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EFFECTS OF SPECIES AND ARRANGEMENT OF FORESTS ON EVAPOTRANSPIRATION

JAMES E. DOUGLASS

Soil Scientist, Coweeta Hydrologic Laboratory, Southeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture, Asheville, North Carolina

ABSTRACT

Hydrologists seek to understand the process of evapotranspiration so that intelligent management of these losses is possible. This paper reviews work concerned with effects of species and their arrangement on evapotranspiration. Findings from early work are sometimes contradictory because of the range in soil, plant, and atmospheric conditions studied, but some generalizations can be made. Grasses usually use less water than forest species because of the shallower rooting habits of grass, but if evapotranspiration differences occur between forest species, they could not be detected except where rooting depths were unequal. Evapotranspiration varies with stand density and vegetative height, at least in humid regions, and evapotranspiration probably varies with slope and aspect as well. But the effect of these factors on the evapotranspiration process changes as soil, vegetative, and atmospheric conditions change. Early work provided valuable information to guide development of more sharply defined research in evapotranspiration processes, but it is important that new research recognize the dynamic nature of the process and provide for measurement of the principal soil, plant, and atmospheric factors controlling evapotranspiration.

APPROXIMATELY two-thirds of all rain falling in continental United States is returned to the atmosphere by evapotranspiration processes. Having estimated the magnitude of this water loss, the hydrologist now seeks to understand the process itself so that he can intelligently regulate these losses for the betterment of mankind. As we understand the process of evapotranspiration today, these management activities revolve around modifying arrangement and composition of vegetative cover. Thus, determining comparative water use by species and effects of arrangement of vegetation on evapotranspiration is a requisite for management.

In the past, evapotranspiration has been estimated from soil moisture, lysimeter, energy balance or vapor transport, and unit watershed studies, but each of these methods has interpretation limitations. Some of the more serious limitations of the soil-moisture method are small plot size, inadequate sampling depth, lack of replication, differing climatic regimen, instrumentation errors, and inability to separate accurately evapotranspiration and drainage. In lysimeter studies, boundary effects, particularly at the bottom of the lysimeter, small size, and "oasis" and "clothes line" effects offer real interpretation problems. Controlled watershed studies are useful for integrating evapotranspiration responses for catchments, but are usually unreplicated observations which provide little information on basic evapotranspiration processes. And the energy balance and mass transport methods, while possibly the most promising methods, have many instrumental and theoretical difficulties to overcome and are not widely used in forest evapotranspiration studies.

Perhaps the greatest single limitation to the interpretation of results from past studies has been the failure to recognize the dynamic nature of the process itself. King (1957), Tanner and Lemon (1962), and many others emphasize that the plant, soil, and atmosphere are all parts of a single dynamic system which transfers water to the atmosphere, yet all three of these factors never have been considered adequately in a single study of evapotranspiration from forest land.

Nevertheless, the large number of observations under a wide range of atmospheric, soil, and plant conditions permits some generalizations and conclusions concerning the effects of plant species, plant height, plant density, slope, and aspect on evapotranspiration. The objective of this review is to determine what has been learned from this work and, where possible, to identify areas where renewed efforts are needed. However, the paper does not consider the special problems associated with evaporation from snow surfaces.

EFFECT OF SPECIES ON EVAPOTRANSPIRATION

Hydrologists need to know whether seasonal or annual evapotranspiration varies between species because control of stand composition offers one means of regulating evaporative losses. There is evidence that some species, particularly seedlings grown under laboratory conditions, use less water than others because of differing vegetative characteristics, such as persistent versus deciduous foliage, leaf structure, arrangement, thickness, surface area and roughness, rooting habits, and other physiological factors (Kramer and Kozlowski, 1960; Kozlowski, 1964). The question of whether evapotranspiration varies between species has also been the subject of numerous field studies.

