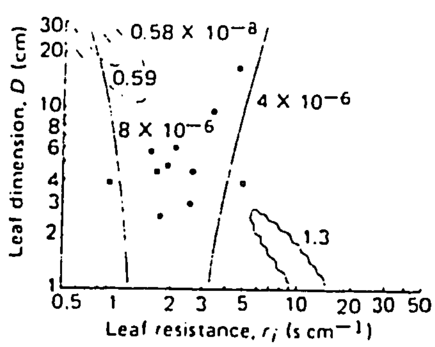


Fig. 5.8. Actual data from the University of Michigan's Biological Station area (July and August 1968) are depicted together with essential elements of Figs. 5.4 through 5.7 to produce a composite nomogram displaying transpiration (solid line), net photosynthesis (dotted-and-dashed line), and water-use efficiency (wavy line) for the actual leaves of each major species of the region (circles). (From Taylor, 1971.)

leaf dimension toward mesophyll–macrophyll class. Most individuals observed exhibited characters midway between greatest water-use efficiency and maximum photosynthesis.

The vegetation of a zone characterized by the climate specified for Figs. 5.4 through 5.7 has, according to the nomograms, no severe environmental limitations to leaf form. Leaves may be very small or very large without severely affecting productivity or being exposed to thermal danger. The tendency of the vegetation to develop toward a characteristic leaf dimension may be considered a response to structural economics or a tendency toward the optimal form that provides the greatest competitive advantage to the species. Harsh environments do, however, restrict leaf form to those characters suitable for survival.

Desert plants, unless capable of enduring leaf temperatures normally considered excessive, must be supplied with copious quantities of water, have small leaf dimension (Fig. 5.9), or be otherwise adapted to arid, harsh conditions with such mechanisms as seasonal dimorphism or defoliation. The nomogram for desert conditions (hot, dry air, moderate wind, bright sun, and high Q_{abs}) shows that the small leaves with very low resistance have optimum net photosynthesis. However, leaves are not expected to function at this maximum because of the excessively great transpiration rate in this energy regime. The leaf exposed to the climate specified for Fig. 5.9 is expected to exhibit resistance greater than 6 s cm^{-1} to maintain water loss within reasonable limits. Leaf temperatures in excess of 50°C are indicated for leaves with dimension greater than 1 cm unless resistance can be maintained at the lower limit of approximately 6 s cm^{-1}. Water-use efficiency is maximum for leaves of small dimension and resistance near 6 s cm^{-1}. The nomogram appears to define the suitable leaf dimension and resistance, but numerous exceptions are noted (Gates *et al.*, 1968) in cases of tolerance to plant temperatures above 50°C.

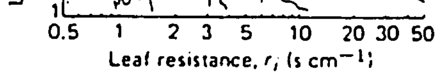


Fig. 5.9. Nomogram typical of desert conditions (hot, dry air; moderate wind; high Q_{abs}; and bright sun). The leaf responses to the environment shown are leaf temperature (dashed line) of 50°C (cooler temperatures occur at lower resistances and/or smaller dimension), transpiration rate (solid line), net photosynthesis (dotted-and-dashed line), which is at maximum for small leaves with low resistance, and the water-use efficiency ratio (wavy line), which is greatest for small leaves with resistance near 7 s cm^{-1}.

Biological Variables

Leaf form and resistance to the diffusion of water vapor are used herein as the primary biological parameters affecting leaf temperature, transpiration, and productivity. Numerous other biological parameters can be evaluated by use of the method discussed above. Leaf orientation, coloration (absorptivity to incident radiation), mesophyll thickness, integument, and the extent to which the surface is convex or concave are significant or potentially significant physical parameters of the leaf. The productivity of the leaf is also affected by numerous biochemical parameters related to the kinetics of photosynthesis and respiration (Gates *et al.*, 1972).

Orientation of the leaf blade significantly affects the amount of radiation absorbed. Numerous species exhibit differential sun-shade leaf orientation, and many have the facility to adjust leaf orientation throughout the diurnal cycle. Orientation with respect to insolation directly affects leaf temperature and light absorbed at the photosynthetic sites. Taylor observed that the variable orientation in *Erythrina berteroana* and *Cercis canadensis* served more as a mechanism for leaf-temperature control than as a water-conservation adaptation. Several other biological parameters were similarly evaluated (Taylor, 1971).

The significance of each biological parameter as it affects water usage, leaf temperature, and net photosynthesis can be evaluated by energy-budget methods.

Conclusions

The model presented in this paper can be used to evaluate the significance of leaf form as it affects water economy, productivity, and leaf temperature. The method has predictive value for agronomy and studies of natural communities. Potentially, the method can be beneficial for defining past climatic conditions from fossil leaf-dimension evidence.

The prime value of the model is its predictive capability, whereby the optimal leaf forms can be defined for any climate. The nature of optimal form is not fully understood because it is not altogether obvious to which effect natural selection tends. It is the task of the informed naturalist to discover this factor. I would encourage other investigators to define "optimal conditions" for themselves whether they wish to do so for maximum productivity or greatest water-use economy.

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APPE 'X E

THERMAL EMISSIVITY: Its Determination and Significance

ABSTRACT

The state of in situ emissivity measurement is reviewed and a field technique developed. The field technique is intended to serve as a tool for the investigator who must use or evaluate remotely-sensed thermal data.

The thermal emissivity of natural surfaces is required for the determination of absolute terrestrial temperatures from remotely-sensed thermal data.

The thermal emissivity of crop and soil surfaces must be determined to effectively utilize remotely-sensed temperature data in models depicting crop production, plant disease development, frost formation and evaporative water use.

Introduction*

The thermal emissivity is a significant property of surfaces which transfer heat by radiation. Emissivity is the radiation from a surface in proportion to black body radiation for the actual surface temperature.

The emissivity of radiating surfaces in heat transfer systems has long been a major design consideration, but the emissivity of natural surfaces until recently was an academic curiosity and measurements in nature were of little utility.

Technological developments from 1950 through the present have made the remote measurement of surface temperatures practical. Multispectral observation, to include temperature of the earth and its atmosphere, has become a prime effort in resources evaluation; but observation of the surface and atmospheric temperatures is not without some technical difficulties. The interpulation of infrared data from the Tiros project was possibly more dependent on surface emissivity than on temperature (Buettner and Kern, 1963a). The principal difficulties in evaluation of satellite data are emissivity and atmospheric emission/transmission properties.

Several Tiros data that were initially unexplained were collected over the Libyan and Egyptian deserts. These data indicated that certain spots were hotter than the surrounding desert. Investigation showed these spots to be oases. The spots were not expected to be hotter than surrounding areas but cooler, which in most cases they were (Buettner and Kern, 1963b). The data, however, represented apparent radiation surface temperature which was greatly affected by the emissivity of the contrasting surfaces (Taylor, 1971). The oases being moist had higher emissivity than the surrounding dry regions, and hence the apparent radiant surface temperature for the oases appeared higher than that observed for surrounding regions when the actual temperatures are similar.

Remote sensing of terrestrial surface temperatures requires that emissivities be known or estimated to the precision that is required for the desired temperature accuracy. Therefore, the usefulness of remotely-sensed thermal data for evaluation of soil surface temperature and crop temperature is dependent upon the accuracy of the emissivity measurement and must be considered in the preparation of temperature data to avoid large errors.

Theory and Methods

Remote sensing of temperatures for the terrestrial surface utilizes instrumentation which determines the thermal flux from the surface. The thermal flux is defined by Planck's Law and its integration is known as the Stephan-Boltzmann Law. The total flux of energy is expressed as

$$Q = \epsilon\sigma T^4 \qquad (1)$$

where Q is the total radiation flux (Wm^{-2}), T is the actual surface temperature (^oK), ϵ is the thermal emissivity (0.0-1.0) and σ is the Stephan-Boltzmann constant (5.6697×10^{-8} Wm^{-2} $^oK^{-4}$). Often the terms cal cm^{-2} min^{-1} have been used for the flux in which case σ is 8.132×10^{-11} cal cm^{-2} min^{-1} $^oK^{-4}$.

The remote sensing instrument does not normally detect the radiation at all wavelengths but is limited to a certain band, often 8-14 μm. Satellite-borne sensors may have an even narrower band to eliminate as much as possible the effects of the intervening atmosphere by utilizing the narrow window regions of the air mass.

The narrow band radiation sensors can be used to determine the actual temperature of the test surface only if the thermal emissivity in the particular band is known. The total energy flux radiated from the surface can be calculated only if the emissivity for all bands is known. Many natural surfaces have an emissivity anomoly in the 10 μm spectral band which must be considered if total flux calculations are to be made from the narrow band data. Examples of spectral thermal emissivity are presented by Buettner and Kern (1963b), Hovis and Callahan (1966), Vincent and Hunt (1968), Lorenz (1966), and Lyon (1964).

Many emissivity data are for polished mineral surfaces and are not directly applicable to natural conditions. However, some authors have evaluated the effects of pits, roughness and particle size (Lyon, 1964; Vincent and Hunt, 1968).

The thermal emissivity for several plant leaves was presented by Gates et al. (1965), and further examples have been published by Idso et al. (1969).

Emissivity values for several surfaces at various temperatures and angles together with basic theoretical discussions are given in most heat transfer texts (for example, Eckert and Drake, 1959; and Kreith, 1961).

Considerable effort in determination of atmospheric effects on the apparent radiant surface temperature is being expended by agencies desiring to utilize satellite data. Particularly involved in the United States are the National Aeronautics and Space Administration, National Environmental Satellite Service, Stanford Research Laboratories and U.S. Army Science Laboratory. A sizeable effort is likewise being made in the USSR. It is not intended to review this effort here. It is sufficient to say that this work is critical to satellite applications and to airborne observations where an atmospheric induced error of 2 to 5°C may exist when sensors are generated at altitudes of 6,000 feet or more (Weiss, 1971).

Apparent temperature

The thermal radiometer detects the apparent radiant surface temperature for objects within its view. When the surface is opaque to infrared transmission, the flux sensed by the detector is either emitted by the test surface or reflected from it. In accord with Kirchhoff's Law, the emitted radiation from a surface at a given wavelength is identical to the absorptivity of the surface to radiation and if the surface is opaque, the reflected radiation is the difference between the absorbed and the total incident radiation such that for opaque surfaces

$$r = 1 - \varepsilon \tag{2}$$

where r is the reflectivity of the surface (0-1) and ε is the emissivity (0-1).

The radiation temperature of a surface is given by equation (1). The flux radiated by the surface is proportional to the fourth power of the actual absolute temperature of the surface reduced by the emissivity of the surface. The radiation temperature will always be less than the value for a perfect black body, but the apparent radiant temperature may exceed it because of the influence of reflected background radiation. The apparent radiant temperature is then determined by the temperature and emissivity of the test surface and the background radiation reflected from the surface (atmospheric effects omitted except as they contribute to background) according to the expression:

$$Q = \sigma\varepsilon T^4 + (1-\varepsilon)\,\sigma\varepsilon_b T_b^4 \tag{3}$$

and

$$T_x = \sqrt[4]{Q/\sigma} \tag{4}$$

where T_x is the apparent radiant surface temperature, ε_b is the emissivity of the background, and T_b is the absolute temperature of the background. Equation 3 is valid when either ε or ε_b is very near unity or very near zero. Under some conditions significant multiple reflections between the test surface and the background exist and necessitate further development of equation 3. This case has been developed in detail by Lowry and Gay (1970) and can be expressed as

$$Q = (\sigma\varepsilon T^4 + (1-\varepsilon)\ \sigma\varepsilon_b T_b^4)(1 - [1-\varepsilon][1-\varepsilon_b])^{-1}\ . \quad (5)$$

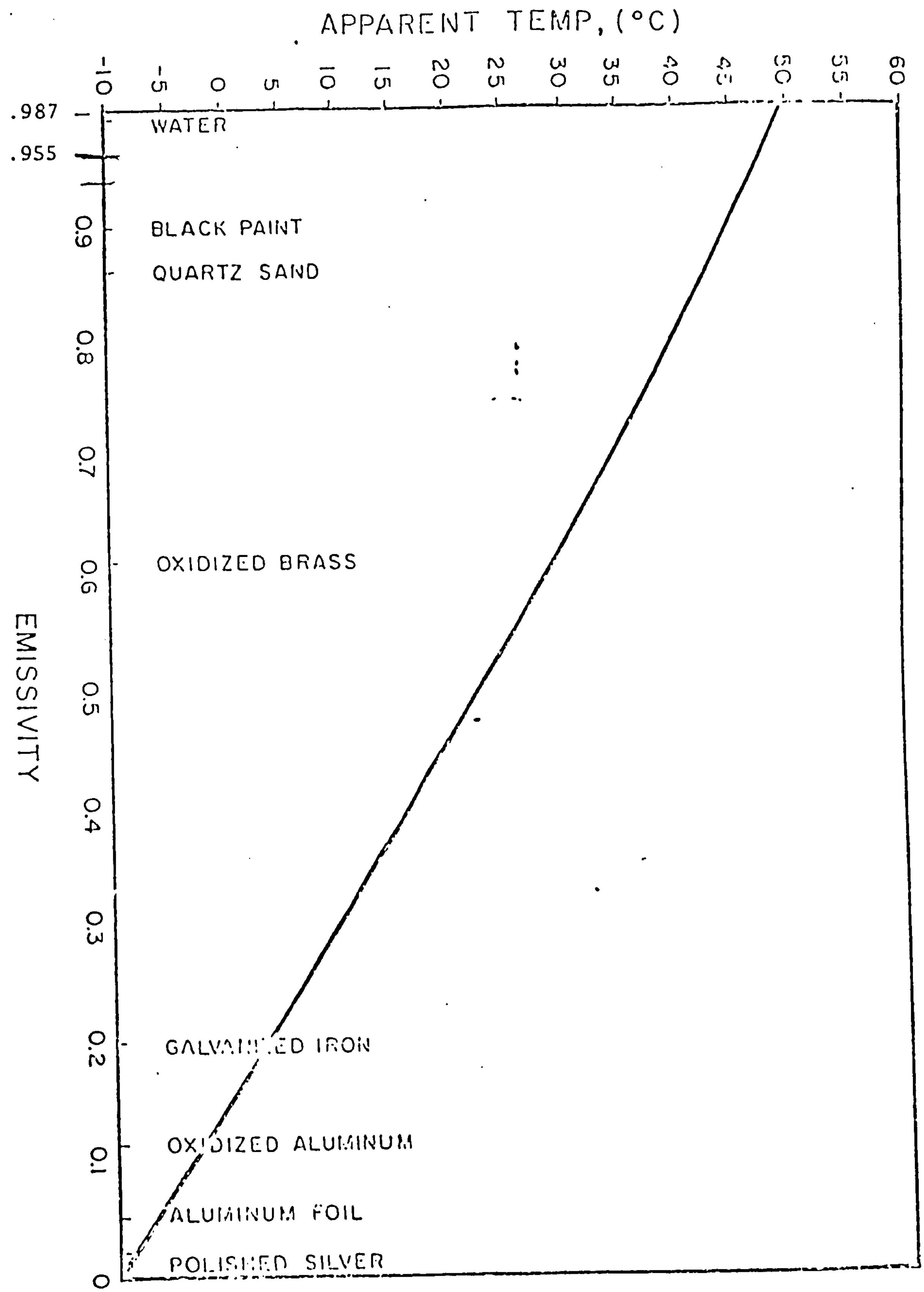
The assumption of thermally opaque test surface and background is included.

