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Tree Water Stress in Relation to Water Yield in A Hardwood Forest

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In a Hardwood Forest

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WATER RESOURCE RESEARCH CENTER
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ABSTRACT

Stomatal resistance, xylem potential, soil-water potential, stem diameter, net radiation, air temperature, humidity and wind were measured through a summer in a northern hardwood forest and on sunny and shady edges of clearings. Rainfall was about normal, and stomatal closure due to water stress occurred only as an ephemeral midday phenomenon. Yellow birch had lower diffusion resistance (2.5 sec/cm) than beech and sugar maple (3.0 and 3.4), implying possible transpirational differences. Diffusion resistance varied by species during leafout; it remained low in autumn until leaves turned color. Several trees were artificially stressed by preventing rain from reaching their roots; after two weeks stomata began to close early in the day, presumably limiting transpiration and growth. The single-leaf energy balance was found to work on leaves in the canopy within the limits of measuring accuracy. Transpiration of trees on the edges of forest openings is probably greater than if there were no opening due to increased radiation and clothesline advection. A single large clearcut will reduce evapotranspiration more and provide greater water yield increase than cutting the same forest area in a number of smaller blocks.

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OBJECTIVES

Forty-five percent of the northeastern United States is covered by hardwood forests. These forests are a major source of water and the demand for this water is increasing very rapidly. About half of the annual precipitation on these forests is evaporated and does not become streamflow. Most of this evaporation loss is transpiration from the trees. In order to manage the water resource in the northeast, we must know more about forest evapotranspiration and how it is altered by land management practices.

This project was established to study in the field the factors that affect transpiration from hardwood trees, and to determine how these factors change following a strip-cutting of the forest. The objectives were given as follows in the project proposal:

(1) To study the microclimate of a stripcut forested site, particularly in relation to differences in water stress across the stripcut, and the resultant influence on water yield.

(2) To study partial and complete daytime stomatal closure in a hardwood forest and evaluate this in terms of actual vs. potential evapotranspiration.

(3) To test the theory of the single leaf energy balance under field conditions for hardwood leaves.

These objectives have been reached for the most part. We discuss our results in the following sections: Water Stress and Stomatal Behavior; Phenology and Transpiration; Single-Leaf Energy Balance; and Strip-Cutting, Microclimate and Streamflow.

FIELD SITES

The major field location for this project was a set of three
micro-meteorological towers located in the strip-cut watershed 4 on the
Hubbard Brook Experimental Forest in central New Hampshire. The cut
strips were 25 m wide, with 50 m of forest between them. The long axis
of the strips ran parallel with the contour in a NE-SW direction. The
watershed has a SE aspect. The three towers were placed in one uncut
strip, one each on the sunny, southeast edge, in the middle, and on the
shady northwest edge. Micro-climatic data was obtained from instruments
at two or three levels on each tower. A centrally located shed housed
data-logging equipment for all three towers. For some techniques, such
as sampling for a pressure chamber and diffusion porometer measurements,
the towers had to be climbed for access to the leaves. Field data were
obtained in the summers of 1971 and 1972.

Several experiments were conducted in greenhouse and growth
chamber facilities at the University of New Hampshire. A field study
of diffusion resistance in spring was carried out in the vicinity of
Durham, New Hampshire.

Diffusion porometer measurement and instruments on the sunny-edge tower.

WATER STRESS AND STOMATAL BEHAVIOR

A diffusion porometer measures the resistance to diffusion of water vapor out of a leaf. This resistance is low when stomata are fully open and high when they are closed. This instrument is still being developed as a research tool and we spent considerable time modifying the calibration and operation procedures.

Stomatal opening changes as a function of light, temperature and water potential. In adequate light and normal temperatures the water relations of the plant control stomatal behavior. Thus diffusion resistance is an indicator of water stress in these conditions. When stomata are partially closed due to water stress, both transpiration and photosynthesis are reduced. Stomatal behavior varies among species of plants. In retrospect, it seems that the most important objective and result of this study has been the compiling of the first available data on stomatal behavior for mature northern hardwood trees, and the first data on any stressed hardwoods.

