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EVAPORATION AND TRANSPIRATION

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For years, the principal objective of evapotranspiration research has been to calculate the loss of water under varying conditions of climate, soil, and vegetation. The early simple empirical methods have generally been replaced by more detailed models which more closely represent the physical and biological processes involved. Monteith's modification of the original Penman evapotranspiration equation to include a term for canopy resistance signaled a shift in emphasis in evapotranspiration research from a physically controlled process to one which can be physiologically controlled. This change in direction was acknowledged by Federer [1975] in his earlier review and has continued for the past four years. The scope of this review, as were the reviews of Ekern [1971] and Federer [1975], is, for the most part, limited to evaporation from terrestrial surfaces rather than from lake or ocean surfaces.

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A review of the literature since 1974 shows that substantial interest has been maintained in understanding the influence of advection and interception on evapotranspiration. As the complexity of the models increases, the data requirements to drive the equations often make the model useless for field applications. Consequently, there is a continual effort to make empirical substitutes to satisfy local conditions. Under a number of circumstances, such modifications work very well. For example, from the Penman-Monteith equation, if the canopy resistance and aerodynamic resistance are of the same magnitude - as for short crops in temperate climates - then evapotranspiration will be fairly insensitive to canopy resistance and an empirical adjustment to the formula will be adequate. If the aerodynamic resistance is much less than the canopy resistance - as it is in forests - the calculated evapotranspiration is greatly affected by the value of the canopy resistances [Rutter, 1975; Tan and Black, 1976].

Canopy Resistance

Canopy resistance is the result of the interaction of the soil-plant-atmosphere system, no one part of which operates independently of the other. The internal water relations within a plant tend toward a steady state in which water uptake, translocation, and transpiration are equal. When evaporative demand exceeds the ability of the roots to supply the necessary water, some species can draw upon water stored within the plant or close their stomata. A prime function of stomata is to prevent leaf desiccation after soil water extraction by the plant has fallen behind the rate of water loss.

The simple Penman-Monteith model assumes that the canopy is isothermal and that the canopy resistance is equal to all of the stomatal resistances acting in parallel. However, canopy resistance has been shown to be largely of a physiological origin and can vary substantially within a plant [Tan and Black, 1976; Sinclair et al., 1976]. The nature of canopy resistance has been found to differ not only between different species, but also between different genetic strains of the same species [Shimshi and Ephrat, 1975; Hall et al., 1976; Jones, 1976] and the stage of crop development [Nkemdirim, 1976]. Some plants have less ability to control water loss than others. For example, Johns [1978] found that stomata closure in a number of temperate herbage species was able to reduce water use by only 20 to 30% and that water use continued at a high rate even when water stress was causing considerable leaf death.

The canopy resistance term found in Monteith's model was expanded by Rijtema and later by Feddes to include terms for stomatal resistance, resistance dependent of the availability of soil moisture and on liquid flow in the plant, and resistance dependent on the degree of soil cover. Although these terms are certainly not independent, the Rijtema-type model has been found to evaluate successfully the surface factors that control evapotranspiration and to be a substantial improvement upon the Penman-Monteith estimate [Grant, 1975; Nkemdirim, 1976; Thom and Oliver, 1977].

Stomata

The role of stomata in the regulation of transpiration has been widely studied. The environmental factors that have a major influence on stomatal resistance are irradiance [Hall et al., 1976], leaf water status [Jarvis, 1976; Shirazi et al., 1976a, b; Denmead and Millar, 1976; West and Gaff, 1976], humidity [Raschke, 1975; Idle, 1977; Rawson et al., 1977; Sheriff, 1977a], leaf temperature [Hall and Kaufmann, 1975; Aston, 1976; Ford et al., 1977], and carbon dioxide concentration [Raschke, 1975; Hall et al., 1976]. Studies of stomatal response to these environmental factors have often yielded contradictory results. Some of these contradictions may be related to methodology, whereby the result is affected by the process of measurement. For example, damaging a Lycopersicon leaf caused a 41% average reduction in transpiration in a neighboring undamaged leaf which persisted for several hours. Such artifacts can influence transpiration from an excised leaf or the entire shoot if endogenous hormones released from the damaged cells gain entry to the transpiration stream [Van Sambeek and Pickard, 1976]. Instrumentation, such as porometers, which do not adequately maintain C02 and humidity gradients may cause changes in stomatal aperature which are independent of the variable being studied. Hall et al. [1976] suggest that porometer systems which maintain the ambient humidity at the leaf surface during measurement are perhaps necessary --even for short measurement periods. Greater care in plant preconditioning must be exercised.