Forest versus Grass

One of the evapotranspiration comparisons most often made is between grass and shrub, chaparral or high forest. In a 7-year comparison of the moisture regimen of the upper 66-in. profile of piedmont soils supporting pine, pine hardwood, and broomsedge grass, Metz and Douglass (1959) found that forest vegetation consistently used more water and used water from deeper depths than the shallower-rooted grass. The difference in water use between forest and grass was attributed to differences in rooting depth; roots of forest species extended below 72 in. whereas broomsedge has few roots below 30 in. Marston (1962) also found that evapotranspiration was less for broomsedge than for oak, brush, or pine cover in eastern Ohio.

In Utah, Croft and Monninger (1953) observed that replacing aspen with a herbaceous understory increased soil water available for streamflow by about 4 in. and removing herbaceous understory further reduced evapotranspiration and made an additional 4 in. of water available for streamflow. Moisture use was closely related to rooting depth; aspen rooted to 6 ft and used all available moisture, whereas herbaceous vegetation only rooted to 4 ft and used very little water from deeper depths. Veihmeyer (1953) found a similar relationship in California when brush-covered plots were converted to grass. And at Black Mesa, Colorado (Anonymous, 1959), high forest used more water than grass.

Rowe and Reimann (1961) studied evapotranspiration from the upper 12 ft of soil beneath a dense oak–chaparral cover, annual grasses, and annual grass–forb plots in California for 4 years. Because rainfall was seasonally distributed, they were able to observe moisture depletion without undue rainfall complications. Evapotranspiration from the deep-rooted chaparral was greater than from the annual grasses. However, they found a distinct seasonal difference in water use: moisture was used most rapidly by grass during the wet winter and spring, but after the grass matured in July, water loss practically ceased, whereas chaparral continued to transpire water throughout the summer. After forbs invaded grass plots, seasonal evapotranspiration losses increased because forbs drew moisture from deeper depths and used moisture for a longer period than the annual grasses. Availability of water also limited evapotranspiration. During 1955, more water was available beneath grass plots than chaparral plots, and evapotranspiration was greatest for the grass–forb cover. During the following year, when water was more nearly equal between plots, evapotranspiration from the chaparral was greatest. They found that seasonal rainfall, rooting depth, season of the year, maturity of grass, species composition, and availability of water all influenced evapotranspiration.

Patric's (1961) lysimeter studies at San Dimas confirm results from these plots. He found that evapotranspiration from both grass and pine was initially more rapid than for oak species, but by the end of the growing season of typically dry years, woody plants used all available water from the 6-ft deep lysimeter whereas approximately 10 in. of available water remained beneath the grass. He also observed that drainage was always greatest from the grassed lysimeter.

These comparisons are all aimed at evaluating possible differences in water yield from watersheds. As plot studies, they represent single observations of the evapotranspiration phenomenon, and extrapolation of results from plots to watersheds is a hazardous step. Evapotranspiration by different species can also be compared using the control watershed approach. Any water yield change following species conversion on a calibrated watershed can be attributed to species change if deep seepage or leakage past the weir does not occur or is constant. One such watershed comparison is underway at the Coweeta Hydrologic Laboratory in the high-rainfall area of the Southern Appalachians. Some preliminary results from converting a 22-acre north-facing watershed from hardwood to Kentucky 31 fescue are presented in Fig. 1. During the first full year under grass, annual yield (therefore evapotranspiration) was about the same for hardwood and grass. Monthly analyses showed that during 1960, evapotranspiration was greater from the perennial grass than from hardwood during March through June when hardwoods were leafing out, and less during the remainder of the growing season. By June, the fescue had matured and a marked color change accompanied heading of grass. With each succeeding year, grass density declined, and by the end of the second