We concentrated our efforts on the three dominant species of the northern hardwood forest, yellow birch (Betula alleghaniensis), beech (Fagus grandifolia) and sugar maple (Acer saccharum). These species have stomata only on the underside of the leaves, so resistances were measured only on that side.

The summer of 1971 was rather wet, and we did not see any obvious evidence of stomatal closure due to water stress. The summer of 1972 was even wetter, but we had fortunately decided to artificially stress several trees. We did this by digging a more or less circular trench around the base of several trees and then covering the soil surface with polyethylene taped around the tree trunks. This effectively prevented rain from entering the soil block, allowed the soil to dry, and produced obvious stomatal closure in about two weeks

Results of our investigations of stomatal behavior on both the artifically stressed trees and normal ("unstressed") trees have been discussed in a manuscript titled "Diffusion Resistance and Xylem Potential in Stressed and Unstressed Northern Hardwood Trees". This manuscript is being submitted to Ecology. We will only summarize our findings here.

In unstressed trees, resistance was high at night when stomata were closed, from 20 to more than 50 sec/cm. As light increased, resistance decreased rapidly as the stomata opened in all three species until the light level reached 1.5 μE cm^{-2} min^{-1},* which is about one tenth of full sunlight. In our trees resistance was virtually independent of light above this level.

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* In discussing light and photosynthetic processes, it is the flux of photons rather than the energy flux or luminous flux that is important. An Einstein (E) of photosynthetically active radiation is defined as 6.02×10^{23} photons in the wavelength band from 400 to 700 nm.

Diffusion resistance has been found to depend on temperature by other workers, but evidence is conflicting on the amount and even the direction of this dependence. We could not find any evidence of a temperature effect on resistance of unstressed trees in the range from 15 to 30° C.

In sufficient light for full opening, there was a substantial difference in mean diffusion resistance among species. Mean values were 2.4 sec/cm for yellow birch, 3.0 for beech and 3.4 for sugar maple. Although the range of values we measured was about 2 sec/cm for each species, yellow birch had lower resistances than beech and maple in 86 out of 87 direct comparisons made at the same time on adjacent trees. Evidently real differences in diffusion resistance exist among hardwood species; these differences may imply differences in transpiration rates from pure stands of these species.

Leaves of beech and sugar maple are all of the same age, but yellow birch has two types of leaves of different ages. In yellow birch early leaves expand simultaneously during the initial leafout period, but late leaves are produced on each shoot at intervals of several days into July. We could not find any difference in resistance between fully expanded early and late leaves.

Xylem potential, which we measured with a pressure chamber, is closely related to the water potential in the leaf, which in turn can affect stomatal aperture. The evaporative demand of the atmosphere is controlled primarily by radiation load, but also by temperature, humidity and wind. As the evaporative demand increases, water evaporates from the leaf, drying it and decreasing its water potential.

The xylem potential in the twig decreases correspondingly, and the result-
ing potential gradient between the soil and the leaf causes water to move--
the transpiration stream. If either the potential gradient is too small or
resistance to flow in the soil-xylem system is too high, the supply of
water to the leaf may not be able to keep up with the evaporative demand.
The leaf then dries further and this loss of turgor causes the stomata to
begin to close. The stomata become closed as much as is necessary to
reduce the evaporation loss to equal the water supply rate and prevent
further leaf drying. We tried to get some initial insight into the relations
of evaporative demand, xylem potential, soil-water potential and stomatal
behavior for mature hardwoods.

At night xylem potential was -4 to -6 bars in our trees. Since
soil-water potential was always between zero and -0.2 bars for our unstressed
trees, this implies either that water was moving into the trees throughout
the night or that there are osmotic potential differences that are not
understood. We found that stem diameter, which has decreased during the
day, does not recover overnight either. A moderate to heavy rain may be
necessary to restore a tree to a fully wet condition after a day or more
of drying.

After sunrise, stomata opened rapidly, reducing diffusion resist-
ance, and xylem potential dropped rapidly, both reaching values that we
now associate with daytime operation. The diffusion resistance has been
discussed above. The xylem potential tended to level off after the net
radiation reached about 0.6 ly/min, with values averaging -17 bars for
yellow birch, -23 bars for sugar maple, and -24 bars for beech.

