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CYCLING OF CESIUM-134 IN WHITE OAK TREES ON SITES OF CONTRASTING SOIL TYPE AND MOISTURE

J. P. Witherspoon, Jr.
S. I. Auerbach
J. S. Olson

OAK RIDGE NATIONAL LABORATORY
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Radiation Ecology Section

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J. P. Witherspoon, Jr.,

S. I. Auerbach, and J. S. Olson

Submitted as a thesis to the Faculty of the Graduate School of The University of Tennessee in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Botany

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ABSTRACT

The cycle of cesium-134 in white oak trees was followed from spring, 1960, to autumn, 1961. Three trees on each of four sites differing in soil type and moisture were each inoculated with 2.0 microcuries of Cs^{134}. Gains, losses, and transfers of this radioisotope were estimated by sampling from inoculated trees, understory, litter, and soil.

With rapid translocation into leaves from initial trunk inoculations in the spring, white oak leaves contained 10^5 to 10^6 dpm per g dry weight by early June. This represented a total transfer of about 40 per cent of the original input. With the first rains following inoculation, loss of radiocesium from leaves began. These losses continued throughout the growing season until September, by which time a total loss of 15 per cent of the observed maximum concentration in leaves had occurred. Approximately 70 per cent of this rain-induced loss reached the mineral soil by September, the remainder located in litter and understory vegetation.

Radiocesium transferred from trees via annual leaf fall was two times greater than the quantity exported by rain. With subsequent leaching over the winter months, the litter produced by inoculated trees lost about half of its radiocesium to the mineral soil.

Passage of this element through trees, litter, and roots was found to be very rapid. Transfers from litter to vegetation were demonstrated, as well as transfers from living leaves to understory vegetation by rain.

Downward transfer of radiocesium in soils under inoculated trees was observed, and soils on wet sites had significantly greater percentages at lower depths down to 12 inches. However, 92 per cent of the total soil radiocesium remained in the top 4 inches one year and seven months after tree inoculation. A definite pattern of distribution, presumably related to rain-leaching and stem flow, was found under tagged trees. Eighty per cent of the soil radiocesium was confined to the area within crown perimeters, and 19 per cent occurred in a small area around the trunks.

Total annual loss of this radioisotope from inoculated trees was estimated at 19 per cent of the original input. Results from analysis of four trees harvested at the end of the study indicated that estimates of radiocesium remaining in trees one year and seven months post inoculation were 13.3 $\pm$ 3.0 per cent high.

Stable cesium determinations for soil horizons and white oak leaves showed that the amounts of Cs^{134} involved in all stages of this experiment were very small compared to natural levels of cesium.

Ascertaining the rates and percentages of Co^{134} transfer from one forest system compartment to another has ecological significance in that knowledge of the natural behavior of a trace element in nature is gained. This knowledge is important in both its relation to chemically related elements such as potassium, and to radiocesium which may enter such a system as fallout or as a product of atomic waste disposal operations.

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I. INTRODUCTION

The present study involves the use of a radioisotope to trace the distribution patterns of an element in a forest ecosystem. Its main objective is to trace the movements of cesium-134 (2.07 year half-life) inoculated into white oak (*Quercus alba* L.) trees on sites of contrasting geological derivation and moisture status.

Increasing attention has recently been given to the study of exchange of chemical elements between vegetation and soil. Such studies are not new, as Rennie's (1955) summary of nutrient composition data for mature temperate forests includes many references to pre-1900 studies. However, the concept of biological cycling of elements in specific ecosystem compartments, and the role of each compartment in the whole ecosystem, is more recent. Knowledge of the behavior of elements in natural systems is essential for the efficient management of forest plantation productivity (Kornev, 1959). It is also essential for the development of rational atomic waste disposal practices. Odum (1959) has pointed out that, while peaceful and military uses of atomic energy have created problems in the release of wastes to the environment, this technology has also furnished us with radioisotopes which are useful in studying these problems in nature.

Quantitative measurements of tracer Cs^{134} through time in forest ecosystem compartments should yield information on the behavior of this significant element. The rapid movement of cesium is of interest for basic biogeochemistry and physiology of the alkali metal elements. Cycling of cesium has practical implications in determining the movements

of the hazardous radioactive isotopes of this element, Cs^{137} and Cs^{134}. It is hoped that the use and evaluation of techniques employed in this study may lead to a more efficient use of radioisotopes in future studies of mineral cycling in forest systems.

White oak was chosen as the experimental species because of its prominence and wide distribution in the deciduous forests of the eastern United States. Although its best development is on deep, moist, and well drained soils, it occurs on a variety of soil types representing diverse geological origins and nutrient capacities. The present study examines the relationship of such site factors to the distribution of radiocesium.

II. REVIEW OF LITERATURE

A. Cycling of Mineral Nutrients

1. General

The biological transfer of elements in forests is a complex, polycyclic process depending on the combination of many factors. To encompass all its aspects in a single study is tempting, but almost impossible (Remezov, 1958). Investigations of such cycles must be developed in successive stages. There are long-term cycles which are composed of many annual cycles in which nutrient content of forest components varies according to age of vegetation, varying nutrient and moisture requirements, variations of light, and soil cover. Annual cycles include the removal of elements from the soil during growth, and the return to the soil, in the same year, of a portion of them in litter fall and dead wood. Subannual cycles are the most difficult to study. Widely variable in duration, some varying hourly, they include such phenomena as leaching of elements from vegetation by rain and dew, formation and dying off of minute roots and root hairs, nutrient excretion from roots, synthesis and decomposition of organic matter, ion exchanges, and reabsorption by roots.

Much of the literature on element exchange between vegetation and soil has originated in Russia where the investigators have stressed the specific nature of biological cycles for various genetic soil groups. Basilevich (1960) traced cycles of nitrogen and ash elements in the process of steppe soil formation. Vinokurov and Tyurmenko (1958) ascertained seasonal contents of nitrogen and phosphorus in humus, upper and lower

soil horizons, and plant leaves and roots. Smirnov (1958) investigated seasonal variations in carbon dioxide, nitrogen, phosphorus, and potassium in a podzol-conifer system.

A recent study involving nutrient cycles in tropical forests has been made by Nye (1961) in Ghana. Amount and composition of litter and rain wash were measured and added with estimates of timberfall, thus establishing rates of nutrient loss from vegetation. Will (1955) made a similar study of nutrient losses in New Zealand conifer stands.

Most of the studies on nutrient cycling have dealth with nitrogen, various ash elements, and carbon. There is little information on the cycling of essential trace elements, and even less on nonessential trace elements in natural forest systems.

Many studies have involved inventories of forest nutrient composition. Lutz and Chandler (1947) summarized the amount and composition of litter fall for a number of temperate region forest types. More recently, Scott (1955) has compiled a summary which lists amounts and chemical composition of organic matter contributed by overstory and understory vegetation. Rennie (1955) reviewed critically some of the early European studies in which leaf and wood composition values were given for a number of different tree species. Ovington (1958a, b; 1959a, b) has studied nutrient levels in soils and vegetation in a number of forest types. Generalizations which can be made about the return to the soil of nutrients through falling litter, twigs, branches, bark, and fruit have been presented by Stenlid (1958).

2. Leaching by rain

Most of the earlier studies on nutrient return from vegetation to soil considered only nitrogen and ash elements leached by rain from litter on the ground, although the existing literature contained many indications that rain leaches elements from living trees. Remezov (1958) and Stenlid (1958) have reviewed much of the literature on "cuticular excretion", as Arens (1934) calls the process to distinguish it from leaching of dead leaves. Much of the existing quantitative data on salt losses through rain have been obtained in experiments with detached branches or leaves. Species, age of leaves, temperature, position of leaves, quality and quantity of applied moisture, and pathological condition have been found to influence the amount of nutrients lost. Tamm (1951), Will (1955) and Mes (1954) have conducted field experiments in which rain water was collected under trees and analyzed chemically. All showed a considerable loss of base elements from the tree crowns. Will's data indicated that rain leached more potassium from tree crowns than was contained in the litter fall. In general, the losses were in decreasing order, Na > K > Mg > Ca.

With radioisotopes as tracers, losses of trace elements have been demonstrated. Long, et al. (1956) investigated the loss of rubidium-86 from bean leaves. Tukey, et al. (1958) found losses of manganese-54, iron-55, strontium-90, yttrium-90, sulfer-35, zinc-65, and chlorine-36 when leaves of bean, corn, and squash were subjected to leaching with distilled water.

3. Root losses

Although they have not been widely investigated, losses of salts through excretion from roots and through decomposition of roots are known to occur. It is often impossible to distinguish between losses from living roots and losses due to the dying of root hairs and small lateral roots. For this reason most of these studies have involved plants growing in nutrient solution or excised roots. While the results of such studies should not be used to calculate losses from plants in soil, they may serve to demonstrate environmental factors favoring root excretion.

Stenlid (1958) lists the following as requirements for the establishment of excretion from plant roots in the field: 1) a decrease must occur in the salt content of the entire plant; and 2) this decrease must be greater than that caused by litter production and leaching through precipitation.

Fujiwara and Iida (1956) and Stenlid (1950) concluded from experiments with excised roots that respiratory inhibitors give rise to increased excretion by causing a decrease in accumulation and, in many cases, an effect on the permeability of protoplasm. Oxygen deficiency is perhaps the most important factor causing increased root excretion (Shive, 1941). In addition to its effect on respiration, it is often associated with high soil water content which could cause salt losses by leaching.

Luttkus and Botticher (1939) found that corn plants in nutrient solution excreted as much as 15 to 30 per cent of their potassium when kept in the dark for 3 to 5 days. There was no nutrient loss detected

in normally illuminated plants.

The production and death of roots occurs throughout the growing season. The influence of this phenomenon on the biological cycling of elements has been shown by Orlov (1955) and Remezov (1959), Orlov, using a laborious method of extracting minute roots from soil monoliths, concluded that the annual death of roots amounted to 0.6 metric tons per hectare in spruce stands on chernozem soil. Remezov, using Orlov's method, studied root systems in a 50 year old oak stand. He estimated that 0.4 metric tons per hectare, half of the amount produced, died per year.

B. Cesium

Cesium is the rarest member of the alkali metal group. Vinogradov (1959) lists world averages of this element as 19 ppm for acid rocks, 12 ppm for sedimentary rocks, and 5 ppm for soils. He also states that Rb and Cs content in soil parallels the content of K, the former two being lost in about the same degree as the latter during podzolization. Alkali metals and alkaline earths such as Li, Rb, Cs, Sr, and Ra, have a tendency to be lost from the soil whatever its nature. Most of these elements occur in the solid phase as trace elements in the crystal lattices of aluminosilicates.

The distribution of stable Cs and Rb in natural plants has been reported by Bertrand and Bertrand (1944, 1949) and Yamagata, et al. (1959). Bertrand's values for land plants ranged from 2.1 to 81 (average 20.3) ppm of Rb and from 3 to 88.5 (average 22) ppm of Cs. The values found by Yamagata, for 50 species of plants in Japan, ranged from 0.6 to 50 ppm

Rb and from 0.002 to 1 ppm Cs. Plant Cs contents in this case failed to correlate as closely with plant K as did Rb.

The uptake of radioisotopes of Cs has been studied by many workers. Relatively low uptake by plants from soils has been reported by Nishita, et al. (1959, 1960), Pendleton (1960), Fredriksson and Eriksson (1958), Klechkovsky (1957), and others. This low uptake may be due to several factors such as ion competition for root exchange sites, fixation of Cs ions in the lattices of clay minerals, hydrogen ion concentration, and plant discrimination.

Epstein and Hagen (1952) presented evidence that K, Rb, and Cs were bound by identical bonding sites in plant root cells while Na did not compete for these sites. Nishita, et al. (1959) and Fredriksson and Eriksson (1958) demonstrated decreases of plant Cs^{137} uptake by adding K to the soil, and increases by adding carrier Cs to the soil. Uptake in both studies varied with soil type. Menzel (1954) observed that ratios of Rb^{86} and Cs^{134} to K in plants were inversely proportional to available soil K. Collander (1941) reported that Rb to K and Rb to Cs absorption ratios did not vary significantly from plant to plant. Yamagata's (1959) data, however, indicate that Cs does not necessarily parallel K in transfer from soil to plant. Moreover, when consideration is taken of the difference of the ionic radii between Rb (1.49 Å) and Cs (1.63 Å), one cannot expect that Cs can replace K (1.33 Å) as freely as Rb does.

Rediske and Selders (1953) found Cs^{137} uptake in crop plant leaves proportional to Cs concentrations added to the nutrient solution, although

distribution factors varied between plant species. They further demonstrated an increasing leaf to root ratio of Cs content with decreasing pH. Middleton (1958), studying Cs and Sr absorption from foliar sprays, found a rapid absorption and translocation of Cs, absorption being higher from foliage than that from soil. In comparing the translocation rates of K^{42} and Cs^{137} with Ca^{45} and Sr^{90}, Glueckauf (1955) found the former pair translocating much more rapidly. The Ca and Sr movements were interpreted as being involved with exchange mechanisms while K and Cs movements seemed to be purely a transport phenomenon.

The behavior of Cs in soils appear to be largely dependent on kind and amount of clay minerals, base status, and soil moisture. Fredriksson and Eriksson (1958), working with pot cultures of red clover, observed a decreasing Cs^{137} uptake with increasing amounts of clay in the soil. The importance of the mica structure in sorbing Cs has been found for Conasauga shale at Oak Ridge (Cowser, et al., 1958). Other Oak Ridge experiments (Tamura and Jacobs, 1959), illustrating the great ability of illitic minerals to fix Cs from solutions, have indicated that a certain level of K concentration tends to collapse the mineral lattice and fix more Cs between the plates than do higher or lower K concentrations. This points to a possible mechanism, other than ion competition, by which K could influence plant Cs uptake.

Rhodes (1957) decreased Cs sorbtion in Hanford soils by increasing the concentration of salts in solution. Klechkovsky (1957), on the other hand, demonstrated that Cs^{137} was sorbed more stably and in a more unexchangeable form in base-saturated soils than in nonbase-saturated

soils. Perhaps mass action principles operated in the former study to release Cs. In the latter study the amount of Cs displacement by additions of $CaCl_2$, $NaNO_3$, and KCl was found to be, in decreasing order, red earth (low base status) > turf-podzol (intermediate) > black earth (high base status). Liming has also been found to displace Cs in both acid and alkaline soils (Amphlett, 1955).

Nishita, et al. (1954) reported that, for a wide variety of soils, the order of decreasing removal by water was Ru > Sr > rare earths > Cs, while the exchangeable activity (leached with 1N NH_4OAc at pH 7) decreased in the order Sr > Cs > Ru > rare earths. Leaching under more acidic conditions would render some of these ions more readily available (Amphlett, 1955). Pendleton and Uhler (1960), studying plant accumulation of Cs^{137} under simulated pond, wet meadow, and irrigated field conditions, found an uptake ratio of 75 to 2 to 1, respectively, after 5 hours and a ratio of 450 to 30 to 1 after 36 days.

III. MATERIALS AND METHODS

A. Experimental Sites

Four sites with contrasting soils were selected for study. These sites, all located within the Oak Ridge Reservation, are on the Monongahela and Sequoia soil series over Conasauga shale and the Landisburg and Fullerton series over Knox dolomite. These soils represent contrasting hydrologic conditions (moist bottomlands versus drier uplands) and contrasting geological derivation (shale versus dolomitic parent materials). In addition, as will be discussed in Chapter IV, the clay mineralogy is different, as the shale-derived soils are dominantly illitic in nature, while the dolomitic soils are dominantly kaolinitic.

B. Inoculation of Trees

Twelve white oak (Quercus alba L.) trees, three per site, were selected for inoculation. These trees ranged from 13.1 to 17.7 feet in height and from 0.82 to 2.77 inches diameter at breast height. Each tree was inoculated with 2.0 mc of Cs^{134}, in the form of $Cs^{134}Cl$ in 100 ml of weak HCl, pH 2.0. Four Mauget feeders were attached to the trunk of each tree at 1.0 m height, and the Cs^{134} solution was introduced as described by Ealy (1957). Trees growing on the dolomitic wet and dry sites and the shale dry site were inoculated during the last week of April, 1960. The shale wet site trees were inoculated during the last week of June and the first week of July, 1960.

In addition, one tree on the dolomitic dry site and one tree on the shale wet site were inoculated with K^{42} simultaneously, in the form

of $K^{42}Cl$ in weak HCl. The respective K to Cs inoculation ratios were 2.23 and 1.89. These "double tags" were used to ascertain the degree of distribution similarity between these two alkali metal elements in white oak.

Radioisotopes were obtained from the Oak Ridge National Laboratory in the following forms: $Cs^{134}Cl$ in HCl solution (2.12 N) with approximately 0.33 mg solids per ml, and $K^{42}Cl$ in HCl solution (2.23 N) with 33.9 mg solids per ml. Volumes of these radioisotope solutions inoculated into each tree were less than 1.0 ml, and the inoculation volumes (100 ml) were made up by adding distilled water to radioisotope solutions.

C. Plant Sampling

Leaves from inoculated trees were collected through the growing season at various branch heights and compass directions. Sample branches (17 to 29 per tree) were chosen to give a good crown representation, the size of the tree determining the number of branches sampled. Twenty or more leaves were taken along the length of each branch. Estimates of total number of leaves per tree were made by applying branch diameter measurements to the regression equations of Rothacher, Blow, and Potts (1954). These estimates were qualified by harvesting four trees, one per site, in September, 1961, and making total leaf counts. These harvested trees also served to assay total Cs^{134} remaining in the trees at that time.

Estimates of Cs^{134} in understory vegetation were made by clip-sampling four 0.5 m^2 quadrats under each inoculated tree.

D. Litter and Soil Sampling

During the 1960 growing season a 3 by 3 m grid, with the inoculated tree trunk at the center, was laid out under each tree. This area exceeded the width of the tree crowns in all directions. One dm^2 litter samples were taken at 20 positions on the grid (Figure 1). Under each litter sample, two soil cores, each 4.0 inches long, were extracted with an Oakfield (0.75 inch diameter) sampling tube. These cores were divided into depth fractions for analysis, and screened to remove roots or organic debris which might contribute Cs^{134} activity.

Activity of samples collected at the same radius around the tree were averaged, and these values converted to an area basis for estimates of total Cs^{134} activity on the ground.

During the 1961 growing season, samples were taken over a wider area underneath the trees. Positions sampled in 1960 were resampled and served as a basis for establishing six concentric sampling zones around the trunk (Figure 2). One dm^2 litter samples were taken, and soil cores 12 inches long were extracted. Cores were divided into depth fractions and composite samples for radiometric analysis were made as follows:

Radial Limits of Zone Sampled in Feet	No. of Cores	No. of Composites
0 to 0.8 (0.2 m)	6	3
0.8 to 2.3 (0.7 m)	8	4
2.3 to 3.6 (1.1 m)	12	6
3.6 to 5.1 (1.5 m)	18	6
5.1 to 6.9 (2.1 m)	24	8
6.9 to 9.2 (2.8 m)	24	8

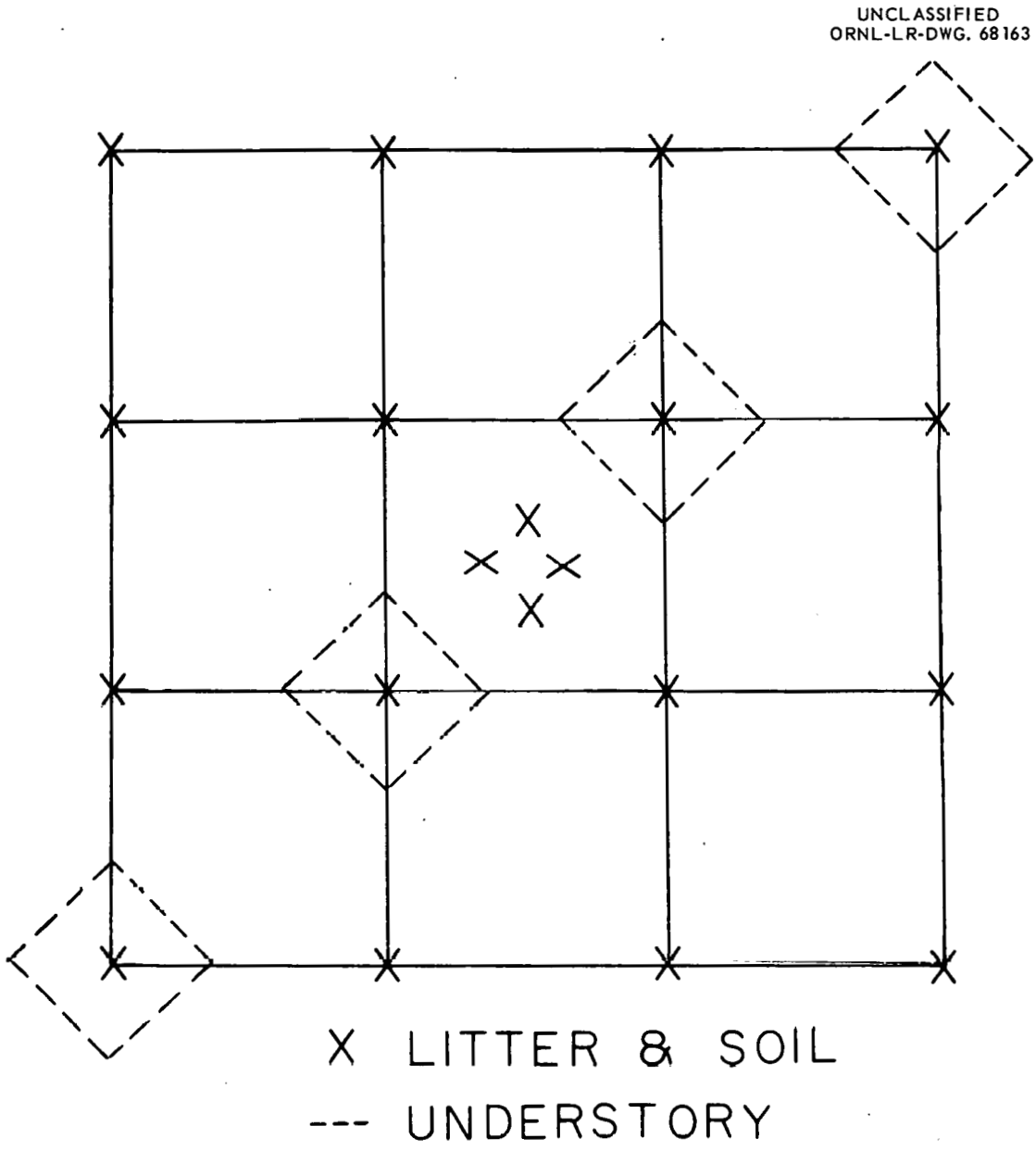

Fig. 1. Location of 1960 Litter, Soil, and Understory Samples.

