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Argonne National Laboratory

RADIOLOGICAL PHYSICS DIVISION
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Environmental Studies

July 1969—December 1970

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FOREWORD

This is the third and final volume of the Radiological Physics Division Annual Report. It encompasses work done from July 1969 through December 1970. Environmental Studies by nature are dependent upon weather, and the major field effort occurs from April through October. It is intended that Part III of subsequent Annual Reports will cover the calendar year, thus permitting a more complete presentation of the results of that particular field year to appear.

Environmental Studies include Atmospheric Sciences, Terrestrial Ecology, the Radiological Physics Division portion of the Great Lakes Research Program, and Bioenvironmental Studies (formerly entitled Fallout Studies).

Atmospheric Sciences still provide some meteorological support, but the major effort is devoted to research. Areas of emphasis have developed around urban meteorology, atmospheric chemistry, and lake meteorology, the latter being an integral part of the overall Great Lakes program. Terrestrial Ecology has, and will continue to, focus on water balance and nutrient (particularly trace elements) flow through local ecosystems. Particular attention has been devoted to tritium behavior between various trophic levels. The Great Lakes research in Radiological Physics is largely field work including physical measurements of existing thermal discharges into Lake Michigan, and investigations of the distribution of radionuclides from the Big Rock Nuclear Plant in water, sediments, and biota. Use of the Grand River outflow as an analog of a power plant discharge has begun as a joint effort between Argonne (including members of the Chemistry Division) and staff of the Great Lakes Research Division at the University of Michigan. The Bioenvironmental Studies program continues to follow fallout radioactivity in air, soil, food, and man, although part of this program has quite naturally switched over into the Great Lakes work.

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In the coming year research in Environmental Studies will become even more sharply focused on the environmental problems attendant on the siting and operations of nuclear power plants.

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TRITIUM STUDIES QUANTIFY WATER MOVEMENT IN AN OLD FIELD ECOSYSTEM

C. F. Jordan and J. R. Kline

Water movement through ecosystems must be quantified in order to estimate rates at which pollutants move through and out of ecosystems. For example, it is not enough to know the concentration of mercury in the water leaving the root zone of the soil. The rate that water leaves the root zone must also be known, because the rate at which mercury leaves the root zone is the product of mercury concentration times the rate of water movement.

Movement of water through ecosystems is also of interest because management of water supplies requires knowledge of transpiration, runoff, and deep drainage. In addition, from a radiological health standpoint movement of water is important because tritiated water is released into the environment from nuclear reactors or plowshare activites.

The objective of the studies reported here is to quantify water flow through and out of an old field ecosystem. This ecosystem was chosen because it is similar in form and structure to ecosystems common in the midwest, and because it is a convenient and readily available place to work.

The general approach taken is to inject tritium labeled water into one compartment of an ecosystem and measure its activity as a function of time in other compartments.* The activity-time curves of the isotope in the compartments then are used to determine transfer coefficients for isotope movement out of every compartment.** The transfer coefficients times the mass of various compartments is the rate at which water moves out of the compartment via transpiration, runoff, evaporation, downward flow, and diffusion.

*A compartment is a portion of an ecosystem small enough to be considered homogeneous within the practical limitations of the experiment.

**A transfer coefficient is the probability of an individual particle moving out of the compartment along a given pathway per unit time.

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Horizontal Movement through Upper Soil

The experimental area was in a field uncultivated for about 20 years and located in an area about 300 yards south of the meteorology building at Argonne National Laboratory. The terrain slopes downward toward the south at about a five degree angle in this area. On April 13, 1970, a hole 10 inches deep and 1/2 inch in diameter was bored in the soil. Twenty millicuries of tritium and one milliliter of water were pipetted into the hole, and the top of the hole was covered with soil. Soil samples were taken periodically in a gridwork pattern surrounding the injection point and down to a depth of 10 inches with a 1/2-inch diameter soil auger. Water was extracted from the soil with a vacuum-drying manifold designed to condense and collect water as it diffuses out of the sample.[1] Samples were counted by standard liquid scintillation techniques, and results were corrected for background and converted to dpm through the use of counting efficiency curves.

It was anticipated that it would be possible to calculate the rate of lateral flow of the tritium by measuring the time for the peak of activity to pass between two downslope sampling locations. However, horizontal movement was much slower than anticipated, and another sampling scheme was required. On May 21, duplicate samples were taken every 2 inches from the injection point for a distance of 2 feet in northerly (upslope), southerly (downslope), and westerly (perpendicular to slope) directions. Single samples were taken every foot from 2 to 6 feet.