During a clear or partly cloudy day with quite wet soil, we
found that diffusion resistance varied by 1 or 2 sec/cm and xylem potential

by several bars through the day. These changes are much smaller than we thought our instruments could detect. We did not realize until we evaluated the field data that we should have taken pressure bomb samples at the same time as we took porometer measurements at each location on each tree. Nevertheless, data for August 1 and 2, 1972, clearly show a slight midday closure of stomata and associated change in xylem potential. The changes occur within an hour or two and analysis is complicated by rapidly changing net radiation on these partly cloudy days. However, from this and from more limited data from other days, we believe that high evaporative demand caused reduced xylem potential and temporary partial stomatal closure in hardwood trees at our site even when the soil was well watered.

When rewetting by rain was eliminated in our stressed plot, the soil dried and after two weeks stomatal closure was severe. Soil dried more rapidly near the surface, so a single value of water potential could not be applied to the whole soil mass. However, once most of the soil had dried to -0.5 to -1 bar, which took about two weeks, stomata failed to open fully in the morning and closed gradually through the day to diffusion resistances of 10 sec/cm or more. However, surprisingly, xylem potentials did not differ by more than 1 bar between stressed trees with closed stomata and unstressed trees. This implies that the relation between xylem potential and diffusion resistance is not a simple one.

After allowing drying through July, 1972, we chose to rewet the plot and duplicate the experiment. Behavior in the second drying period in August was similar to behavior in July. Premature senescence occurred in September in the stressed trees. Once the stomata have closed and can no longer limit further (cuticular) transpiration, xylem potential must

decline as the plant desiccates. However, in our study the soil did not dry enough to cause this behavior.

For several reasons our data were insufficient to define the relationship between soil-water potential, leaf-water potential, evaporative demand and stomatal behavior in the range when stomata are closing. First, there is still no simple way to specify the appropriate depth -- integrated value of soil-water potential. Second, we have not determined the relation of pressure bomb reading to total leaf-water potential, osmotic potential and turgor potential. However, we do believe that such relations must be determined in situ on stressed, mature trees rather than on seedlings or on cut twigs allowed to desiccate. Third, most of our data were taken during partly cloudy conditions with varying evaporative demand. This made our diffusion resistance and xylem potential data difficult to interpret.

PHENOLOGY AND TRANSPIRATION

In spring and autumn stomatal behavior and thus transpiration are affected by morphological and physiological changes in the leaves. Prior to our studies, little was known about these effects. In the autumn of 1971 we measured daytime diffusion resistance and chlorophyll content of leaves at our main study site throughout the color change period. The results of this study have been published in Water Resources Research as "Stomatal Resistance During Senescence of Hardwood Leaves." In the spring of 1973 we conducted a study in the Durham area of diffusion resistance during leaf development in the spring.

In the early autumn, green leaves had resistances measured in summer. However, as chlorophyll was destroyed sufficiently so that the leaves became yellow-green, their resistances were frequently quite high and covered a range from 3 to more than 35 sec/cm. With complete chlorophyll destruction and yellow or brown leaves, resistances were always more than 10 sec/cm and averaged about 30 sec/cm. This is equivalent to night-time values and indicates either closed stomata or lack of water supply to the leaf, or both. We conclude that in autumn transpiration continues unabated in green leaves, but declines to small values when leaves turn color.

Preliminary work on leafout in the spring of 1972 showed us the great differences in kind and rate of leaf development among species. In 1973 we measured diffusion resistance at about 5-day intervals on one to three trees each of ten species (Table 1). The spring was very rainy and phenologically late.

We measured black, paper and river birches and found no important differences among them. Yellow birch is hard to find around Durham in the

exposed sites with leaves at ground level that we needed for this study. Generally in the birches 2 leaves are produced from each bud. These are the "early" leaves; the "late" leaves develop some weeks later as the shoot elongates, and we did not measure them in this study. The early leaves were green when the buds broke around April 20 and their diffusion resistance was low, about 5 sec/cm even when the leaves were only 4 cm long, the smallest leaves we could measure. Resistance declined through the month required for expansion and continued to decline for 10 more days before reaching summer values of about 3.5 sec/cm by June 5.