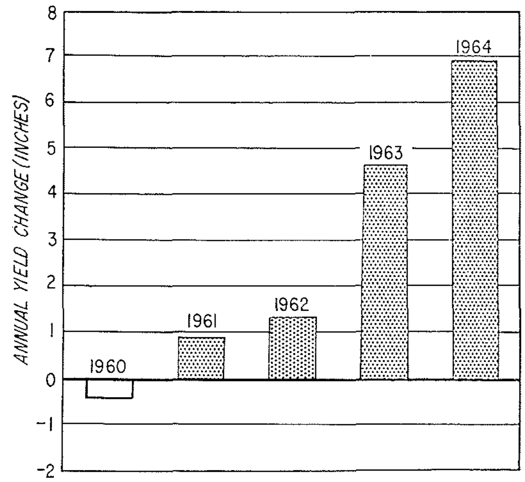

FIG. 1. Change in water yield after a hardwood forest on Watershed 6 was converted to grass.

year, differences in seasonal water use were not as pronounced and a significant annual yield increase (evapotranspiration decrease) occurred. By the fifth year after conversion, evapotranspiration from the hardwood was equal to or greater than evapotranspiration from grass during all months of the year, and total water use by hardwoods was about 6 in. greater than use by grass.

Study of long-term moisture records led Helvey and Hewlett (1962) to conclude that under the humid climatic conditions prevalent at Coweeta, vegetation seldom suffers from drought. Under these conditions, upward diffusion of water along potential gradients can occur (Patric *et al.*, 1965). Even with recharge by rainfall prevented for three consecutive years by sealing the soil surface with plastic, mobility of water remained high beneath forest plots. Each year after leaves fell, the moisture deficit of 20-ft profiles was partially replenished by water diffusing upward and laterally from wetter surrounding soil (Fig. 2). Water probably moved upward during the growing season but was masked by rapid root absorption. Gardner and Ehlig (1962, 1963) also report that water loss from deep soils which were not fully occupied by roots was both by local absorption and upward movement along potential gradients. Perhaps this mobility of water partially explains why a shallow-rooted but dense stand of grass at Coweeta used as much water as a forest stand.

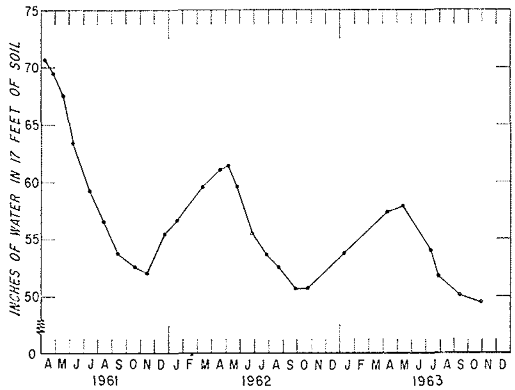

FIG. 2. Soil-moisture fluctuation in a forested mountain plot covered with plastic continuously for 3 years.

Rooting depth has its greatest effect on evapotranspiration in regions characterized by distinct wet and dry seasons. Under these conditions, soil moisture is rapidly depleted from the root zone, matric potential is high, and gradients from wet to dry soils are often abrupt. These conditions are associated with low capillary conductivity at the wet–dry soil interface, a condition which can sharply limit upward movement of water.

The grassed watershed at Coweeta and studies by Patric (1961), Rowe (1963), and Rowe and Reimann (1961) suggest that early maturing of grass is another important factor in evapotranspiration differences between forest and grass cover. The correlation found at Coweeta between evapotranspiration and grass density suggests that density also affects water use by grass. Hewlett (1961) found that both length and density of grass growing in a sloping soil model varied with distance from the water table. Perhaps slope and distance from water table indirectly affects evapotranspiration from grass by reducing density of the transpiring surface.

Height differences may be contributing factors in the lower evapotranspiration from grass vegetation, particularly in humid climates when soil moisture is not limiting. Lemon *et al.*, (1957) found greater evapotranspiration from tall than short cotton in Texas because more advective heat was trapped by taller cotton. Greater air circulation and turbulence in forest than in grass may also be important. However, in less humid regions the limited availability of water beneath shallow-rooted grasses is probably responsible for the lower seasonal evapotranspiration from grass.