Actual surface temperature

The usefulness of the apparent radiant temperature data depends on its relationship to the actual temperature of the test surface. Calculation from equations 3 and 4 for a test surface with an actual temperature of 50°C and a background apparent temperature of -10°C shows that the apparent radiant temperature of the test surface is lower than the actual temperature according to the emissivity of the test surface (Fig. 1). The limits are apparent temperature -10°C
1 if ε=0, and 50°C if ε=1. Nature is between these extreme values. Equations 3 and 4 have been developed into a nomogram for the graphic solution of the apparent vs. true temperature for any surface and any background (Bliamptis, 1970).

The difference between actual temperatures and apparent radiometric temperatures may exceed 10°C in natural conditions for natural surfaces and be much greater for artificial surfaces. When effects of intervening atmosphere are included errors can be even greater. Several methods for determining the infrared emittances of various surfaces have been

Figure 1. The apparent radiation temperature of surfaces is between the actual surface temperature and the temperature of the background (sky). Surfaces with low emissivity appear to be near background temperature while high emissivity surfaces are near their true temperature. The apparent temperature of the background is -10°C and the actual temperature of the surfaces is +50°C for the case shown.


APPARENT TEMP, (°C)
-10
-5
0
5
10
15
20
25
30
35
40
45
50
55
60
EMISSIVITY
.987
.955
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
WATER
BLACK PAINT
QUARTZ SAND
OXIDIZED BRASS
OXIDIZED ALUMINUM
ALUMINUM FOIL

developed which are suitable for use by the investigator in the field. These are discussed herein together with a detailed description of one method.

Determination of emissivity

The difference between actual and apparent temperatures for natural surfaces calculated from laboratory data by Fuchs and Tanner (1966) showed that errors beyond toleration were to be expected unless the apparent temperatures were corrected to actual temperatures. Numerous methods for determining the emissivity of test surfaces in the field have been developed which make it practical to calculate the actual temperatures from the apparent radiant values.

The true temperature of a surface is commonly determined either from a thermometer in close contact with the surface or radiometrically by placing the surface within a background of near zero emissivity. The apparent temperature approaches the actual temperature as the background reflects emitted radiation back to the surface to be reflected to the sensor, and the background appears to be a continuation of the test surface. A black body condition would be achieved if the emissivity of the background were truly zero and the radiometer itself extremely small.

The true temperature together with the apparent surface temperature and the incident flux from the background are required to calculate the emissivity of the test surface from equation 3. The background flux is a global (or hemispherical) measurement which can be achieved by makirg a series of measurements of the background with the sensor (measurements appropriately related by geometry) or by viewing a mirror of known temperature, emissivity and hemispherical view. Some investigators have enclosed the test surface in a box of known background temperature.

The above methods are discussed in detail in the following references to which the investigator is referred for further details: Fuchs and Tanner (1966), Conaway and Van Bavel (1967), Idso and Jackson (1968), Fuchs and Tanner (1968), Idso and Jackson (1969), Buettner and Dana (1969), Idso, et al. (1969), Lowry and Gay (1970), Davies et al. (1971), Idso et al. (1971), and Lowry and Gay (1971).

The several methods have been subject to some discussion between various authors and each is somewhat awkward for field use.

The emissivity of test surfaces in the field can be determined without a low emissivity enclosure or controlled temperature background device if natural background temperature can be determined. The technique for determining apparent background or "sky" temperature and for calculating the emissivity of natural surfaces which I have used extensively in field tests is described below.

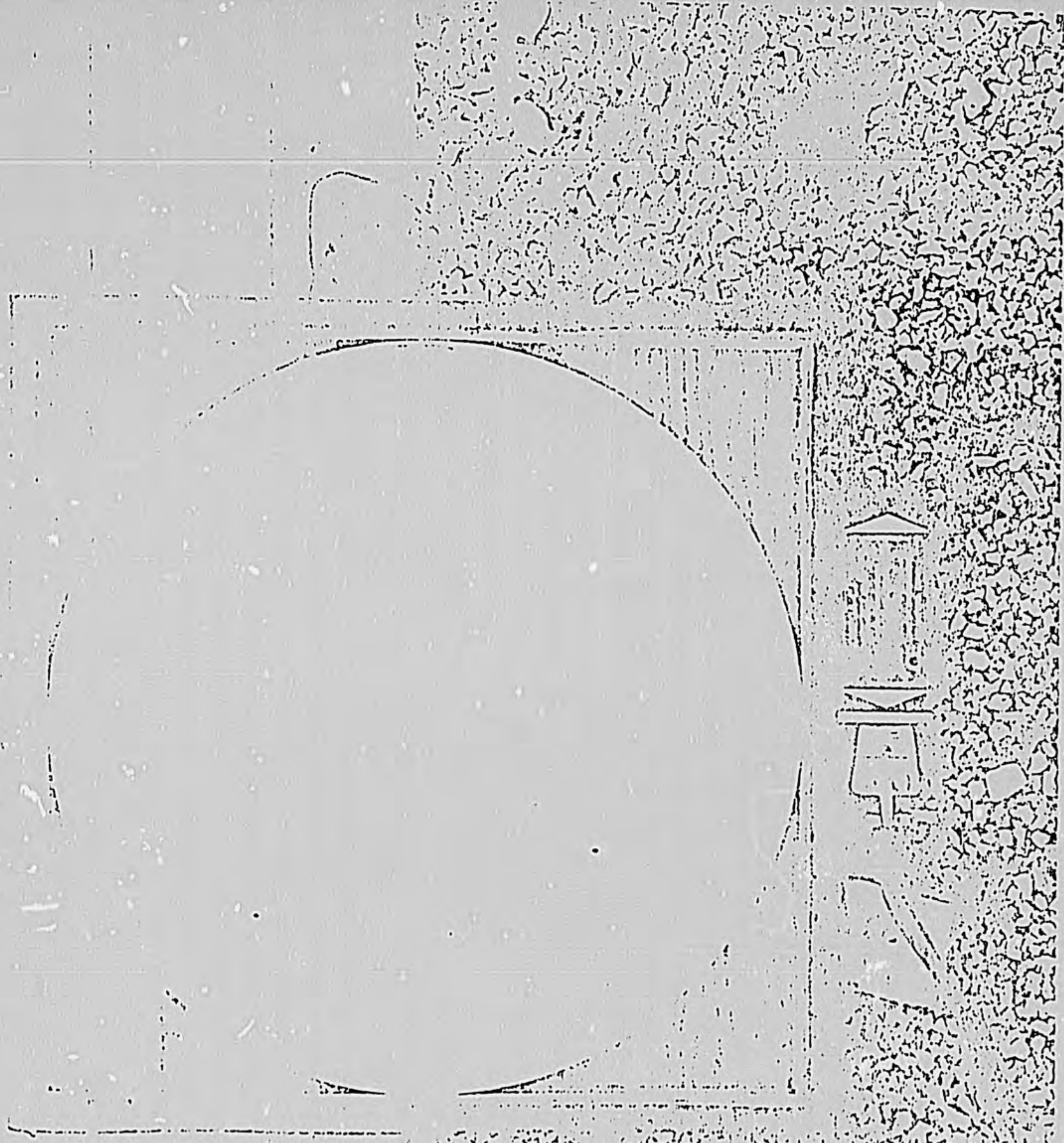
Sky temperature

The thermal radiation received from the hemispherical background is required for the calculation of emissivity and/or actual surface temperature by equations 3 and 4. The background radiance was measured directly by Lorenz (1966). Direct measurements at various angles can be mathematically related to produce the global value of significance to a flat diffusing test surface. Conaway and Van Bavel (1967) and several subsequent investigators have used a flat mirror of known emissivity (near 0.5) and temperature to determine background radiation. The design required a mixing of metallic and non-metallic paints until the proper emissivity was achieved. The mirror surface was, however, difficult to duplicate and because of the nature of paints could be expected to change emissivity with weathering and contamination.

To circumvent emissivity changes due to weathering and contamination, a mirror for Global measurement of thermal flux was fabricated by the author from an aluminum disk 14 inches in diameter and one inch thick. The mirror was prepared by sand etching the aluminum disk fact to a uniform beaded surface and condensing a layer of gold on it. The
ig. 2 "gold mirror" (Fig. 2) provided a reference surface of low emissivity that has shown no change of emissivity over a three-year period of use and is easily duplicated (if the gold and a mirror coating facility are available). The actual temperature of the gold mirror is determined from imbedded thermocouple sensors.

The sky radiance is calculated from equation 3 where the terms are redefined such that "T" is the temperature of the gold mirror measured by thermocouple, ε is the emissivity of the Gold surface (0.14622), Q is the flux from the mirror measured by the radiometer, ε_b is considered to be 1.0 for the natural sky and T_b the sky temperature is the unknown term. Equation 3 can then be rewritten as

Figure 2. The hemispherical thermal radiation of the background incident on a flat surface is determined from the apparent radiation temperature of a gold surfaced mirror of aluminum having known temperature and emissivity. A thermocouple and reference junction provide the actual mirror temperature data.



$$T_{sky} = ([T_{app}^4 - 0.1462\ T_g^4]\ 1.17126)^{1/4} \qquad (6)$$

where T_{sky} is the apparent radiant temperature of the sky, T_{app} is the apparent radiant mirror temperature measured by radiometer and T_g is the actual temperature of the mirror from the thermocouple sensors. All temperatures are °K.

The radiometer should be held at a shallow angle to the mirror when determining the apparent radiant temperature. This insures that the radiometer itself does not constitute a significant portion of the sky. Care must be taken that the mirror "fills the radiometer's view" (Fig. 3).

ig. 3

The emissivity of the gold mirror was calculated from its apparent radiant temperature with a known "sky" temperature and known actual mirror temperature. The emissivity value is valid only for the particular mirror and radiometer used and separate evaluations must be performed for each mirror component or radiometer. A clear day is not satisfactory for determination of mirror emissivity because an absolute measure of the global flux from the sky is difficult. The overcast day provides an "infinite" plane of known radiant temperature. Equation 3 was rewritten for evaluation of mirror emissivity as

$$T_{app}^4 = \varepsilon_g T_g^4 + (1-\varepsilon_g) T_{sky}^4 \qquad (7)$$

where ε_g is the emissivity of the mirror (unknown). The equation solved is

Figure 3. The radiant temperature of the background (sky) is determined from the "gold mirror" of known emissivity and temperature by holding the radiometer at a shallow angle to detect the apparent mirror temperature.

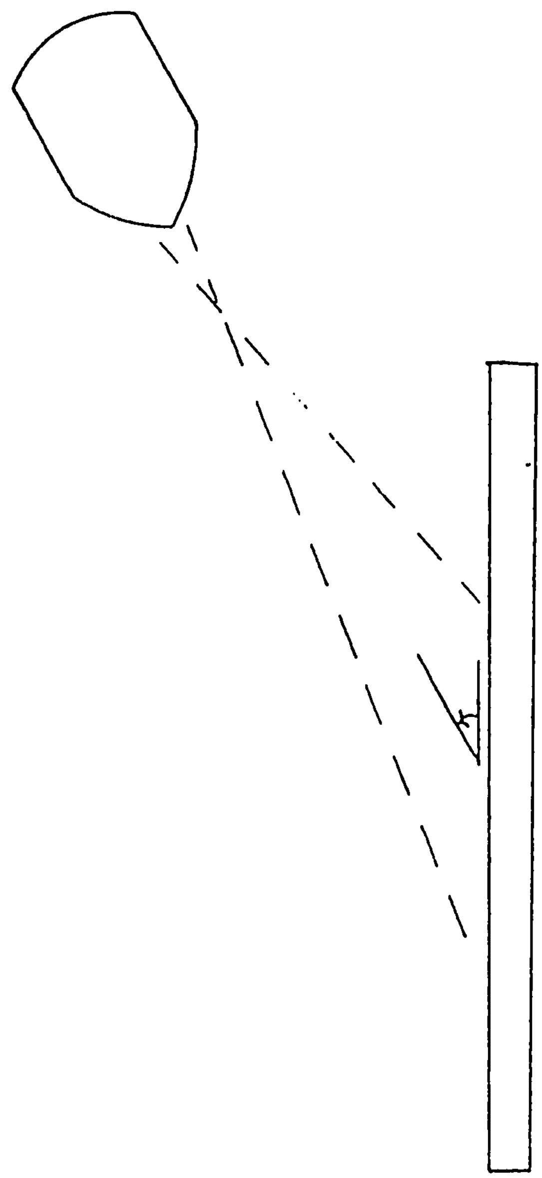


Figure 3. The radiant temperature of the background (sky) is determined from the "gold mirror" of known emissivity and temperature by holding the radiometer at a shallow angle to detect the apparent mirror temperature.

$$\varepsilon_g = (T^4_{app} - T^4_{sky}) \ / \ (T^4_g - T^4_{sky}) \tag{8}$$

The mirror must differ in temperature from the background. A large temperature difference between the mirror and the background is desirable for precise emissivity determination.