Time-dependent effects of environmental stresses on stomatal responses is an important consideration. Stomata of plant material suddenly exposed to water stress do not respond similarly to those of plant material growing in a field situation where stresses are slowly and continually changing and tissue-solute concentrations are allowed to adjust over relatively long periods [Begg and Turner, 1976; Brown et al., 1976; Johns, 1978]. After-effects of water stress on subsequent stomatal responses also have been observed [Hall et al., 1976]. The age of the leaf or its position in the canopy is an additional source of variation which must be considered when evaluating stomatal resistances in a plant [Hsiao et al., 1976; Aslam et al., 1977; Rawson et al., 1977].

Soil Moisture Availability and Plant Conductance

The effect of soil drying on the transpiration rate requires consideration of the simultaneous interaction of the atmospheric demand, the water potential of the leaf, the resistance to water movement in the plant, and the soil water potential. For years there have been conflicting views about the manner in which transpiration rate responds to the drying of soil. There is increasing, evidence that the form of this relationship can be explained in terms of varying climate, plant, and soil factors [Rutter, 1975; Sterne et al., 1977; Calder, 1978]. Afshar and Marino [1978] propose a model that considers potential transpiration and effective root density. Their model does not account for the ability of the plant to control water uptake when soil water is limiting, however. Root density functions are often taken as a function of root biomass, and such data are often difficult to obtain. The development of root systems can be quite dynamic and vary with species, season, and depth [Hsiao et al., 1976].

The task of evaluating root densities of forest vegetation is a major undertaking. Ziemer [1978] found soil moisture was actively depleted by forest trees to a depth in excess of 7 m. Maximum soil moisture extraction by the roots occurred between a depth of 3 to 5 m. Feddes et al. [1976] proposed a root extraction term which depends on potential evapotranspiration, soil moisture content, and the depth of the root zone. A modification of their model, in which the soil moisture term is replaced by one related to the soil moisture pressure head, produced results which agreed with data collected in a field planted with red cabbage [Feddes and Zaradny, 1978]. Although progress has been made in understanding the interaction of transpiration and drying soils, the ability to apply these principles to field situations continues to be limited because of the difficulty of acquiring the necessary data [Rutter, 1975; Seaton et al., 1977; Lauenroth and Sims, 1976; Calder, 1976; Jensen and Wright, 1978]. To avoid the data acquisition problems related to direct measurements of soil water availability, predawn xylem pressure potential has been found to be a useful substitute [Ritchie and Hinckley, 1975; Fetcher, 1976]. Other studies have related xylem water potential to transpiration rate [landsberg et al., 1976].

Aerodynamic Resistance

Rijtema suggested that the aerodynamic resistance in the Penman-Monteith equation could be related to the inverse of a roughness function. He defined the function as the product of crop height and a dimensionless function of windspeed. Although the relationship was originally established for grass in the Netherlands, the addition of the roughness function produced a marked improvement over the original Penman equation for calculating evapotranspiration by a number of crops in arid and semi-arid regions [Slabbers, 1977]. Nkemdirim [1976] found a progressive increase in the roughness parameter as a potato crop developed. The roughness parameter was highly correlated with crop height and spread. Roughness length is also influenced by crop flexibility. As wind velocity increases, a flexible canopy may irregularly deform which increases the roughness length and, therefore, evapotranspiration relative to a rigid canopy [Heilman and Kanemasu, 1976]. With increasing height of the vegetation there is a corresponding increase in the roughness length and, for a given windspeed, a decrease in the aerodynamic resistance. When the roughness length becomes very large, as in a forest, the calculated evapotranspiration can substantially exceed open water evaporation [Thom and Oliver, 1977]. A diurnal variation in aerodynamic resistance was noted by Nkemdirim [1976] in his potato crop study with variations up to 48% in hourly values in early spring. Later in summer, such variability was usually less than 10%. High values were found to correspond to periods of active convection. In addition, spring weather was much more unsettled than was the more stable summer weather.