Between Forest Species

The possibility of transpiration differences between conifers and deciduous hardwood has intrigued foresters and hydrologists alike, and many comparisons of moisture depletion under conifers and hardwoods have been made (Lull and Axley, 1958; Metz and Douglass, 1959; Moyle and Zahner, 1954; Patric, 1961; Zahner, 1955). Most investigators report that well-stocked forest vegetation appears to use water at about the same rate regardless of species. Urie (1959) reports that red pine rapidly uses moisture from the upper 7 ft of deep sand soil of northern Michigan from April until June while oak stands are leafing out, but the two types did not differ in total soil-water utilization. Because some water may have drained through the profile, equal seasonal moisture deficits may not represent equal evapotranspiration. One of the clear-cut differences in water use by coniferous and hardwood species occurred at Black Mesa, Colorado (Anonymous, 1959), where aspen used about 6 in. more water from the surface 8 ft of soil than spruce during the same time period. This difference was attributable to rooting differences.

As with grass, variations in rooting depth seem to cause the only significant difference in seasonal evapotranspiration from pine and hardwood stands. Variations in rates of water use have been observed in early spring when hardwood is leafing out, but whether or not they cause significant seasonal differences in evapotranspiration depends on the amount and distribution of rainfall, soil depth, and possibly other factors as well. Limitations, such as sampling depth, instrument errors, moisture variability, and the inability to separate evapotranspiration and drainage have prevented detection of differences if they exist. Inability to separate evapotranspiration and drainage is critical during the dormant season. Comparison of net radiation measurements during winter months might give quicker and more reliable indications of differences than studies based on moisture sampling.

EFFECTS OF VARYING STAND DENSITY ON EVAPOTRANSPIRATION

Vegetative density, by modifying the area of transpiring surface, net radiation, interception, wind patterns and turbulence, and root distribution, affects evapotranspiration rates from forest stands. Bay and Boelter (1963), Bethlahmy (1962), Della-Bianca and Dils (1960), Douglass (1960), McClurkin (1961), Moyle and Zahner (1954), Tarrant (1957), Zahner (1958), and Zahner and Whitmore (1960) studied effects of basal area reductions by logging, thinning, or other silvicultural treatments. In many cases, failure to sample the entire root depth and inability to account for drainage loss prevent direct comparison of evapotranspiration rates, but a tendency is clear—reducing stand density reduces evapotranspiration, and the greater the density reduction, the greater the evapotranspiration reduction. Under some climatic regimens, small density reductions may not be great enough to affect seasonal or annual evapotranspiration savings. Zahner (1955, 1958) and Bay and Boelter (1963) observed that small density reduction on study plots in Arkansas and northern Minnesota was not severe enough to affect seasonal moisture deficits even though treatments changed evapotranspiration rates.

Evapotranspiration savings obtained by reducing stand density can be attributed partly to changes in root distribution and interception losses. Roots of fully stocked stands are approximately evenly distributed horizontally (Coile, 1937; Patric *et al.*, 1965). When trees or groups of trees are removed, the uniform pattern of rooting is interrupted; roots are concentrated near trees and few roots occur in openings. Figure 3 illustrates an extreme example of variation in moisture distribution in the surface 8 ft of soil beneath a loblolly pine plantation thinned from a 6- by 6-ft to an 18- by 18-ft spacing. Rainfall and moisture changes during the 1959 growing season (Fig. 4) show continuing growing-season moisture accretion to, and