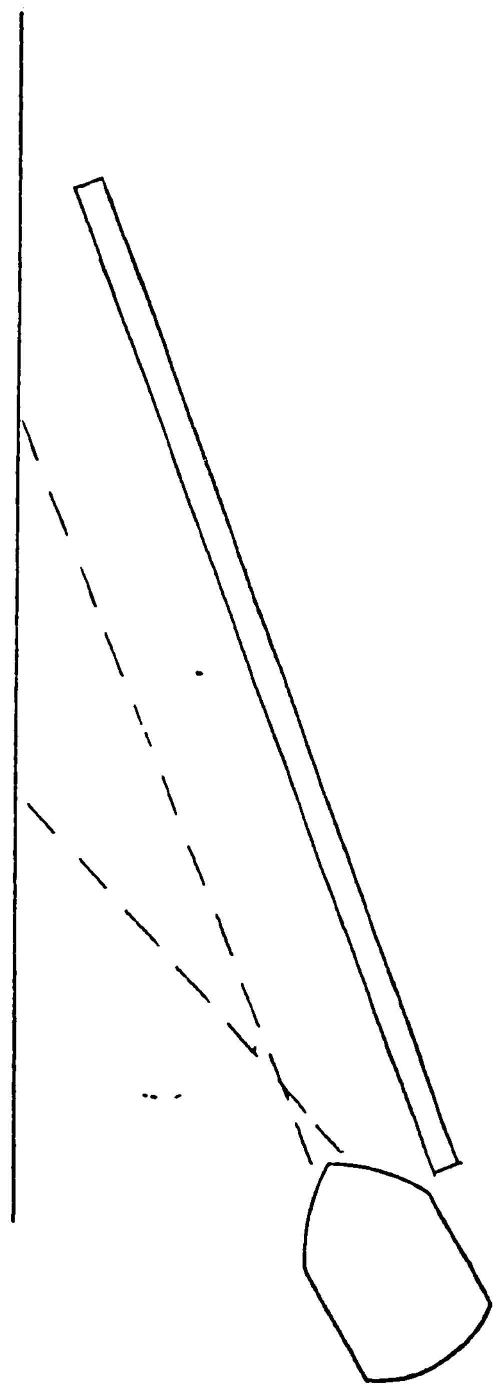
Artificial Sky Technique

The actual temperature and the emissivity of the test surface (soil, plant, etc.) is determined from the apparent-radiant temperature under the natural sky background and the change in that temperature when the test surface is covered by an artificial sky of known radiant flux.

The artificial sky may be an "emissivity box" as utilized by several of the above-cited authors or a plane surface held over the test surface in such a manner as to appear as an "infinite plane" to the area of test surface being observed. View factor calculations determine that a plane surface artificial sky held three inches above the test surface must extend 13 inches beyond the edges of the viewed area to provide a 95 percent sky coverage. A detailed analysis of global view factor is given in Reifsnyder and Lull (1965). Careful positioning of the sky over the test surface can be done rapidly so that negligible change in actual surface temperature occurs as a result of the covering/uncovering operation.

The emissivity determination is made by initially observing the radiation from the test surface with an infrared thermometer. With the radiometer indicating the apparent radiant temperature of the test surface, the artificial sky is positioned and the change in apparent radiation temperature is noted (fig. 4). The difference obtained is a result of the change in reflected background radiation and is determined

Figure 4. The apparent radiation temperature of the test surface increases when an "artificial sky" which is thermally warmer than the natural sky, is positioned over the test surface. The change in the apparent temperature is a result of the thermal emissivity of the surface and the thermal contrast of the natural and artificial skies.



by the emissivity of the test surface and the thermal contrast of the artificial and natural backgrounds.

Analysis of Data

The data required for the determination of sky temperature and the actual temperature and emissivity of the test service are (1) millivolt thermocouple reading for gold mirror temperature, (2) apparent radiant temperature of gold mirror, (3) apparent radiant temperature of artificial sky over typical test surface, (4) apparent temperature of the test surface when exposed to natural sky, (5) change in apparent temperature of test surface when shaded by artificial sky, and (6) repeat observation of (4) above after artificial sky is removed to verify negligible change.

The analysis requires that millivolts (1) be converted to °K according to the thermocouple calibration and this value together with the apparent radiant temperature of the mirror (2) be utilized to calculate sky temperature from eq. 6.

Equations 3 and 4 are used to calculate the true temperature and emissivity of the test surface. Equations 3 and 4 combine to give

$$T_x^4 = \varepsilon T^4 + (1-\varepsilon)T_{sky}^4 \tag{9}$$

where the emissivity of the sky is dropped since T_{sky} is an apparent radiant temperature rather than the true sky temperature.

Equation 9 is used twice to solve for the two unknowns, ε and T. The solution can be expressed as

$$T_{xN}^4 = \varepsilon T^4 + (1- \ )T_{skyN}^4 \tag{10}$$

and

$$T_{xa}^4 = \varepsilon T^4 + (1-\varepsilon)T_{skya}^4 \tag{11}$$

where T_{xN} is the apparent radiant temperature of the test surface under the natural sky, T_{xa} is the apparent radiant temperature of the test surface under the artificial sky, and T_{skya} is the apparent radiant temperature of the artificial sky. The apparent radiant temperature of the test surface when covered by the artificial sky is found as

$$T_{xa} = T_{xN} + \Delta T_x \tag{12}$$

where ΔT_x is the change in apparent radiant temperature of the test surface when the artificial sky shades it. This change in apparent temperature is more accurate than two absolute readings.

Some thermal radiometers have recorder outputs sufficiently stable for determining temperature differences over short periods of time to ± 0.01 °K or better.

The solution to equations 10 and 11 can be expressed as

$$\varepsilon = 1 - \frac{T_{xa}^4 - T_{xN}^4}{T_{skya}^4 - T_{sky}^4} \tag{13}$$

The actual temperature of the test surface is then found from either equation 10 or 11.

Low Emissivity Chamber Technique

A second method for determining the actual temperature of a surface and the emissivity of the surface utilizes the low emissivity background surface mentioned above. This technique is considered satisfactory for general field determination of emissivity.

A polished metalic cone is utilized which permits the radiometer to view the test surface from the apex. The procedure involves the determination of the natural sky temperature (Tsky) as discussed above, the observation of the apparent radiation temperature under the natural sky and the observation of "True" surface temperature of the test surface under the metalic cone. As with the artificial sky technique the apparent temperature should be observed a second time to confirm negligible change during the observational sequence.

The emissivity is found using the Tsky temperature derived from equation (6) and the expression

$$\varepsilon = (T^4_{app} - T^4_{sky}) / (T^4_{true} - T^4_{sky}) \qquad (14)$$

which is derived directly from equation (3) (Appendix C). T_{true} is the actual surface temperature as observed for the surface when covered by the cone.

The method assumes that the cone has emissivity very near zero and that the effects of any deviation from unity for the cone are negligible. Precision observations utilizing the polished cone method require that equation (5) be applied to account for the emittance from the cone and its multiple reflectance. Further discussion of this method is given by Fuchs and Tanner 1968.

Emissivity Determinations

Determination of the emissivity of natural surfaces by the techniques described here is not difficult when the proper instruments are available including a programmable calculating device. Care must be exercised, however, to select sites typical of areas viewed by the satellites or other remote sensing platforms and to use a radiometer in the determinations having a thermal band compatible with that of the satellite in both wave length and band width.

Selected observations of emissivity in the 8 to 14 μm band taken at White Sands Missile Range are presented in Table 1. These data were obtained with a hand held precision radiation thermometer designed to

Table 1. Emissivity (8-14 μm) of natural surfaces on and near White Sands Missile Range, NM. Broad band determinations are utilized with DAP thermal data. Emissivities for narrow band instruments such as SMS-GOES (9.5-10.5 μm) must be determined with a narrow band radiometer.

Surface	Emissivity 8-14 μm
Gypsum Sand (White Sands National Monument)	
Drift	.932 ± 0.002
Flats	.9583
	.9400
Moist Dunes Slope	.9734 ± .0009
Moist Flats	.973 ± .002
Moist Dune Top	.970 ± .002
Tortugas Mountain 22 Nov 71	
Dominant substrate rock	.9568 ± .0014
Chert	.9772
Soil	.9520
Quartz (white)	.8655
Q weathered	.9137
Q fresh broken	.8513
Rhyolite	
Weathered	.9430
Fresh broken	.9173
Course gravel	.9703
Plya Soil (MARS)	
Dry cracked	.930
Smooth clay	.9375
Mule Peak, NM	
Limestone	.9570
Dead grass	.9924
Oak leaves	.9775
Juniper	.9901
White Sands Soils	
*Type 1	.955
*Type 2	.963
Dunes/Mesquete	.9275 ± .0005
Interdune caliche-coated gravel	.9400

*Type 1 soil is located

*Type 2 soil is located

measure thermal radiation from 8 to 14 μm. The values given are compatible for use with broad band, 10 μm, airborne thermal scanners.

Several satellites have utilized broad band thermal sensors, however, the SMS-COES now in use uses a narrow band sensor and measurements of surface emissivity must be made with a narrow band instrument to be valid for calculation utilizing SMS-GOES thermal data. Narrow band filters are available from manufacturers of precision radiation thermometers to identically match the satellite optical system as required by the investigator.

The emissivity of most surfaces varies somewhat depending upon the composition of the surface at any time. The effect on moisture upon the surface emissivity is especially significant. A moist surface will have an emissivity approaching that of free standing water (.97-.98 depending on pureness of water and the band observed). Emissivity measurements must be reported for a surface at intervals appropriate to the frequency of satellite observations and the environmental modifications of the surface which affect its emissivity. The wetness or dryness of a calibration site should likewise be monitored regularly.

The effect of emissivity on the apparent radiation temperature of a surface depends not only upon the temperature of the surface but also depends upon the background thermal radiation. The apparent radiation temperature of a low emissivity surface is a reflection of the background radiation environment. The apparent radiation temperature for a surface with emissivity at unity is independent of background radiation. Examples depicting the effects of surface emissivity and background temperature on apparent radiation temperature are given in figures 5, 6, and 7. The

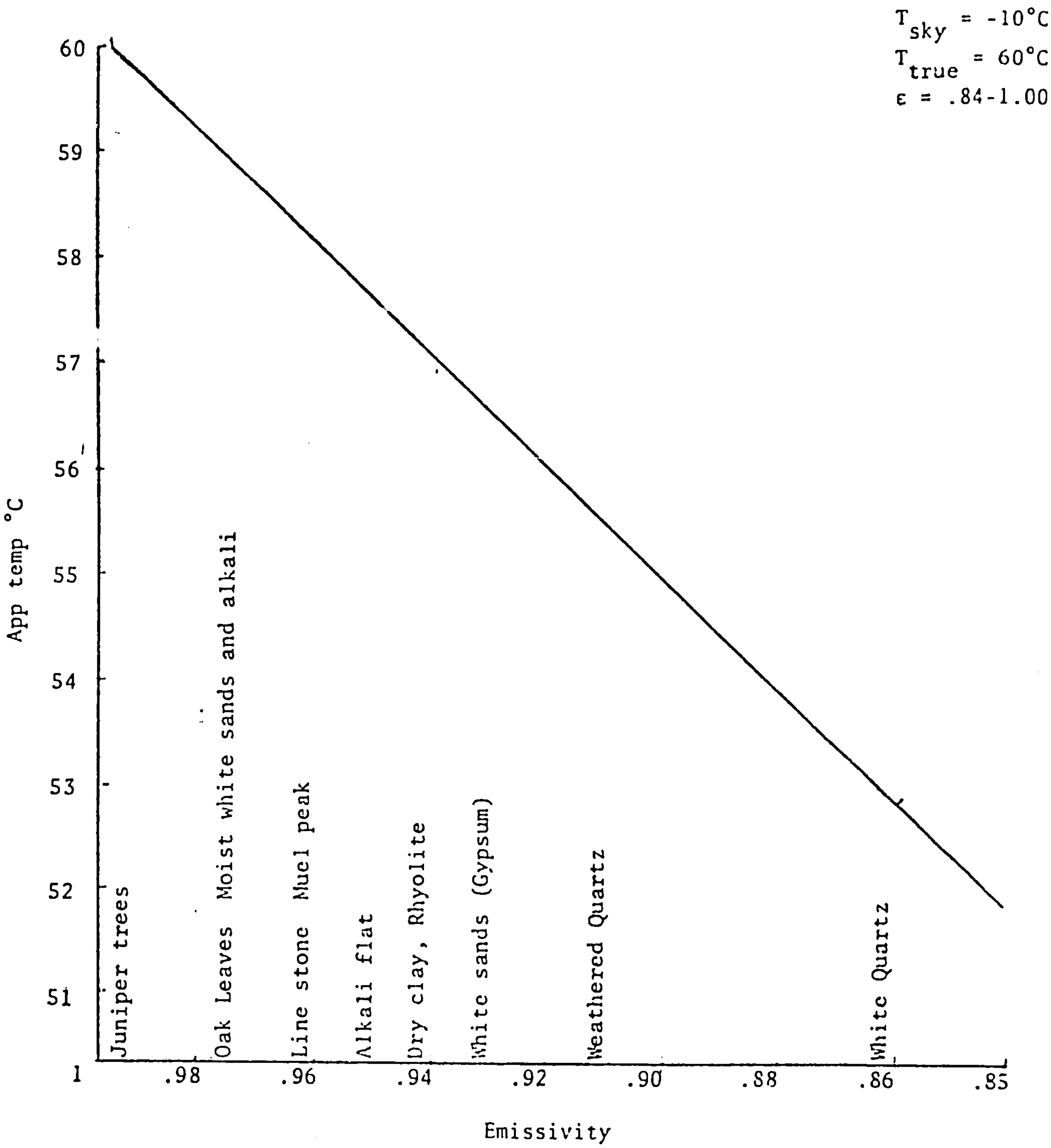


Figure 5. Apparent radiation temperatures for selected natural surfaces. The actual temperature of each surface is 60°C and the background radiation is equivalent to -10°C. Juniper trees appear 0.5°C cooler than their true temperature and weathered quartz stone appears nearly 5°C cooler than its true temperature.