Interception

The calculation of evapotranspiration of intercepted precipitation is a special application of the Penman-Monteith equation. In this application, canopy resistance is negligible when the canopy is completely wet [Shuttleworth, 1975], but increases slowly as a larger portion of it dries [Gash and Stewart, 1975]. Rutter et al. [1975] developed a physically based model for forests which calculates a running water balance of the canopy and trunks using hourly rainfall and the necessary meteorological data to use the Penman-Monteith equation. Their model was tested against records from a wide range of forest canopies and was able to account for differences in measured interception loss between species and between leafy and leafless deciduous stands. Rutter [1975] reasoned that in herbaceous communities, where the aerodynamic and canopy resistances are approximately equal, the evapotranspiration rate of intercepted water will be about equal to the potential evapotranspiration rate. However, in forests where the dry canopy resistance greatly exceeds the aerodynamic resistance, the rate of evaporation of intercepted water might be 3 to 5 times the rate of potential evapotranspiration. Predictions based on the model have been verified through subsequent studies by Calder [1978], Gash and Stewart [1977], and Stewart [1977].

Rutter [1975] states that the temperature of a wet canopy is often lower than that of the surrounding air and that the small aerodynamic resistance found in forests allows a rapid sensible heat flux to move down such a temperature gradient into the canopy. This same principle was demonstrated in a model developed by Murphy and Knoerr [1975], who concluded that such enhanced evaporation can occur for forests of large areal extent, where horizontal advection may be small. This point was questioned by McNaughton [1976], who concluded that without the contribution of advected energy there would be no increase in the evaporation rate of intercepted water when the canopy is wet. Rutter [1975] observed that the rate of interception loss in the winter in coniferous forests may be as rapid as that in summer. He explained that this is possible because (1) the energy for evaporation of intercepted water comes mainly from the air, as previously discussed, rather than net radiation; (2) that temperature and saturation deficits differ much less between summer and winter on rainy days than on dry days, at least in England; and (3) that windspeeds tend to be higher in winter and thus aerodynamic resistance is lower. Calder [1977] found that reliable predictions from the Rutter-type interception model were very sensitive to small errors in the measurement of vapor pressure deficit. He concluded that without improvements in the measurement of such meteorological variables, there is little to be gained in further development of transpiration and interception models.

Advection

The influence of the advection of sensible heat from a relatively dry area to a more moist area is a problem which has long plagued attempts to evaluate evapotranspiration. In such cases, the energy used for evapotranspiration by well-watered crops can exceed the energy supplied by net radiation by a factor of 2 [Verma et al., 1978]. When this difference occurs, the saturation pressure deficit term in the numerator of the Penman-Monteith equation becomes relatively more important [Rutter, 1975; Jury and Tanner, 1975]. This relationship reiterates the importance of accurately measuring vapor pressure deficit in the field, as discussed by Calder [1977]. The Bowen ratio-energy balance method has been widely used as an indication of the performance of other models, including the Penman-Monteith equation. The Bowen ratio technique has been found to be reasonably accurate under non-advective conditions. However, under advective conditions, Verma et al. [1978] found that the Bowen ratio consistently underestimates evapotranspiration from well-watered alfalfa growing in a lysimeter by 20 to 30%. This underestimation was in response to advection of a regional scale, not from local influences due to insufficient fetch. The Bowen ratio approach assumes that the exchange coefficient for sensible heat is equal the exchange coefficient for water vapor. During advective conditions, the transfer of heat and water vapor is often in opposite directions [Verma et al., 1978]. Warhaft [1976] has shown theoretically that under such situations large differences in the two exchange coefficients will occur. Morton [1975, 1976, 1978] has proposed a complementary relationship between potential evapotranspiration estimated at a climatological station and the evapotranspiration from the surrounding area. In other words, the potential evapotranspiration is viewed as both the cause of areal evapotranspiration and the effect of areal evapotranspiration. This view is consistent with that of the relative importance of regional advection discussed above. Thus, rather than this being an iconoclastic view, as suggested by Morton, it is one further example of the importance that evapotranspiration models adequately evaluate the influence of regional as well as local advection.