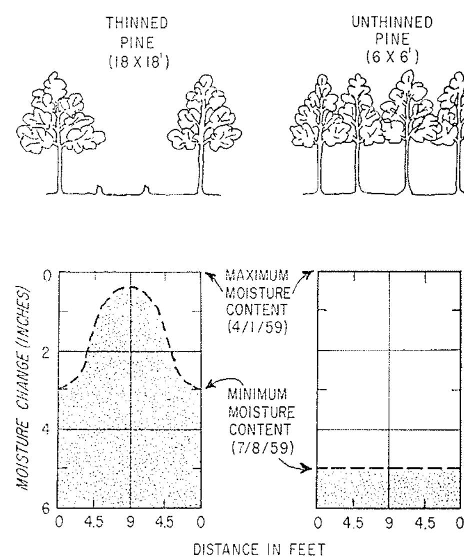

FIG. 3. A comparison of soil moisture distribution beneath a thinned and unthinned stand of loblolly pine. The thinning was done during April 1959.

some drainage through, the 4- to 8-ft profile of the thinned stand. The large storms of May, July, and August–September barely penetrated to 5 ft in the adjacent unthinned

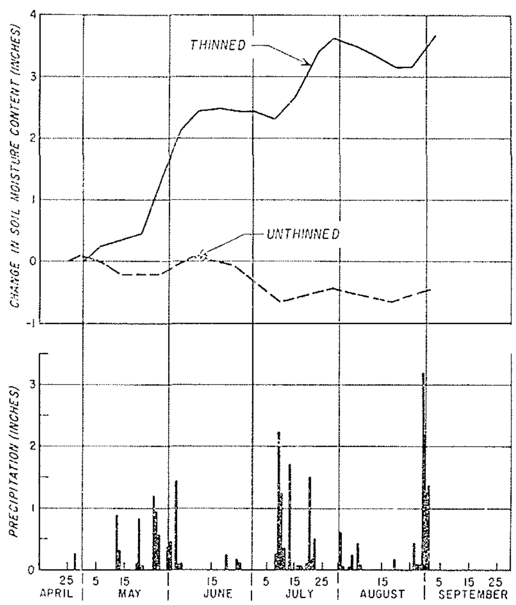

FIG. 4. Change in average soil-moisture content of the 4- to 8-ft depth under a thinned and unthinned loblolly pine plantation.

stand, and water did not drain from the profile. Zahner and Whitmore (1960) found that a similar treatment in a 9-year-old loblolly plantation (thinning to a spacing of approximately 21 by 21 ft) produced an unequal distribution of roots in the top 2 ft of soil which lasted 5 years.

Effects of reducing stand densities on net evapotranspiration savings on a monthly, seasonal, and annual basis are best shown in unit watershed studies where deep seepage or by-pass at the weir do not occur or are constant during calibration and treatment periods. In such studies, Reinhart *et al.* (1963) found that a commercial clearcut and a diameter limit cut which removed 86 and 59 percent, respectively, of the board-foot volume of hardwood stands in mountains of West Virginia resulted in increased growing season streamflow (evapotranspiration savings), but had no significant effect on dormant season flow. An extensive selection cut (removing 31 percent of board-foot volume) significantly increased growing-season flow (reduced evapotranspiration) but did not increase annual flow significantly. An intensive selection (removing 20 percent of board-foot volume) did not significantly alter seasonal or annual streamflow. Goodell (1958) also reports streamflow increases from a 40 percent reduction in basal area by timber cuttings in Colorado, but Rich (1959) found that removing 36 percent of the basal area of a mixed conifer stand in Arizona by logging and timber stand improvement work did not increase streamflow significantly. Hewlett and Hibbert (1961) report that a cove hardwood and a riparian cut in the Southern Appalachians did not increase annual flow, whereas other cuttings that removed 22 to 100 percent of stand basal area significantly increased annual water yield. Much of the increase came during the growing season, and the increases obtained by cutting north-facing watersheds were roughly related to the basal area removed. Large basal area reductions gave yield increases all through the year, but yield increases from small basal area reductions tended to be restricted to the season during which evapotranspiration savings actually occurred.