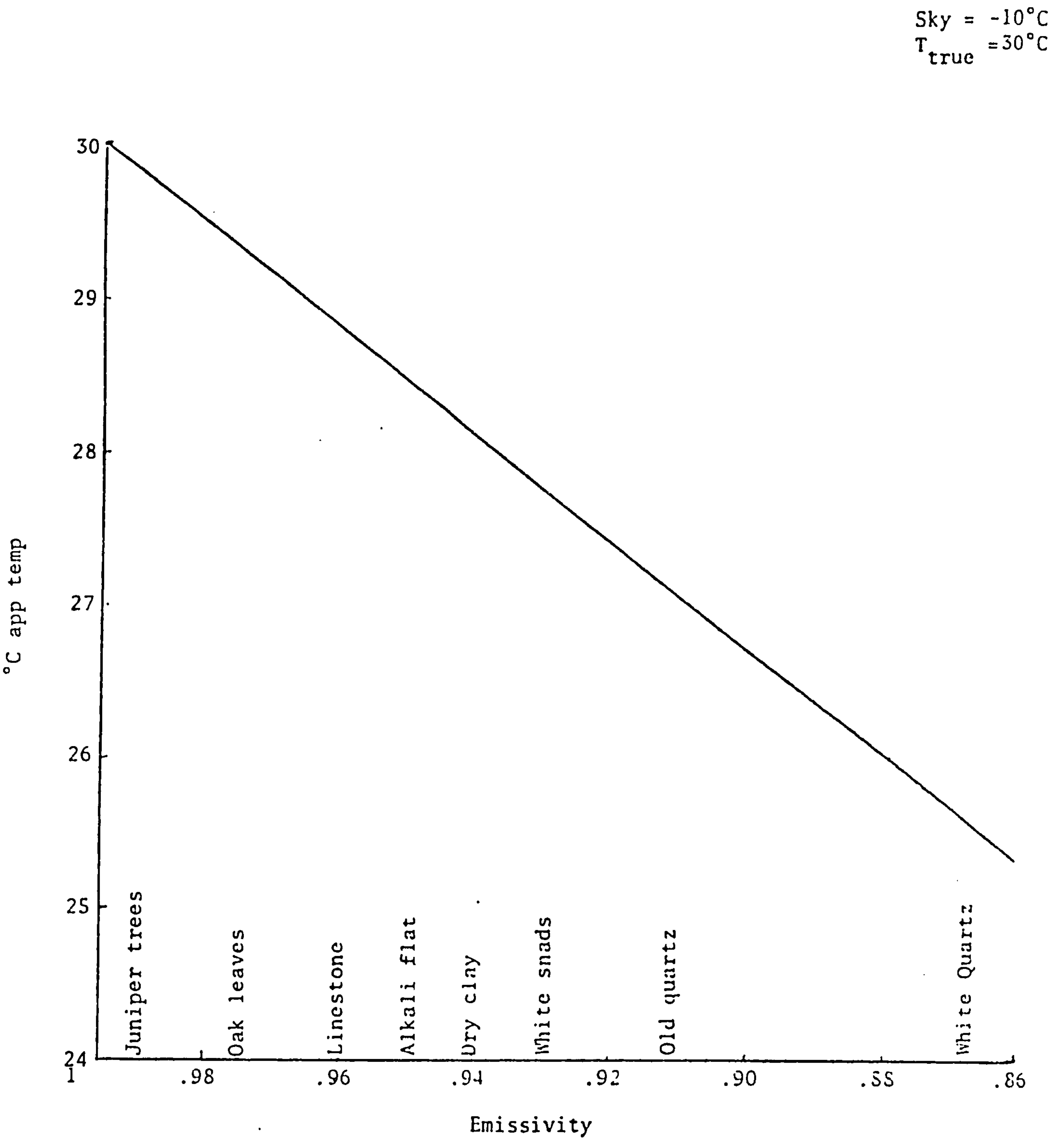


Figure 6. Apparent radiation temperatures for surfaces at 30°C as observed by radiation thermometer when equivalent background temperature is -10°C.

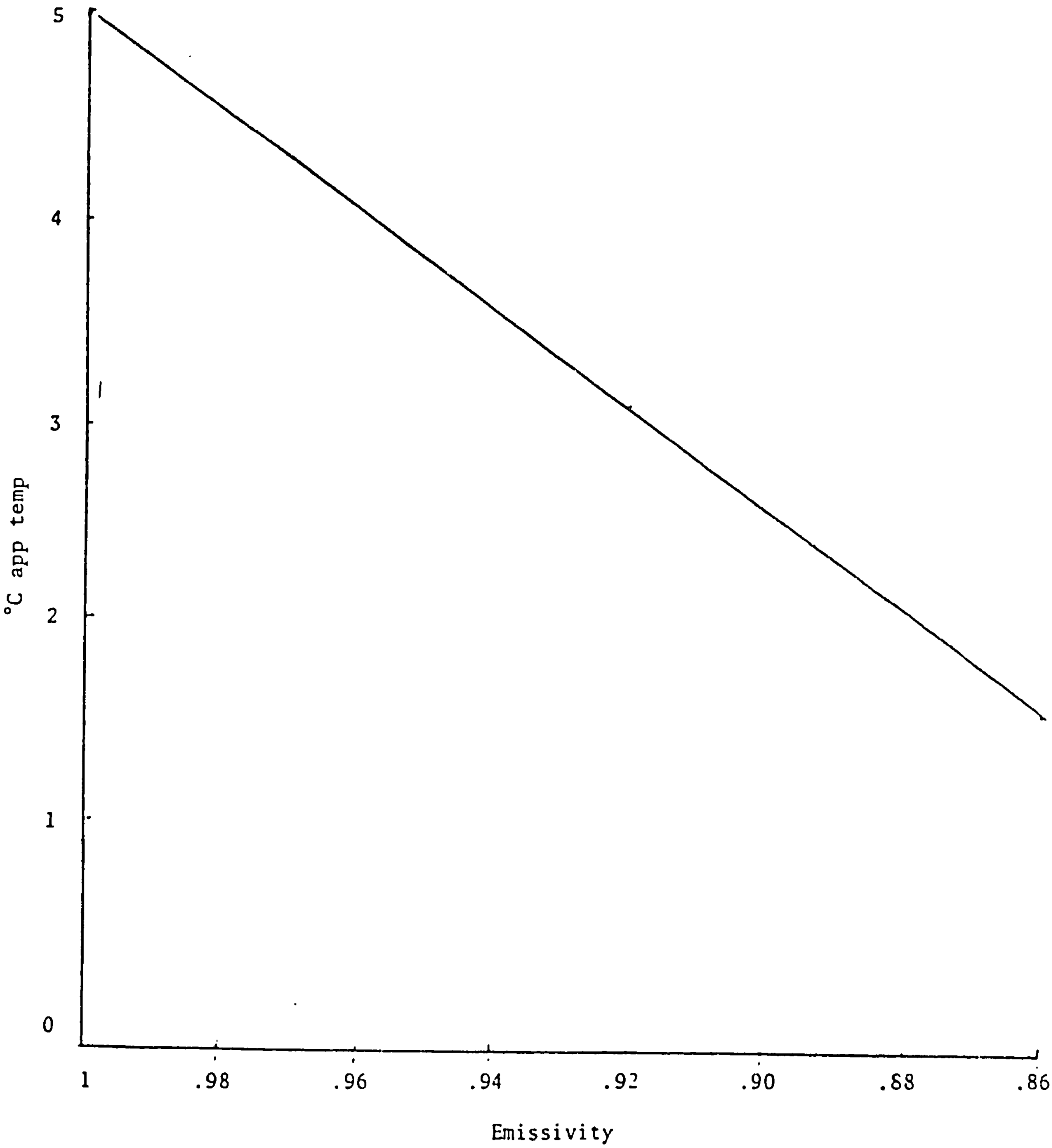


Figure 7. Apparent radiation temperatures of surfaces at 5°C when the background radiation is equivalent to -22°C.

value for sky temperature is the black body equivalent temperature representing the background hemispherical radiation from the atmosphere or other objects above the surface plane.

Conclusion

Thermal emissivity of natural surfaces can significantly affect data collected by remote sensing techniques. Actual temperatures of natural surfaces cannot be determined by thermal radiometer observations unless the emissivity of the surface is known together with the background thermal radiation and the attenuation and contribution of the intervening atmosphere.

Techniques for field determinations of background radiation and surface emissivity utilized in this paper are sufficient for most contemporary studies of energy exchange at the earth's surface including micro and mesometeorology, and earth resources investigations.

The thermal effects of the atmospheric path as they affect the apparent radiation temperature between the surface and the sensor have not been discussed herein. It must be emphasized, however, that these effects are significant when thermal sensors are at distances exceeding one hundred meters. The investigator is referred to the referenced literature for detailed treatment and observations of atmospheric effects. Particularly significant are Bliamptis (1970), Lorenz (1966), Weiss (1971), Kondratyev (1972).

These techniques for determination of emissivity have proved convenient for field applications in the southwestern United States. The common occurrence of clear, thermally cold skies and low dew point is conducive to satisfactory measurements. Thermally cold skies allow large thermal differences between natural and artificial skies. The accuracy of the calculations is enhanced by the large thermal differences. The low dew point assumes that the mirror and the test surfaces are free of dew, the presence of which would modify their emissivity to near that of water. The importance of thermally cold skies and low dew point should be considered in applying the techniques to diverse geographical areas.

Simple programs have been developed for computer aided analysis of required observations (see Appendix). The required operations for calculating emissivity are within the capability of most programmable desk-top calculators.

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Appendix

Two field methods are utilized for the determination of thermal emissivity. Both methods give comparable results but the "emissivity box" method is more conducive when narrow view radiometers with longer working distances are involved. The artificial sky technique is slightly more precise since the actual radiation from the cover is measured while the emissivity box is assumed to have negligible thermal emissivity, which is valid only when the temperature of the sample is within a few degrees of the wall temperature of the box.

The emissivity of a point was determined as follows:

1. The data, location, and sample description were recorded on field data sheet.

2. A thermal radiometer having a spectral response identical to the ITOS (NOAA) and SMS (GOES) satellites was used to determine radiation from urfaces and background. In this study the instrument utilized was a modified Barnes PRT-5.

3. The global background radiation contribution to the surface of the sample was determined. The background data were calculated from the apparent radiation temperature of a sky-looking cosine response, low emissivity mirror of known temperature and emissivity. Observations required are listed below and lettered to correspond to entry positions in the data sheets (Figure 3).

a. Actual temperature of mirror

b. Apparent radiation temperature of mirror as measured with radiometer with mirror horizontal and in vicinity of sample.

4. The background hemispherical radiation calculated from a & b above (c).

5. The measured apparent radiation temperature of the surface, (d).

6. a. The emissivity box (an aluminum foil lined cone) was placed over the sample and the apparent radiation temperature of the sample in the box recorded (e). The box was removed and step 5 above repeated to ensure that no significant temperature change had occurred.

6. b. When an artificial sky technique was used step 6.a. was omitted and the apparent radiation temperature of the artificial sky measured (3). The apparent radiation temperature of the sample was recorded e_2 and step 5 repeated to ensure no significant temperature change.

7. The emissivity was calculated according to the Stephan-Boltzman radiation expression.

8. Moisture content of the sample and weather observations were recorded.

The vegetation was sampled in its natural configuration and then standard releve' techniques (Dansereau 1957) are used to evaluate the proportion of surface types in the area of interest. The emissivity of each significant surface type was weighted according to its areal proportion as viewed by the satellites to determine the characteristic emissivity of the surface.

Figure 3 Emissivity data sheet for field use.

* calculated values

EMISSIVITY BOX						WEATHER			ARTIFICIAL SKY								SOIL	
T_m	T_{appm}	T_{sky} *	T_s	T_{apps}	ε *	TA	wet rh	wind sun	T_m	T_{appm}	T_{sky} *	T_{art} sky	T_{samp} app	T_{samp} shade	ε *	T_{true} *	Wet weight	Dry wt.
a	b	c	e	d					a	b	c	c_1	d	c_2				

T_m mirror temperature, $Tapp_m$ apparent radiation temperature of mirror, T_{sky} calculated, T_s actual temperature of sample, T_{apps} -apparent radiation temperature of ample, E-emissivity calculate, T_{true} calculated surface temperature.

APPENDIX C

DERIVATION OF EQUATION 14

APPENDIX C

DERIVATION OF EQUATION 14

The fundamental equation for energy emitted and reflected from a surface (equation 3). The expression describing the non-emissivity chamber is directly derived from this equation:

$$Q = \sigma\varepsilon T^4_{true} + (1-\varepsilon)\sigma\varepsilon_b T^4_b \qquad (3)$$

now Q is σT^4_{app}, T_b is T_{sky} and ε_b becomes unity since the T_{sky} is an apparent radiant temperature.

Hence:

$$T^4_{app} = \varepsilon T^4_{true} + (1-\varepsilon)\, T^4_{sky}$$

which yields

$$\frac{T^4_{app}}{T^4_{true}} = \varepsilon + \frac{(1-\varepsilon)T^4_{sky}}{T^4_{true}}$$

$$= \varepsilon + \frac{T^4_{sky}}{T^4_{true}} - \varepsilon\frac{T^4_{sky}}{T^4_{true}}$$

$$= \frac{T^4_{sky}}{T^4_{true}} + \varepsilon\left(1 - \frac{T^4_{sky}}{T^4_{true}}\right)$$

$$\frac{T^4_{app} - T^4_{sky}}{T^4_{true}} = \varepsilon\left(1 - \frac{T^4_{sky}}{T^4_{true}}\right)$$

$$= \frac{\varepsilon(T^4_{true} - T^4_{sky})}{T^4_{true}}$$

$$\varepsilon = \frac{T^4_{app} - T^4_{sky}}{T^4_{true} - T^4_{sky}} \qquad (14)$$

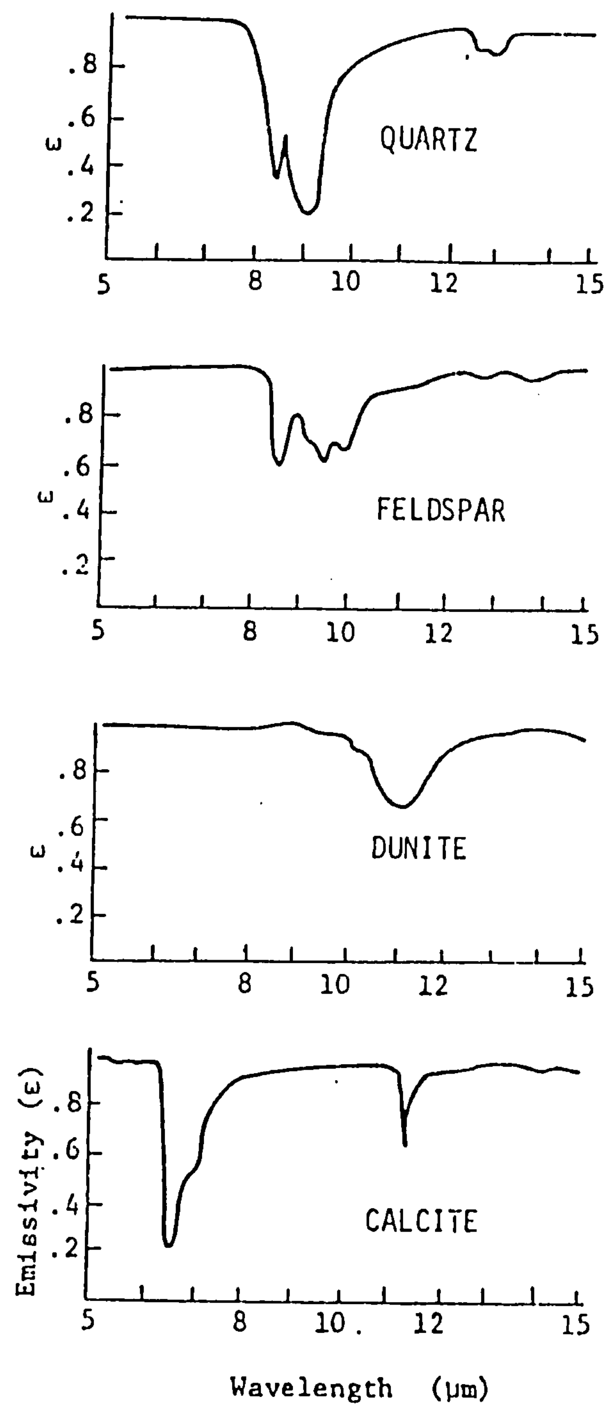

Figure 2 . The emissivity (ε) of four common minerals is shown as a function of wavelength in the mid thermal band (after Buettner and Kern, 1963).