Activity of tritium on May 21 as a function of distance upslope and downslope from the injection point is shown in Figure 1. The shape of the curve is a result of two processes, diffusion and mass transport, acting simultaneously on the tritiated water. There has been movement of tritium both upslope and downslope from the injection point due to diffusion.

Movement due to mass transport is in a downslope direction only. There is spreading of tritium away from the peak due to the mass transport process as the peak moves downslope. This spreading occurs because soil, a porous medium, acts as a series of small dams which block some of the tritiated water molecules as they flow downslope. Consequently, part of the distribution of activity in Figure 1 is due to mass transport alone. Shortly after injection, this distribution is highly skewed because it is possible for some molecules to move downslope ahead of the peak, but molecules can lag behind only the distance from the peak to the injection point. As the peak moves further from the injection point, the shape of the curve gradually tends toward a normal distribution.

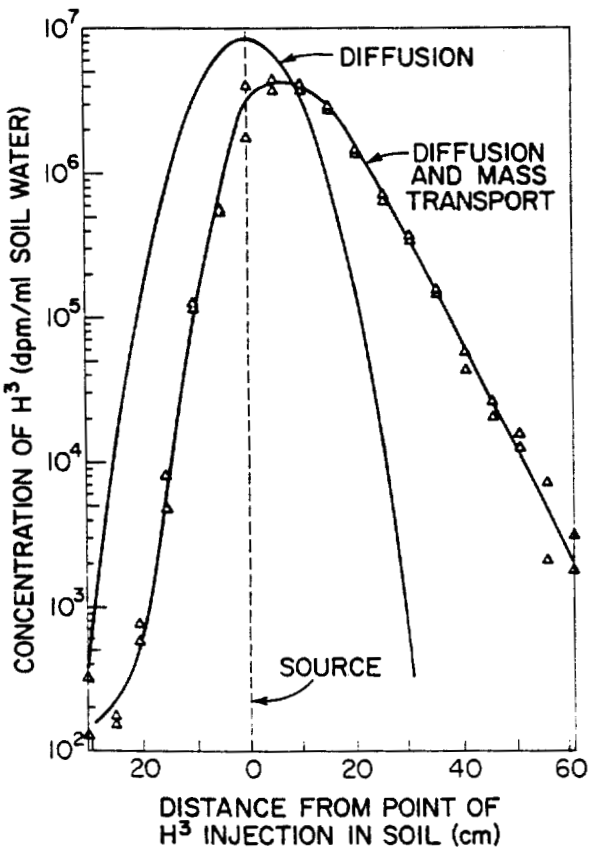

FIG. 1.--Observed distribution of activity along slope 38 days after injection at 0 cm, and predicted distribution due to diffusion process alone.

For purposes of modeling water movement through ecosystems, it is necessary to calculate the diffusion coefficient of water in the soil and the rate of water flow in a lateral direction. These calculations were made by D. Sasscer, visiting scientist from Puerto Rico Nuclear Center.

The curve of activity of tritium as a function of distance from the injection point in a direction perpendicular to the slope of the topography (Figure 2) was assumed to result only from the diffusion process. The data in Figure 2 were replotted in Figure 3 with the abscissa scale in

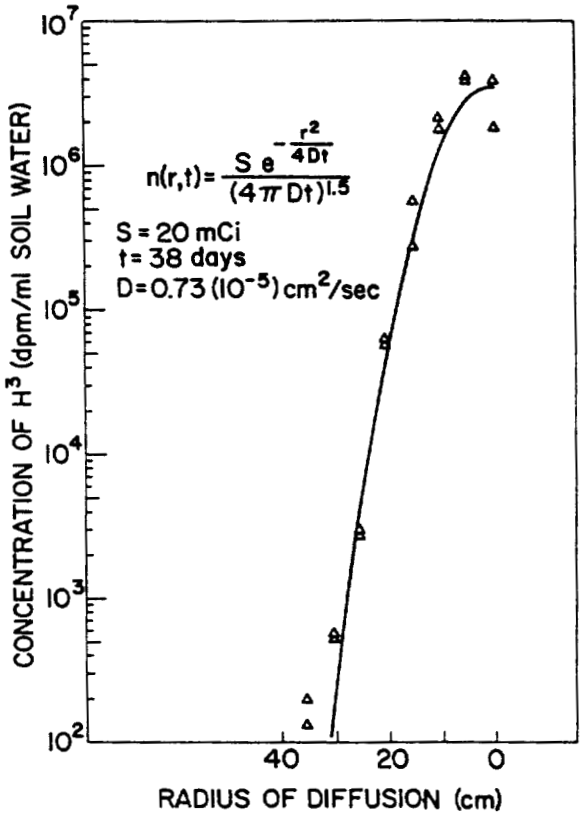

FIG. 2.--Observed distribution of activity perpendicular to slope 38 days after injection at 0 cm and predicted diffusion curve calculated from these data.