Trembling aspen has four to six early leaves, which, like the birches, develop to full size before shoot elongation begins and late leaves are formed. The aspen also broke its buds about April 20 but took only about 20 days to reach full size. Resistance declined from 7 sec/cm with small leaves to summer values of about 3 sec/cm after June 1. Leaves became darker green through this period so the rather prolonged resistance decline may be related to chlorophyll buildup even after the leaves reached full size.

Making diffusion porometer measurements on the sunny-edge tower.

Table 1. <u>Dates of bud break, full leaf expansion, and beginning of</u>

<u>minimum or summer resistances and the associated diffusion</u>

<u>resistances, by species.</u>

Species	Budbreak		Full expansion		Summer resistance	
	Date	Resistance[1]	Date	Resistance	Date	Resistance
birches	Apr 20	5.0	May 25	4.0	June 5	3.5
aspen	Apr 20	7.0	May 10	5.0	June 1	3.0
cherries	Apr 20	5.5[2]	June 5	4.5	June 15	4.0
beech	May 5[3]	7.5	May 25[3]	6.0	June 20	4.0
sugar	May 5	7.5	May 25	6.0	May 10	6.0
maple[4]	May 5	14.0	May 25	5.5	June 10	4.0
red oak	May 1	13.0[5]	June 10	4.0	June 15	3.5
scarlet oak	May 5	11.0[5]	July 1	3.5	June 15	3.5

[1] Resistance on leaves as soon as they were large enough to be measured.

[2] Cherry resistances increased to 6.0 sec/cm around May 20.

[3] One tree of the three was about 10 days later.

[4] Two individuals on first line, one individual on second line.

[5] Resistance increases to 18 sec/cm several days later.

Pin cherry and black cherry buds also broke about April 20 and like the birches and aspen had green leaves and resistances about 5.5 sec/cm from the time the leaves were large enough to measure. Expansion of the early leaves was completed by June 5, when late leaves, produced after flowering is completed, were expanding rapidly. Diffusion resistance appeared to increase to 6 sec/cm during flowering and then declined to summer values of 4 sec/cm by June 15.

Beech and sugar maple are determinate species in which all the leaves of the year expand simultaneously from the bud. Beech buds extend greatly before they open. The leaves are green and 5 cm long when they unfold; this occurred about May 5 on two trees and May 15 on a third. Resistance at these times was about 7.5 sec/cm. The beech leaves grew very rapidly, reaching full size in 20 days. Resistance was about 6.0 sec/cm at that time and continued to decline to summer values around 4.0 by June 20.

In all three sugar maple trees the expansion phase lasted from May 5 to May 25. But in diffusion resistance one sugar maple behaved quite differently from the other two. All three were saplings from 8 to 20 feet tall and were in rather shaded and widely separated locations. One tree had a resistance that was 14 sec/cm after budbreak, and declined to 5.5 sec/cm at full expansion and 4.0 sec/cm by June 10. Except for the high initial resistance this behavior was similar to other species and appears to be normal. The other two began with resistances about 7.5 sec/cm and maintained high and variable resistances of 5 to 9 sec/cm through the spring and summer. The behavior was similar to stomatal closure observed on mature trees after two rainless weeks (see above) but the spring was very rainy and the trees were moderately shaded saplings.

The oaks differ greatly from the other species studied. They are determinate, like beech and sugar maple, but the leaves are very small and very low in chlorophyll after bud break. Leaf development was slow, taking 40 days in red oak and nearly 2 months in scarlet oak; and it occurred simultaneously with shoot elongation. In the other determinate species leaf expansion is completed before elongation begins. Diffusion resistance was high on the small pinkish leaves. It was around 12 sec/cm after bud break, and then increased a few days later to 18 sec/cm, perhaps due to cuticle formation. Resistance remained above 10 sec/cm until May 25, then dropped rapidly to 6 sec/cm and more gradually thereafter to 3.5 sec/cm by June 15. The oaks maintained a strikingly higher resistance later in the spring than any other species.