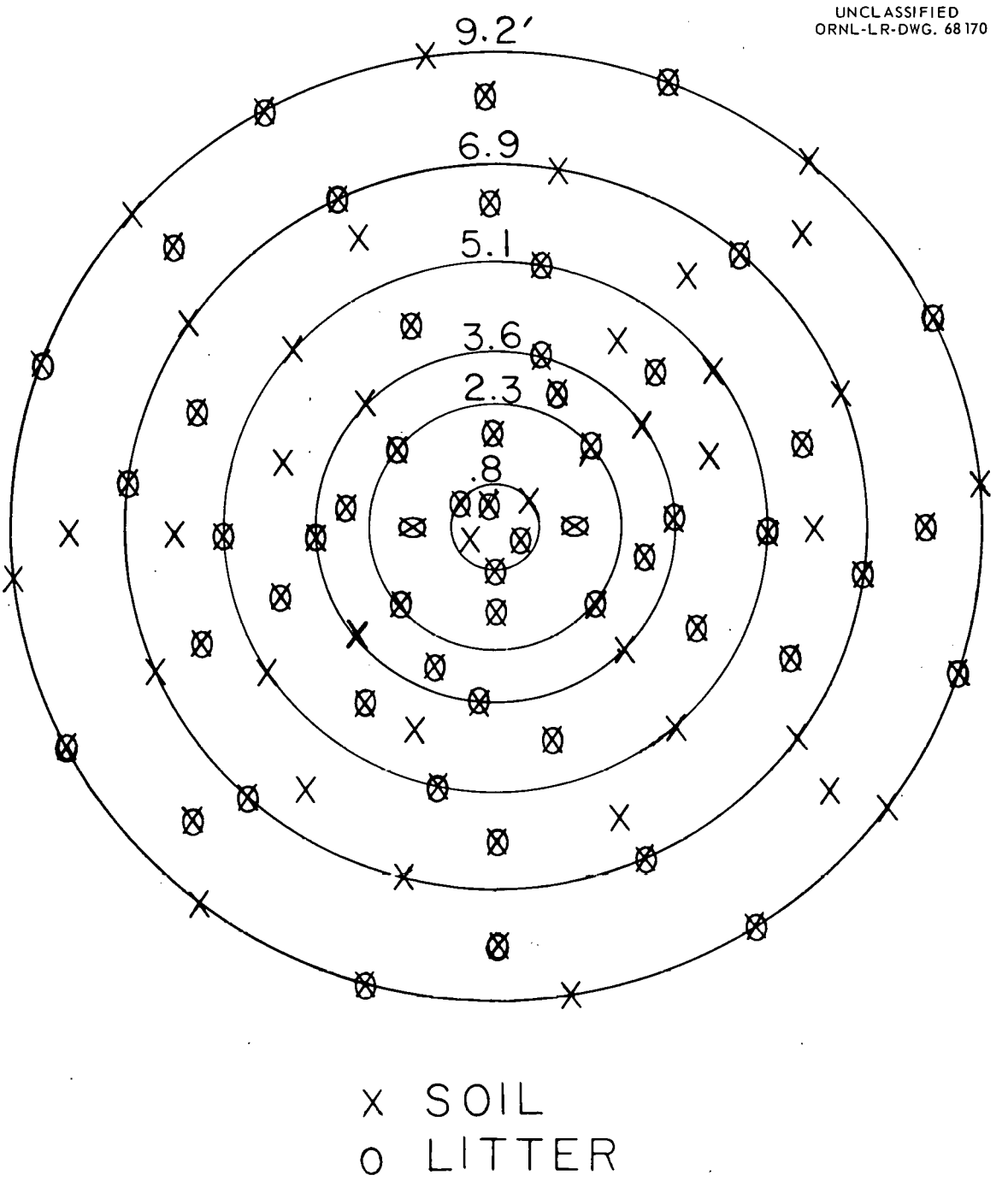

Fig. 2. Location of 1961 Litter and Soil Samples.

The composite samples were assayed for Cs^{134} activity, and zone values averaged and converted to an area basis. Four 0.5 m^2 understory clip samples were taken as in the 1960 sampling.

E. Determination of Radioactivity

Plant materials were assayed for Cs^{134} activity by means of a single channel gamma spectrometer with a 3.0 by 1.5 inch NaI detector. Leaves and litter were placed intact in 0.75 by 2.75 inch circular plastic containers, and woody tissue was ground in a Wiley mill before counting.

Soil samples were counted, air dry, in 25 by 150 mm glass tubes in a Packard Instrument Company Auto-gamma spectrometer system containing a 3 by 3 inch NaI well detector. All soil samples and low level plant samples were counted in the 0.50 to 0.90 Mev portion of the gamma spectrum where Cs^{134} exhibits characteristic photopeaks.

Control plant and soil samples were collected 75 to 100 feet from inoculated trees with each set of experimental samples. These controls were used as background values to minimize counting errors due to the presence of natural radioactivity or fallout. Cellulose sponges cut to appropriate dimensions were placed in the same kind of containers as the samples, and, with the addition of a known Cs^{134} solution, served as standards for calculation of counting efficiencies.

F. Tree Harvesting

Four trees (one per site) were harvested in November, 1961. In addition to the total above-ground growth, an estimated 75 per cent (by

weight) of the root systems was extracted. Branches, trunk, and roots were divided into diameter size classes and oven dry weights were recorded. Number of leaves was recorded by branch diameter, and leaf weights recorded for random samples.

Samples taken from the wood diameter size classes were ground in a Wiley mill and assayed for Cs^{134} activity. Total activity in the tree was ascertained as a check on estimations of remaining activity from previous soil and litter values.

G. Site Analysis

Soil profile pits were dug on each site to differentiate and characterize the soil series. Color, depth, structure of each horizon, and site moisture were determined in the field. Bulk samples from each horizon were obtained for laboratory determinations of soil texture (mechanical analysis), pH, exchangeable bases, stable cesium, and dominant clay minerals.

1. Site moisture

Relative soil moisture conditions were determined by measuring electrical resistance of gypsum blocks placed in the soil. Sixteen moisture blocks (Bouyoucos Model Cel-WWD) were placed in the field after heavy rains with the soils approximately at field capacity. In each of the four soils, two blocks were placed at 6 and 12 inch depths. Soil structure was disturbed as little as possible in burying the blocks, and in all cases the burial sites were in open areas under herbaceous ground cover. Resistance readings were made during a 30 day period of moisture

depletion (August 26 to September 24, 1961) with a Bouyoucos Moisture Meter, Model BN-1.

2. Mechanical analysis of soils

Air dry samples of 50.0 g weight were dispersed in 100 ml of water and 100 ml of 0.1 N sodium hexametaphosphate, mixed with a mechanical stirrer for 15 minutes, and transferred to 1000 ml graduated cylinders, then diluted to 1.0 liter with distilled water. Bouyoucos hydrometer readings were taken at 2 minutes 40 seconds and at 25 hours 17 minutes to determine per cent of particles less than 0.05 mm diameter and less than 0.002 mm, respectively.

3. Soil acidity

Determinations of pH were made on 1 to 1 soil and distilled water mixtures with a Beckman Model N pH Meter of the glass electrode type.

4. Exchangeable bases

Air dry soil samples of 50.0 g each were wet with 150 ml of 1 N ammonium acetate (pH 7.0), placed in stoppered flasks, and agitated overnight in a mechanical shaker. Samples were then poured onto Whatman number 42 filter paper in Buchner funnels and filtered into suction flasks with an additional 350 ml of ammonium acetate.

Aliquots of these leachates were analyzed for Ca, Mg, Na, and K in a Beckman Model DU Flame Spectrophotometer.

5. Stable cesium

Stable cesium was determined in the soil samples by activation analysis as follows. Oven dry (100°C for 24 hours) samples of 1.000 g from each soil horizon were placed in plastic vials which were then

stacked into a 1 quart polyethylene bottle. Three vials, each containing 60.000 mg of stable $CsNO_3$, were placed at various positions in the stack of samples as standards. The polyethylene bottle was placed in the ORNL Graphite Reactor and neutron-irradiated for one week. After removal from the reactor, samples were stored with appropriate shielding for 18 days. This storage period allowed for the decay of short-lived radioisotopes, and reduced high initial radioactivity (approximately 900 mr per hour per g soil) by a factor of about 10.

Activated soil samples were digested in platinum crucibles with HF as described by Jackson (1958). Digestates were taken up in 20 per cent HCl and 10 ml aliquots, representing 0.4 g soil, were removed and made slightly basic with 1.0 M sodium carbonate. These basic samples were scavenged with 0.5 ml each of ferric chloride solution (10 mg Fe^{+++} per ml) and yttrium nitrate solution (10 mg Y^{++} per ml). The resulting precipitates of ferric hydroxide and yttrium carbonate were removed by centrifugation. Precipitates were washed once with distilled water, the wash being added back to the supernatant fluid. This precipitation process was repeated two more times to insure removal of Fe and Sc which, in quantities of less than 1 ppm, interfere with the radiometric determination of Cs^{134}.

After the three-step scavenging process, samples were brought up to 50 ml volume with 0.1 N HCl. Aliquots of the activated $CsNO^3$ standards were also made to 50 ml volume. Three unactivated 1.000 g soil samples were each tagged with 7.18×10^5 dpm Cs^{134} and carried through the digestion and scavenging operations as a check on Cs yield. The

Cs^{134} activity of all samples was determined in a 200 channel gamma spectrometer with a 3 by 3 inch NaI detector. With the amount of Cs activated in the $CsNO_3$ standards as a basis, stable Cs quantities in soil samples were calculated from the amount of Cs^{134} activity measured after activation.

Levels of stable Cs which might be available for plant uptake were determined by activation analysis of ammonium acetate leachates. Samples representing composited A and composited B (Bm horizons excluded) soil horizons were prepared for each site. Each composite weighed 300 g (air dry) and was leached with 3000 ml 1 N ammonium acetate, pH 7.0. Methods used were the same as those for extraction of exchangeable bases. Leachates were evaporated, slowly, to dryness and brought up to 15 ml volume in 20 per cent HCl. Activation analysis for Cs^{134} was made as described for soil samples.

Stable Cs levels in leaves of uninoculated white oaks growing on experimental sites were determined by activation analysis of leaf digestates. Approximately 100 leaves were collected in July, 1961, from trees on each site. Leaves were selected at random over the tree crown. After oven drying, the leaves were ground in a Wiley mill, and 5 to 10 g of ground material from each site were wet digested with nitric and perchloric acid (Piper, 1950). Digestates were taken up in 20 per cent HCl, aliquots of which were treated as previously described for activation analysis.

6. Clay mineral analysis

Identification of dominant clay minerals was made by X-ray

diffraction analysis of clay from each soil horizon. Two ml aliquots of Na-saturated clay suspension (less than 0.002 mm diameter particles) were placed on glass slides, air dried, then oven dried. Clay minerals present were determined with a Norelco X-ray Diffractometer. A wide range goniometer rotated the slides from 3 to 27° at a rate of 1° per minute. Thus, clay minerals present with diffraction spacings of approximately 3 to 18 Å were recorded. The presence and relative abundance of vermiculite with chlorite and montmorillonite, hydrous micas (illite), kaolinite, and quartz were recorded. This procedure did not separate vermiculite, chlorite, or montmorillonite.

H. Transfer of Cs^{134} from Litter to Vegetation

To trace the movement of radiocesium from litter into vegetation, Cs^{134} tagged leaves (from inoculated trees) were placed around 10 white oak saplings (1.5 to 4.0 feet height) growing on each of two sites. Old litter was removed from a circle of 20 inches diameter around each sapling, and air dry tagged litter was substituted. Applications were made during the last week of June, 1960.

On Landisburg silt loam soil each sapling received an average application of 10.23 x 10^{7} dpm Cs^{134} in 36 g litter. An additional four saplings, with old litter removed, each received 19.60 x 10^{7} dpm Cs^{134} in aqueous form (Cs^{134} Cl in weak HCl in a volume of 100 ml) in an attempt to compare uptake rates.

On Litz (a shallow counterpart of Sequoia) silt loam soil each sapling received an average application of 9.96 x 10^{6} dpm Cs^{134} in 14 g

litter. Samples of 10 leaves per sapling were removed periodically during the growing season, and their Cs^{134} activity determined. At the end of the growing season, selected saplings were harvested to ascertain total uptake values.

I. Seedling Root Losses of Cs^{134}

Germinating acorns, collected November 2, 1961, were planted in 12 ounce containers with perforated bottoms in Ottawa sand (Baker and Adamson, Code 2170). The sand was periodically saturated with Knop's nutrient solution, and cultures were maintained in the laboratory.

Eighty days after planting, when shoots were 5.5 to 8.0 inches high and with five leaves, $Cs^{134}Cl$ solution (pH 6.5) was applied to one leaf. The recipient leaf was immersed into a 15 by 52 mm plastic vial, and Cs^{134} solution was added until the entire leaf blade was submerged.

After 72 hours treatment, vials and recipient leaves were removed. Distilled water was leached through the containers in amounts equivalent to 1.5 inch of rain per day for two days. Leachates were collected in waxed paper cups for analysis.

Plant parts were separated for analysis to determine amount of foliar absorption, and leachates and sand were analyzed to determine Cs^{134} losses from roots.

IV. PHYSICAL AND CHEMICAL CHARACTERISTICS OF STUDY SITES

A. Description of the Soil Profiles

The Monongahela soil (Table I) occurred in a bottomland topographic position, and it was developed from old alluvial sediments washed from soils underlain by acid shales and sandstones. Soil texture ranged from silt loam to loam, and a well-developed hardpan occurred in the subsoil. It was strongly acid in reaction. This site was formerly a cultivated field, but it is now occupied by mixed hardwoods of which white oak (*Quercus alba* L.), red maple (*Acer rubrum* L.), and yellow poplar (*Liriodendron tulipifera* L.) are overstory dominants.

The Sequoia soil (Table II) occurred in a gently sloping, south facing, upland position on a strongly weathered residuum of acid shale. Texture ranged from silt loam at the surface to clay in the subsoil. It was well drained with medium runoff and acid in reaction. An even aged stand of post oak (*Quercus stellata* Wang.), white oak, and pignut hickory (*Carya glabra* Mill.) dominates the overstory vegetation. Building remains indicated that this area was formerly cut over as part of a home site.

These wet and dry shale sites are both located on a belt of Conasauga shale running in a northeast to southwest direction between Haw Ridge and Copper Ridge in Roane County, Tennessee.

The Landisburg soil (Table III) was in a bottomland position (toe slope) over Knox dolomite. This was a strongly acid colluvial soil high in chert content, and a well-developed fragipan was found in the subsoil

Table I

Profile Description, Monongahela Silt Loam, Shale Wet Site

Horizon	Depth (Inches)	Texture (Per Cent) Sand	Silt	Clay	Color (Moist)	Structure	pH
A_p	0-7	33.2	57.7	9.1	Dark grayish-brown (10 YR 4/2)	Moderate medium granular, very friable	5.2
B_{21}	7-12	29.9	51.5	18.6	Yellowish-brown (10 YR 5/4)	Weak to moderate medium subangular blocky, friable to firm	4.7
B_{22}	12-17	29.9	52.1	18.0	Yellowish-brown (10 YR 5/4)	Moderate medium subangular blocky, firm	4.8
B_{3M1}	17-24	29.4	44.7	25.9	Mottled; pale yellow (2.5 YR 7/4), light gray (10 YR 7/1), and yellowish-brown (10 YR 5/6)	Massive	5.3
B_{3M2}	24-40	40.7	41.0	18.3	Mottled; dark gray-brown (10 YR 4/2), pale brown (10 YR 6/3), and yellow (10 YR 7/6)	Massive	5.7

Table II

Profile Description, Sequoia Silt Loam, Shale Dry Site

Horizon	Depth (Inches)	Texture (Per Cent) Sand	Silt	Clay	Color (Moist)	Structure	pH
A_1	0-2	24.4	66.7	8.9	Dark grayish-brown (10 YR 4/2)	Weak medium crumb, very friable	5.3
A_2	2-8	24.3	60.0	15.7	Pale yellow (2.5 YR 7/4)	Moderate medium granular, friable	4.8
B_1	8-12	19.9	50.0	30.1	Brownish-yellow (10 YR 6/6)	Moderate small and medium subangular blocky, moderately firm	4.9
B_2	12-18	16.6	39.6	43.7	Yellowish-brown (10 YR 5/8)	Moderate fine subangular blocky, firm	4.9
C	18-27	20.0	37.5	42.5	Variegated; strong brown (7.5 YR 5/8), yellowish-red (5 YR 5/8), and brownish-yellow (10 YR 6/6)	Massive	5.1

Table III

Profile Description, Landisburg Silt Loam, Dolomitic Wet Site

Horizon	Depth (Inches)	Texture (Per Cent) Sand	Silt	Clay	Color (Moist)	Structure	pH
A_1	0-1	26.1	65.1	8.8	Dark grayish-brown (10 YR 4/2)	Moderate medium crumb, very friable	6.3
A_2	1-8	21.6	66.7	11.7	Pale brown (10 YR 6/3)	Moderate fine and medium granular, very friable	6.2
A_3	8-10	19.8	61.7	18.5	Yellowish-brown (10 YR 5/6)	Strong medium granular friable	5.8
B_1	10-14	18.2	61.5	20.3	Brownish-yellow (10 YR 6/6) to yellowish-brown (10 YR 5/8)	Moderate medium subangular blocky, friable	5.5
B_2	14-26	16.9	60.5	22.6	Strong brown (7.5 YR 5/6)	Moderate medium subangular blocky, moderately firm	5.1
B_{3M1}	26-34	20.1	59.3	22.1	Reddish-yellow (7.5 YR 6/6) with light brownish-gray (10 YR 6/2) and strong brown (7.5 YR 5/6) mottles	Strong medium angular blocky	5.2
B_{3M2}	34-65	21.9	54.5	23.6	Brownish-yellow (10 YR 6/6) with strong brown (7.5 YR 5/6), and light brownish-gray (10 YR 6/2) mottles	Moderate medium platy	5.6

at 26 inches. The texture was silt loam throughout the profile, but internal drainage was slow due to the presence of the fragipan. Site location was in a stream cut running north to south through Chestnut Ridge, Roane County, Tennessee. Once cut over as a home site, the dominant overstory was white oak with scattered beech (Fagus grandifolia Ehrh.) and blue beech (Carpinus caroliniana Walt.).

The Fullerton soil (Table IV) was an upland residual soil over Knox dolomite. It was deep and well drained with depth to bedrock ranging from 10 to 30 feet. Texture ranged from silt loam at the surface to clay in the subsoil and the reaction was acid. Slope at this site was 10 to 15 per cent with slightly eroded areas giving the surface an irregular configuration. Located on a north facing slope of Chestnut Ridge, Anderson County, the overstory was dominantly oak-hickory.