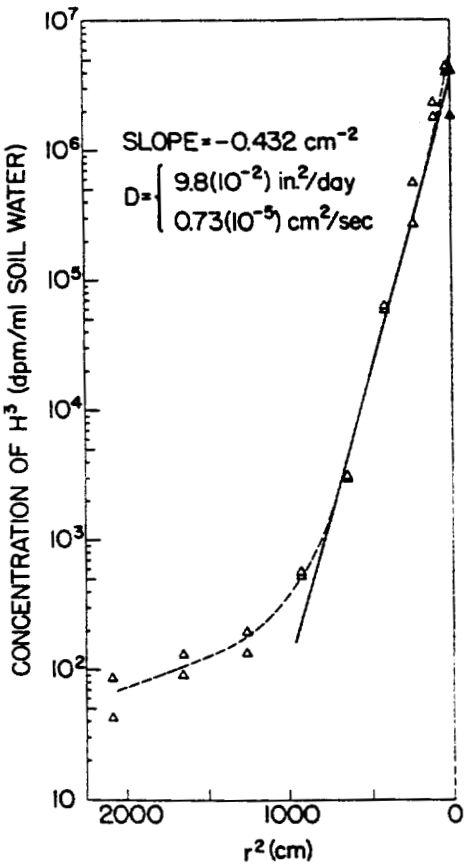

FIG. 3.--Observed and predicted distribution of activity perpendicular to slope 38 days after injection at 0 cm. Scale of abscissa is in units of distance squared so that any predicted distribution due to diffusion will be a straight line.

units of r^2 instead of r (r = radius of diffusion), thereby facilitating comparison of the observed curve with the calculated curve. With the abscissa in units of r^2, a diffusion curve is a straight line on log-normal paper (Figure 3).

The equation describing the diffusion from a point source is

$$n(r,t) = S \frac{e^{\frac{-r^2}{4Dt}}}{(4\pi Dt)^{3/2}} \qquad (1)$$

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where

n = activity at distance r from the source at time t

D = diffusion coefficient

S = activity of source.

Thus, at a given time, t = T,

$$\ln\left[\frac{n(r_1 T)}{n(r_2 T)}\right] = -\frac{(r_1^2 - r_2^2)}{4Dt} ,$$

or $-\frac{1}{4Dt}$ equals the slope of ln [n(r,t)] when plotted as a function of r^2.

From Figure 3 we obtain

$$-\frac{1}{4Dt} = \frac{\ln(10^3)}{(122.5 - 786.9)\text{cm}^2}$$

and since T = 38 days (April 13 to May 21)

$$D = 0.75(10^{-5})\text{cm}^2/\text{sec}$$

or

$$D = 9.8(10^{-2})\text{in}^2/\text{day}.$$

Bulk density of the upper soil horizon in the experimental area was 1.27, and the average water content during the experiment was 32%.

The self-diffusion coefficient value of $0.73(10^{-5})\text{cm}^2/\text{sec}$ for the experimental soil (Morley silt loam) during April and May of 1970 appears to be similar to values obtained from other soils in laboratory experiments. The self-diffusion coefficient of a Missouri soil with approximately the same texture as the Morley silt loam is given by Brees and Graham[2] as $0.417(10^{-5})\text{cm}^2/\text{sec}$ at a soil temperature of 21°C. The largest value of the diffusion coefficients observed in that study was $0.833(10^{-5})\text{cm}^2/\text{sec}$ for Beulah loam. Nakayama and Jackson[3] report considerably higher values of the diffusion coefficient. Values for agar gel, glass beads, and various Colorado soils range from $2.40(10^{-5})\text{cm}^2/\text{sec}$ for agar gel to a minimum of $0.87(10^{-5})\text{cm}^2/\text{sec}$ for Colorado clay loam.

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The calculated diffusion curve for T = 38 days is plotted in Figure 1 to give an impression of the relative contribution of diffusion towards the observed downslope distribution plotted in Figure 1.