APPENDIX F

Climatic Change, Weather Variability, and Corn Production[1]

Louis M. Thompson[2]

ABSTRACT

A crop/weather model was used to determine the impact of changes in climate and weather variability on corn (*Zea mays* L.) production from 1891 to 1983. Five Corn Belt states, Illinois, Indiana, Iowa, Missouri, and Ohio, were included in the study. These states produce over 50% of the U.S. corn crop. A cooling trend from 1930 to 1972 was accompanied by increasing rainfall in July and August, and by decreasing weather variability. These three factors were favorable for corn yield increase. Simulated corn yields, calculated from weather data, increased 970 kg ha $^{-1}$ from 1930 to 1972 because of improved weather for corn. After 1972 there was greater weather variability and higher intensity rainfall events. Fertilizer use on corn increased substantially in the 1960s and increased at slower rate after 1972. The annual increase in corn yield with normal weather after 1972 was less than half as much as it was from 1960 to 1972. Highest yields of corn have been associated with normal preseason precipitation, normal June temperature, below normal temperature in July and August, and above normal rainfall in July and August. The period after 1970 was expected to warm but weather variability has masked the identification of a trend.

Additional index words: *Zea mays* L., Rainfall intensity, Nitrogen fertilizer rates, Temperature trends, Rainfall trends, Technology trends, Carbon dioxide effect.

YIELDS of corn (*Zea mays* L.) started climbing after 1930 with genetic improvement along with mechanization and improved fertility practices. In 1960 a record yield of 3431 kg ha $^{-1}$ was produced in the USA (17). This was about twice the yield of 30 yr earlier. By 1972, the yield had reached 6084 kg ha $^{-1}$, which was 77% increase in just 12 yr. Another record was set in 1982 in the USA with a yield of 7106 kg ha $^{-1}$. The annual rate of increase in yield from 1972 to 1982 was less than half of what is was from 1960 to 1972.

The two major factors contributing to increases in corn yield are genetic improvement and higher rates of fertilizer applications (2,15). There are several other factors of technology, including: higher plant densities; chemicals to control insects, diseases, and weeds; better mechanical practices; and better management. Russell (13) recently provided evidence that genetic gain from 1922 to 1980 accounted for about 75% of the gain in yield of corn for Iowa. Although the large increase in the yield of corn in the last 50 yr may be due primarily to genetic improvement, higher fertility levels were also necessary. The rates of fertilizer applied to corn reached a level in the USA that averaged 148, 74, and 93 kg ha $^{-1}$ respectively, of N, P_2O_5, and K_2O from 1978 to 1982 (4).

While the upward trend in corn yields have generally been attributed to improved technology, there are other factors to consider. The increase in CO_2 in the atmosphere is considered to be a significant factor in the increase in corn yields. When CO_2 is increased under controlled conditions, corn benefits from increased photosynthesis and accompanying water use efficiency (12,21,25). Climatic change is another factor, but it is difficult to separate this factor from changes in technology.

This article is an effort to provide a quantitative estimate of the effects of changes in climate and weather variability on yields of corn in the U.S. Corn Belt. The climatic changes in the U.S. Corn Belt during the past have been roughly parallel to global changes in climate.

The global warming trend that started in about 1880 reached a peak at the end of the 1930s (10). A global cooling trend occurred from about 1940 to about 1970 (16). There is lack of agreement about a trend since 1970 (6,8). The warming trend followed by a cooling trend may have been due, in part, to changes in incoming radiation associated with changes in transparency of the atmosphere (1). During the past decade there has been a great deal of interest in the possible effects of increasing amounts of CO_2 in the atmosphere (1,14). At this time, however, there is not adequate evidence that a CO_2 induced warming trend has started (5,22,23). The most important change in climate during the past decade has been the increase in weather variability (9). In 1982 Willett showed that, since 1976, summers were getting warmer and winters were getting colder in the USA (24).

Figure 1 shows the changes in July–August temperature in the five central Corn Belt states from 1891 to 1984. There appears to have been a cooling trend from the 1930s through the 1960s. It should be recognized that the cooling trend for the Corn Belt has not been well established. Nelson, Dale, and Schaal (11) found that for the central Indiana district this trend was smaller than published estimates when corrections were made for widespread changes in the time of reporting by weather stations. It was in the period from 1930 to 1972 that remarkable advances were made in corn production. Figure 1 also shows increasing variability after 1972. In this paper a crop/weather model was used to evaluate the influence of the cooling trend on the yield of corn. The model was also used to evaluate the changes in weather variability on the yield of corn. The term variability in this article means departures from normal.

METHODS AND MATERIALS

A crop/weather model is an equation to estimate the effects of departures from normal weather on crop yield. The equation for the model is:

$$Y = a + bX - cX^2,$$

where X is the weather variable (departure from normal) and Y is the simulated corn yield.

A multiple curvilinear regression analysis of corn yields and weather was run for each of five states: Illinois, Indiana, Iowa, Missouri, and Ohio for the period 1930 to 1983. These five states produce over 50% of the U.S. Corn Crop (17).

The variables included three time trends and six weather factors. The weather factors were preseason precipitation (September through June), June temperature, July rainfall,

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[2] Emeritus professor of agronomy, Iowa State Univ., Ames, IA 50011.

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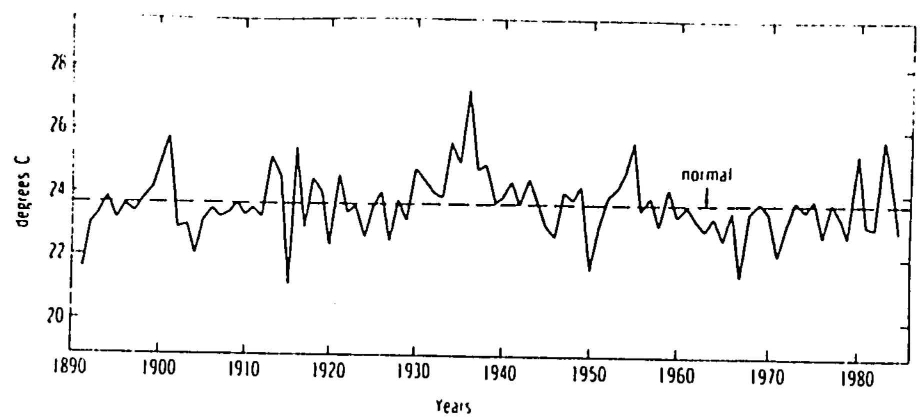

Fig. 1. The fluctuations in July-August temperature from 1891 to 1984 in the five central Corn Belt states.

July temperature, August rainfall, and August temperature. The three time trends were 1930 to 1959, 1960 to 1972, and 1973 to 1983.

The time trends were programmed as follows: 1930 was Year 1, 1931 was Year 2, etc., with 1959 as Year 30, and each year after 1959 as Year 30. The second time trend began with Year 1 for 1960, Year 2 for 1961, etc., with Year 13 for 1972, and Year 13 for each year after 1972. The third time trend began in 1973 as Year 1, 1974 as Year 2, etc., with 1983 as year 11.

The weather variables were programmed by using departures from normal and departures from normal squared. Normal was the average from 1891 to 1983. Weather data from 1891 to 1948 were taken from USDA Statistical Bull. 101 (18). Data after 1948 were taken from Climatological Data of the National Oceanic and Atmospheric Administration (19). The data are published on a district basis, and were converted to state averages with coefficients provided by NOAA.

Corn yield data were taken from USDA Statistical Bull. 101 from 1891 to 1948 (18). Yield data after 1948 were taken from USDA *Agricultural Statistics* (17).

The purpose of the multiple curvilinear regression analysis of each of the five states was to determine the trend with normal weather. The r^2 for each regression analysis was: Illinois, 0.97; Indiana, 0.96; Iowa, 0.96; Missouri, 0.93; and Ohio, 0.96. The yield with normal weather for each year for each state was calculated by assuming no deviations from normal weather and using the intercept and three time trend coefficients.

The yield with normal weather each year was used as a new variable to replace the intercept and time trends in the next analysis. The data from the five states were pooled and run as one regression of corn yield on six weather factors and the corn yield with normal weather. The r^2 for the pooled analysis was 0.94. The coefficients from this analysis are shown in Table 1.

The coefficients from Table 1 were used to illustrate the response of corn to weather variables shown in Fig. 2. The next step was to use the coefficients from Table 1 to calculate the effect of departures from normal weather for each year from 1891 to 1983 for each of the five states. By adding (or subtracting) the departure from normal to the expected yield

Table 1. Regression coefficients for the crop/weather model. $Y = a + bX - cX^2$.

Weather variables (departure from normal)	Coefficients *b*	*c*
Preseason precipitation	-0.4040	-0.0022
June temperature	-2.5176	-27.5150
July rainfall	+9.5604	-0.0416
July temperature	-101.7318	-7.6832
August rainfall	+1.0902	-0.0026
August temperature	-90.8361	-16.2131

The *a* values are yields with normal weather for each state. See Table 2.

Table 2. Trends in corn yield with normal weather, kg ha⁻¹.

	Normal yield in 1930	Annual increase in yield 1930-1959	1960-1972	1973-1983	Normal yield in 1983
Illinois	3007	41	186	57	7241
Indiana	2762	40	168	58	6744
Iowa	3036	37	193	30	6948
Missouri	1826	38	163	20	5267
Ohio	2742	51	106	97	6679

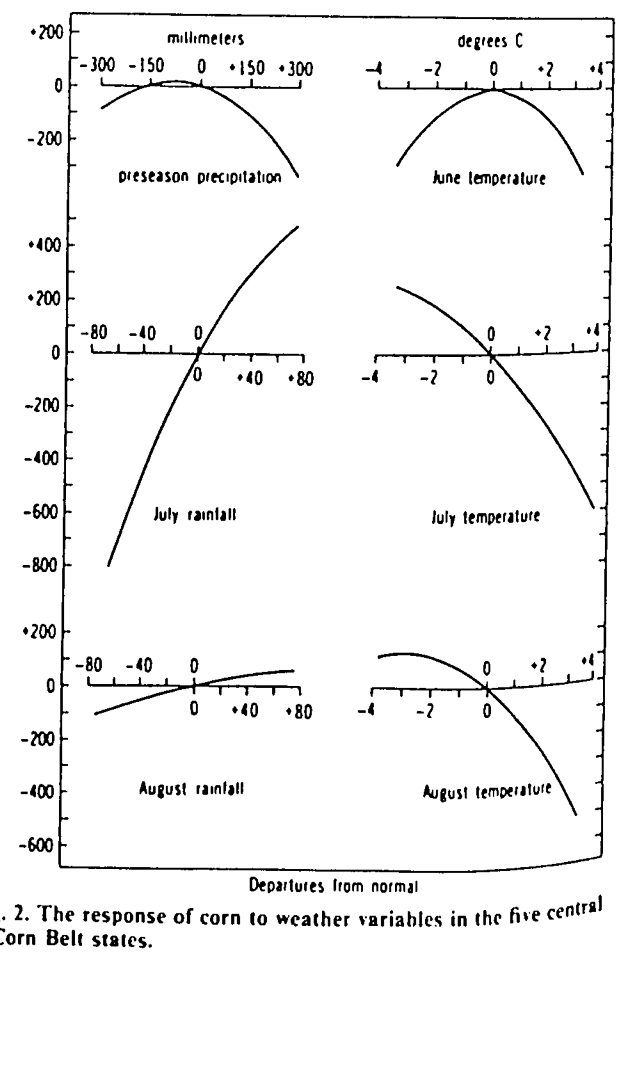

Fig. 2. The response of corn to weather variables in the five central Corn Belt states.

ıth normal weather one may estimate the crop yield. The ıeld of corn calculated from weather data will be referred) as a simulated yield.

RESULTS AND DISCUSSION

Table 2 shows the yields with normal weather in 930 and 1983 for each state along with the annual ncrease in corn yield in kilograms per hectare for each of the three time periods. The rate of increase in yield rom 1960 to 1972 was two to four times greater than it was each year before 1960 in the five states. This change in rate of yield increase was related to the steep uptrend in the use of fertilizers after 1960. For example, about 45 kg ha^{-1} of N was applied to corn in the five-state area in 1960 compared with 135 kg ha^{-1} of N applied to corn in the same area in 1970 (15). The rate of increase in yield with normal weather was lower after 1972 and more like it was before 1960.

It is recognized that the trend is not a perfectly straight line for a decade or more, but the trend line provides a means of separating nonweather factors from weather factors. To overcome some of the objection of linear trend, three time trends were used. The three time trends were related to changes in fertilizer use.

Figure 3 shows the average corn yields plotted against the trend in yield with normal weather for the five-state area. The yields were weighted averages based on area planted to corn. The weights were Illinois, 0.30; Indiana, 0.15; Iowa, 0.33; Missouri, 0.11; and Ohio 0.11. The trend with normal weather from 1930 to 1959 appears to be high, but this was a time when there were many years with warmer and drier than normal weather, particularly in July and August. The yields were very close to the trend with normal weather from 1960 to 1972. This was the period of steep trend in increase in fertilizer use, and a time when single cross hybrids became popular. The favorable weather trend in this period caused farmers to also increase

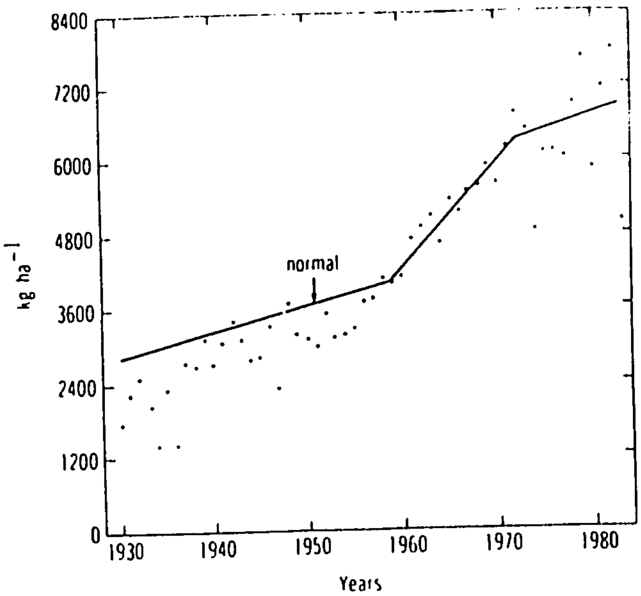

Fig. 3. The trends in yield of corn in the five central Corn Belt states with normal weather and average corn yields each year from 1930 to 1983.

plant densities. The variability in yield after 1972 is most striking and appears more like the variability of the 1930s with an important exception. There were both unusually high yields and unusually low yields after 1972.