B. Site Moisture

Resistance readings taken after heavy rains (soils approximately at field capacity) through a relatively dry period (four rains) of 30 days indicate relative soil moisture conditions. Figure 3 illustrates the per cent "available water" readings at 6 and 12 inch depths for each soil. The surface layers in the upland sites tend, initially, to lose moisture faster than the bottomland sites. Data for the latter half of the 30 day period indicated much more available moisture in the bottomland soils at both depths. In general, bottomland soils contained about 14 per cent more available water after the 10 day dry period from September 14 to 20.

Table IV

Profile Description, Fullerton Silt Loam, Dolomitic Dry Site

Horizon	Depth (Inches)	Texture (Per Cent) Sand	Silt	Clay	Color (Moist)	Structure	pH
A_1	0-1	20.5	70.0	9.5	Dark grayish-brown (10 YR 3/2)	Moderate fine crumb, very friable	6.7
A_2	1-7	14.7	64.5	20.8	Brownish-yellow (10 YR 6/6)	Strong medium granular, friable	5.2
A_3	7-9	11.6	55.7	32.7	Strong brown (7.5 YR 6/6)	Strong medium granular, friable	4.8
B_1	9-11	8.9	40.3	50.8	Yellowish-red (5 YR 4/8)	Moderate medium subangular blocky, firm	4.9
B_2	11-26	6.9	30.5	62.6	Yellowish-red (5 YR 4/9)	Moderate medium subangular blocky, firm	5.0
B_3	26-48	9.5	23.3	67.2	Variegated; yellowish-red (5 YR 4/8) and brownish-yellow (10 YR 6/8)	Moderate medium and large subangular blocky, firm	5.2
C	48-60	8.0	23.4	68.6	Variegated; yellowish-red (5 YR 4/8) and brownish-yellow (10 YR 6/8)	Weak medium subangular blocky, firm	5.3

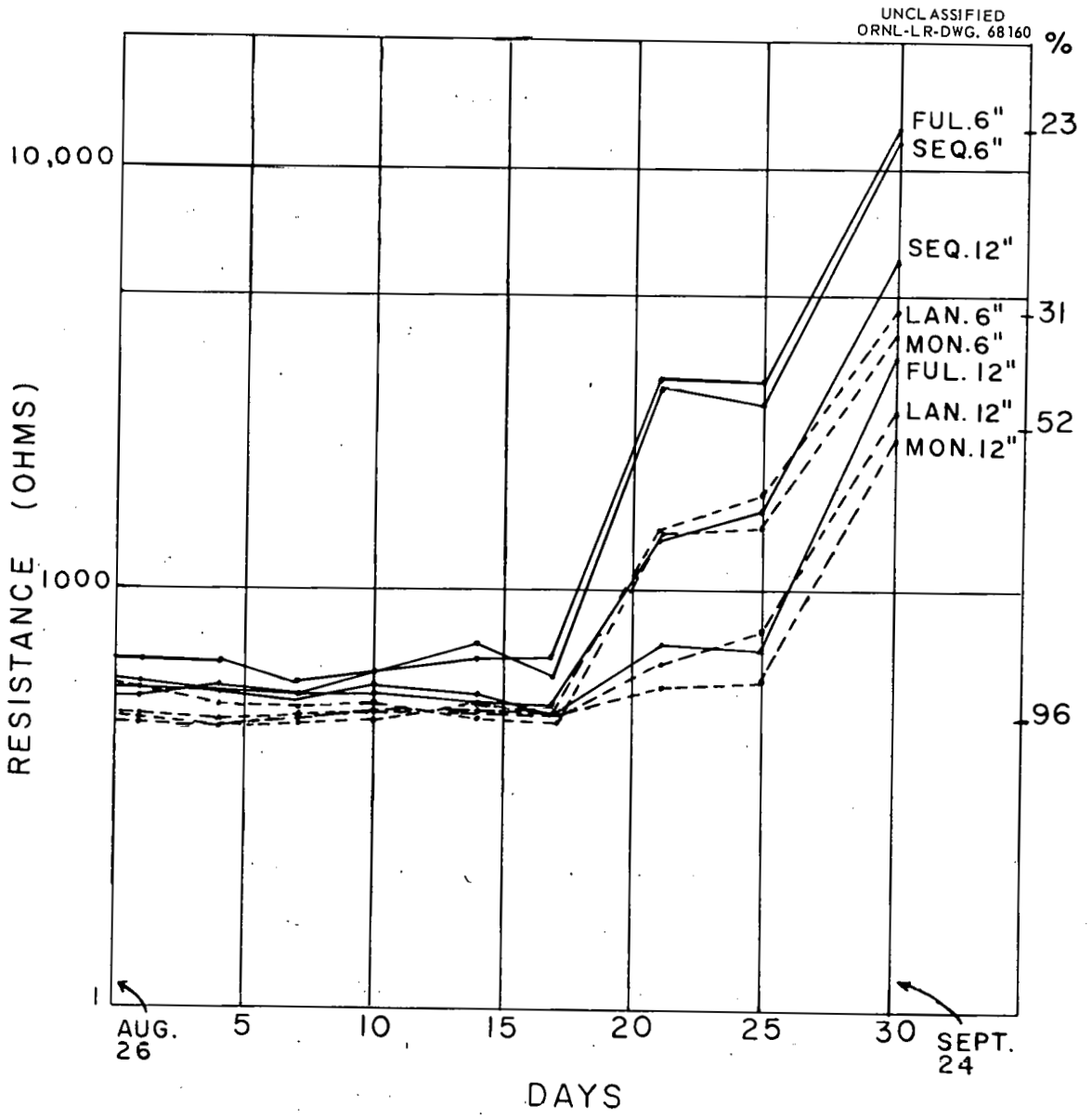

Fig. 3. Soil Moisture at 6 and 12 Inch Depths.

Both bottomland soils (Monongahela and Landisburg) are situated between prominent ridges, and receive runoff and probably internal drainage from adjacent soils.

C. Exchangeable Bases and Clay Mineralogy

Ammonium acetate, pH 7.0, exchangeable bases for each soil profile are presented in Table V. In general, the shale soils were richer in exchangeable Na, K, and Mg than the dolomitic soils which were richer in exchangeable Ca. Figures 4 and 5 show exchangeable K by soil depth, and each profile illustrates the characteristic accumulation of this element in the B horizon of podzolic soils.

The wet soils tend to be higher in Na and K content in the surface and subsoil. The dry soils have slightly more Mg in the subsoil.

Profile distributions of clay (particles less than .002 mm diameter) are shown in Figure 6. The dry soils show a much greater increase in clay with depth than the wet soils. The Fullerton and Sequoia subsoils have over 40 per cent clay, whereas the Landisburg and Monongahela do not exceed 26 per cent.

X-ray diffraction analyses of B_2 horizons for each soil are shown in Figure 7. Dominant clay minerals, in order of decreasing abundance are: kaolinite, illite, vermiculite (with montmorillonite), and quartz in the Fullerton; koalinite, vermiculite (with montmorillonite), quartz, and illite in the Landisburg; hydrous micas (illite), kaolinite, and quartz in the Sequoia; and hydrous micas (illite), vermiculite (with montmorillonite), kaolinite, and quartz in the Monongahela.

Table V

Exchangeable Bases in Soil Profiles

Soil and Horizon	Depth (In.)	1 N Ammonium Acetate Exchangeable me/100 g			
		Na	K	Ca	Mg
Fullerton					
A_1	0-1	.045	.325	11.250	1.266
A_2	1-7	.013	.085	.765	.216
A_3	7-9	.018	.082	.415	.225
B_1	9-11	.018	.146	.500	.325
B_2	11-26	.018	.249	.360	1.058
B_3	26-48	.013	.151	.145	.466
C_1	48-60+	.018	.118	.115	.250
Landisburg					
A_1	0-1	.045	.597	5.250	1.083
A_2	1-8	.027	.174	.470	.308
A_3	8-10	.018	.141	.300	.208
B_1	10-14	.018	.158	.425	.275
B_2	14-26	.027	.369	.410	.875
B_{3M1}	26-34	.022	.174	.125	.525
B_{3M2}	34-65	.032	.192	.120	.333
Sequoia					
A_1	0-2	.050	.487	4.250	1.416
A_2	2-8	.054	.123	.160	.542
B_1	8-12	.013	.333	.130	.533
B_2	12-18	.022	.461	.050	1.000
C_1	18-27	.068	.251	.020	1.666
Monongahela					
A_p	0-7	.059	.523	2.940	1.283
B_{21}	7-21	.045	.394	.220	.566
B_{22}	12-17	.040	.351	.150	.741
B_{3M1}	17-24	.054	.505	.310	.875
B_{3M2}	24-40	.050	.358	.155	.766

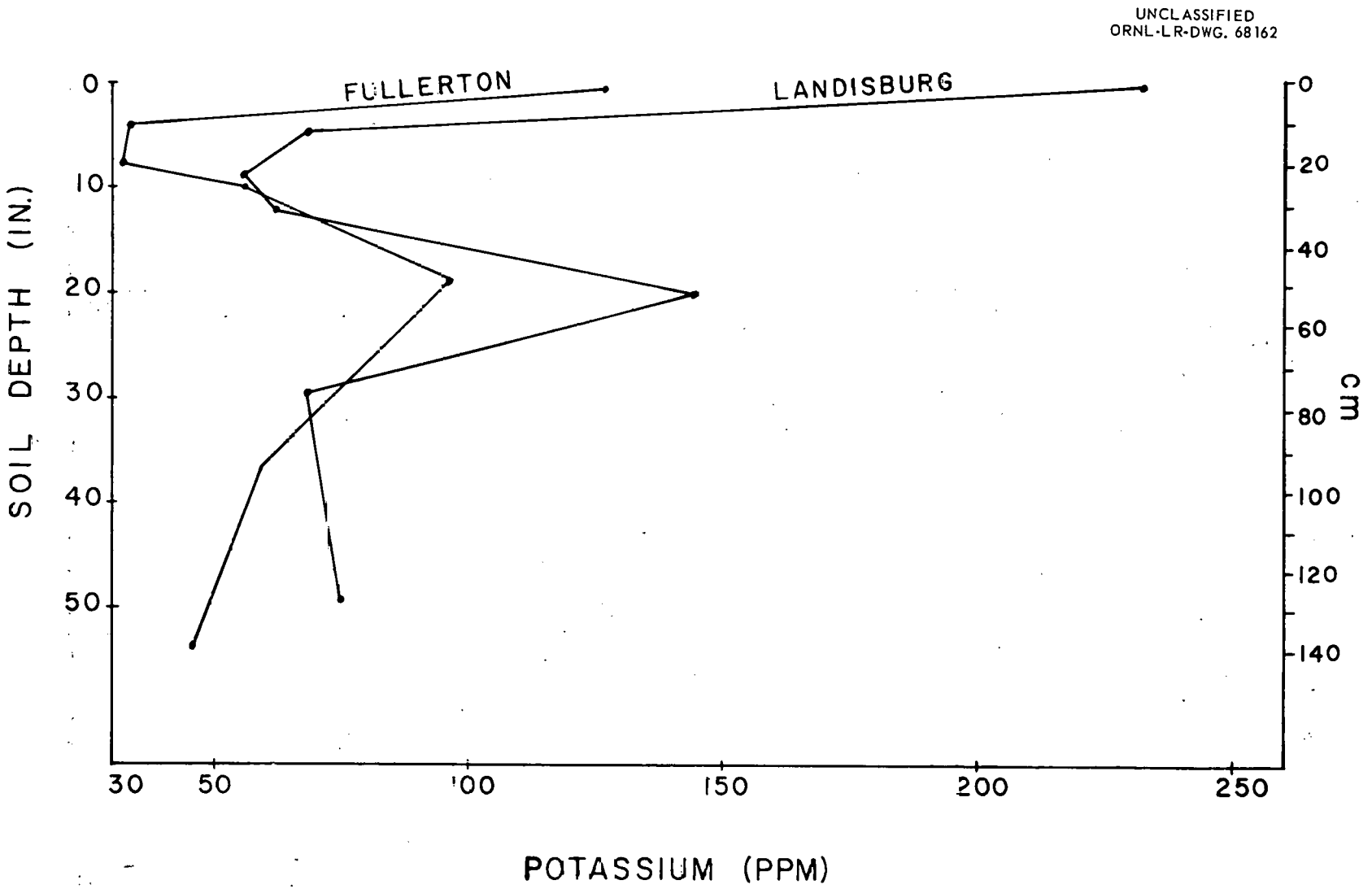

Fig. 4. Ammonium Acetate Exchangeable Potassium in Dolomitic Soil Profiles.

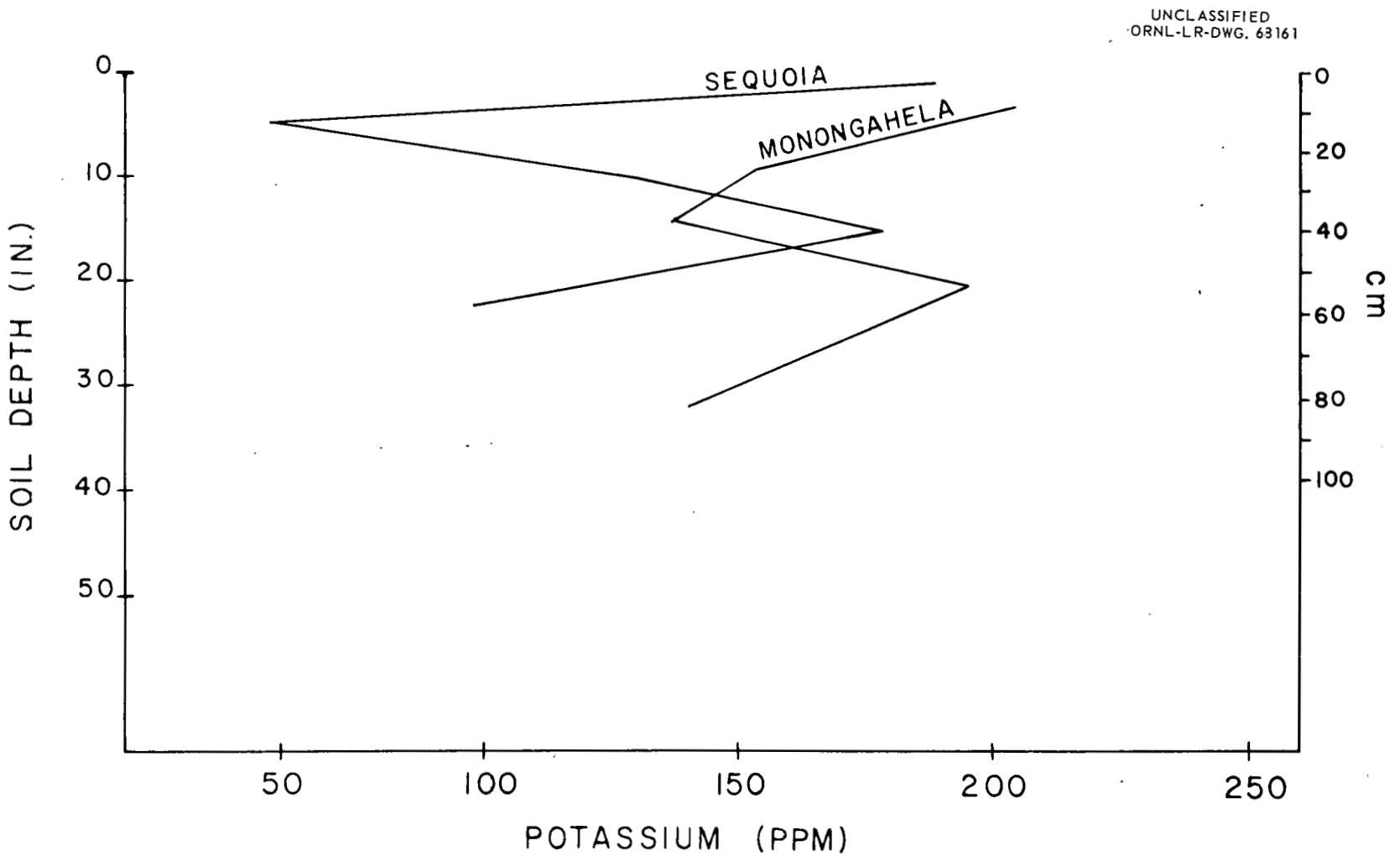

Fig. 5. Ammonium Acetate Exchangeable Potassium in Shale Soil Profiles.

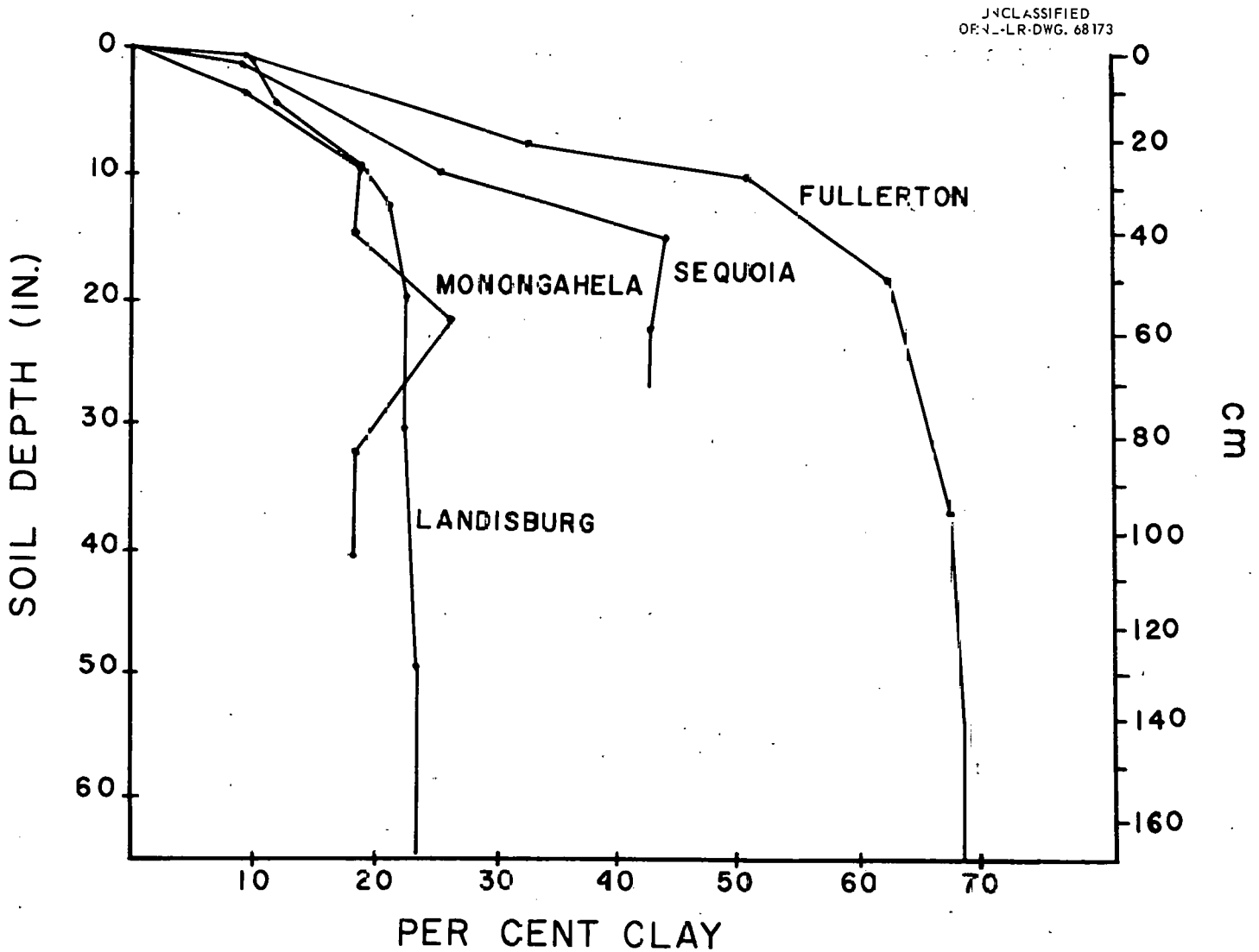

Fig. 6. Soil Depth and Per Cent Clay.