The average distance that water molecules moved downslope due to mass transport was calculated in two ways: 1) the displacement downslope of the point at which the average number of molecules occurs is due to mass transport only because movement due to diffusion is equal in all directions. This displacement is assumed to be equal to the activity weighted average downslope movement of the tritium obtained through the use of Figures 1 and 2. It was calculated to be at a distance of 9.02 cm directly downslope from the injection point. Because it required 38 days for the average water molecule to move that distance, the rate of water flow is 0.24 cm/day. 2) If it is assumed that the molecules upslope from the peak of the activity curve in Figure 1 have moved upslope only through the process of diffusion, it is possible to calculate the displacement of the peak of the activity due to mass transport alone. The activity at the center of the curve after 38 days due to diffusion alone, would be $8.5(10^6)$ dpm/ml. We know the activity at some offset distance, r, from the source after 38 days is $3.5(10^6)$ dpm/ml (from Figure 1). Therefore, from Eq. 1, r = 8.382 cm, and the rate of water movement is 0.22 cm/day.

Vertical Movement of Soil Water

High moisture conditions

For this experiment, zero tension lysimeters[4] were used to collect water moving through saturated soil. These lysimeters are troughs one foot in length and two inches deep, and connected by tubing to collection jugs. The lysimeters are installed in narrow tunnels bored horizontally from a pit adjacent to the experimental plot. Two lysimeters were installed at each of four depths: beneath the litter, and at 5, 10, and 15 inches. Tunnels and pit were filled in after installation.

On April 13, 1970 40 mCi of tritium in 6 liters of water were sprinkled uniformly over an area 73.7 cm by 261.6 cm above the bank of lysimeters.

Collection jugs were pumped out weekly, and the water was analyzed by standard liquid scintillation techniques.

During the data analysis, it became apparent that concentrations of tritium in the lysimeters closest to the edge of the plot were lower than those towards the center, probably because of diffusion of tritium away from the plot, and for that reason only the data from the innermost lysimeters were used.

Activity as a function of depth at a series of times after tritium application is shown in Figure 4. Curves connect data points, but the shapes of the curves were adjusted so that a single exponential function could describe the amount of tritium in the soil as a function of the time since application, for the early spring period. The function is

$$Y_t = Y_0 e^{-0.693t}$$

where

Y_t = amount of tritium in the soil at a given time

Y_0 = amount of tritium initially in the soil

t = time in weeks.

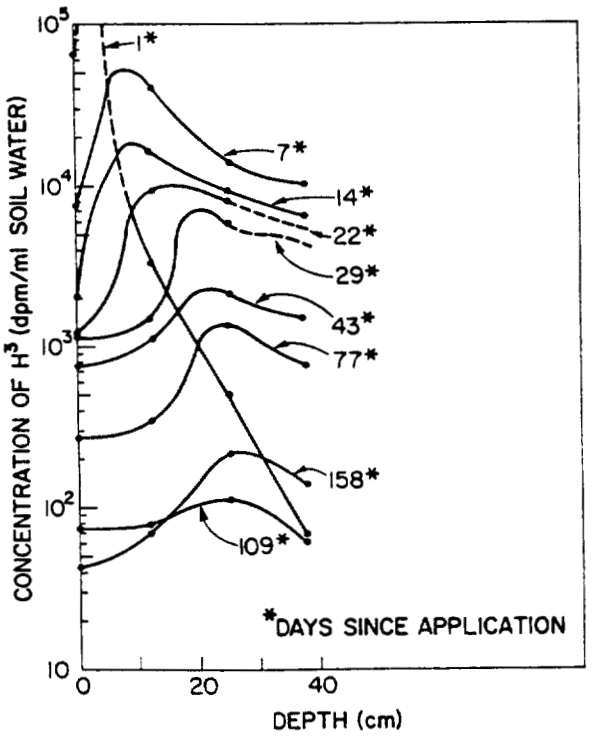

FIG. 4.--Concentration of tritium in the soil water as a function of depth at a series of times after the start of the experiment. Lines are drawn to connect data points. Where curves had to depart drastically from the data (days 1 and 29) for reasons explained in the text, or where data were missing (day 22), lines are dashed.

The movement of the peak of tritium activity shown in Figure 4 is interpreted as follows: The peak moves downward during each storm in proportion to the amount of rainfall after the soil above the peak reaches a saturation value (about 42%). Regardless of whether it is raining, tritium continually diffuses away from the peak in an

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at a rate similar to the diffusion in the horizontal movement experiment described previously. Upward movement away from the peak is much faster than downward movement in the vegetated plot, apparently because of the moisture gradient set up by transpiration. In the herbicide treated plot, diffusion away from the peak is about equal in upward and downward directions.