Figure 4 shows simulated yields for the five-state area from 1891 to 1983 with a constant level of technology at the 1983 level. The yield with normal weather in 1983 from Table 2 was used as the a value in calculating simulated yields each year from 1891 to 1983 for each state. The simulated corn yields in Fig. 4 are weighted averages. As indicated in Fig. 2, highest yields were associated with normal preseason precipitation, normal June temperature, below-normal temperature

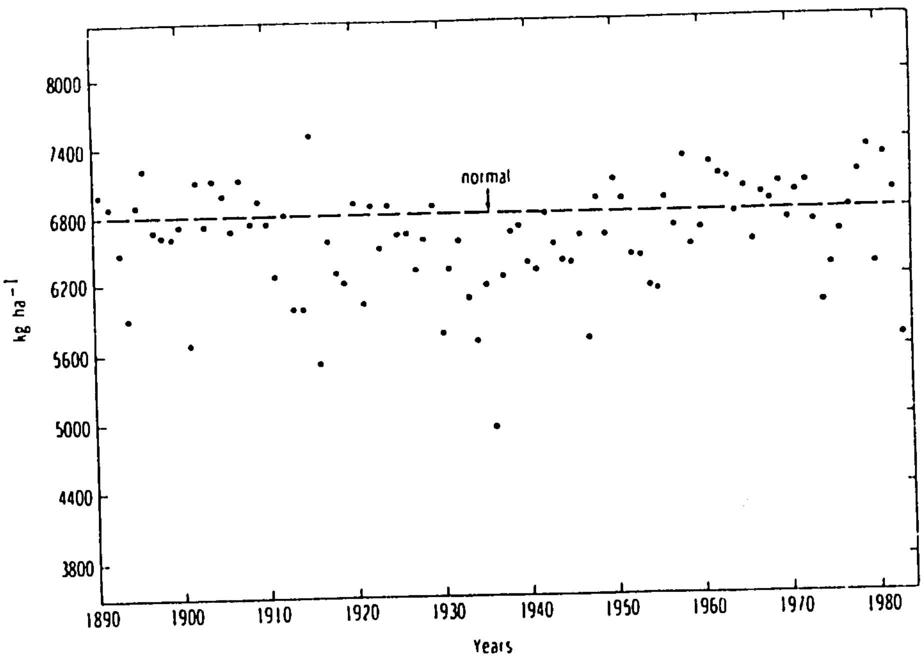

Fig. 4. Average simulated corn yields calculated from weather data at 1983 level of technology each year from 1891 to 1983 for the five central Corn Belt states.

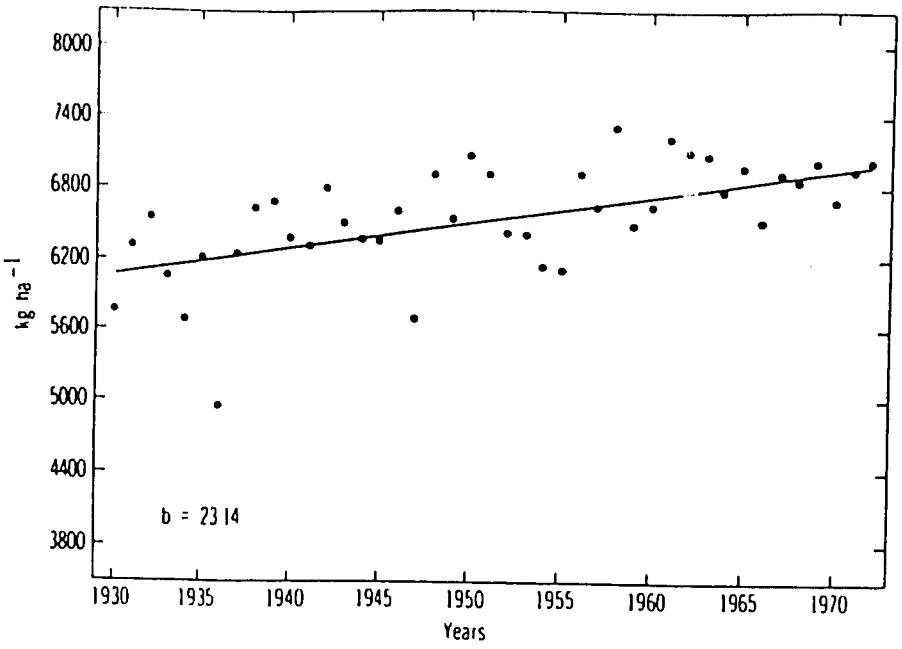

Fig. 5. Simulated yields of corn from Fig. 4 for the period 1930 to 1972 plotted against a regression line for 1983 level of technology. The *a* value is 6063.

in July and August, and above-normal rainfall in July and August. The four best years of weather for corn since 1930 were 1958, 1961, 1979, and 1981. The four worst years since 1930 were 1936, 1947, 1974, and 1983. There was a run of 18 yr, from 1956 to 1973, when simulated yields of corn were 95% of normal or better. This period of benign weather was followed by a period of greater weather variability like that of the early part of this century.

The simulated yields for the period 1930 to 1972 from Fig. 4 are shown plotted against a regression line in Fig. 5. The equation for this regression analysis was:

$$Y = a + bX,$$

where Y was the simulated corn yield and X was the year. Year 1930 was Year 1, 1931 was Year 2, etc., with 1972 as Year 43. The b value in Fig. 5 is 23.14 kg ha^{-1}, which is the annual rate of increase in yield. This was the time of the cooling trend. The average July–August temperature was 2°C cooler in the 1960s than in the 1930s. The cooling trend was also associated with increasing amounts of July and August rainfall. Figure 6 shows the fluctuations of July plus August rainfall from 1891 to 1984 for the five-state area. The decade of lowest July plus August rainfall was in the 1930s. The decade of highest July plus August rainfall was from 1973 to 1982, with a run of 6 yr of unusually high rainfall from 1977 to 1982. The increase in rainfall in July and August along with the cooling trend caused an increase in corn yields apart from the trend caused by improved technology. This climatic change caused simulated corn yields to be 970 kg ha^{-1} greater by 1972 than they were in 1930, as indicated in Fig. 5.

The more variable weather after 1972 caused both higher and lower simulated yields than the yields that occurred from 1963 to 1972. The greater weather variability after 1972 was also accompanied by higher-intensity rainfall events. Changnon (3) showed a decrease in frequency of heavy rains (> 51 mm in one day) in Illinois from 1956 to 1970, and an increase in frequency of heavy rains after 1970. The decade of the 1970s had the greatest frequency of heavy rains of any decade since 1916. Hillacker (7) analyzed records of recording rain gauges in Iowa from 1940 to 1982. The 5-yr period from 1977 to 1982 had more record break-

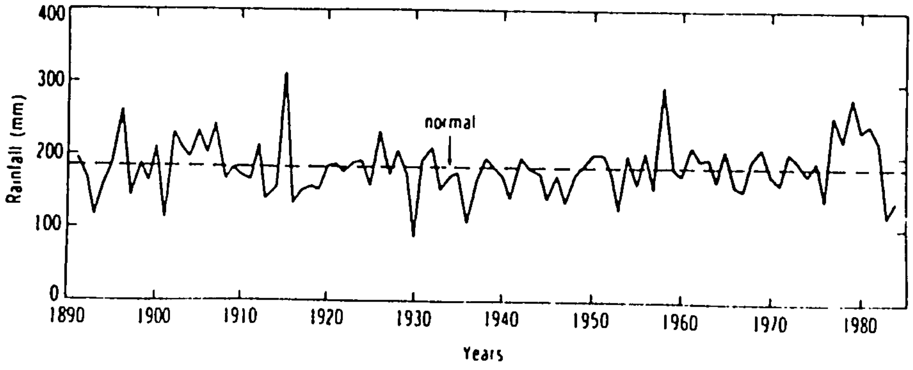

Fig. 6. The fluctuations in July plus August rainfall from 1891 to 1984 in the five central Corn Belt states.

ing rainfalls of one hour duration than any other 5-yr period. The U.S. Geological Survey (20) reported that in 1983 Iowa had the second highest year of runoff since records have been kept, despite the summer drought.

If there should be a warming trend over the next several decades, gains in corn yields will become more difficult. If climatic change takes us back to conditions of the 1930s, and if there were to be a leveling of the trend in technology, there might be a reduction in corn yields. Whether the cultivars developed in a favorable climatic trend will perform as well in an unfavorable climatic trend remains to be seen. This is not to suggest a leveling of technology; there is good reason to be optimistic about continued genetic improvement that will accommodate moderate climatic changes.

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APPENDIX G

Soil Moisture and Moisture Stress Prediction for Corn in a Western Corn Belt State*

R. H. Shaw**

美國 옥수수 西部主産地帯에서의 土壤水分과 作物水分障害 豫測研究*

로버트 쇼**

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로버트 쇼**

INTRODUCTION

Iowa is in a very interesting position for a climatologist with respect to soil moisture. It is located in a transition zone between humid climates to the east, and dry climates to the west. As a result of this, soil moisture reserves may vary widely from year to year, and even from place to place within a year. A wet situation may prevail where free water can be found in the 5 foot profile and the tile are running.

We may have the maximum available water without any free water being present, a field capacity condition. In many of Iowa's soils this can mean a 10 to 12 inch reserve in the 5-foot profile. Or there may be very little available water in the profile. This variation in soil moisture reserves was what stimulated us to start our statewide soil moisture survey in 1954.

My talk will cover a soil-moisture program developed from these data and used to predict the moisture under corn at any time during the growing season. It is therefore keyed to Iowa's "deep soil" conditions. As simple an approach as possible was used in developing the program. The idea was to develop a program that would predict soil moisture program. On an extremely variable glacial till soil, our samples have a standard error of ± 1 inch. For a more uniform loess soil, this sampling error is less than ½ inch. Many tests over the years indicate we are estimating soil moisture within those numbers. Some of you will immediately be con-

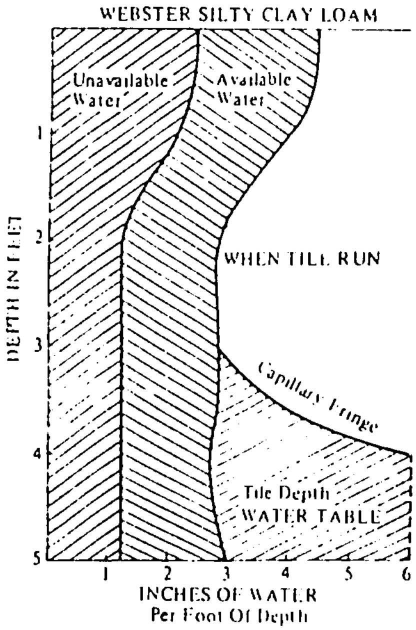

Fig. 1. Soil moisture profile with free water

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* Special lecture presented to the central region members of the Korean Society of Crop Science at the College of Agriculture, Seoul National University on May 6, 1982. ** Distinguished Professor of Agricultural Meteorology, Iowa State University, Ames 50011, U.S.A. Invited for the Memorial Symposium on the 20th Anniversery of the KSCS

* 韓國作物學會 創立 第20周年 [illegible] 發表 特講. ** 美國 아이오와州立大學校 敎授

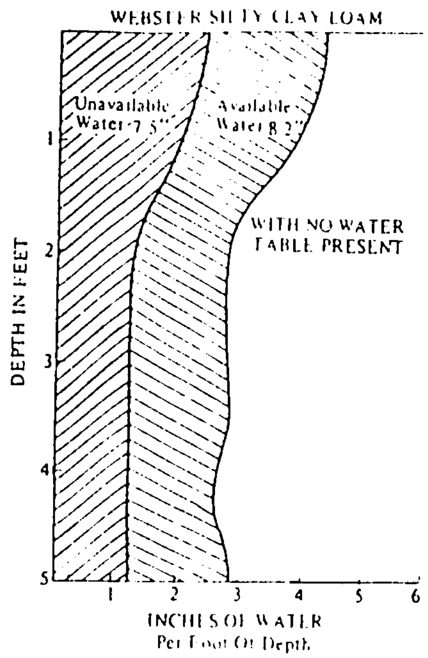

Fig. 2. Soil moisture profile at field capacity

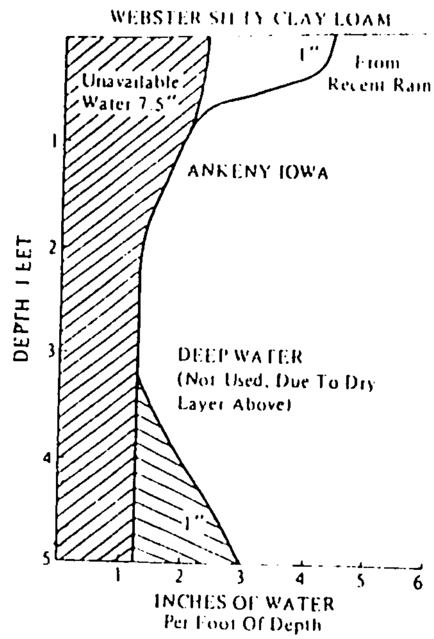

Fig. 3. Soil moisture profile with a dry condition

within the limits of the soil-moisture sampling cerned about the size of these limits with sampling errors much larger than daily ET losses which may be only 0.2 to 0.25 inch or less. Even though we estimate day to day changes in soil moisture our goal is to estimate values on selected dates that are a considerable number of days apart. This we seem to be able to do. We can further explain a significant portion of our yield variation of corn, using a stress index developed from the soil-moisture program.

With that background, let me proceed and explain our program. First let's look at items that need to be considered, then I'll explain what we do.

SOIL MOISTURE PROGRAM

Saxton, Johnson and Shaw developed a flow chart for a soil moisture program (Figure 4). Potential ET, expressed by some measure of the drying power of the atmosphere, can be subdivided into 3 components, evaporation of intercepted water, soil evaporation, and transpiration. My program does not include intercepted water directly, but I would like to comment on it. Work that Leo Fritschen and I did many years ago indicated a full corn canopy could intercept almost 0.15 inch of rainfall in rains over 1/2 inch. For research studies this could be very important if disregarded. For my purpose I ignored it, which says that it will be indirectly included in the transpiration term.

Next, one must separate evaporation and transpiration according to the crop cover. Evaporation will be a function of the atmospheric demand as well as the availability of water for evaporation from the top few inches of soil. Transpiration will obviously be a function of the amount of crop cover or stage of crop development. The depth where roots are extracting water must also be considered. If soil moisture is not "completely available" for transpiration, then the degree of reduction in transpiration must be considered. One must also decide how runoff will be handled, and how moisture will infiltrate into the soil.