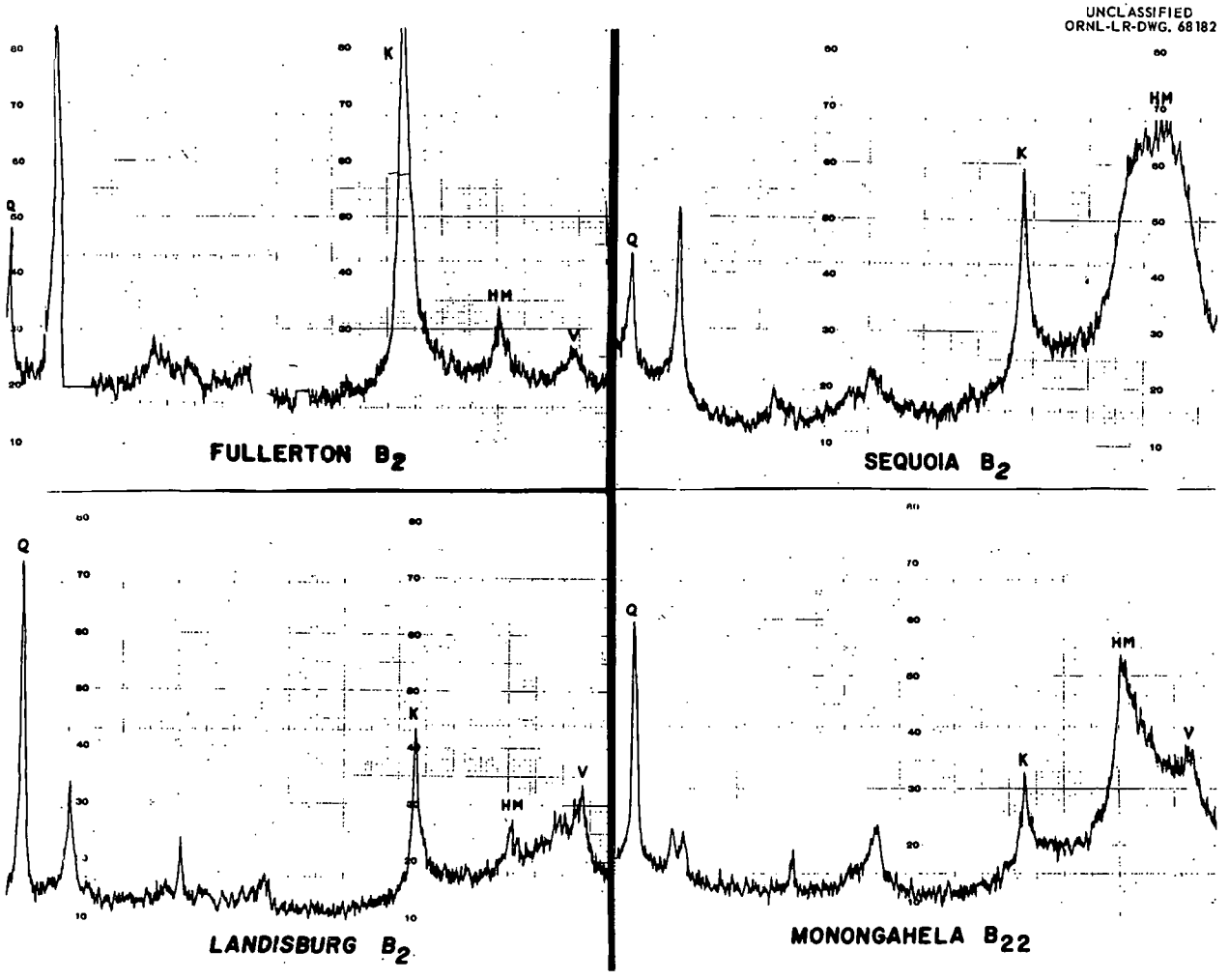

Fig. 7. X-ray Diffraction Analyses for B_2 Horizons

(K = kaolinite, V = vermiculite - montmorillonite, I = illite, HM = hydrous micas, Q = quartz)

Clearly, the Sequoia and Monongahela soils are illitic in nature. This would be expected to give them a greater capacity to fix K and Cs than the Fullerton and Landisburg soils.

The presence of the 2 to 1 type lattice clay minerals such as illite and vermiculite would enhance total cation exchange capacity other factors being equal. In decreasing order of cation exchange capacity, the clay minerals are montmorillonite > vermiculite > illite > kaolinite.

X-ray diffraction analyses for Landisburg horizons are shown in Figure 8. The weathering sequence in profile development is illustrated by increasing prominence of vermiculite and decreasing prominence of kaolinite from lower to upper horizons. The presence of relatively large amounts of vermiculitic minerals in this soil (dolomitic wet) would appear to give it a greater Cs-fixing potential than the Fullerton soil (Tamura and Jacobs, 1959).

D. Stable Cesium

The quantities and distribution of stable Cs in this area were unknown. Determination of stable Cs values (Table VI) by activation analysis gave new information on the natural occurrence of this element. A yield of 84.5 ± 3.6 (s.e.) per cent of total cesium was achieved in activated soil samples after digestion and separation of iron and scandium. Table values have been adjusted accordingly.

Cesium values increased with soil depth in each profile. The linear relationship between clay content of soil horizons and total cesium is illustrated in Figure 9. The coefficient of correlation is 0.871,

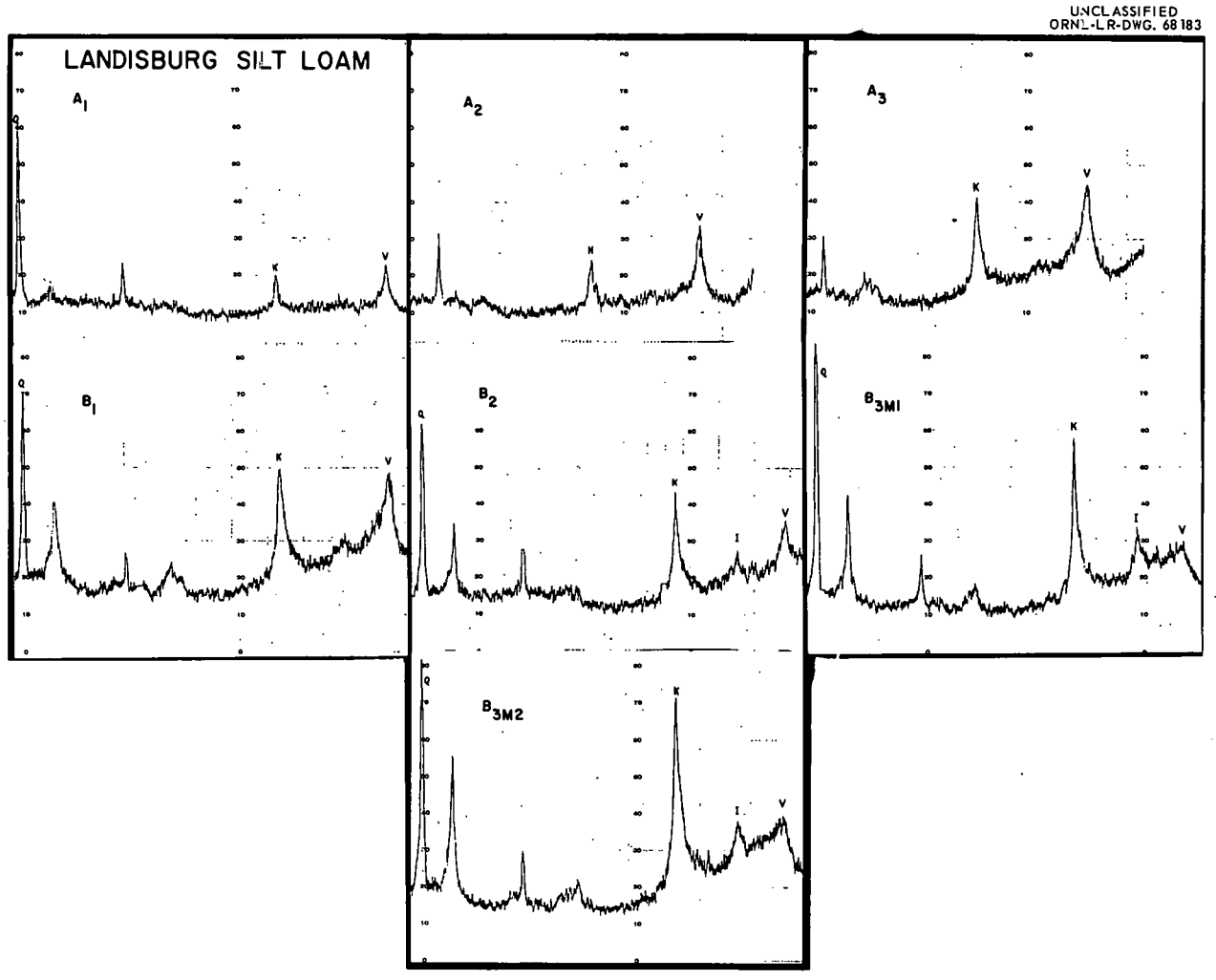

Fig. 8. X-ray Diffraction Analyses for Landisburg Soil Horizons.

(K = kaolinite, V = vermiculite - montmorillonite,
I = illite, Q = quartz)

Table VI

Results of Activation Analyses of Cesium in Soils and White Oak Leaves

Source of Sample	ppm Cs	Mean ± s.e.
Fullerton Horizons		
A_1	2.96	
A_2	3.57	
A_3	5.12	
B_1	6.38	
B_2	8.53	
B_3	8.39	
C_1	7.90	6.11 ± 0.77
Ammonium Acetate		
Exchangeable $A_{1,2,3}$	0.02	
$B_{1,2,3}$	0.06	
White Oak Leaves	2.71	
Landisburg Horizons		
A_1	2.40	
A_2	2.96	
A_3	3.63	
B_1	3.93	
B_2	3.94	
B_{3M1}	3.71	
B_{3M2}	3.65	3.45 ± 0.21
Exchangeable $A_{1,2,3}$	0.01	
$B_{1,2}$	0.03	
White Oak Leaves	1.43	

Table VI, continued

Results of Activation Analyses of Cesium in Soils and White Oak Leaves

Source of Sample	ppm Cs	Mean ± s.e.
Sequoia Horizons		
A_1	1.81	
A_2	2.41	
B_1	4.60	
B_2	5.40	
C_1	5.72	3.95 ± 0.75
Exchangeable $A_{1,2}$	0.01	
$B_{1,2}$	0.04	
White Oak Leaves	1.38	
Monongahela Horizons		
A_p	3.34	
B_{21}	4.07	
B_{22}	4.94	
B_{3M1}	5.36	
B_{3M2}	7.39	4.99 ± 0.78
Exchangeable A_p	0.02	
B_2	0.03	
White Oak Leaves	1.04	
Grand Means		
Soil Horizons		4.67 ± 0.35
Ammonium Acetate Exchangeable		0.027 ± 0.006
White Oak Leaves		1.64 ± 0.41

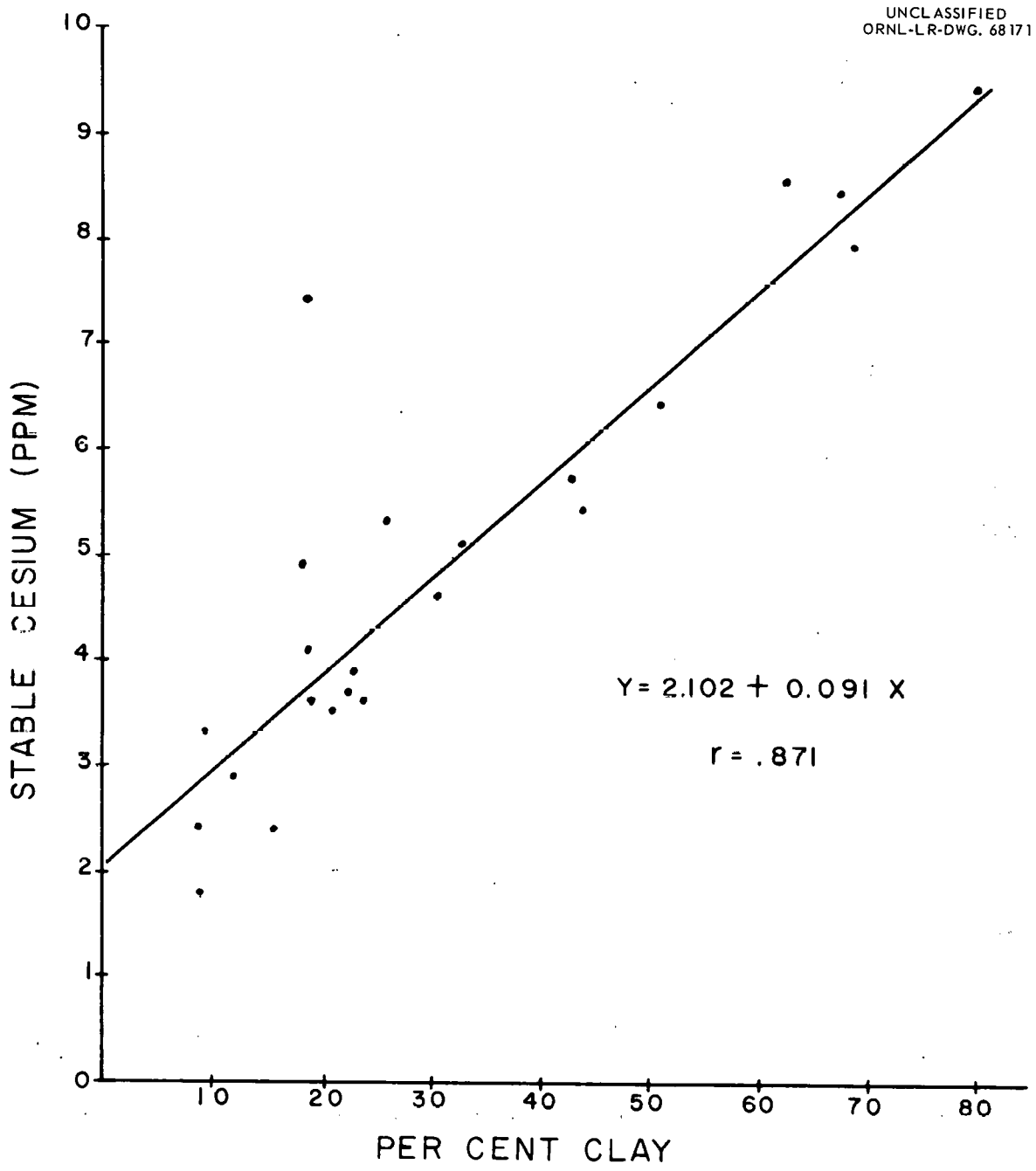

Fig. 9. Regression of Stable Cesium on Clay Content of Four Soil Profiles.

which is significant at the 1 per cent level. The standard error of estimate is 1.03 for observed Cs values. The mean values for profiles cluster around the 5 ppm world average for soils given by Vinogradov (1959).

The quantity of ammonium acetate exchangeable Cs (presumably available for plant uptake) is small, 0.027 ± 0.006 ppm. In all soils the B horizons had a higher value than the A horizons. Expressed as per cent of total Cs, the grand soil mean is 0.61 ± 0.06 per cent exchangeable.

The most site variation in stable Cs was found in white oak leaf contents, which ranged from 1.04 to 2.71 ppm. Leaves from shale sites with higher available K values tended to have lower Cs contents than those from dolomitic sites. The ratio of mean leaf Cs to mean total soil Cs was 0.351 which is similar to the average ratio of 0.400 found by Yamagata, et al. (1959) for native Japanese plants growing on a variety of soils.

Stable Cs concentrations in leaves, though small, were large compared with quantities of Cs^{134} reaching leaves after inoculation. With almost 40 per cent of inoculated Cs^{134} moving into leaves during the growing season, the ratio of stable Cs to Cs^{134} was 2.1×10^{3}. Total stable Cs in leaves, calculated from the mean leaf value of 1.64 ± 0.41 ppm and a mean total leaf weight per tree of 907.0 ± 9.9 g dry weight (12 trees), was 1.48 mg per tree. With 40 per cent of the inoculated Cs^{134} in leaves, a value of 6.88×10^{-4} mg per tree was attained.

Figure 10 represents the cycle of stable Cs in white oak trees.

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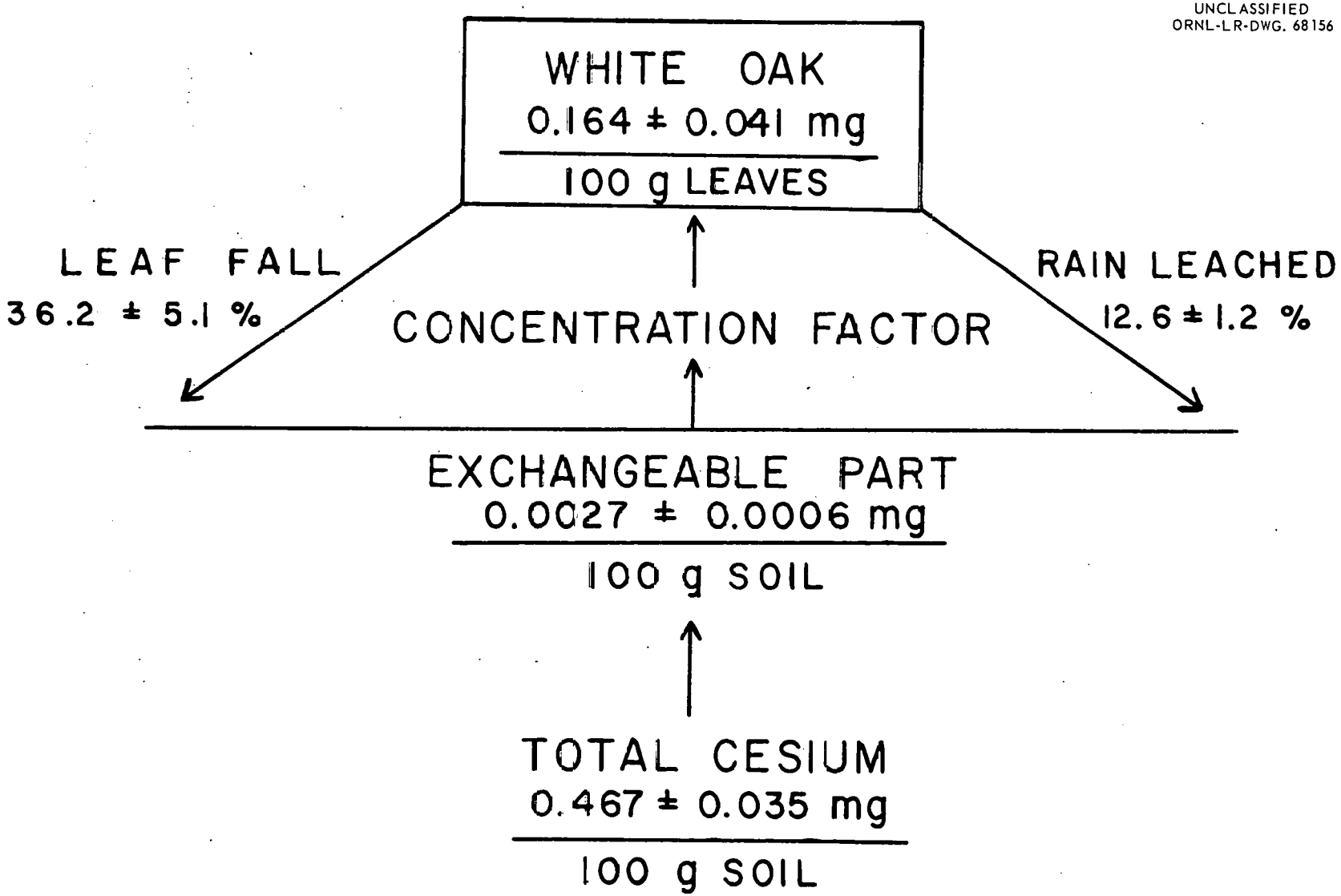

Fig. 10. Stable Cesium Cycle in White Oak.

With estimates of 1960 losses due to leaching by rain and litter fall as a basis, a little over 0.2 mg of stable Cs would be leached out of the leaves and slightly over 0.5 mg would reach the ground as litter fall each growing season.

V. GAINS AND LOSSES OF CESIUM-134, 1960 GROWING SEASON[1]

A. Potassium-42 and Cesium-134 Inoculations

Rapid movement of both K^{42} and Cs^{134} into leaves occurred in two trees double tagged with these radioisotopes. The Mauget feeders on the tree growing on Monongahela soil (shale wet site) emptied in less than 1.5 hours. Table VII gives leaf concentrations of radioisotopes 1.5 and 21.5 hours post inoculation. After 1.5 hours the total gamma activity ranged from 2.82×10^6 to 1.74×10^2 dpm per g dry weight of leaves. Limb-to-limb variation was large, but an appreciable amount of both radioisotopes was distributed over the entire crown. The mean K to Cs ratio in leaves after 1.5 hours was 1.44 ± 0.07 (s.e.), and after 21.5 hours it was 1.34 ± 0.11 with more total activity present. Potassium appeared to be preferentially taken into buds (K to Cs of 3.99) sampled at the top of the crown. This might in part explain a tendency for the K to Cs ratio in leaves to be below that expected from the initial ratio of the two radioisotopes (1.89). A rainfall sample collected under the tree during the night following inoculation (0.8 inch rain) also showed a tendency for enrichment of the K to Cs ratio (4.05, based on 75 dpm Cs^{134} per ml).