In general, the results indicate that indeterminate species that are also generally shade-intolerant and early succession species, open their buds and expand their leaves earlier than other species. They also have low diffusion resistance early in the spring. Both in leafout and in diffusion resistance they get a jump on the other species in photosynthesis, and coincidentally in transpiration.

Beech and sugar maple, both shade-tolerant, late successional, determinate species are slower to produce their leaves and to reduce diffusion resistance. All of these species except the oaks are diffuse porous and the transpiration stream involves the several outer annual rings. Oak is ring porous, water conduction is mainly in the large vessels of the current annual ring. This ring is about half developed by the time of bud break in the spring. The slow leaf development and high resistance appear to be a mechanism to reduce water loss in spring until the ring is developed sufficiently to conduct adequate water.

Evidently transpiration in species like the birches is limited by leaf area but not by diffusion resistance in spring and can reach maximum values by May 20. On the other hand, in oak, transpiration is limited both by leaf area and by high diffusion resistance until June 1 or later. We are planning on simulating the effect of these differences on soil-water and streamflow in the near future. This will tell us if the differences are important with respect to streamflow. The results of this field study and the simulation will be published together as one paper.

Sealed plot to create artificial water stress and base of shady-edge
tower.

SINGLE LEAF ENERGY BALANCE

Canopy modelling, or simulation of the water, heat, and CO_2 fluxes in a canopy, has become an important tool in plant science. The simulation is based on the application of the energy balance to single leaves at several different levels in the canopy. Theory provides an equation for the energy balance of single leaves, but this equation had never been tested on leaves in their natural condition in a hardwood forest canopy. We set out to make such a test as part of this study, since we were already measuring the important variables--radiation fluxes, air temperature, humidity, wind and diffusion resistance. By adding measurement of incident solar radiation and leaf temperature for individual leaves, we were able to calculate net radiation, sensible heat flux, and latent heat flux for the leaf independently. The algebraic sum of the three fluxes should equal zero due to conservation of energy. Failure of this to occur implies either error in the theory and its assumptions or error in the measurements.

Measurements were made on yellow birch and sugar maple leaves at four heights on the tower in the uncut strip on August 30 to September 1, 1972, and at two heights on one artificially stressed and one unstressed yellow birch on September 6, 1972. All data were averaged over half-hour intervals before the calculations were made.

Difficulty of measuring the average irradiance of the leaf surface caused balance errors as large as 0.25 ly/min for partially shaded leaves in the upper canopy. Balance errors for leaves in full sun were less than 0.1 ly/min. Evidently the 1/2 x 1/2 cm solar cell we used to measure irradiation on the leaf did not provide an adequate estimate of the average irradiation over the whole leaf. Often, because of nearby leaves, one part of a leaf is in the sun and the remainder in shade for time intervals

nearly as long as the half-hour everaging period. For shaded leaves during the day, balance error was less than 0.02 ly/min; this was caused by error in measuring longwave radiation.

The measurement of leaf temperature was also difficult and led to some error. To measure leaf temperature properly, the sensor should be inside, rather than on the surface of the leaf. However, our leaves were very thin and we did not develop a technique for inserting a sensor. Any sensor on the leaf surface risks being in the boundary layer of the leaf and thus not having the same temperature as the leaf. We applied a layer of insulation over the sensor. However, we are not very satisfied with the results.

For leaves in the sun, the ratio of sensible heat loss to latent heat loss (by transpiration) was usually between 1 and 3. For shade leaves the sensible heat loss was close to zero since the leaf temperature was close to air temperature, while the latent heat loss remained positive. Sugar maple leaves had higher stomatal resistances than yellow birch leaves and hence partitioned less heat into transpiration and more into sensible heat.

In summary, our measurements showed generally that the theory is satisfactory. We attribute the errors we found to measurement error rather than to theoretical error. Repeating the experiment with better measurements might be desirable but would be difficult.

This experiment is described more completely in a M.S. thesis by William Wenkert, "Testing an energy balance model on individual leaves in a hardwood canopy." A manuscript based on this thesis has been prepared but we have not yet decided whether to submit it for publication.