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TRANSPIRATION MEASUREMENT IN PINES USING TRITIATED WATER AS A TRACER

J. R. Kline, C. F. Jordan, and R. C. Rose*

Introduction

The measurement of transpiration of water by plants in the field is a problem which has not been solved, and yet this is one of the important variables needed in attempts to evaluate and quantify ecological theory, hydrological budgets, or compute plant moisture consumption in situations such as the irrigation of crops where water is a scarce resource. Approximations to transpiration or evapotranspiration have been obtained by tent methods, the cut leaf methods, heat pulse methods, or watershed balance techniques.[1,2] Recently, Taylor and Gates[3] proposed a modification of the cut leaf method which involves remote measurement of black body leaf surface temperature of both leaves which have been excised for weight loss determination and those which remain attached to the plant. Equal surface temperatures of both are taken to indicate that both are losing water at the same rate. Equations are given for correction of the loss rate from non-excised leaves when the surface temperatures are not equal. This method would require measurements on many leaves and a knowledge of the total leaf surface area of the plant for estimation of total water consumption rate by the plant.

Penman,[4] Thornthwaite,[5] and Blaney and Criddle,[6] working on evidence that transpiration is closely coupled to the regional energy budget, have proposed equations relating evapotranspiration, which is the sum of evaporation and transpiration, to such meteorological variables as temperature or, in some cases, humidity, solar radiation, wind speed, and rainfall. Pelton and Korven[7] have recently examined the approaches of these authors and found both the Thornthwaite and Blaney-Criddle methods inadequate for predictions of daily evapotranspiration but able to predict

*Honors student in the Radiological Physics Division during the summer semester, 1970.

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weekly values with reasonable accuracy for alfalfa in a semiarid climate. The Penman method accounted for 65% of the daily variation in evapotranspiration but requires extensive modification. Total evaporation in the field is often measured in these methods by the use of lysimeters which are normally expensive and delicate instruments. With lysimeters transpiration can be determined by measuring the soil evaporation separately or by eliminating soil evaporation.

Kline, et al.[8] proposed that transpiration by plants in the field could be measured with tritiated water, using the theoretical equations for flow problems which were presented by Orr and Gillespie[9] and which have been reviewed by Bergner[10] for applications in biology and by Ljunggren[11] for applications in engineering. This method cannot be used at this time for measurement of true daily transpiration rates. It gives, instead, average daily rates for whole plants during the interval of the experiment, which may vary from 10 days in mid-summer to 4 weeks in spring and fall. The purpose of the work, reported here in part, is to extend the basic method to the measurement of water consumption by plants on a seasonal basis, to search for improved relationships between transpiration and environmental variables, and to continue development of the basic method, particularly to shorten the time interval of the measurements.

Materials and Methods

Theoretical

The method for determining transpiration rates in trees is based explicitly on the theoretical analysis of tracer dynamics in flowing biological systems which was presented by Orr and Gillespie.[9] Their equation is given by Eq. 1:

$$C = F \int_0^\infty f(t)dt, \qquad (1)$$

where C is the total capacity of the system for the flowing material, F is the flow rate of the material, and f(t) is the fraction of the total initial

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tracer which is present in the system at any time subsequent to its introduction. In principle Eq. 1 should make it possible to measure transpiration in trees by injecting them with tritiated water and determining the resulting activity-time curve in some down-stream component of the tree. It is not possible, however, to obtain either the capacity, C, of a tree or the fraction of originally injected activity, f(t), because of the size of trees. Another form of Eq. 1 is given in the review by Ljunggren[11] and is shown in Eq. 2.

$$M = F \int_0^\infty f'(t)dt \qquad (2)$$

where M is the total activity originally injected, F is the flow rate through the system, and f'(t) is the specific activity of the tracer at any time subsequent to its introduction into the system. Equations 1 and 2 are analytically equivalent forms. The transformation from Eq. 1 to 2 has been demonstrated by Kline, et al.[8] The form of Eq. 2 is experimentally convenient, however, since specific activity of tissue water of plants is easily obtained and the amount of activity originally injected is under experimental control. This is the form of the expression which was used in these experiments.

Experimental

Fourteen red pine (*Pinus resinosa*) trees growing in a uniform stand in an introduced plantation on the Argonne site were injected two at a time with tritiated water in known amounts at approximately monthly intervals throughout the growing season of 1970. One milliliter of tritiated water of known specific activity (3.72×10^8 dpm/ml) was pipetted into each of four holes which had been bored at equal spaces around the base of the trees. The total injection was, therefore, 4 ml or 14.9×10^8 dpm. After injection the holes were sealed with a commercial tar-like grafting compound.