A second double-tagged tree growing on Fullerton soil (dolomitic dry site) exhibited a similar pattern of distribution (Table VIII). From an initial K^{42} to Cs^{134} ratio of 2.33, leaves attained a mean ratio of 1.32 ± 0.29 after 24 hours.

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[1]Material in this chapter has been published (Witherspoon, 1962) using a 2.3 year half-life for Cs-134 instead of the more recently determined 2.07 year half-life now used.

Table VII

Gamma Activity in White Oak (*Quercus alba* L.)

Original quantity of tracer introduced: K^{42}, 3.78 mc; Cs^{134}, 2.00 mc. K/Cs ratio: 1.89

Height Above Inoculation (Feet)	Part Sampled and Designation	Gamma Activity (dpm/g) and K/Cs Ratios			
		1.5 hr After Inoculation		21.5 hr After Inoculation	
		Cs-134	K/Cs*	Cs-134	K/Cs*
		x 10^4		x 10^4	
	Leaves				
0.6	N	177.41	1.59	298.94	1.53
1.9	N	5.77	1.31	3.96	1.19
1.9	S	0.007	1.49	0.15	2.15
1.9	E	1.13	1.25	1.94	1.05
3.6	N	31.31	1.60	33.77	1.70
3.6	W	40.42	1.69	46.08	1.34
5.6	E	16.70	1.77	1.94	1.27
8.2	N	7.61	1.36	7.48	1.01
8.2	W	41.39	1.68	59.91	1.28
8.2	E	0.86	1.68	1.01	1.21
14.7	N	6.06	0.90	1.10	0.87
14.7	S	6.93	0.98	8.86	1.28
14.7	Buds	--	--	22.19	3.99

*Corrected for decay.

Table VIII

Gamma Activity in White Oak

Original quantity of tracer introduced:
K^{42}, 4.46 mc; Cs^{134}, 2.00 mc.
K/Cs ratio: 2.23

Height Above Inoculation (Feet)	Part Sampled and Designation	Gamma Activity (dpm/g) and K/Cs Ratios 24 hr After Inoculation	
		Cs-134	K/Cs*
	Leaves	x 10^4	
0.6	W	1210.16	1.20
2.3	S	2.01	1.33
2.3	E	4.65	0.92
4.2	S	1.77	1.04
4.2	W	1.66	3.90
6.5	N	.49	1.49
6.5	E	.83	1.09
10.2	E	9.21	1.01
10.2	W	12.71	0.91
15.7	N	37.42	0.77
15.7	S	21.55	0.86

*Corrected for decay.

On the basis of these observations, the movement of Cs^{134} in trees seems to have been about as rapid as that of K^{42}, and the quantities involved were also similar shortly following trunk inoculation. There was no significant difference between trees in mean K to Cs ratios in leaves after 24 hours. Apparently site characteristics, such as available K in soil, which might tend to reduce Cs movement or favor K movement, did not influence initial Cs movements from inoculated trunks into leaves.

B. Movement of Cesium-134 into Leaves

The early activity levels in foliage was related to the emptying rate of the Mauget feeders. Time of emptying varied from 1.5 hours to 9 days. Feeders on shale dry site trees emptied in 7 to 9 days, probably because they were inoculated just as their leves were emerging from the buds. Once the leaves reached a size of three-fourths inch in length, feeder emptying proceeded more swiftly. Feeders on trees at the other three sites emptied in from less than 1.5 hours to 3 days. Variation in emptying rate between feeders on the same tree was probably due to lack of feeder contact with enough vascular tissue to insure maximum translocation. All trees were inoculated on days favorable for transpiration, i.e. hot and dry. It was necessary to drive the feeder tubes about one-half inch into the trunk, and, with trees of 0.8 to 2.7 inches dbh, the tubes undoubtedly passed through the main sap stream in many cases.

In all 12 trees, leaf activity levels increased up to three or four weeks following inoculation when concentrations of 10^5 to 10^6 dpm per g dry weight were observed. After this time decreases in activity

were observed until the end of the growing season. Figure 11 shows these trends in mean leaf activity for all trees during the growing season.

Total movement of inoculated Cs^{134} into leaves was estimated by multiplying mean leaf values per tree by estimated total leaf weight per tree (see Chapter IX on mensuration of harvested trees). Table IX gives mean leaf values for each tree at time of observed maximum concentration and at the end of the growing season. The variation between leaf contents of sampled branches tended to decrease during the season, as illustrated by smaller standard errors of means at the end of the season.

Maximum movement into leaves was greater on the dolomitic sites, both wet and dry, with 58.0 ± 4.2 and 51.7 ± 14.0 per cent of the original inoculation, respectively, moving into leaves. The shale dry and wet sites with 40.9 ± 16.7 and 7.8 ± 1.8 per cent, respectively, were significantly different (1 per cent level) from dolomitic sites in an analysis of variance comparing site geology and moisture (Table X). Since shale dry site trees reached maxima almost as great as those on dolomitic sites, it is probable that the low values for shale wet site trees were due to their inoculation at a time in the growing season less favorable for translocation. By the end of the growing season, a mean reduction from observed maxima of 63.8 ± 5.1 per cent (range, 30.6 to 88.4 per cent) was found. No significant difference was found between sites (Table X).

C. Losses from Leaves

The first rains following inoculation started leaching Cs^{134} from the leaves. Rain water samples collected under the crowns of four trees

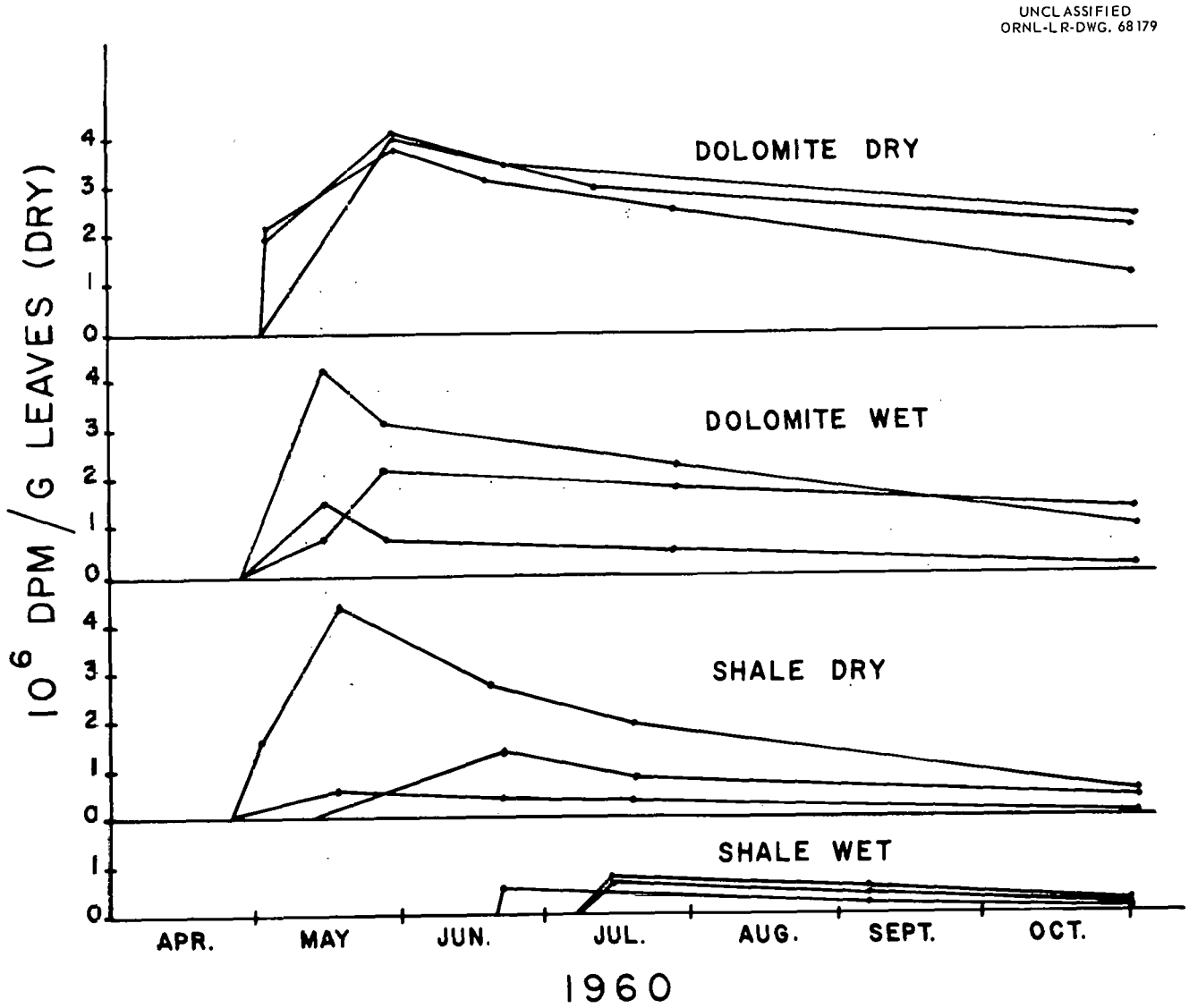

Fig. 11. Cesium-134 Activity in White Oak Leaves, 1960 Growing Season.

Table IX

Mean Cesium-134 Activity in White Oak Leaves, 1960 Growing Season

Site and Tree	Number of Branches Sampled	Mean dpm per g dry wt. ± standard error	
		Observed Maximum x 10^6	End of Season x 10^6
DD1	17	4.12 ± 1.12	2.39 ± 0.91
2	20	3.89 ± 0.97	1.12 ± 0.12
3	22	4.11 ± 1.03	2.46 ± 0.38
DW1	26	4.28 ± 0.94	0.98 ± 0.36
2	21	1.55 ± 0.31	0.18 ± 0.05
3	28	2.18 ± 0.65	1.33 ± 0.13
SD1	29	0.56 ± 0.21	0.11 ± 0.01
2	20	4.36 ± 0.98	0.50 ± 0.03
3	22	1.31 ± 0.26	0.41 ± 0.04
SW1	23	0.53 ± 0.23	0.10 ± 0.03
2	19	0.77 ± 0.19	0.21 ± 0.04
3	14	0.65 ± 0.21	0.23 ± 0.02

Table X

Analyses of Variance

Stages of Cs^{134} Transfer, 1960 Growing Season

Source	Degrees of Freedom	SS	MS	F Calculated	F.05	F.01
Maximum Per Cent of Inoculation Reaching Leaves						
A. Moisture	1	1229.18	1229.18	3.65	5.12	
B. Geology*	1	2704.50	2704.50	8.01	5.12	10.56
C. Interaction	1	503.45	503.45	1.72	5.12	
D. Subtotal	3	4437.13	1479.04			
E. Within	8	2334.58	291.82			
F. Total	11	6971.71	633.79			
G. Residual	9	3038.03	337.56			
Per Cent Reduction of Leaf Maximums During Season						
A.	1	17.28	17.28	0.05	241.00	
B.	1	1134.91	1134.91	3.72	5.12	
C.	1	219.48	219.48	0.60	239.00	
D.	3	1371.67	457.22			
E.	8	2519.82	314.98			
F.	11	3891.49	353.77			
G.	9	2739.30	304.37			
Per Cent of Leaf Maximum Leached Out by Rain						
A.	1	89.65	89.65	2.42	161.00	
B.	1	67.38	67.38	1.81	4052.00	
C.*	1	37.08	37.08	8.50	5.32	11.26
D.	3	194.11	64.70			
E.	8	34.91	4.36			
F.	11	229.02	20.82			
G.	9	71.99	7.99			
Per Cent of Leaf Maximum Returned to Wood						
A.	1	107.05	107.05	0.34	241.00	
B.	1	501.81	501.81	1.58	5.12	
C.	1	584.36	584.36	2.06	5.32	
D.	3	1193.22	397.74			
E.	8	2270.06	283.76			
F.	11	3463.28	314.84			
G.	9	2854.42	317.16			

*Significant at 5% level.

contained Cs^{134} activity well in excess of control rain samples collected some distance away from inoculated trees (Figure 12). Light drizzling rains tended to leach out more radiocesium than similar quantities of rain falling as heavy showers. Rain after a dry period tended to leach out more than rain in the middle of a wet period. Five ml rain samples contained as little as 19 dpm and as much as 780 dpm above control rain samples. Figure 13 shows the activity of several rain collections and random litter samples under an inoculated tree on the dolomitic wet site. The increase in litter activity varied as a function of kind and amount of rain.

At the end of the growing season (late September), radiometric analyses of understory, litter, and soil indicated that appreciable quantities of radiocesium had been leached out of inoculated trees. Table XI gives quantities of Cs^{134} found in a 9 m^2 grid under the trees. Understory, litter, and soil values were added as an estimate of the total leached out of each tree by rain. Measured total activity in leaves at the end of the season was added to rain loss, and this sum was subtracted from maximum leaf values to obtain estimates of radiocesium movement from leaves back into woody tissues. Table XII gives percentages involved in these stages of transfer during the growing season.

Losses due to rain ranged from 7.4 to 21.1 per cent (average, 12.6 ± 1.2) of observed leaf maxima in the 12 trees. The significant interaction in the analysis of variance of per cent of leaf maximum leached out by rain (Table X) may have been due to the timing of the experiment. The shale site trees tended to lose a larger percentage of radiocesium

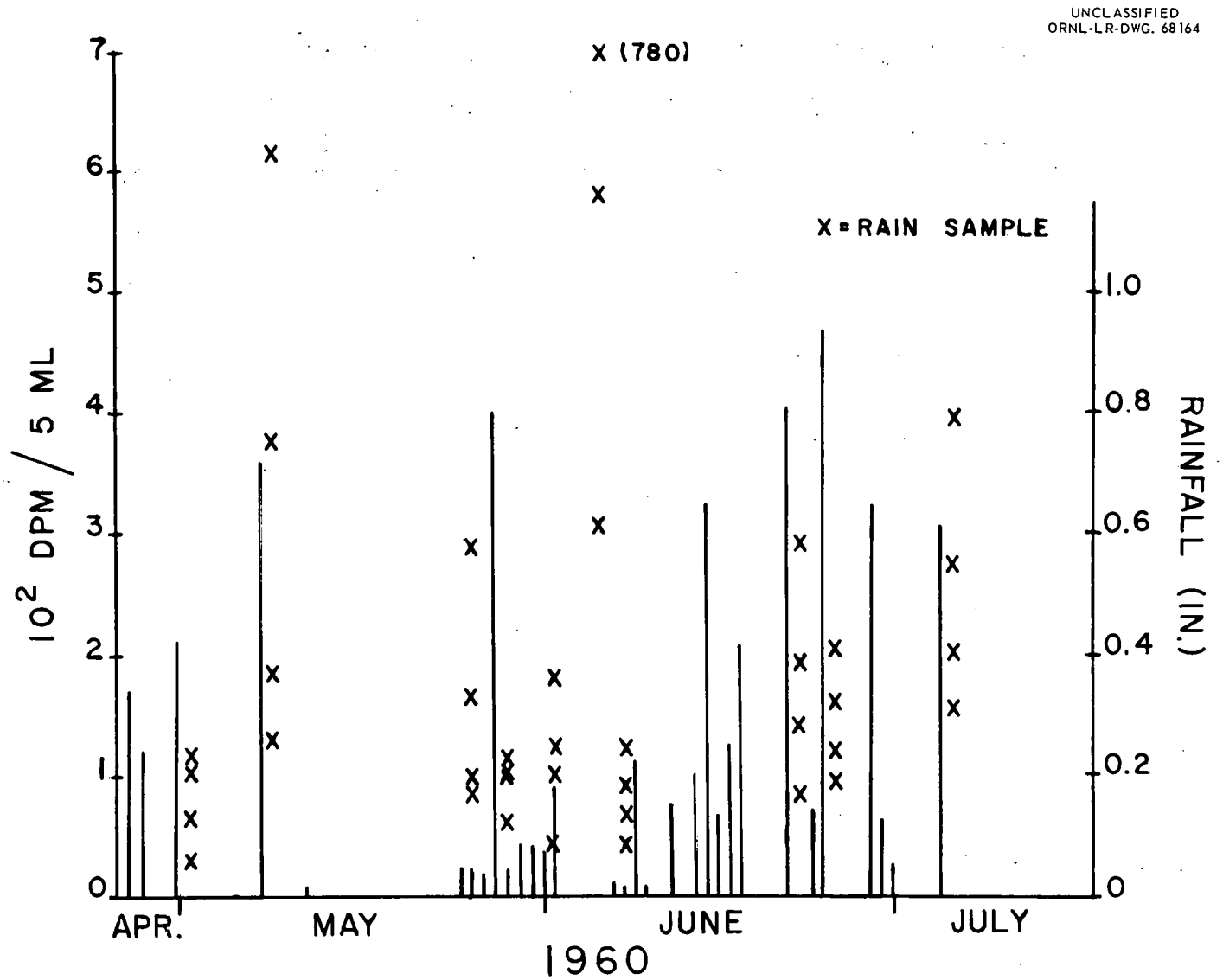

Fig. 12. Cesium-134 Activity in Rain Collections.

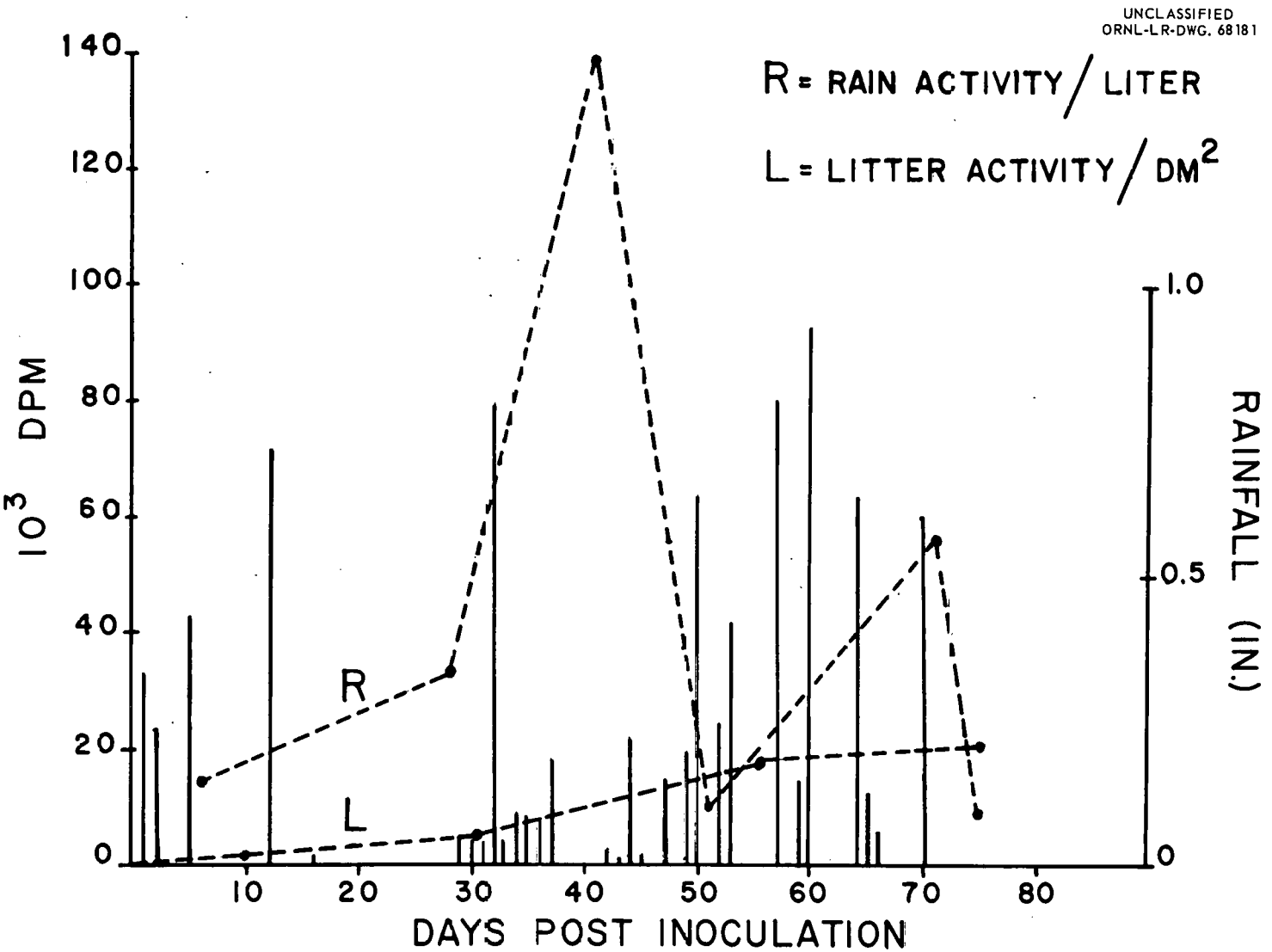

Fig. 13. Cesium-134 Activity in Rain and Litter Collected Under an Inoculated Tree.