Soil Water Evaporation

Evaporation of water from the soil is controlled by the availability of energy and the rate of water conduction to the soil surface. As the soil dries, energy availability becomes less important and the rate of soil water conduction becomes more important. The Priestly-Taylor formula, which uses only the radiant energy portion of the Penman-Monteith equation and a proportionality constant, a, has been successfully used to evaluate soil water evaporation when energy is limiting [Jackson et al., 1976; Stewart and Rouse, 1976a; Tanner and Jury, 1976, Woo, 1976; Mukammal and Neumann, 1977]. Substantial discussion has centered on the appropriate value for a. As drying progresses and soil water evaporation moves from the energy-limiting phase to the soil-limiting phase, the Priestly-Taylor approach becomes less applicable. Evaporation during the soil-limiting phase has been estimated for a number of years by using a simple relationship proportional to the square root of the time since the start of the soil-limiting phase. Jackson et al. [1976] proposed that since albedo is proportional to the surface water content of soil, the rate of change in albedo would be indicative of that fraction of the soil surface in which water is evaporating at the soil-limiting rate. Thus, the soil surface could be proportioned into fractions, a portion of which would evaporate at the energy-limiting rate and a portion which would evaporate at the soil-limiting rate. However, Van Bavel and Hillel [1976] state that the transition to the soil-limiting phase is not due to changes in albedo, but to the hydraulic properties of the soil and to a reduction of the relative humidity at the surface to less than 1. The transition between phases can be identified by a rapid increase in the amplitude of the surface temperature.
Van Bavel and Hillel propose an extension of the Penman equation by incorporating terms related to the hydraulic and thermal properties of the soil profile.

Transpiration Modification

The reduction of evapotranspiration to increase water supply or reduce irrigation requirements has been a long standing goal in arid and semi-arid regions. Most of the recent work has been directed toward modifying canopy resistance through the use of chemical antitranspirants [Kreith er al., 1975]. Several of the suggested chemicals, however, are toxic to plants or animals. In some cases, the reduction of transpiration is accompanied by a reduction in photosynthesis; the water use efficiency of the plant is, therefore, unaffected. A naturally occurring plant hormone, abscisic acid (ABA) has shown promise to be a non-toxic antitranspirant. Abscisic acid content has been shown to increase in leaves which are exposed to water stress [Vaadia, 1976] and has the effect of reducing the stomatal aperture in light [Raschke, 1975]. Nordin [1976] found that exogenous applications of ABA lowered the amplitude of transpiration in the light. Talha and Larsen [1975] found an approximately linear relationship between transpiration rate and the logarithm of the concentration of exogenously applied ABA. The magnitude and persistence of the effect was related to the ABA concentration. However, in a later study on plants subjected to water stress, Talha and Larsen [1976] concluded that once a sufficient concentration of endogenous ABA has built up in the stressed plants, no further reduction of transpiration can be expected by additional exogenous applications of ABA. Thus, ABA might be most effective as an antitranspirant at intermediate soil water potentials.

The effectiveness of ABA applications in reducing transpiration seems to be related to species. A single exogenous application of ABA has been reported to reduce transpiration for several hours in wheat plants [Bengtson et al., 1977] to 21 days in young ash seedlings [Davies and Kozlowski, 1975b]. However, the ABA content of water-stressed plants has been observed to fall rapidly to the pre-stress level upon watering while stomatal resistances remain high. Thus, there seems to be no direct correlation between residual ABA concentration and the delayed recovery of transpiration rate [Beardsell and Cohen, 1975; Bengtson et al., 1977]. There is increasing evidence that the duration of the reported reduction of transpiration cannot be explained entirely by stomatal closure [Lancaster and Mann, 1977]. Consequently, the mechanism of ABA induced changes to transpiration rate remains obscure.