Composite needle samples were collected from each tree twice daily for the first week of the experiment and daily thereafter until tritium was no longer detectable in the tissue water. The needle samples were sealed in plastic bags and stored in a deep freeze prior to analysis. Tissue

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water was extracted from the needles by a freeze dry technique described by Koranda.[12] The water was counted by standard liquid scintillation counting methods. The results were corrected for background and counting efficiency and were expressed as dpm/μl of the tissue water.

The resulting data for each tree were plotted as a function of time from the initial injection on linear coordinates. The response curves were integrated, and the value of the total integral was used to solve Eq. 2 for flow which in trees is transpiration. Details of the methods for data handling and known sources of error in the method are given in Kline et al.[8]

The trees for this experiment were selected from a closed stand of uniform age (about 18 yr) red pines. The trees varied in height from 6.4 to 7.9 meters and averaged 7.6 meters. The average diameter was 11.6 cm measured 1.9 meters above the ground, and the stand density was 2905 trees per hectare. All trees for the experiment were selected from the interior of the stand.

Results

Transpiration

Transpiration by red pines on the Argonne site for the growing season of 1970 is given in Table 1. The results show a generally increasing transpiration rate in the early part of the season, which continues through late July and then abruptly falls off during the latter part of July, August, September, and October. The increasing early season values are consistent with Penman's view[4] that transpiration is under control of external meteorological factors, such as temperature or solar radiation, when soil water is not limiting. The sharply declining values in August indicate that transpiration control shifts at that time from meteorological factors to a water limited situation in which the available soil moisture limits the rate in spite of the fact that temperature and solar radiation remain high. In the fall of the year control shifts back to meteorological factors since autumn rains tend to restore the moisture. The values at this

TABLE 1. Transpiration in Red Pines at Argonne National Laboratory as Related to Season of the Year and Meteorological Variables[a]

Tree	Time interval of estimate	Transpiration[b] ml/hr/tree	Transpiration[b] cm/day	Mean solar radiation, langleys/day	Mean daily temperature (°C)
A-B	3/30-4/24	436	0.30	410	6.7
1-2	5/5-5/26	913	0.64	498	16.7
314	6/17-6/30	1170	0.82	538	20.3
5-6	7/7-7/20	1108	0.77	512	22.5
7-8	7/21-8/6	569	0.40	526	22.6
9-10	9/1-9/25	219	0.15	320	19.2
11-12	10/8-10/23	371	0.26	237	11.1

[a] Meteorological values were provided by Dr. H. Moses from Argonne Climatological Station data. The data are not taken from the actual forest location but from an open field some 300 yards away.

[b] Values are average of two for each time interval.

time remain low because temperatures and solar radiation are at lower levels than in midsummer. For the year 1970 transpiration was limited by low availability of soil moisture only for a period of 5 to 6 weeks during the late summer.

The onset of transpiration in the spring is not controlled by either meteorological variables or available soil moisture. The primary control at this time is soil temperature. The relationship between soil temperature and the time of onset of transpiration is shown in Figure 1. In the spring frozen soils tend to thaw from the surface downward. As the soils warm a lens of frozen soil remains for a short time between the thawing front advancing downward from the surface and the region below the surface which was never frozen. The final lens of frozen soil remains at approximately 10 cm below the surface. Figure 1 shows that transpiration in red pines began within hours of the time that the final lens of frozen soil reached temperatures above the freezing point. The control of the onset of transpiration by soil temperature is consistent with the view of

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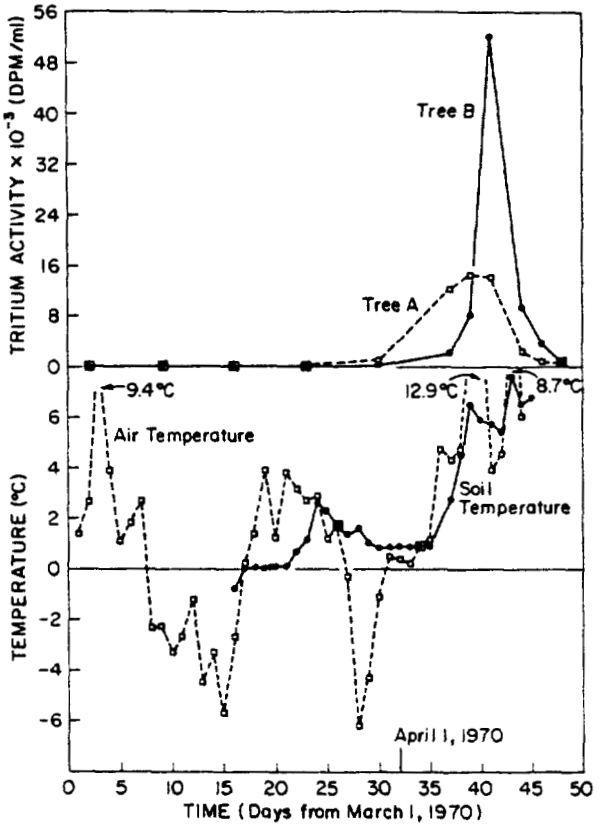