Table XI

Microcuries of Cs^{134} In and Around Inoculated Trees at the End of the 1960 Growing Season

Site and Tree	Growing Season Maximum in Leaves	In Leaves End of Growing Season	Rained Out	In Vegetation (N = 4)	In Litter (N = 20)	Total in Soil	Soil Depths 0-1" (N = 40)	1-2" (N = 40)	2-4" (N = 40)
DD1	1109.72	643.89	121.92	4.10	19.51	98.31	64.47	27.29	6.55
2	1220.93	355.37	92.10	2.74	38.85	50.51	43.39	3.27	3.85
3	1253.10	750.01	118.08	3.02	28.15	86.91	60.98	19.74	6.19
DW1	1501.80	712.02	110.86	14.31	10.44	86.11	56.40	12.26	17.45
2	686.89	80.65	84.68	3.45	7.25	73.98	47.72	9.37	16.89
3	912.43	632.94	128.83	13.97	12.84	102.02	67.93	11.55	22.54
SD1	405.35	81.07	41.72	4.79	7.33	29.60	19.67	8.06	1.87
2	1373.71	158.15	153.74	3.07	34.05	116.62	80.74	28.99	6.89
3	675.41	212.44	68.74	6.33	10.63	51.78	36.68	13.67	1.43
SW1	207.16	73.63	43.87	5.05	3.97	34.85	11.59	12.67	10.59
2	156.77	43.16	29.22	0.95	3.20	25.07	6.95	8.72	9.40
3	103.93	34.04	19.51	0.39	2.41	16.71	4.22	7.01	5.48

Table XII

Stages in Transfer of Cesium-134, 1960 Growing Season

Parent Material	Dolomite		Shale		
Topography	Dry	Wet	Dry	Wet	
Soil Series	Fullerton*	Landisburg*	Sequoia*	Monongahela*	Grand Means
Per Cent of Input					
Maximum in leaves	58.0 ± 4.2	51.7 ± 14.0	40.9 ± 16.7	7.8 ± 1.8	39.6 ± 6.2
Per Cent of Leaf Maximum					
In leaves end of season	48.9 ± 10.6	42.8 ± 19.6	20.9 ± 6.8	30.9 ± 2.7	36.2 ± 5.1
Returned into tree wood	41.8 ± 11.2	45.9 ± 14.6	68.6 ± 6.5	49.6 ± 3.1	51.2 ± 4.5
Rained out	9.3 ± 1.2	11.3 ± 2.3	10.5 ± 0.3	19.5 ± 0.9	12.6 ± 1.2
Per Cent of Activity Rained Out					
In understory	3.0 ± 0.3	9.3 ± 3.0	7.6 ± 3.3	5.6 ± 3.3	6.3 ± 1.0
In litter	27.3 ± 9.0	9.3 ± 0.5	18.4 ± 2.3	10.8 ± 1.1	16.5 ± 3.0
In soil	69.7 ± 8.9	81.4 ± 3.3	74.0 ± 1.7	83.6 ± 2.2	77.2 ± 2.9
Per Cent of Activity in 0 to 1 In. Soil					
0 to 1 in.	73.9 ± 7.0	65.6 ± 0.7	68.8 ± 1.5	28.7 ± 2.8	59.2 ± 5.5
1 to 2 in.	19.0 ± 7.3	12.7 ± 1.0	26.2 ± 0.8	37.7 ± 2.5	23.9 ± 3.1
2 to 4 in.	7.1 ± 0.3	21.7 ± 0.9	5.0 ± 1.2	33.6 ± 2.4	16.9 ± 3.1

*Mean of three trees ± s.e.

than those on dolomitic sites.

Only a small portion of this Cs^{134} was contained in understory vegetation, 6.3 ± 1.0 per cent of the total leached out by rain. Quantity of understory vegetation, however, varied greatly from tree to tree. By the end of the growing season, 77.2 ± 2.9 per cent of the rain-transferred radiocesium had reached the mineral soil.

A definite pattern of activity distribution was found around trees. Larger quantities were found in soil and litter near the trunks than in any area of similar size under the crown. This was presumably due to larger amounts of rain flowing down the stem. Most of the activity was found under the crown with only small amounts found at distances several feet from crown perimeters. This distribution pattern is discussed in detail in Chapter VIII.

Estimates of radiocesium which had moved back into woody tissue did not vary significantly from site to site (Table X). A mean value of 51.2 ± 4.5 per cent of leaf maximums was presumed to have returned to wood by the end of the growing season, leaving 36.2 ± 5.1 per cent to fall to the ground as litter. This annual litter fall would add about three times more radiocesium to the forest floor than rain. Much of this amount would be subsequently leached from litter and transferred into the mineral soil.

Figure 14 depicts the mean gains and losses of Cs^{134} in white oaks during the 1960 growing season. From a maximum of about 40 per cent of the inoculation which reached the leaves, almost 49 per cent was lost during the growing season. A little over one-fourth of this loss was

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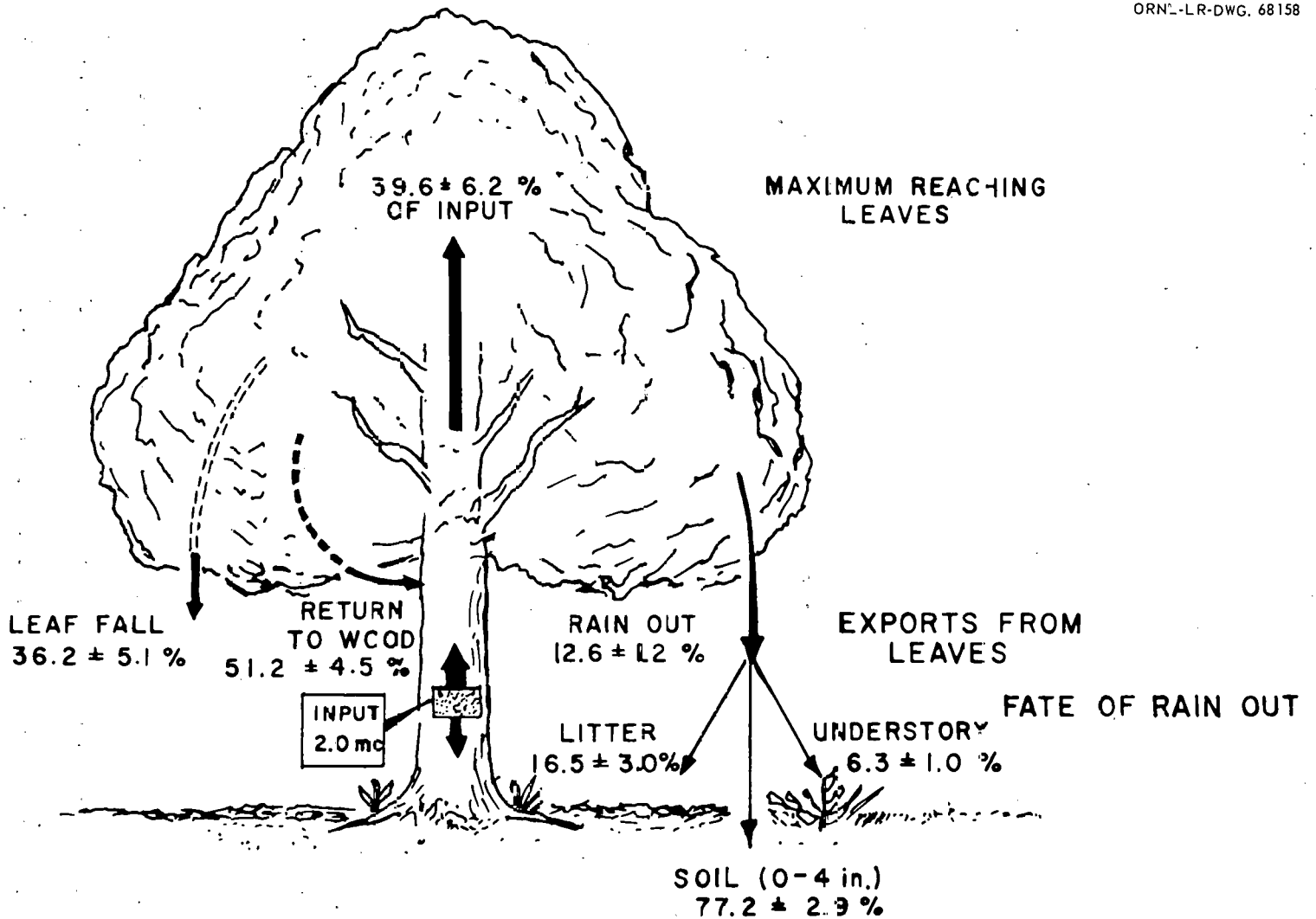

Fig. 14. Cycle of Cs^{134} in White Oak. Average of 12 Trees at End of Growing Season.

due to the leaching action of rain, the remaining three-fourths due to annual litter fall.

D. Cesium-134 Mobility in Litter and Soil

The fate of radiocesium reaching the ground in rain varied from site to site. The percentages of rain-exported Cs^{134} in the litter layer of wet sites were significantly lower (5 per cent level) than those of dry sites (Table XIII). Dolomitic dry and shale dry sites held 27.3 ± 9.0 and 18.4 ± 2.3 per cent, respectively, of the rain loss in their litter layer. The dolomitic and shale wet sites held only 9.3 ± 0.5 and 10.8 ± 1.1 per cent, respectively. For all sites, 16.5 ± 3.0 per cent remained at the end of the growing season, while 77.2 ± 2.9 per cent had reached the mineral soil.

Site differences in downward movement were found between soils. Mobility was greater in the Landisburg and Monongahela (wet site) soils. Figure 15 indicates the mean percentages of total soil Cs^{134} found at three soil depths. In the 0 to 1 inch layer three sites showed no significant difference (Table XIV), but the shale wet soil was significantly lower (1 per cent level) than the others. In the 1 to 2 inch layer the shale wet soil was significantly higher in Cs^{134} than the dolomitic wet or dry soils. Percentages in the 2 to 4 inch layer of wet soils averaged 4.5 times higher than for dry soils. These differences in mobility were probably functions of both moisture status and soil morphology, and they will be discussed in Chapter X.

Table XIII

Analyses of Variance

Cesium^{134} in Litter and Soil at End of 1960 Growing Season

Source		Degrees of Freedom	SS	MS	F Calculated	F.05	F.01
			Per Cent of Rained Out Cs^{134} in Litter Layer				
A.	Moisture*	1	493.44	493.44	9.42	5.12	10.56
B.	Geology	1	42.07	42.07	0.80	241.00	
C.	Interaction	1	82.01	82.01	1.68	5.32	
D.	Subtotal	3	617.52	205.84			
E.	Within	8	389.49	48.69			
F.	Total	11	1007.01	91.55			
G.	Residual	9	471.50	52.39			
			Per Cent of Total Soil Cs^{134} in 0-1 In. Soil Layers				
A.		1	1883.76	1883.76	2.25	161.00	
B.		1	1418.98	1418.98	1.69	161.00	
C.**		1	837.17	837.17	12.13	5.32	11.26
D.		3	4139.91	1379.97			
E.		8	551.88	68.98			
F.		11	4691.79	426.53			
G.		9	1389.05	154.34			
			Per Cent of Total Soil Cs^{134} in 1-2 In. Soil Layer				
A.		1	20.96	20.26	0.08	161.00	
B.		1	774.41	774.41	3.27	161.00	
C.*		1	236.93	236.93	6.70	5.32	11.26
D.		3	1032.30	344.10			
E.		8	282.81	35.35			
F.		11	1315.11	119.55			
G.		9	519.74	57.75			
			Per Cent of Total Soil Cs^{134} in 2-4 In. Soil Layer				
A.		1	1397.30	1397.30	9.54	161.00	
B.		1	70.52	70.52	0.48	161.00	
C.**		1	146.38	146.38	31.08	5.32	11.26
D.		3	1614.20	538.07			
E.		8	37.69	4.71			
F.		11	1651.89	150.17			
G.		9	184.07	20.45			

* Significant at 5% level.

** Significant at 1% level.

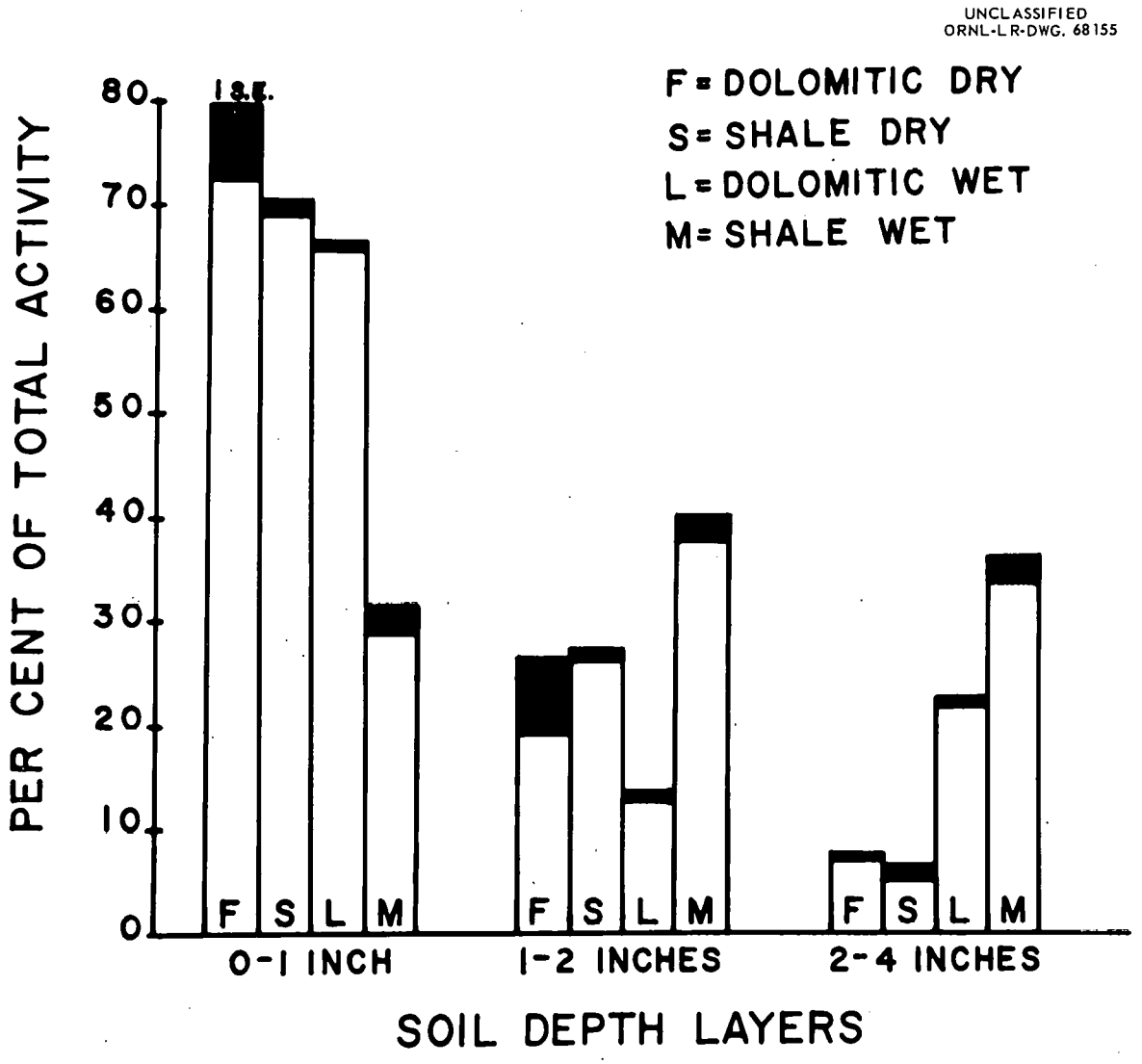

Fig. 15. Average Per Cent of Total Soil Cs^{134} in 0 to 4 Inches Depth at End of 1960 Growing Season.

Table XIV

Comparisons[1] of Site Mean Cesium-134 Values in Litter and Soil on the Four Sites, 1960 Growing Season

Mean Per Cent of Rained Out Cs-134 in Litter Layer

	DW 9.3	SW 10.8	SD 18.4	DD 27.3
DD	18.0 (20.7)[2]	16.5 (20.1)	8.9 (19.1)	
SD	9.1 (20.1)	7.6 (19.1)		
SW	1.5 (19.1)			

Mean Per Cent of Total Soil Cs-134 in 0-1 In. Depth

	SW 28.7	DW 65.6	SD 68.8	DD 73.9
DD	45.2** (24.6)	8.3 (23.9)	5.1 (22.7)	
SD	40.1** (23.9)	3.2 (22.7)		
DW	36.9** (22.7)			

Mean Per Cent of Total Soil Cs-134 in 1-2 In. Depth

	DW 12.7	DD 19.0	SD 26.2	SW 37.7
SW	25.0** (17.6)	18.7** (17.2)	11.5 (16.3)	
SD	13.5 (17.2)	7.2 (16.3)		
DD	6.3 (16.3)			

Mean Per Cent of Total Soil Cs-134 in 2-4 In. Depth

	SD 5.0	DD 7.1	DW 21.7	SW 33.6
SW	28.6** (6.4)	26.5** (6.3)	11.9** (5.9)	
DW	16.7** (6.3)	14.6** (5.9)		
DD	2.1 (5.9)			

[1]Duncan's multiple range test.

[2]Number in parenthesis is significant studentized range for the 1% level.

**Significant at 1% level.

VI. TRANSFER OF CESIUM-134 FROM LITTER TO VEGETATION

A. Uptake by Leaves Through Growing Season

Although total uptake values were low, radiocesium movement from litter into white oak saplings was very rapid. On Landisburg silt loam six days after application of litter, and with 1.7 inches of rain, samples of 10 leaves per sapling contained from 23 to 206 dpm per g dry weight (mean, 100 ± 30). Figure 16 shows average uptake by leaves of 10 saplings growing on each of two soils (Landisburg and Litz) through the growing season. The activity of these samples increased with time, but plant to plant variations were large, particularly in those on the Landisburg soil. Higher quantities of radiocesium which moved into leaves in saplings on the Landisburg were presumably due to higher initial application. When leaf uptake is expressed as percentage of applied litter activity (Figure 17), saplings on the Litz soil appeared to take up more radiocesium than those on the Landisburg. The plant to plant variations were large on both soils, however, and the overlapping of standard errors of the means plotted in Figure 17 indicate that leaf uptake on the two soils did not differ significantly.

The per cent uptake from litter was almost as rapid as that from solution applications (Figure 18). Radiocesium quantities were greater in leaves of saplings around which solution applications were made (Figure 19). This is because approximately two times more radiocesium was involved in the solution treatments, and this was reflected in quantities which reached the leaves.