STRIP-CUTTING, MICROCLIMATE AND STREAMFLOW

We knew that the strip-cutting of watershed 4 would reduce its evap-
otranspiration and thus increase its streamflow. However, we did not know
by how much. There was a possibility that trees on the sunny edge of the
openings would transpire rapidly and become water stressed. We did not know
the effect this would have on streamflow.

The microclimate, soil-water regime and resulting evapotranspiration
in and around a series of forest openings are very complicated. We did not
set out to measure all this variation. We decided to measure microclimate
at the edge and center of the uncut strips around the tree crowns, and to
measure soil water at two locations in the cut strips and two in the uncut
strips. A great deal of data was obtained and it has been only partially
analyzed. Further analysis would be time-consuming and is complicated by
some instrumentation difficulties so we do not intend to do it at this
time. We have been able to develop some hypotheses based on the analyzed
data.

The changes in streamflow resulting from cutting one-third of the
watershed in strips has been documented.[1] Streamflow increased (and thus
evapotranspiration was reduced) by 28mm the first summer and 36 mm the
second summer. These figures contrast with the average increase of 290 mm
following complete devegetation of a nearby watershed. Since only one-
third of the strip-cut watershed was cut, we expected one-third of 290 mm

[1] Hornbeck, J. W., G. E. Likens, R. S. Pierce and F. H. Bormann.
1974. Stripcutting as a means of protecting site and streamflow quality
when clearcutting northern hardwoods. Proc. 4th North American Forest
Soils Conf., Quebec. (in press)

Hornbeck, J. W. 1973. Changes in yield and quality of stream-
flow after stripcutting northern hardwoods. Ph.D. thesis, State Univ. of
New York, College of Environmental Sci. and Forestry, Syracuse, N.Y., 98p.

or 97 mm as a first guess at the increase produced by strip-cutting. The measured increase in streamflow was much less than that. The mean summer evapotranspiration from a fully forested watershed is about 450 mm. This was decreased only 32 mm or 7% by the strip-cutting even though one-third of the trees were removed. Before we suggest the reasons for this, let's look at the microclimate results.

Transpiration is affected by four atmospheric variables: net radiation, air temperature, humidity and wind. We measured each of these at two heights on each of the three towers, but in not more than four of the six possible locations at one time. The upper height was near the top of the tree crowns and the lower height was near the base of the crowns.

Above a closed canopy wind speed decreases as the canopy is approached from above. Within the canopy speed drops rapidly, and then if there is a stem-space, more slowly as the ground is approached. But speeds at the bottom of the crowns are much less than at the tops of the crowns. In a strip-cutting, the clearings are great holes through the canopy that allow wind to penetrate the stem space from the side, so that differences in speed between the tops of the crowns (upper level) and the bottom (lower level) are less. On the edge of the clearings, the speed at the lower level was about 20% less than at the upper level, while in the center of the uncut strip the speed at the lower level was one-third to one-half that at the upper level. Compared with a complete cover then, the ventilation of the crowns in a stripcut is increased since crowns on the clearing edges are exposed and lower crowns in the center are affected by blow-through in the stem space.

Wind speeds around the tree crowns are remarkably steady in summer. We found very few daytime periods with winds less than 0.5 m/sec or more

than 2.0 m/sec. Both calm periods and strong winds were rare. Even within the uncut strip at night, slope-induced winds maintained speeds of greater than 0.3 m/sec. This implies that heat loss from the leaves in the strip-cut forest is dominated by forced convection.

Wind direction affected the relative speeds on the opposite edges of the clearing (Fig. 1). With south winds, the sunny-edge wind was higher, and with north winds, the shady-edge wind was higher. The differences were on the order of 30%.

Overall the picture is one of a well-ventilated canopy in which wind speed differences among locations are probably too small to be important.

With such good ventilation and mixing, air temperature and humidity should also be well-mixed and this is what we found (Fig.1). Temperature differences among locations were seldom more than 2°C and often were less. Vapor pressure differences seldom exceeded 3 mb. More detailed study of the differences is hampered by the necessity for more data analysis and by a questionable calibration of one of the four sensors. We can state that there are no large differences in temperature and humidity among locations.