The accuracy of the equation for predicting streamflow response limits the accuracy of estimating evapotranspiration. In some cases, density reductions may produce evapotranspiration reductions which are too small to detect. Also, timing of the evapotranspiration reduction cannot be judged from water yield data because of the lag between rainfall occurrence and reappearance as streamflow. In the dormant season, for example, an increase in flow may originate from either a dormant-season evapotranspiration reduction or a growing-season evapotranspiration reduction which only appears in the dormant season because of this lag response.

EFFECT OF STAND HEIGHT ON EVAPOTRANSPIRATION

Empirical formulas for estimating potential evapotranspiration from vegetated surfaces have been useful for setting limits on evapotranspiration. However, Rider (1957) cautioned that the concept of equal potential evapotranspiration, irrespective of crop size or character, should be approached with utmost caution. Lemon *et al.* (1957) observed that evapotranspiration from cotton fields varied with heights and leaf surface area. They found that evapotranspiration exceeded that possible from the net radiation received, and concluded that taller plants were receiving more advective heat by horizontal energy transfer than smaller plants growing under similar soil, moisture, and radiation intensity levels. Bahrani and Taylor (1961) observed greater evapotranspiration than could be explained from net radiation measurements, and Rutter (1963) found that evaporation from intercepted rainfall during the winter was sometimes greater than could be accounted for by empirical formulae.

Results from watershed treatments at the Coweeta Hydrologic Laboratory indicate that stand morphology strongly modifies evapotranspiration (Patric, 1962). Rainfall at Coweeta averages 80 in. per year, average monthly rainfall exceeds potential evapotranspiration computed by the Thornthwaite method (1955), and moisture is almost always readily available to plants (Helvey and Hewlett, 1962). Matric potential records from forested plots which had the soil surface covered with plastic to prevent recharge show that even after a complete growing season, matric potential at 1 ft did not exceed 2 bars (Patric *et al.*, 1965). Under these conditions, change in water yield with time as clearcut watersheds regrew can be taken as evidence of evapotranspiration changes with changes in vegetative height.

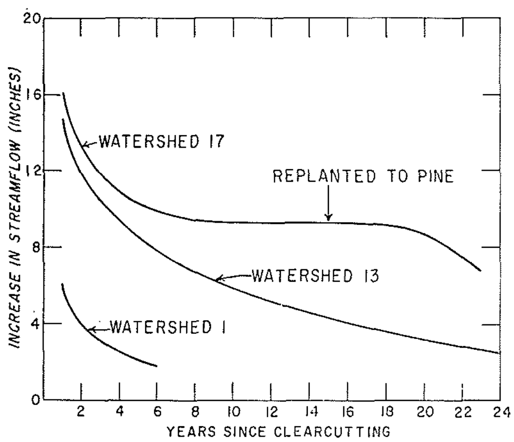

FIG. 5. Changes in water yield from three clearcut watersheds caused by an increase in evapotranspiration with regrowth of forests.

Figure 5 shows the effect of vegetative regrowth on the yield increase obtained after clearcutting three Coweeta watersheds. As the forest regrew on Watershed 13, yield decreased and calculations indicate that yield increases will become negligible after 35 years. Watershed 17 was clearcut, and sprout growth was cut annually until 1955, except for 4 years during World War II. From 1947 through 1955, cover consisted of seedlings, sprout growth, blackberry, blueberry, and miscellaneous forbs and grasses. In 1956 white pine was planted, and pines were released by cutting or spraying competing hardwood sprouts from 1956 to 1962. During this period, yield leveled off 9.3 in. above pretreatment levels. Since about 1959, or the 18th year after treatment, yield appears to be diminishing similarly to the decrease on Watershed 13. On Watershed 1 (the only south-facing clearcutting) yield increase diminished much more rapidly than on 13 and 17, but the same time trend is apparent.