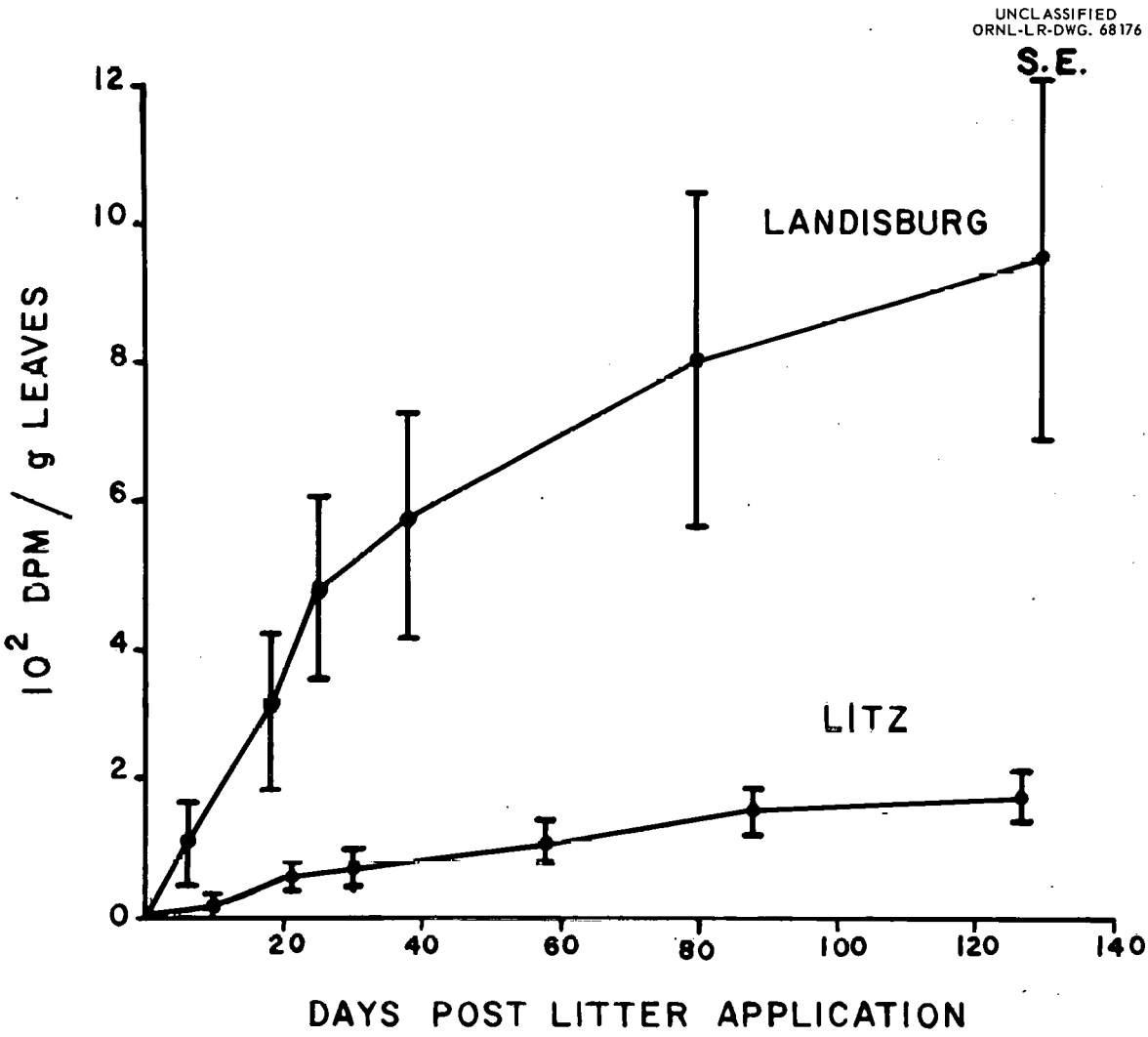

Fig. 16. Average Cs^{134} Uptake by Leaves of 10 White Oak Saplings from Tagged Litter on Each of Two Soils.

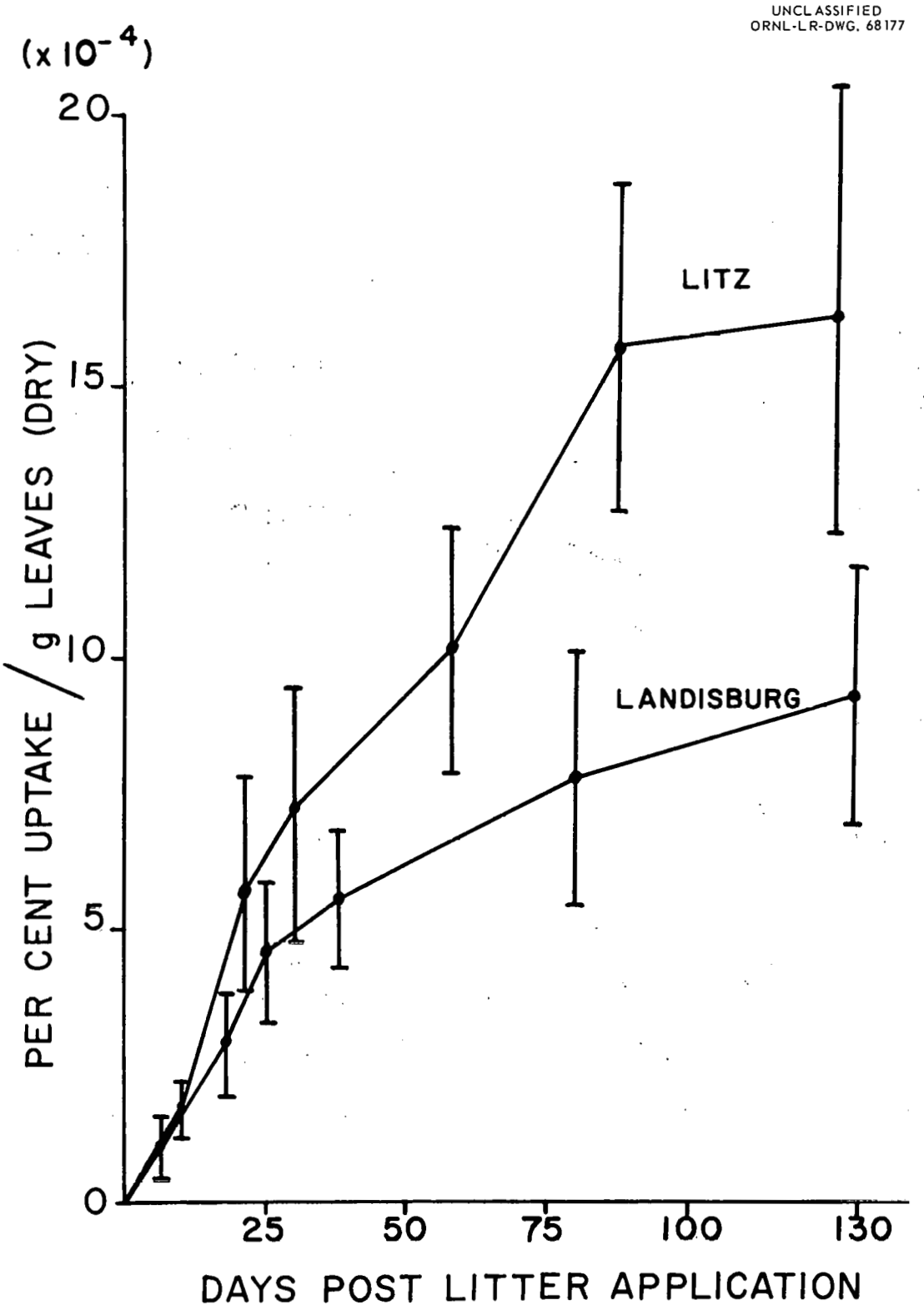

Fig. 17. Average Per Cent Uptake of Cs^{134} by Sapling Leaves From Tagged Litter Applied to Two Soils.

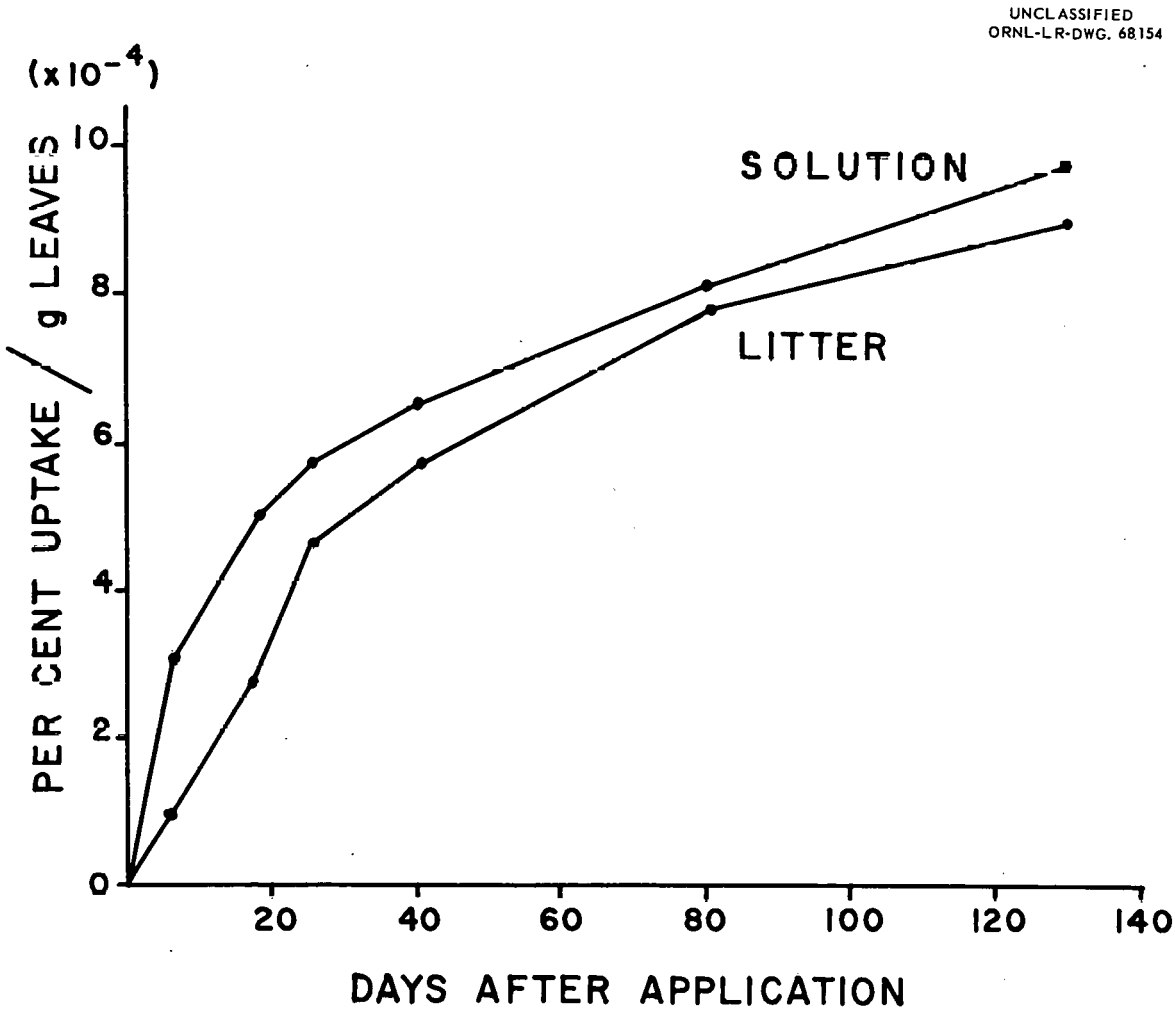

Fig. 18. Per Cent Uptake by White Oak Saplings from Tagged Litter and Solution Applied to Landisburg Soil.

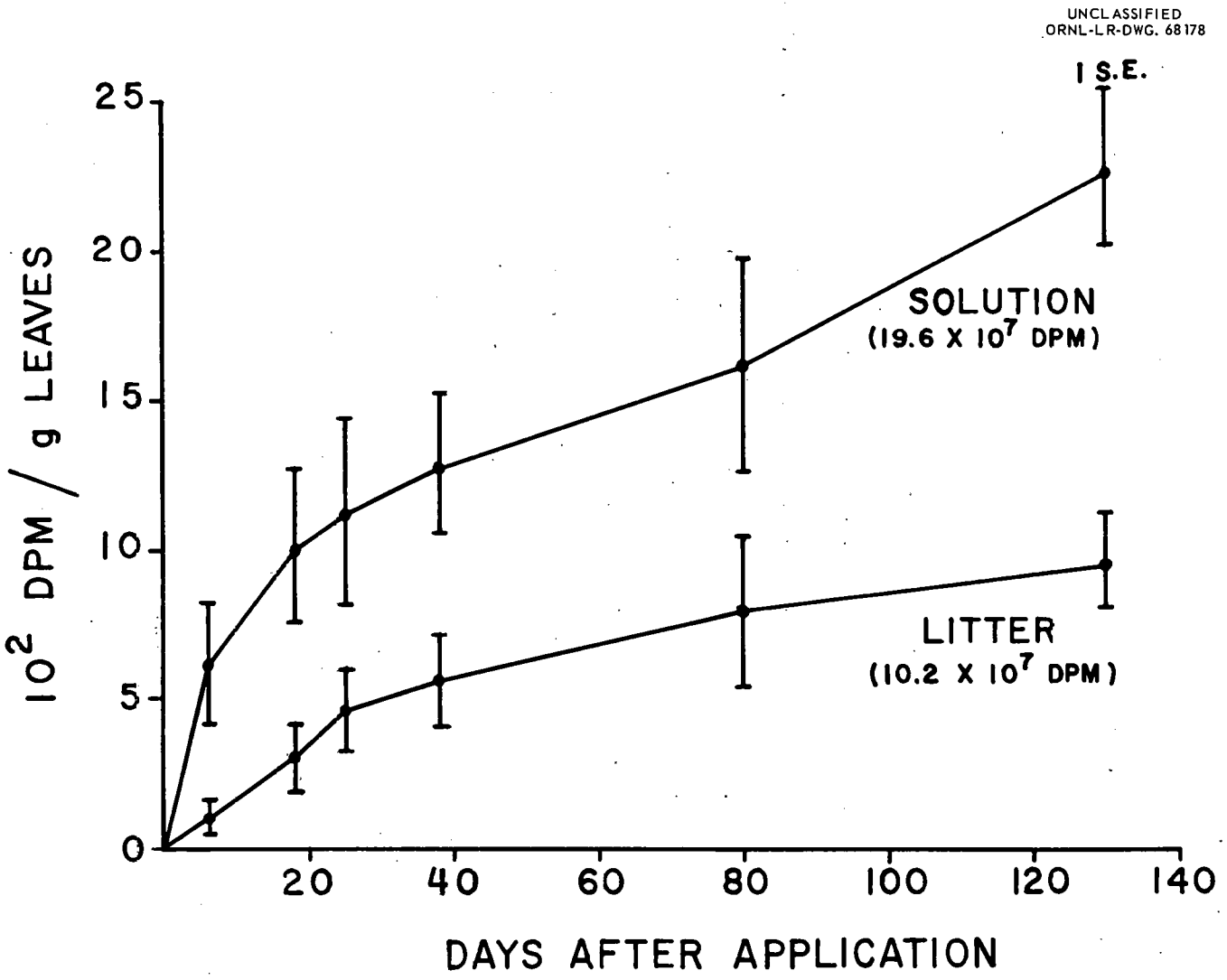

Fig. 19. Average Uptake of Cs^{134} by White Oak Sapling Leaves from Tagged Litter and Solution Applications to Landisburg Soil.

By the end of the observation period (first week in November), leaves contained from 0.9 to 1.6×10^{-3} per cent per g dry weight of the litter activity. This is a very small quantity, but the rapidity with which this tranfer begins illustrates how a trace of radiocesium contamination can complete a plant to litter to plant cycle in a brief portion of the growing season without going through the normal processes of leaf fall and decay.

B. Total Sapling Uptake

Shoots of 16 saplings were harvested in November, 1960, and the root systems of 10 of these were extracted from the soil. Table XV gives the size and dry weight measurements of harvested saplings. Mean root to shoot ratios were 1.86 ± 0.12 for saplings on Landisburg soil and 1.81 ± 0.30 for those growing on Litz soil.

Sapling uptake values are given in Table XVI. Little difference was observed in the per cent uptake from litter between plants on the two soils, total uptake averaged 0.325 ± .06 and 0.346 ± .03 per cent on the Landisburg and Litz soils, respectively. Uptake from solution applications was slightly less in shoots and roots than that from litter. Of the total uptake, approximately 80 per cent was in the root system at harvest time.

Differences in concentrations of radiocesium were observed between various plant components. Mean dpm per g dry weight concentrations for Landisburg saplings serve to illustrate these differences:

Table XV

Size and Weight Measurements of Harvested White Oak Saplings, November, 1960

Soil	Stem Diameter 2 In. Height (Inches)	Sapling Height (Inches)	Number of Leaves*	Oven Dry Weights (g) Shoot Wood	Shoot Leaves	Roots	Root to Shoot Ratio
Landisburg	0.82	44.6	224	129.09	36.96	289.47	1.74
	0.49	26.6	232	40.69	36.19	133.50	1.73
	1.04	54.5	369	203.74	45.75	399.75	1.60
	0.49	16.2	127	18.58	16.89	60.32	1.70
	0.51	20.1	118	31.08	16.87	93.47	1.95
	0.96	23.3	421	195.95	53.04	--	
	0.65	55.3	404	105.07	58.17	--	
	0.77	36.8	620	141.14	94.40	430.65	1.83
	0.51	42.1	106	23.75	42.40	--	
	0.81	26.0	105	86.25	37.01	--	
	0.49	29.7	164	24.90	19.18	109.73	2.48
Litz	0.61	40.7	265	116.05	31.93	209.94	1.42
	0.82	37.5	411	165.32	49.97	--	
	0.70	30.1	205	71.80	31.49	--	
	0.55	22.7	172	30.08	18.60	11.67	2.29
	1.00	39.4	503	163.55	90.54	440.01	1.73

*Includes samples taken through the growing season.

Table XVI

Percentage Uptake of Cs^{134} from Litter and Solution Application to Soil Found in Sapling Shoots and Roots, November, 1960

Soil	Application	Per Cent of Application		
		In Shoot	In Roots	Total
Landisburg	Litter	0.116	0.388	0.504
		0.054	0.207	0.261
		0.025	0.159	0.184
		0.047	0.230	0.277
		0.077	0.326	0.403
		0.102	--	--
		0.069	--	--
		0.070 ± .01*	0.262 ± .04	0.325 ± .06
	Solution	0.083	0.213	0.296
		0.222	--	--
		0.053	--	--
		0.043	0.291	0.334
		0.050 ± .01	0.252 ± .05	0.315 ± .02
Litz	Litter	0.078	0.225	0.303
		0.093	--	--
		0.062	--	--
		0.068	0.319	0.387
		0.070	0.280	0.350
		0.074 ± .006	0.274 ± .03	0.346 ± .03

*Mean ± s.e.

leaves.	955 ± 253
buds.	660 ± 259
stem, less than 0.2 inch diameter	537 ± 145
stem, greater than 0.2 inch diameter.	529 ± 157
Cynipid wasp galls (stem)	835 ± 139
roots, greater than 0.5 mm diameter	5,986 ± 315
roots, less than 0.5 mm diameter.	82,301 ± 4,781

Leaves and galls tended to concentrate more radiocesium than stems, on a dry weight basis, and roots contained much higher concentrations. Roots less than 0.5 mm diameter contained approximately 13 times more than larger roots up to 50.0 mm diameter. Most of the minute roots which contained this high concentration were in the top 6 inches of soil. Some of them probably received Cs^{134} directly from the litter or humus layer.

Soil samples taken 140 days after tagged litter application showed available Cs^{134} in the top 2 inches of mineral soil under tagged litter to be 11.0 ± 1.7 per cent (five observations) of the total soil content (determined by extracting with 1 N ammonium acetate at pH 7.0).

VII. LEACHING LOSSES OF CESIUM-134 FROM ROOTS

Germinating white oak acorns grown in the laboratory in Ottawa sand, with periodic additions of Knop's nutrient solution, attained a mean seedling dry weight of 1.06 ± 0.03 g in 80 days and a mean shoot height of 6.4 ± 0.2 inches. Table XVII gives size and dry weight measurements of experimental seedlings. Growth of these plants may have been less than normal as the amount of sunlight was limited to that reaching the plants through windows adjacent to a bench supporting plant containers. The mean root to shoot weight ratio (1.31 ± 0.05) may have been less than normal due to shading. Root systems seemed well developed, however, with large tap roots and many second and third order roots. Fourth order roots were few in number. A typical seedling had an 8.5 inch long tap root with 81 second order roots having a total length of 811.3 inches.

Cesium-134 application by submerging a recipient leaf into a vial of $Cs^{134}Cl$ solution (pH 6.5) left recipient leaves discolored (brown) after 72 hours treatment. It is not known whether this was a pH effect or due to oxygen deficiency. Total uptake of 20 seedlings, excluding recipient leaves, averaged 0.13 ± 0.02 per cent of the total Cs^{134} in applied solutions after 72 hours. With recipient leaves included, the total uptake was 3.4 ± 0.5 per cent. Table XVIII gives the distribution of foliar absorbed radiocesium in seedlings and the amounts lost from roots by leaching with distilled water. The mean distribution in shoot components was similar, with leaves containing 35.7 ± 1.3 and stems

Table XVII

Size and Weight Measurements of 80 Day Old White Oak Seedlings

Shoot Height (Inches)	Number of Leaves	Oven Dry Weight (g)				Root to Shoot Ratio
		Leaves	Stem	Roots	Total	
6.0	5	0.258	0.188	0.476	0.922	1.07
5.8	5	0.194	0.123	0.609	0.926	1.92
7.4	5	0.376	0.242	0.631	1.249	1.02
5.5	5	0.302	0.188	0.520	1.010	1.06
5.8	5	0.179	0.161	0.570	0.910	1.68
7.1	5	0.295	0.204	0.563	1.062	1.13
6.2	5	0.390	0.197	0.662	1.249	1.13
7.3	5	0.356	0.247	0.679	1.283	1.12
6.1	5	0.274	0.178	0.583	1.035	1.29
7.0	5	0.209	0.144	0.540	0.895	1.53
7.0	5	0.264	0.203	0.610	1.077	1.31
6.6	5	0.314	0.190	0.703	1.207	1.39
5.3	5	0.211	0.152	0.587	0.950	1.62
5.9	5	0.239	0.187	0.516	0.942	1.21
8.0	5	0.373	0.206	0.674	1.253	1.16
6.4 ± 0.2*		0.282 ± 0.01	0.187 ± 0.01	0.595 ± 0.01	1.064 ± 0.03	1.31 ± 0.05

*Mean ± s.e.