Even with small temperature gradients, a clothesline effect can still exist if wind speed is high enough as it was here. Warm air from the opening, with its lower evaporative rate and thus more heating of air, could be transferred laterally to the adjacent forest strip, and help to increase its transpiration rate. This is called the clothesline effect. The temperature differences involved need be only on the order of a degree. No theory exists for calculating the magnitude of this effect. However, we cannot doubt that it exists in this strip-cut situation.

Differences in net radiation at the upper levels were slight when the radiometers were exposed to direct sun. Radiation on the lower sensors was generally low except in the presence of sunflecks (Fig. 1), since the
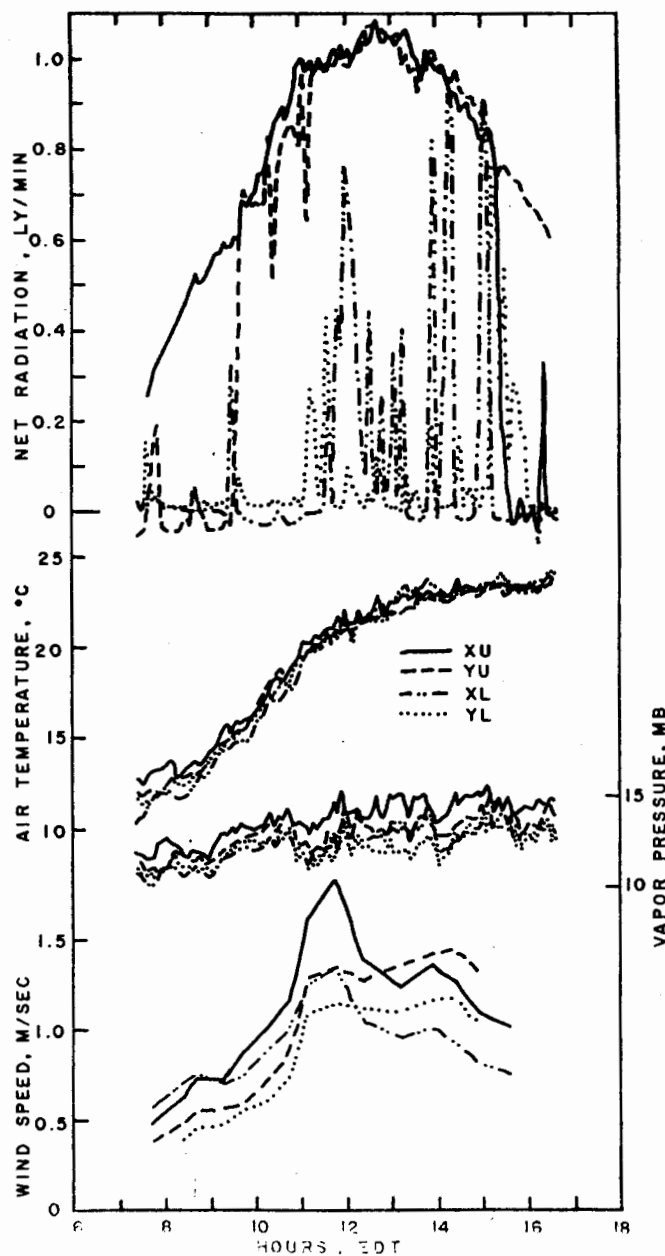
Figure 1.--Net radiation, air temperature, humidity and wind speed
at 4 locations on August 13, 1971. XU--upper level on
sunny edge of opening, XL--lower level on sunny edge,
YU--upper level on shady edge, YL--lower level on shady
edge.

sensors were located somewhat into the canopy from the true edge of the clearing. In the early morning, the upper sensor on the shady edge remained shaded by higher crowns until 9 a.m. EST. In the late afternoon the sun to the west illuminated the shady edge, which faced northwest, while the sunny southeast-facing edge became shaded.

Net radiation was measured with horizontal sensors. In terms of radiation load on the trees on the edge of the clearing, sensors oriented at some angle, say 45° facing the clearing, would have been better. Then they would have been parallel to the outer surface of the crowns of the edge trees. In order to eveluate the increased absorption of solar radiation by the sunny edge trees, we developed a model of direct solar radiation on the strip-cutting.