In the few studies where antitranspirants have been applied to plant communitites, only modest success has been obtained in altering the areal water balance. However, Belt et al. [1977] reported a 12% increase in summer streamflow after a 5% aqueous emulsion of silicone oil was sprayed on a 26-ha catchment in Idaho.

Instrumentation and Methods

Measurement of transpiration by mature forest trees presents a number of obvious problems. One procedure, that of measuring the velocity of the sap flow in the water conducting systems of plants, has been used with varied success for over 40 years. A well developed method of measuring sap flow velocities has been to measure the velocity of heat pulses in the stem. Lassoie et al. [1977] compared the temporal and spatial variation of heat pulse velocities in Douglas-fir stems with various direct measurements of evapotranspiration. They found the technique provided good correlations with foliar water loss and was sensitive enough to detect rehydration of tissues when water loss terminated. A modification of the measuring system by Kucera et al. [1977] allows quantitative measurements of changes in the transpiration flow rate to within a time increment as small as 1 minute. This system has been successfully used to correlate changes in transpiration flow with short-term microclimate data [Cermak et al., 1976; Huzulak and Elias, 1976; Balek and Pavlik, 1977]. Another method of evaluating transpiration rates by measuring water movements in the stem is through injection of some tracer into the stem and measuring the rate and location of arrival at the transpiring surface. Using a tritium injection method, Kline et al. [1976] found a linear relationship between transpiration and sapwood area of each tree. By knowing such a relationship, the transpiration of an entire forest could be approximated by using the estimated sapwood area of the forest and the measured relationship between transpiration and sapwood area [Jordan and Kline, 1977]. The sites and pathways of water movement at the cellular level within leaves has also been traced by using monosilicic acid [Aston and Jones, 1976] and Prussian blue [Burbano et al., 1976; Pizzolato et al., 1976].

There have been several improvements in instrumentation to evaluate plant water status. New porometers have been described for measuring conductance and transpiration of conifers and other species with irregularly shaped foliage [Bingham and Coyne, 1976; Kaufmann and Ekern, 19771. Thermocouple psychrometer instrumentation and methodology continues to be improved for measurement of leaf water potentials in situ [Hoffman and Hall, 1976; Brown and McDonough, 1977; Zanstra and Hagenzieker, 1977] or of excised samples [Manohar, 1977; Nelson et al., 1978] and for the measurement of soil water potential [Brown and Johnston, 1976].

The physically and biologically oriented evapotranspiration models are not practical for regional estimations because the detailed meteorological and vegetative data required are not available. The data restrictions are even more severe when such models are applied to mountainous forested regions or to countries where meteorological data are essentially lacking. Efforts continue to develop models which utilize data which can be collected with sensors located in aircraft or spacecraft [Idso et al., 1975; Heilman et al., 1976; J.E. Jones, 1977; Kanemasu et al., 1977] or stochastic simulation of the hydrologic cycle [Magyar et al., 1978]. Though improvements are being made, estimates derived from such methodology leave much to be desired. A promising and novel approach to calculate regional evapotranspiration uses rawinsonde data which are routinely collected at about 70 stations throughout the United States [Brutsaert and Mawdsley, 1976; Mawdsley and Brutsaert, 1977]. Such application of planetary boundary layer theory to estimate evapotranspiration requires additional research into the functional form of the similarity functions for sensible heat and bulk water vapor transfer under various conditions of atmospheric stability [Brutsaert and Chan, 19781.

Future Needs

We have advanced a great deal in understanding the physical and biological controls on evapotranspiration. The ability to apply models to field situations is less successful, particularly in forested areas and in other areas where data are lacking. We are still unable to predict the effect of timber cutting, wildfire, changes in species composition, or other cultural activities on watershed water balances. In many wildland areas, we are unable to measure adequately even areal precipitation - let alone the rather detailed meteorological data required to calculate evapotranspiration with the Penman-Monteith equations.

The ability to evaluate effectively the influence of regional and local advection upon calculated evapotranspiration needs to be more strongly addressed. Our ability to calculate accurately evapotranspiration within that cover condition between bare soil and full cover is still weak, particularly as to areal water loss from scattered vegetation of different species and sizes.

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