FIG. 1.--Relationship between soil and air temperatures and the onset of spring transpiration in red pines (Pinus resinosa).

transpiration as a capillary flow phenomenon since flow through a capillary cannot take place if any portion of it, regardless of how small, is plugged by ice crystals. Experiments are underway at this writing to determine what factors control the cessation of transpiration by conifers in early winter.

Confirmation of Measurements

Attempts to measure transpiration by individual plants in the field are usually subject to criticism based on the fact that the techniques required alter the quantity measured to a significant but unknown degree. Lysimeters yield the most reliable transpiration data, but these are expensive permanent installations which are restricted in their range of applicability. It is, therefore, difficult, if not impossible, to confirm the tritium method for measurement of transpiration by comparison to some other independent method. Indeed, the purpose of developing this method was that no convenient and reliable alternate method exists. Confirmation of the method by direct independent measurement on field grown plants, which would be the most desirable procedure, is therefore not feasible.

There are numerous approaches to confirmation which are individually less rigorous than direct measurement but which collectively may provide an index of reliability. These approaches can be categorized as 1) examination of the model and its assumption by theory and experiment; 2) performance of controlled but artificial experiments and comparison with data

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of other investigators; and 3) indirect methods.

We have previously examined several sources of error in the first approach (Kline et al.[8]). These include theoretical and practical problems of complete mixing assumptions, the isotopic mass effect, and pathway assumptions. Details of this analysis will not be repeated. A serious source of error has recently been found, however, which has not been discussed in this context elsewhere. This is related to the assumption that tritium escapes from the tree via only one pathway, that being the transpiration stream. In reality it apparently also escapes by isotopic or molecular exchange with atmospheric water vapor. This was demonstrated by comparison of the specific activity of tritium in pine needles with that of the woody twigs on which they were growing. The expected value of A_n/A_w, the needle-to-wood activity ratio, where no isotopic exchange takes place is 1.0-1.1 because tritiated water has a lower vapor pressure than ordinary water.[13] Experimental values of the above ratio average about 0.65 during the summer months but varied from 0.9 during dry (low humidity) conditions to 0.5 during rainy conditions. The use of uncorrected specific activities from foliage would have the effect of decreasing the integral of the activity-time curve and increasing the estimate of transpiration relative to the true value. While the error is serious if neglected, it can be corrected by simple experimental methods. The data of this report are corrected for the average value of A_n/A_w, which values were collected simultaneously with the routine foliar sampling. In other situations the corrections could be avoided by simply using specific activity of water in twigs as the primary response variable since these have little contact with environmental water vapor.

One controlled experiment involving plants grown in pots has been performed, but data have not yet been analyzed. Results of this and other experiments which are being contemplated will appear in a subsequent progress report. Directly comparable results of other investigators are difficult to interpret. Penman,[4] for example, has given transpiration values in the mid-western region for a variety of vegetation types under

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conditions where ground cover is complete and transpiration is at a maximum. His values range from 0.25 to 0.35 inches/day, or an average of 0.76 cm/day. Our values are 0.82 and 0.77 cm/day for June and early July, respectively, during periods when soil moisture availability was not rate limiting. Penman's data incidate that when ground cover is complete, transpiration rate is not strongly related to vegetation type. Thus, the foregoing comparisons may have validity even though the vegetative cover is different.

Rutter[14] has tabulated a large number of estimates of forest transpiration, none of which are rigorously comparable with values in this report. For a forest growing under negligible water deficit in Australia, Rutter gives total evaporation values ranging from 684 to 861 mm for the annual evaporation. The 1970 Argonne values for transpiration from April 1 to October 31 is 892 mm. The precipitation during this period was 857 mm which exceeds the 15-year average input for this period by 43.3%.[15] Rutter gives average daily transpiration of spruce and Douglas fir of 5.4 and 5.3 cm/day. The comparable figure for the Argonne red pines for a 200-day period is 4.45 mm/day. It is apparent that literature values can be used only to establish the order of magnitude of transpiration. The values obtained by the proposed method agree well with the tabulated ones, however, and establish that this method is at least as reliable as those which have been in previous use.