Although the yield reduction with regrowth may not be altogether a response to vegetative height, neither can it be attributed to changes in ground cover, rooting, leaf surface, or moisture differences. By about the 3rd year after cutting, ground cover is complete. Rooting patterns are altered by the cuttings, but roots reoccupy the upper profile rather quickly, and Kovner (1955) found that leaf production on Watersheds 13 and 17 was slightly greater than for the control watershed after 13 years. Because a water surplus exists during every month, height is the best remaining explanation for these time-yield changes. A similar tendency has been observed following re-establishment of vegetation in several other watershed studies.

EFFECT OF ASPECT AND SLOPE ON EVAPOTRANSPIRATION

Many scientists have noted the correlation of slope and aspect with vegetation and environmental factors. Croft (1944) studied the effect of slope and aspect on snowmelt and streamflow in the Wasatch Mountains of Idaho. Hydrologists in the West, concerned with snowpack management, recognize that microclimate differences due to aspect and slope affect spring snowmelt. Although radiation is recognized as the energy source for evaporation, the effect of aspect and slope on energy available for evaporating water has only recently received serious attention. Swift (1960) computed theoretical differences in intensity and quantity of solar radiation available for evapotranspiration in sloping topography. He prepared a series of curves expressing extraterrestrial radiation on various slopes and aspects as a percentage of that on a horizontal surface, the common standard for radiation tables and field measurements. These corrections ranged from 0 to over 300 percent, depending on season, aspect, and inclination of slope.

Figure 6, taken from Swift's work, compares extraterrestrial radiation theoretically available on two watersheds at Coweeta. This figure illustrates that aspect and slope profoundly affect theoretical extraterrestrial radiation receipt, particularly in the spring, fall, and winter. If actual radiation differs by this order of magnitude, aspect and slope can be expected to have a significant effect on evapotranspiration. Pending completion of a study of actual net radiation retained by clearcut and forested north- and south-facing slopes, radiation differences on north-facing Watershed 17 and south-facing Watershed 1 are taken as a major reason for the approximately threefold difference in yield response of these watersheds to clearcutting.

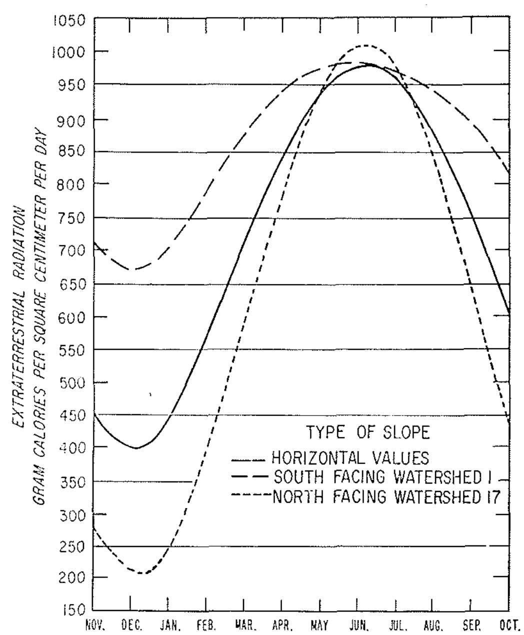

Fig. 6. Comparison of extraterrestrial radiation for two watersheds and the horizontal at latitude 35°N.

CONCLUSIONS

Greatest differences in evapotranspiration from wildland cover types are found for forest and grass. Under humid climatic conditions and readily available moisture, evapotranspiration may not differ between forest and dense grass cover. However, the bulk of evidence shows that grass uses less water than forest, primarily because less water is available to the shallower-rooted grass. Physiological factors account for variations in timing of water use, and moisture availability and rainfall distribution can cause important variations in seasona water use by grass and forest. Effects of stand height, density, and color on evapotranspiration probably are important factors but have not yet been assessed. Additional work is needed to evaluate the effect of variation in soil, plant, and atmospheric factors on evapotranspiration by grass.