The model assumes an infinitely long opening of a given width with the long axis parallel to a slope of given angle and azimuth. The opening has vertical walls, the canopy top is a plane parallel to the ground slope, and the canopy top and sides are impenetrable to light. We wrote a computer program that calculates at half-hour intervals the fraction of the direct solar radiation reaching the canopy top, the canopy side, and the ground, and integrates these fractions over the day by weighting with potential insolation. The model works for any slope, aspect, date, crown height and ratio of cut to uncut strip width.

For the openings in watershed 4, 2/3 of the direct radiation always falls on the top of the uncut strips. The remaining 1/3 reaches either the walls of the opening or the floor. For a slope of 15 degrees and an aspect of S 40°E on June 21, 7.5% reaches the wall and 25.8% reaches the floor. On Sept. 15, 10.7% reaches the wall and 22.6% reaches the floor. The 7.5 to 10.7% reaching the walls can be used for additional transpiration from the mature trees. The sunny-edge trees thus have a greatly

increased radiation load on them after the cutting. If they can get an adequate water supply, they presumably have greatly increased transpiration rates.

Tensiometer data obtained in 1971 show that there was consistently higher soil-water content in the openings. Soil-water potential was about -0.04 bars immediately after a heavy rain in both cut and uncut strips. Within 1 week potential declined to -0.12 bars in the uncut strip, but only to -0.07 bars in the cut strip. These are rough averages of values that varied with depth. The root systems of trees in a hardwood forest are extensively overlapping or interlocking. The roots of trees on the edge of the openings extended far out into the wetter soil in the openings. Also, competition for water under the remaining trees at the edges was reduced since roots from adjacent cut trees no longer demanded water. We found no evidence of any greater water stress, as indicated by either pressure chamber or stomatal closure, on sunny-edge trees than on forest trees. Evidently, even though transpiration rates on sunny-edge trees were undoubtedly greater, greater water supply to them prevented any greater water stress.

Regeneration, composed of stump sprouts, seedlings, herbs and root suckers was prolific in the cut strips. By the end of the second summer a nearly complete green cover existed of one to six feet in height. Transpiration from such a cover can be nearly as great as in a mature forest.

Three reasons exist for the small decrease in evapotranspiration (about 30 mm for a year) following cutting one-third of a watershed in strips: (1) increased radiation load on trees on the sunny edges increases their transpiration, (2) clothesline effect increases transpiration of remaining trees, particularly those adjacent to the openings, and (3) regeneration in the cut strips transpires. As the size of cut openings

increases, the first two effects decrease in importance. If a given fraction of a watershed is to be cut, the water yield increase will be largest if the fraction is in a single clearcut block rather than in more, smaller openings.

CONCLUSIONS

All conclusions stated here are hypotheses regarding northern hardwood forests in New England. These hypotheses have been developed as a result of our work, and need further study before they are proven for the northern hardwood region.

1. In years of uniformly distributed, normal to high rainfall, stomatal closure due to water stress occurs only as an ephemeral midday phenomenon under high radiation loads.

2. When there has been little or no rain for two weeks, significant stomatal closure occurs early in the day, and transpiration and growth become limited by water stress.

3. Yellow birch has lower diffusion resistance (average 2.5 sec/cm) than beech or sugar maple (3.0 and 3.4 sec/cm). This may imply differences in transpiration among these species. The differences may be related to shade tolerance.

4. In spring, some species, especially oaks, have higher diffusion resistance and thus presumably lower transpiration than other species.

5. In autumn, diffusion resistance remains low and thus, presumably, transpiration remains high, until leaves turn color.

6. The theory of the single-leaf energy balance applies to leaves in a hardwood canopy, at least within the limits of our measurement accuracy.

7. Transpiration from trees on the edges of forest openings is probably greater than if there were no opening, due to increased radiation load and to the clothesline effect.

8. Cutting one-third of the trees on a watershed in narrow strips decreases evapotranspiration from the watershed by less than one-tenth due to increased transpiration from edge trees and to regeneration.

9.   If a given fraction of a watershed area is to be cut, water yield will
     increase most if the cutting is in one large block.

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    hardwoods in central New Hampshire.

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