An indirect method of validation has recently been developed which is sufficiently important to be dealt with separately in the next section.

Measurement of Plant Biomass

In the equation of Orr and Gillespie the term C is called capacity, which in trees is simply the total water content of the tree. This is also given by the difference between the wet and dry weight of the tree. Thus, the equivalences of Eq. 3 can be stated:

$$C = (W - D) = Wm = F \int_0^\infty f(t)dt, \qquad (3)$$

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where W is wet weight, D is dry weight and m is plant moisture percentage. The total integral of the activity-time curve in the above expression can be interpreted as being the mean residence time, T, of water in the plant. Under certain conditions the mean residence time can also be derived from the slope of the exponentially declining response curves of activity versus time. This is not universally true but approaches truth when the system is well mixed, when the initial time of mixing of the tracer is short with respect to the mean residence time, and when the slope of the curve is described by a single exponential function. Neither the extent to which these conditions are obtained in trees nor the sensitivity to deviations from ideal conditions is known at this time. Nevertheless there is reason to believe that the slope of the declining response curve is a limiting approximation of the mean residence time which would be given by the integral of the fractional activity time curve if it could be obtained. With these assumptions, Orr and Gillespie's equation can be transformed to give Eq. 4.

$$W = \frac{T}{m} F, \tag{4}$$

where T is the mean residence time of water in the plant, and the other variables are as defined in Eq. 3. Equation 4 is a modified version of one obtained by Zierler[16] for application to such problems as determination of blood volume in animals.

Equation 4 makes it possible in principle to measure the total weight of a tree nondestructively. This is of significance for two reasons. First, the calculated weight of the plant depends on the transpiration rate, which is given by the tritium method. Since the tree can be independently cut down and weighed, agreement between calculated and observed weight is evidence that the transpiration rate is correct. Second, the weight of a tree is itself a valuable quantity. As in almost all other areas of quantitative biology it frequently becomes necessary for an investigator to weigh the organism with which he is working. If the organism is a large tree, obtaining its weight presents some difficulty. In practice this can only be

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resolved by cutting and weighing the tree although many attempts are made to obtain correlations between weights and tree dimensions so that all trees in a stand can be estimated (see Ogawa et al.[17] and Young et al.[18] for example). Correlations obtained by this method are at best valid only where they were established, and reviewers of manuscripts are justifiably critical when attempts are made to apply empirical equations from one location to plants in another, even if the same species are involved.

Eight red pines from the Argonne site which had received tritium injections were cut down and weighed in total, including roots. Tree biomass was calculated using Eq. 4. Comparisons between observed weights and calculated weights are given in Table 2. The results indicate generally good agreement, with some exceptions, between calculated and observed weights.

TABLE 2. Comparison of Directly Observed Tree Biomasses with Those Calculated by the Tritium Method

Tree	Measured dry biomass, kg	Calculated dry biomass, kg	Deviation from measured, %
1	21.3	16.9	-20.6
3	49.4	54.5	10.3
4	13.8	16.2	17.4
5	29.4	31.5	7.1
6	41.0	43.1	5.1
7	32.6	24.0	-26.4
8	13.6	13.7	0.7
10	23.6	22.5	- 4.7

It appears that the method of estimating weights by the tritium method is unbiased although at present the variability is greater than desired. When the calculated weights of trees agree repeatedly with observed weights, the assumptions required for Eq. 4 are substantiated. In particular, agreement tends to confirm the observed transpiration rate for that tree. When agreement in weights is poor, however, this does not necessarily imply equally poor estimates of transpiration since the quantities T and m could also be

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in error.

Conclusions

It is concluded that the tritium method for estimating plant water consumption and plant biomass in the field is sufficiently promising to warrant further developmental work to eliminate experimental sources of error so that the method can be routinely applied. Water consumption by plants is one of the fundamental life processes. Many ecological theories relating to the distribution of plants on the earth's surface, for example, depend heavily on knowledge of the availability and use of water by plants. Quantification of theory depends in part upon the ability to measure water consumption directly with precision. Wide application of the method depends on its being simple to use, versatile, and precise. The tritium method with further development may meet these criteria well enough to make significant contributions in plant water research.

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