Except where gross differences in rooting occur, annual evapotranspiration does not appear to differ between forest species grown at the same location under similar soil and atmospheric conditions, but the evidence is not conclusive. Perhaps evapotranspiration does vary between species; if so, the methods and equipment used in the past were not sufficiently sensitive to detect the difference. Comparison of evapotranspiration between species, particularly coniferous versus hardwood species, needs additional study. Data from soil moisture measurements cannot be relied upon for accurate dormant season evapotranspiration measurements because of simultaneous evapotranspiration and drainage, but net radiation measurements may be valuable indicators of evapotranspiration differences.

Stand density and reductions in stand density cause evapotranspiration to vary. Experience has shown that when less than 20 percent of the basal area of well-stocked forest stands is cut, usually neither growing- nor dormant-season evapotranspiration (as measured by streamflow increases in controlled watershed studies) is changed significantly. In humid regions, cutting more than 20 percent of basal area usually reduces evapotranspiration and increases streamflow. Streamflow response is limited to the growing season when the density reduction is small, whereas large cuttings can produce streamflow responses in both dormant and growing season. However, clarification is needed on whether the dormant-season increase is a watershed lag response to lower growing-season evapotranspiration rates or whether there is actually less evapotranspiration during the dormant season. In locations where precipitation is seasonally distributed, and in areas where most precipitation occurs as snow, evapotranspiration patterns and resulting water yield responses need additional study.

There is some evidence that evapotranspiration increases with stand height in humid regions, possibly because of a greater utilization of radiant energy and advective heat and increased air turbulence with increasing stand height. Study is needed to identify which atmospheric factors cause evapotranspiration to increase with vegetative height and to determine whether vegetative height has a significant effect on seasonal evapotranspiration in drier climates where soil moisture is limiting.

The amount of solar energy available for evaporating water varies with slope and aspect. Failure to account for slope and aspect effects can cause errors in estimating potential evapotranspiration from empirical formulae. Comparisons of solar energy actually received on various slopes and aspects are needed. The water manager also needs to know how much water is lost to the atmosphere under various physiographic, soil, atmospheric, and vegetative conditions.

Results from early studies have aided in developing a better understanding of some of the effects of species and arrangement of forests on evapotranspiration. This understanding is helpful in developing a more perceptive future program of research in evapotranspiration. But in the future we cannot be content with yesterday's studies, equipment or methods for they are not likely to produce really new information. The main difficulty in interpreting earlier work was that no sound base for interpreting or comparing results existed because some needed atmospheric, soil and plant parameters were not measured or varied widely between and sometimes within studies. Future work should provide for measurement of as many of the variables affecting evapotranspiration as practical. As a minimum, measurements should include matric potential of soil water, diffusion pressure deficit within the plant, and net radiation above the stand. Although these measurements certainly do not encompass all the needed information, they provide better data for interpretation and comparison of study results than was available in the past.

Tanner once commented that studies of the energy balance are not for the novice. However, until we fully consider atmospheric factors causing moisture to move from earth to atmosphere, we cannot hope to answer the piercing questions facing us today. Neither can we continue to consider the plant as a passive medium transmitting moisture only when the atmosphere calls. Nor can we ignore the soil, which freely passes or tenaciously clings to each particle of water. We know that evapotranspiration is the interaction of interdisciplinary processes, and if we are to gain the maximum information from our efforts, our research approach must also be interdisciplinary.

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DISCUSSION

ZINKE: Have you noticed any typical parameters of configuration of conifer crowns and any systematic variation in these with regard to latitude? In the case of configuration of conifer crowns in an array of foliage in relation to incoming radiation in a northern latitude, have you made any measures of angles of slope of these crowns?

DOUGLASS: No.

ZINKE: If you look at the different species and the way they array in North America, it is apparent that crowns become more sloping in angle as you go farther north. One could say, perhaps, that this is a genetic response to incoming radiation, but this might be an oversimplification.