The program calculations are all made in terms of plant-available moisture. The soil profile is divided into 6-inch increments down to 5 feet. In special cases a 7-foot depth is used. A "field capacity" value and a "wilting point" value must be determined for each increment. We determined field capacity from field measurements. Wilting point values are

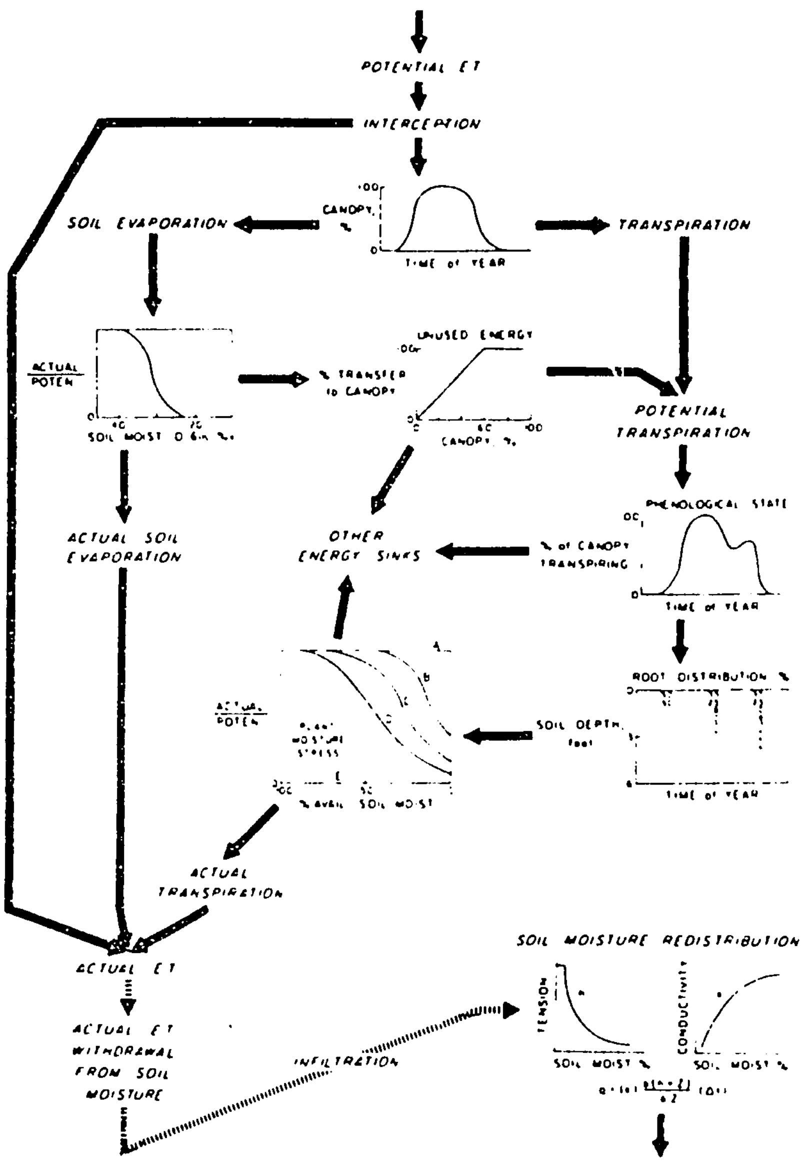

Fig. 4. Flow chart of ET calculations and soil moisture movement

determined using the 15 bar value

RUNOFF

An antecedent precipitation index was used to calculate runoff. All our soil moisture sites were located on relatively flat land from which runoff could occur, but with no runon and ponding of any significance. Obviously, predicting values where runon could occur would be much more complicated. Two equations were used

$$API = P_1/d_1 + P_2/d_2 + \quad + P_i/d_i \qquad (1)$$

$$API = P_1/d_1 + P_2/d_2 + \quad P_i/d_i + P_0/2 \qquad (2)$$

P_1 is the rainfall for d_1, yesterday, P_2 is for 2 days past and P_0 is for today, the day for which the API is being calculated.

Equation 1 is used after Aug. 31. Equation 2 is used during the spring months when the ground is bare, or cover is sparse when runoff will be relatively high, and in the summer when high-intensity rains are expected to occur. P_0, the rainfall amount for the day being calculated, is used only for values

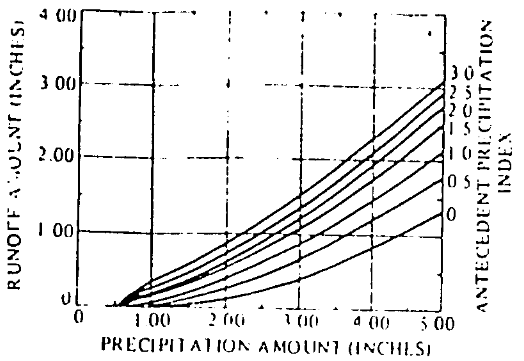

Fig 5 Prediction of runoff from precipitation and antecedent precipitation index (after Buss and Shaw, 2)

greater than 1 inch. If 1 inch or less P_0 = 0 and Equation 1 = Equation 2.

The API value was then used in Figure 5 to compute the runoff. This procedure does not directly take into account intensity of the rainfall.

INFILTRATION

The precipitation remaining after runoff was infiltrated into the soil with the following simple procedure. The first increment (0-6 inches) is allowed to fill to field capacity. Any amount above this immediately moves to the second increment and the process is repeated. The process is repeated until all the water has been used or until all layers are at field capacity. If all layers are at field capacity and water remains it is percolated out the bottom of the profile in what might be called "instant drainage". In poorly drained soils this step would require modification, i.e. as done by Dale in Indiana. It seems to promote no measurable error under Iowa conditions at the sites used. By midsummer we rarely measure free water in the 5-foot profile. Also remember - low elevation sites where water runs on are not included in our survey.

EVAPORATION AND EVAPOTRANSPIRATION

Early April through June 6

There may be a variable ground condition in the spring from plowed to crop residue to small corn plants. If a growing meadow crop, this procedure would require modification. All water loss was assumed to be by evaporation from the top 6 inches of soil. Solar radiation is relatively high during much of this period. The availability of water for evaporation is believed to be the prime factor that limits water loss. Water loss was assumed to average 0.1 inch/day. Water was assumed to be lost at this rate as long as any available water was present in the top 6 inches of soil. This ignores meteorological factors, and also any change in the rate of moisture transfer to the soil surface. Ideally, daily demand and soil dryness should be included, but they would complicate the program. During the test period using 7 years of data, the average deviation or difference between the value measured by soil sampling in mid-June and that predicted from the program using the April sample was only 0.05". Over half the values were predicted within ½". We were as likely to overpredict as underpredict but the error was small for the period used.

June 7 through September 30

As the corn plant grows considerable change

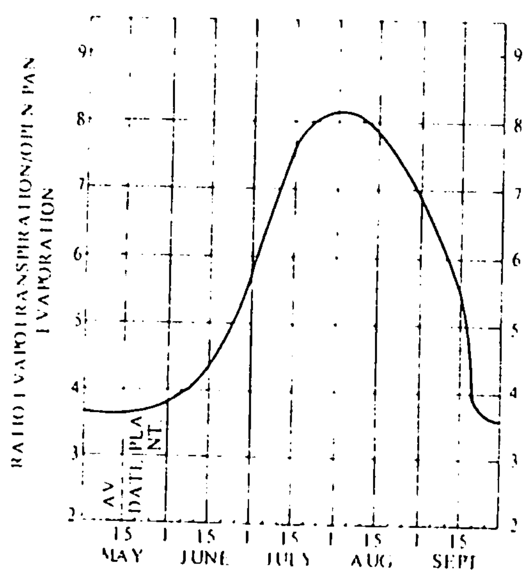

Fig 6 Ratio of evapotranspiration of corn to open pan evaporation throughout the growing season (after Denmead and Shaw, 3). On the average, 50% of the corn in Iowa is silked by July 31.

takes place in the ground cover. June 7 was selected as the arbitrary date when the prediction technique was changed. About that date a marked change is taking place in the ratio of ET to open pan evaporation, and it is a start of a week in the standard climatological year. Starting June 7, Class A pan evaporation was used as the starting point for estimating evapotranspiration. The daily pan evaporation is multiplied by the factor obtained from Figure 6. This relationship was developed assuming moisture was readily available for transpiration but the soil surface condition was not specified. The dates used in this figure represent average values for Iowa. To adjust for seasonal development the silking date is input into the program (Ave. July 3). This is used as a floating reference point. If the crop is 10 days ahead of normal (silked July 21) the program automatically shifts all calendar dates 10 days earlier, for example this phase of the program would start May 28 instead of June 7. When soil moisture is not limiting ET = Pan x Conv. factor from Figure 6.

Data that Denmead and I obtained indicated a relation exists between the atmospheric demand and the level of soil moisture needed to meet that demand. Relationships obtained from his thesis study are shown in Figure 7. The θ_{TL} points represent the conditions when visible signs of stress (wilting) were evident. Notice that these points occurred at quite different levels of soil moisture for the 3 days shown. Also notice how the transpiration decreased from the potential value at different soil moisture values for the different demand levels. Defining the points where these breaks occur has had considerable discussion in the literature. This discussion has become confused because of different terms used. We used available water (FC - WP). Ritchie has used extractable water. I don't have time to define it—but the two terms are different and most of the disagreement in the literature is due to not reconciling the differences in definition before comparing results. Because our original work was done with restricted rooting volumes, and because a rather unusual soil was used in the containers, some adjustments had to be made to fit our original data to field conditions. The curves we now use for the period up to silking are shown in Figure 8.

A high demand day is one in which Class A pan evaporation is greater than 0.30 inch. A low demand day is one in which Class A pan evaporation is less than 0.20 inch. A medium demand day is then from 0.20 to 0.30 inch. One could use other systems, i.e. Penman, Thornthwaite, or Priestley to do the same thing. I felt that pan evaporation was a simple, but sensitive way, of doing it.

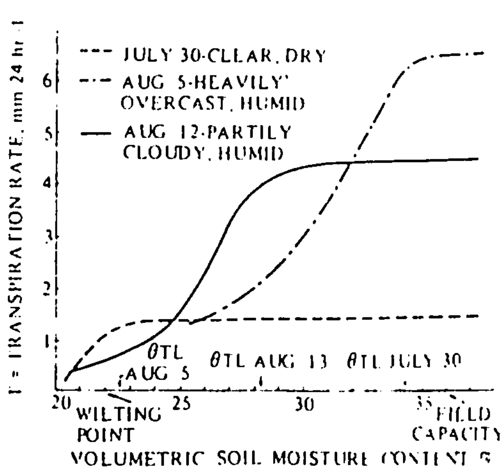

Fig 7. Daily transpiration for 3 days plotted as a function of soil moisture (Denmead and Shaw, 1962)

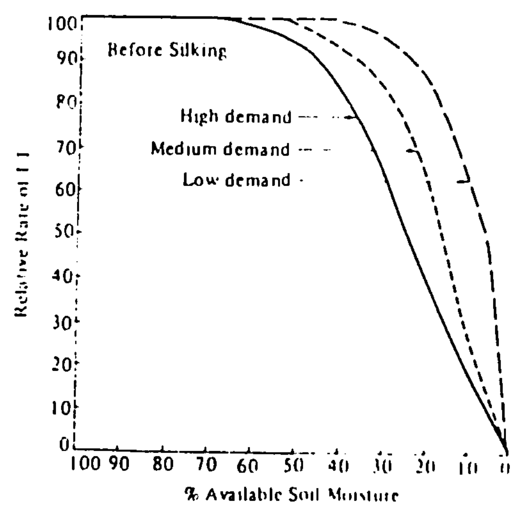

Fig. 8 Relative ET rates for different atmospheric demand rates prior to Aug. 1

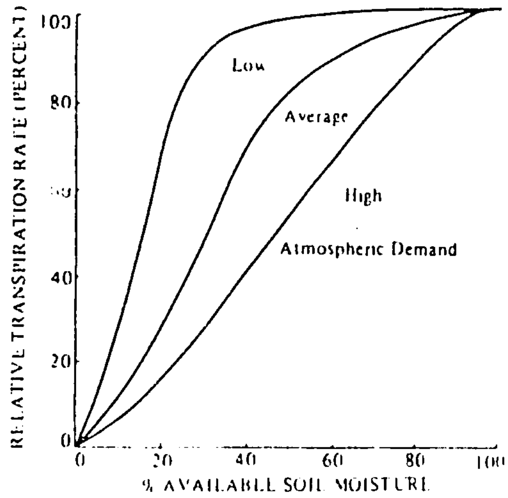

Fig. 9. Relative ET rates for different atmospheric demand rates for Aug 1 and later

The percent available soil moisture in the root zone (I'll define that in just a minute) is used for each day to determine the relative ET. For example, if we have a day in which there is 70% available in the root zone, the relative ET rate would be 100% of potential, regardless of the type of day. If there was only 40% available moisture in that root zone, ET would be 82% of potential for a high demand day, 91% for a medium demand day, and 100% for a low demand day. These would be the values before silking. After silking, because we assume that roots are not growing into areas of new moisture, another set of curves are used which give greater ET reductions for comparable soil moisture conditions (Figure 9). Comparable values then were 55%, 80%, and 100%.

Table 1. Water extraction from the soil profile at different depths during the growing season. Values for each date are given as the percentage of evaporation or evapotranspiration that occurs from each of the depths listed

Dates	Percent of E or ET which comes from respective depths	Depths from which water was extracted
to June 7	100	1st 6 inches
June 8 to 14	100	1st foot (equally from each 6 inches)
June 15 to 27	67.7, 33.3	1st, 2nd foot
June 28 to July 4	60, 20, 20	1st, 2nd and top half of 3rd foot
July 5 to 11	60, 20, 20	1st, 2nd and 3rd foot
July 12 to 18	60, 15, 15, 10	1st, 2nd, 3rd and top half of 4th foot
July 19 to 25	60, 15, 15, 10	1st, 2nd, 3rd and 4th foot
July 26 to Aug 1	60, 10, 10, 10, 10[a]	1st, 2nd, 3rd, 4th and upper half 5th foot
	60, 15, 15, 10[b] 10[a]	1st, 2nd 3rd and 4th foot
After Aug 1	60, 10, 10, 10, 10[a]	1st, 2nd, 3rd, 4th and 5th foot
	60, 15, 15, 10	1st, 2nd, 3rd and 4th foot

To compute the percent available soil moisture in the rooting zone, the depth of rooting also had to be estimated. The following table shows how rooting depth progresses. It also shows the amount of water extracted from each depth (Table 1). As now used, our program has three different rooting depths, or more correctly, depths of extraction. Normal conditions use a depth of 5 feet, if certain wet conditions are met extraction is only to 4 feet and if certain "dry" conditions are met in May and June, water can be extracted from a depth of 7 feet. If moisture is not available in any scheduled increment, that moisture extraction is prorated among those scheduled increments which do have moisture

Evapotranspiration per day then is equal to

PAN EVAP X RATIO FOR CROP DEV
X STRESS OR RELATIVE ET FACTOR

On days when the ET loss was reduced because of stress, one other factor was considered If recent rains had added water to the surface soil, some of the reduced transpiration could be replaced by soil evaporation As long as water was available in the top 6 inches of soil up to 0 1 inch evaporation could be taking place if the energy was present to cause this evaporation For example on a day in which the potential rate was 0 25" and ET was calculated as only 0 14" (down 0 11 from potential), evaporation of 0 10 inch could take place, making the total loss 0 24" On a day when the potential rate was 0 25" and ET was calculated as 0 20", evaporation of 0 05" could occur ET + added evaporation could not exceed the calculated potential

October and Later

Transpiration was assumed to essentially cease after Oct 1 because of maturation of the crop Loss was assumed to be only by evaporation from the top 6 inches of soil and was computed as 0 35 x pan evarpoation

HOW WELL DOES IT WORK

As I mentioned earlier, we started sampling soil moisture in 1954 and have continued it each year since then Originally we sampled four times a year Mid-April, mid-June, early August and early October This gave us many pieces of data to check the program We are confident enough in the program now that we only sample in mid April and early October These times provide a check point at the end of the season Also since I seldom have the weather data assembled until November or December, the fall survey also gives Extension people information at the time they need it on next years moisture reserve, an item of much interest to our farmers The spring sample gives us a starting point for the new season, plus checking for any changes which took place over the winter In our climate, gains in soil moisture during the winter are usually small because of a frozen soil and low precipitation When significant precipitation does occur, changes in the soil moisture are difficult to predict, but on the average are about 25% of the precipitation which occurs

STRESS INDEX

An an extension of the soil moisture program we now computed a seasonal stress index for corn This is now computed from two simple equations

$$SI = 1 - (STET + EVAP)/ET \quad (1)$$

or

$$SI = 1 - STET/ET \quad (2)$$

where STET is the actual ET which occurs, EVAP is the evaporation from the surface 15 cm of soil and ET is evapotranspiration when the moisture supply is not limiting The second equation is used only when STET is less than or equal to 0 04 inch (1 mm) and pan evaporation is greater than 0 30 inch (a high demand day) whatever evaporation occurred under those conditions (high demand-low soil moisture) was considered as having no effect on reducing stress on the plant The index for each day can range from 0 (no stress) to 1 (no STET)

The stress index is calculated for each day for a period from 40 days before to 44 days after silking

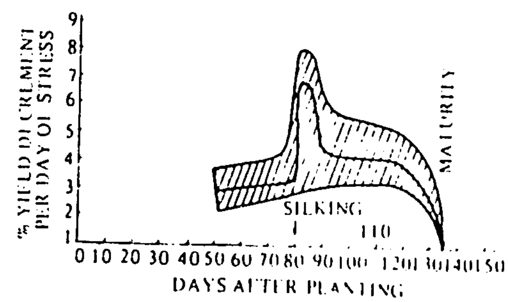

Fig 10. Schematic diagram of relationship between age of crop and percentage yield decrement due to one day of moisture stress

(85 days) with relative weighting factors assigned to each 5-day period relative to silking. The weighting factors were based on data accumulated by a number of researchers (Figure 10). Actual weighting factors used are shown in Table 2. Accumulative effects due to severe stress are given additional weighting factors:

a) When 2 or more consecutive 5-day unweighted stress index values were both 4.5 or greater, an additional weighting factor of 1.5 was used.

b) when the index for two of the periods 1 before, 2 before or 3 before silking were 3.0 or greater, an additional weighting factor of 1.5 was used.

c) when the unweighted index for both the 1 before and 1 after periods are both 4.5 or greater a crop failure is indicated.

Table 2. Relative weighting factors used to evaluate the effect of stress on corn yield. Periods are 5-day periods relative to silking (after Shaw, 1974)

Period[a]	Weighting factor	Period	Weighting factor
8 before	0.50	1 after	2.00
7 before	0.50	2 after	1.30
6 before	1.00	3 after	1.30
5 before	1.00	4 after	1.30
4 before	1.00	5 after	1.30
3 before	1.00	6 after	1.30
2 before	1.75	7 after	1.20
1 before	2.00	8 after	1.00
		9 after	0.50

The sum of all the 5-day weighted values is the seasonal stress index.

The stress index-yield relation has undergone a number of revisions over the years. Our current relation used is shown in Figure 11. These are sites where no excess water occurred and represent data over several recent years. This relationship assumes a potential yield of 9682 kg/ha (154 bu/A). One can convert this to other potential yield levels by letting the 0 stress intercept be that yield value, and the 0

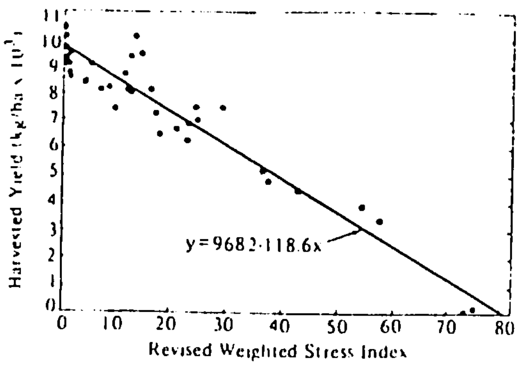

Fig. 11. Weighted stress index-yield relationship using optional 152-cm or 213-cm rooting depth, Nicollet silt loam moisture characteristics and the modified stress index equation.

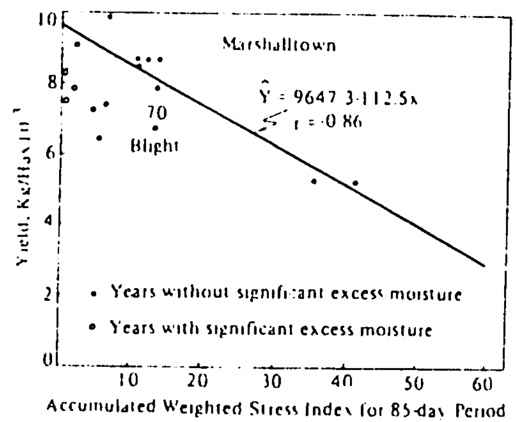

Fig. 12. Relationship between weighted-stress index and corn yield near Marshalltown.

yield value 81.6 + units of stress. The same number of units of stress are assumed to produce 0 yield, regardless of the potential yield. Our data indicate the regression lines for different yield levels converging near the same stress value. In using this equation we start with the potential yield and reduce the yield as the season progresses. This gives us an estimate of how much yield has been lost at any desired date during the season.

Some interesting side-benefits have developed from this work. In the early years of testing we frequently found a wide range of yields occurring low-stress values. Low stress occurred when we had a good growing season, as well as those that were too wet in the spring, and had good moisture later

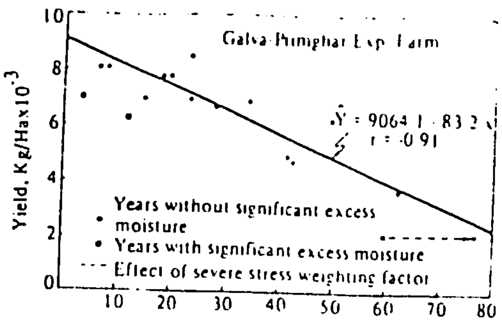

Fig. 13. Relationship between weighted-stress index and corn yield at the Galva-Primghar Experimental Farm

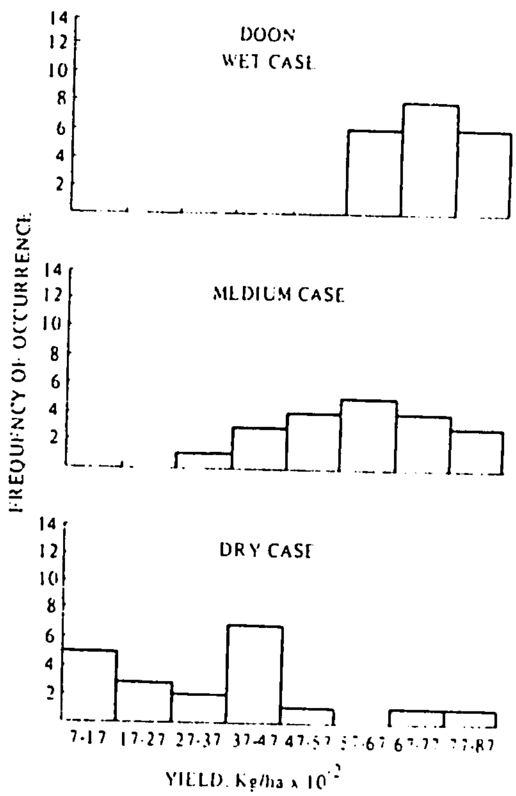

Fig. 14 Distribution of corn yields at Doon, as predicted by Y = 8616.8 x 135.3X over the period 1951 to 1970 for three different spring moisture conditions

The squares shown in Figure 12 represent years when it was too wet in May and June the profile was filled to field capacity with percolation at least once during each month in that period and with one month having at least 2 inches of percolation. We cannot predict how much the yield will be reduced only that it will be reduced.

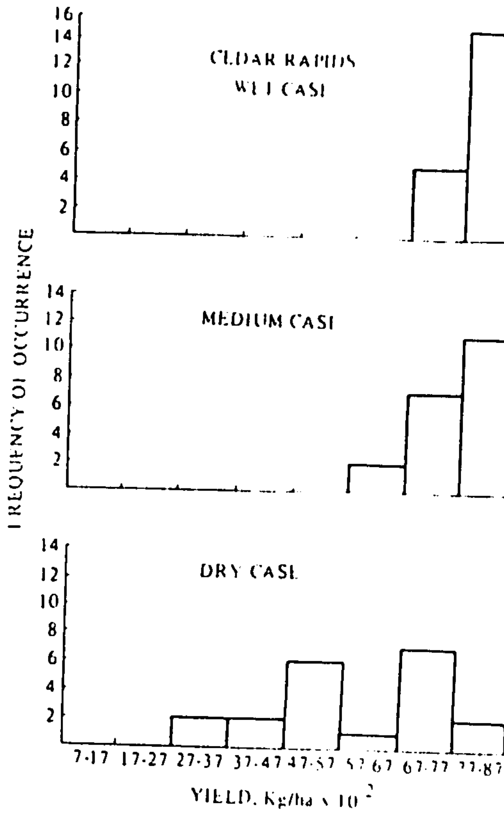

Fig. 15. Distribution of corn yields at Cedar Rapids, as predicted by Y = 8616.3 x 135.3X over the period 1951 to 1970 at three different spring moisture conditions

As we move toward northwest Iowa excess water occurs much less frequently. Only two years showed this at the Galva-Primghar Research Center. The bottom dashed arrow shows an example of what the additional weighting factor for severe stress does. This yield relation was developed several years ago at a lower yield base than we use now.

We've also used the procedure to project yield outlooks with different levels of soil moisture reserve in the spring. Over a 20-year period we assumed that soil moisture on April 15 of each year started out at 20%, 60% or 100% of field capacity in the 5-foot profile. However the actual weather data for each year subsequent to April 15 were used to

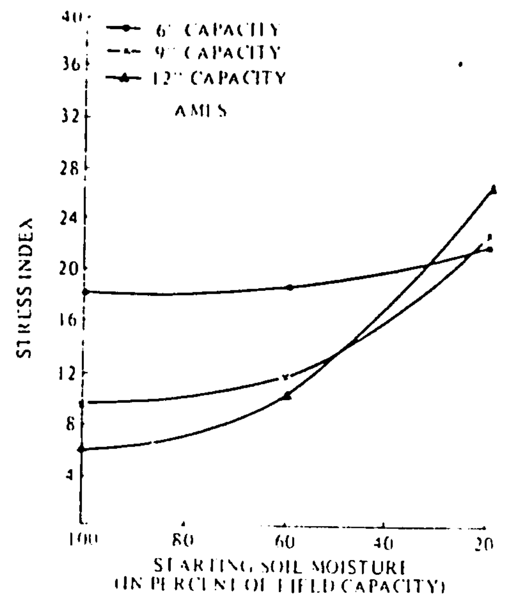

Fig 16 Relationship between a moisture-stress index and starting soil moisture for field capacity values of 6, 9 and 12 inches at Ames

calculate the stress index. Doon in extreme north west Iowa shows high yields produced if they start at field capacity. Unfortunately they seldom start there, but are usually in the low to medium starting situation. At Ceder Rapids in east central Iowa they usually start out with good moisture so yield reductions due to stress are small. Remember though that these calculations do not take into account excess moisture. By knowing the soil moisture situation in the early spring, we can project the probabilities of getting different yield reductions due to stress. The farmer can use this information in his planning. We use the fall information for a preliminary outlook.

We've also used the program to see how the capacity of the soil and the starting moisture interact to affect the index and the seasonal outlook with a low capacity soil. Where you are in the spring makes little difference. Spring rains usually fill the profile. With a high capacity soil the starting level is very important.

Questions were asked in the mid 70's about the severity of the recent droughts. We went back in history and estimated the drought conditions using the soil moisture program. The 1977 drought is not included here. It would rate near the top in central Iowa. The 1974 drought ranked 6th in west central Iowa. The 1975 drought was 7th in west central Iowa, 6th in central Iowa and 5th in eastern Iowa.

By combining stress index values from the soil moisture sites with a simple technology relation provided by Louis Thompson I compared the estimated corn yields in countries where we had mois

Table 3 Ranking and stress index values for the 13 most severe moisture stress years out of the 26 years 1933-36 and 1954-75

Western Iowa			Central Iowa			Eastern Iowa		
Year	Rank	Index	Year	Rank	Index	Year	Rank	Index
1936	1	100*	1956	1	64.6	1936	1	52.3
1955	2	84.2	1936	2	63.6	1957	2	37.2
1970	3	69.5	1934	3	61.8	1934	3	33.4
1934	4	60.5	1933	4	32.4	1955	4	31.4
1956	5	41.5	1966	5	31.1	1975	5	26.6
1974	6	40.8	1975	6	31.1	1966	6	19.2
1975	7	40.2	1971	7	29.9	1958	7	17.0
1971	8	33.0	1955	8	29.1	1935	8	16.5
1933	9	30.5	1954	9	21.9	1933	9	15.6
1959	10	30.4	1935	10	21.6	1964	10	15.1
1968	11	30.4	1970	11	20.9	1965	11	13.6
1935	12	26.8	1965	12	20.4	1960	12	11.2
1967	13	24.6	1967	13	19.7	1963	13	10.0

* Indicates crop failure