Table XVIII

Distribution of Foliar Absorbed Cs^{134} in White Oak Seedlings and Leaching Losses From Roots After Two Daily 1.5 Inch Simulated Rains

Cs^{134} Applied to Recipient Leaf (10^6 dpm)	Per Cent of Applied Taken in by Plant in 72 Hours	Per Cent of Total Uptake					
		In Plant			Leached from Roots		
		Leaves[1]	Stem	Roots	Remaining in Sand	In Leachate	Total
2.52	0.07	40.4	32.7	21.7	2.2	3.0	5.2
2.52	0.09	30.9	50.1	17.4	0.9	0.7	1.6
2.52	0.13	25.7	41.6	25.3	4.8	2.6	7.4
3.78	0.25	36.6	42.1	15.1	3.0	3.2	6.2
2.52	0.17	39.7	37.5	19.4	1.6	1.8	3.4
3.78	0.29	42.5	33.9	19.6	2.1	1.9	4.0
2.52	0.06	40.3	30.4	27.0	1.4	0.9	2.3
2.52	0.13	42.0	26.4	24.8	3.3	3.5	6.8
2.52	0.04	38.1	28.9	22.6	4.7	5.7	10.4
3.78	0.19	33.5	46.7	12.5	3.3	4.0	7.3
3.78	0.10	24.9	36.0	34.9	2.2	2.0	4.2
3.78	0.14	32.7	37.5	26.1	2.5	1.2	3.7
3.78	0.08	42.0	31.3	23.8	2.1	0.8	2.9
2.52	0.16	29.8	37.9	25.8	4.2	2.3	6.5
2.52	0.13	37.1	43.2	14.7	3.2	1.8	5.0
Mean ± s.e.	0.13 ± 0.02	35.7 ± 1.3	37.1 ± 1.8	22.1 ± 1.7	2.8 ± 0.3	2.3 ± 0.4	5.1 ± 0.6

[1]Excluding leaves receiving Cs^{134} application.

containing 37.1 ± 1.8 per cent of the total plant radiocesium. But on a dry weight basis, stems concentrated radiocesium approximately 1.5 times more than leaves.

After 72 hours treatment and removal of recipient leaves, two daily applications of distilled water were made to the sand growth medium. Each application consisted of the equivalent of 1.5 inches of rain (175 ml) added instantaneously to the surface of the sand. Before the first daily leaching, the sand was brought to approximately field capacity. The mean total loss of Cs^{134} observed after two leachings was 5.1 ± 0.6 per cent of the total plant concentration. Assuming that all of this amount came from the roots, an average of 18.7 per cent of the root radiocesium was lost. Of the total leached out, slightly over half remained in the sand while the remainder came through in the leaching medium.

The quantities lost probably represent a leaching loss greater than that occurring under natural conditions in the field. Distilled water may have leached out more radiocesium than rain with its accompanying ions, and the sand with its very low exchange capacity may have induced depletion of ions in the roots (Stenlid, 1958). In addition, the physiological behavior of seedlings might be expected to differ from that of other stages of white oak.

This experiment points out again the rapid movement of Cs^{134} in and out of white oak, in this case, very young oaks. It also illustrates the ability of radiocesium to enter plants through a foliar route with subsequent prompt translocation to major plant components.

VIII. GAINS AND LOSSES OF CESIUM-134, 1961 GROWING SEASON

A. Movements Into Leaves

Cesium-134 which had remained over the winter in woody tissue of inoculated trees was found to be extremely mobile when trees leafed out. Young leaves collected in the middle of May, 1961, had radiocesium concentrations ranging from $0.29 \pm 0.10 \times 10^6$ to $2.51 \pm 0.43 \times 10^6$ dpm per g dry weight. Maximum concentrations in leaves were observed in early June, and they were as high as those observed in 1960 from initial inoculations. Figure 20 shows the average leaf activity for all trees during the growing season. Decreases in activity were again observed from time of maximum content to early November.

Mean maximum movements of radiocesium into leaves were similar in trees on the dolomitic dry and wet and the shale dry sites with 44.1 ± 3.7, 40.2 ± 6.8, and 47.5 ± 7.0 per cent of the original input (2.0 mc), respectively. The trees on the shale wet site reached a maximum of only 26.6 ± 15.0 per cent. Two trees on this site were small and had fewer leaves. This may, in part, explain the smaller quantities of radiocesium reaching leaves in these trees. No statistically significant differences were observed between sites in an analysis of variance comparing sites by moisture and geological derivation (Table XIX). By the end of the growing season, a mean reduction from observed maximums of 71.2 ± 3.9 per cent (range 41.4 to 85.1) was found. No significant differences were found between sites (Table XIX), although trees on the dolomitic sites tended to have smaller reduction percentages.

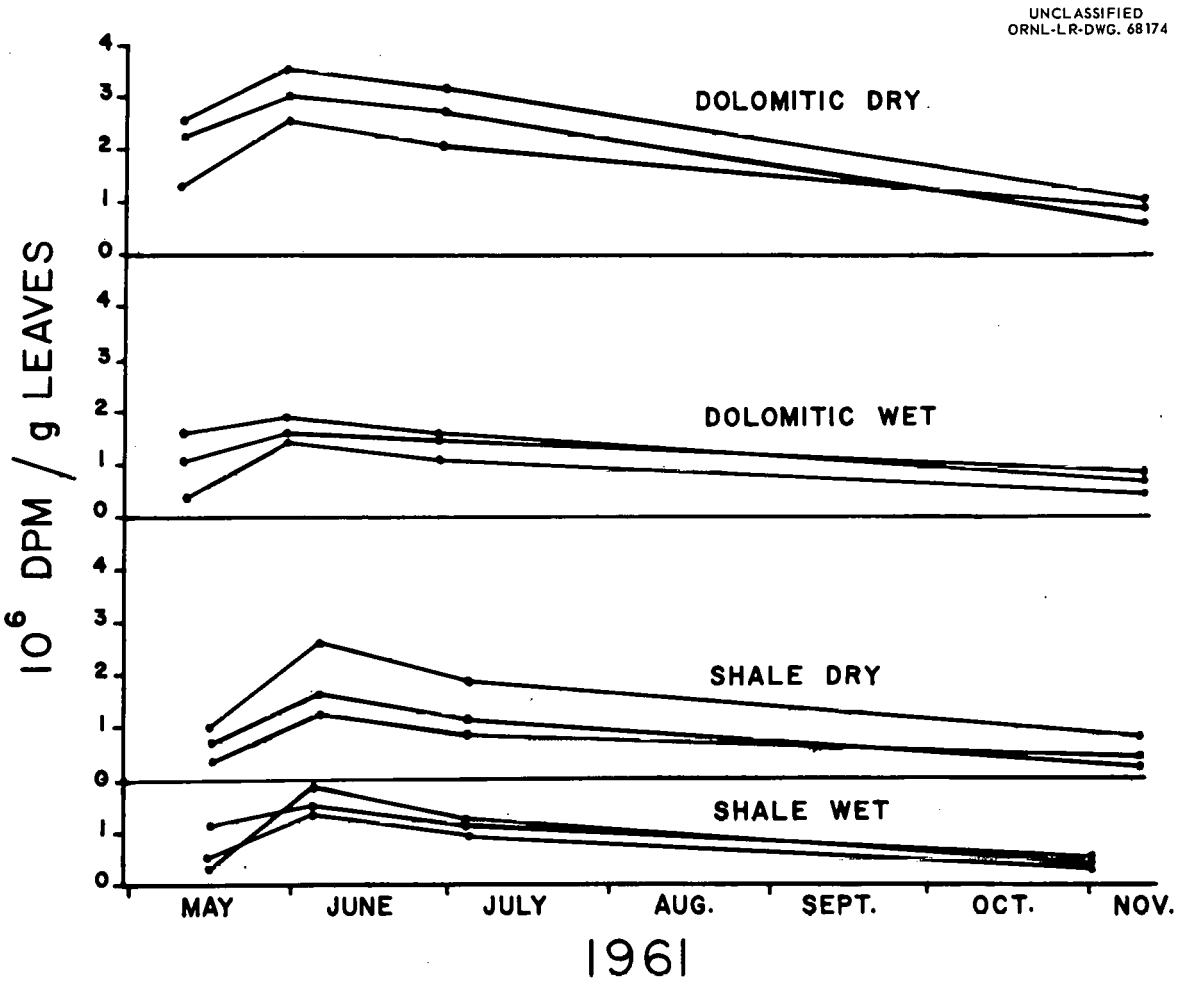

Fig. 20. Average Content of Cs^{134} in Leaves of Inoculated White Oak Trees, 1961 Growing Season.

Table XIX

Analyses of Variance

Stages of Cesium Transfer, 1961 Growing Season

Source		Degrees of Freedom	SS	MS	F Calculated	F.05	F.01
	Maximum Per Cent of Original Inoculation Reaching Leaves						
A.	Moisture	1	448.60	448.60	2.31	5.12	
B.	Geology	1	83.48	83.48	0.43	241.00	
C.	Interaction	1	228.03	228.03	1.19	5.32	
D.	Subtotal	3	760.11	253.37			
E.	Within	8	1521.53	190.19			
F.	Total	11	2281.64	207.42			
G.	Residual	9	1749.56	194.39			
	Per Cent Reduction of Leaf Maximums During Season						
A.		1	125.84	125.84	1.27	5.12	
B.		1	329.91	329.91	3.32	5.12	
C.		1	156.39	156.39	1.69	5.32	
D.		3	612.14	204.05			
E.		8	737.48	92.18			
F.		11	1349.62	122.69			
G.		9	893.87	99.32			
	Per Cent of Leaf Maximum Leached Out by Rain						
A.		1	163.62	163.62	4.87	5.12	
B.*		1	272.75	272.75	8.12	5.12	10.56
C.		1	4.02	4.02	0.11	239.00	
D.		3	440.39	146.79			
E.		8	298.13	37.27			
F.		11	738.52	67.14			
G.		9	302.15	33.57			
	Per Cent of Leaf Maximum Returned to Wood						
A.		1	588.14	588.14	3.77	5.12	
B.		1	3.53	3.53	0.02	241.00	
C.		1	203.45	203.45	1.35	5.32	
D.		3	795.12	265.04			
E.		8	1201.19	150.15			
F.		11	1996.31	181.48			
G.		9	1404.64	156.07			

*Significant at 5% level.

B. Losses From Leaves

Quantities of Cs^{134} found in understory vegetation, litter, and soil are given in Table XX. By the time of these observations, one year and seven months post inoculation, a considerable portion of the radiocesium had been transported out of trees by rain and the 1960 leaf fall. Total radiocesium losses from each tree observed in 1960 (rain leaching and leaf fall) were subtracted from total quantities found in understory, litter, and soil in November, 1961, as an estimate of rain-induced losses during the 1961 growing season. The 1961 rain losses were added to leaf radiocesium contents at the end of the growing season, and these sums were subtacted from leaf maximums to obtain estimates of radiocesium movement from leaves back into wood. Table XXI gives percentages involved in radiocesium transfers during the 1961 growing season. Losses due to the leaching action of rain in the 12 trees averaged 17.6 ± 2.6 per cent of observed maximum leaf contents. Rain exports from trees on dry and wet shale sites with 19.2 ± 1.7 and 25.4 ± 7.1 per cent, respectively, were significantly greater (5 per cent level) than those from trees on dry and wet dolomitic sites with 8.5 ± 2.1 and 17.1 ± 3.1 per cent, respectively (Table XIX). The per cent of observed leaf maxima returning to wood averaged 52.9 ± 4.2 (range 37.6 to 65.8) per cent for all trees. No significant differences between sites were observed (Table XIX). An average of 29.5 ± 3.9 per cent of observed maxima remained in leaves in early November immediately prior to leaf fall.

Of the total radiocesium on the ground, only a small portion was contained in understory vegetation. Site to site variations were large

Table XX

Microcuries of Cesium-134 In and Around Inoculated Trees, 1961 Growing Season

Site and Tree	Maximum in Leaves	Rain-leached	End of Growing Season			
			In Leaves	In Understory (N = 4)	In Litter (N = 54)	In Soil (N = 235)
Dolomitic dry						
1	955.06	72.09	288.10	13.63	285.16	539.11
2	951.86	56.83	280.00	7.94	163.49	322.87
3	738.65	89.25	167.88	9.41	359.33	588.60
Dolomitic wet						
1	975.31	185.77	571.90	21.07	300.04	687.54
2	609.09	125.78	185.02	9.11	32.14	249.86
3	850.75	98.20	286.68	8.72	239.47	611.78
Shale dry						
1	772.92	161.93	230.63	7.79	59.63	217.30
2	1181.65	246.01	320.81	6.80	92.10	459.00
3	847.47	134.94	200.01	6.97	132.05	277.13
Shale wet						
1	1051.81	157.57	225.99	21.42	69.13	184.52
2	360.32	92.63	77.13	3.81	33.90	127.30
3	181.28	64.69	48.44	2.59	26.18	89.47

Table XXI

Stages in Transfer of Cesium-134, 1961 Growing Season

Parent Material	Dolomite		Shale		
Topography	Dry	Wet	Dry	Wet	
Soil Series	Fullerton	Landisburg	Sequoia	Monongahela	Grand Means
Per Cent of Original Input					
Maximum in leaves	44.1 ± 3.7	40.2 ± 6.3	47.5 ± 7.0	26.6 ± 15.0	39.7 ± 4.4
Per Cent of Leaf Maximum					
In leaves end of season	27.2 ± 2.8	40.9 ± 9.7	26.9 ± 5.4	23.3 ± 1.8	29.5 ± 3.9
Returned to tree wood	64.3 ± 1.2	42.0 ± 11.1	53.9 ± 3.8	51.3 ± 8.9	52.9 ± 4.2
Rained out	8.5 ± 2.1	17.1 ± 3.1	19.2 ± 1.7	25.4 ± 7.1	17.6 ± 2.6
Per Cent of Total Cs^{134} on the Ground					
In understory	1.4 ± 0.2	2.1 ± 0.7	1.9 ± 0.5	4.1 ± 1.9	2.4 ± 0.6
In litter	34.7 ± 1.8	22.9 ± 6.4	23.1 ± 5.2	22.6 ± 1.6	25.8 ± 2.3
In soil	63.9 ± 1.6	75.0 ± 6.1	75.0 ± 5.4	73.3 ± 3.5	71.8 ± 2.1

due to kind and amount of understory, but an average of only 2.4 ± 0.6 per cent of the total was observed in this ground compartment. This percentage is lower than that found in September, 1960, but the 1961 Cs^{134} activity was approximately 150 per cent greater. The litter contained an average of 25.8 ± 2.3 per cent of the total ground radiocesium. Most of this litter was from the 1960 fall of inoculated tree leaves, and activities were of appreciable magnitude (Table XX). The soil with 71.8 ± 2.1 per cent of the total, was the principal depository of radiocesium lost from trees in early November, 1961. When radiocesium content of litter in September, 1960, was added to the 1960 laf fall (source of 1961 litter) and compared with November, 1961, litter content, an average decrease in Cs^{134} content of 46.2 ± 4.1 per cent was obtained. Since 1961 rains have added radiocesium to this litter, the loss was actually greater than 46 per cent. This implies that large quantities of radiocesium exported from trees by leaf fall were leached into the soil before the litter had reached an advanced stage of decay.

The estimated loss per tree of Cs^{134} after two growing seasons is detailed in Table XXII. The mean loss one year and eight months post inoculation was 37.6 ± 6.2 per cent of the original input, or 752 ± 124 μc. Table XXIII gives mean site distribution, after 1961 leaf fall, of losses and radiocesium remaining in trees. Expressed as per cent of original inoculations, the understory contained 0.5 ± 0.1; the litter layer, 19.2 ± 3.5; and the soil, 17.9 ± 2.6; which left, by difference, 62.4 ± 6.2 per cent in the leafless trees.

Table XXII

Percentages of Original Inoculation Lost From Trees After Two Growing Seasons

Site and Tree	Remaining in Trees After 1961 Leaf Fall (μc)	Per Cent of Original	Per Cent of Original Lost After Two Growing Seasons	Site Means Per Cent Lost
Dolomitic dry				
1	874.00	43.7	56.3	
2	1215.70	60.8	39.2	50.5 ± 5.9
3	879.81	44.0	56.0	
Dolomitic wet				
1	419.45	20.9	79.1	
2	1573.87	78.6	21.4	52.6 ± 19.9
3	853.35	42.7	57.3	
Shale dry				
1	1484.65	74.2	25.8	
2	1121.29	56.1	43.9	32.3 ± 6.3
3	1458.05	72.9	27.1	
Shale wet				
1	1498.94	74.9	25.1	
2	1757.86	87.9	12.1	15.2 ± 5.8
3	1833.32	91.7	8.3	
			Grand Mean	37.6 ± 6.2

Table XXIII

Compartment Distribution of Cs^{134} by Site After 1961 Leaf Fall

(one year, eight months post inoculation)

Site Compartment	Per Cent of Original Inoculation[1]				Grand Means
	Dolomitic Dry	Dolomitic Wet	Shale Dry	Shale Wet	
Tree Losses					
In understory	0.6 ± 0.2	0.6 ± 0.2	0.4 ± 0.1	0.5 ± 0.3	0.5 ± 0.1
In litter	26.6 ± 2.3	26.9 ± 11.3	16.1 ± 2.7	8.0 ± 3.8	19.2 ± 3.5
In soil	24.3 ± 4.4	24.2 ± 7.5	15.9 ± 4.2	6.9 ± 1.5	17.9 ± 2.6
Remaining					
In tree wood	49.5 ± 5.9	47.3 ± 19.9	67.6 ± 6.3	84.6 ± 5.6	62.4 ± 6.2

[1]Mean ± s.e. of three trees per site.

C. Distribution and Mobility in Soil

By November, 1961, radiocesium was found to soil depths of 10 to 12 inches, indicating considerable downward movement since observations of September, 1960. The quantities found under each inoculated tree at seven soil depth layers between the soil surface and 12 inches are given in Table XXIV. Mean site percentages of total soil radiocesium in these layers are shown in Figure 21. Downward movement was greater and penetration deeper in the Landisburg and Monongahela (wet) soils. Statistically significant differences in radiocesium distribution were observed between wet and dry soils (Table XXV). In the 0 to 1 inch layer, the wet soils contained a significantly (1 per cent level) smaller percentage of radiocesium than dry soils. In the 1 to 2 inch layer, wet soils contained more than dry soils, but the differences were not significant at the 5 per cent level. In both the 2 to 4 and 4 to 12 inch layers, wet soils held significantly (1 per cent level) higher percentages than dry soils. Even though these differences existed between wet and dry soils, the former still held approximately 73 per cent of the total soil radiocesium in the top 2 inches.

The average distribution of soil radiocesium for all sites observed in September, 1960, and November, 1961, is given in Table XXVI. In the 1960 observations the top 4 inches held all of the observed activity. Approximately one year later, and with the addition of more radiocesium via rain and leaf fall, the top 4 inches held 92 per cent of the soil total. Soil penetration during the year had been 8 inches.

The horizontal pattern of radiocesium distribution in soil around

Table XXIV

Microcuries of Cesium^{134} in Soil Around Inoculated Trees, End of 1961 Growing Season

Site and Tree	Soil Depth (Inches)						
	0 to 1 (N = 35)	1 to 2 (N = 35)	2 to 4 (N = 35)	4 to 6 (N = 35)	6 to 8 (N = 35)	8 to 10 (N = 35)	10 to 12 (N = 35)
Dolomitic dry							
1	345.95	113.99	50.83	12.46	9.59	1.29	N.D.[1]
2	229.56	56.47	22.73	8.34	5.19	0.58	N.D.
3	376.24	153.05	34.84	17.89	6.06	0.52	N.D.
Dolomitic wet							
1	392.87	128.92	78.58	48.13	27.29	9.62	2.13
2	122.70	39.53	50.38	19.52	13.31	2.67	1.75
3	376.73	166.04	48.39	6.24	13.03	1.35	N.D.
Shale dry							
1	153.62	40.70	17.14	3.11	2.56	0.17	N.D.
2	338.92	52.46	39.84	18.32	8.08	1.38	N.D.
3	191.66	53.40	19.16	11.35	1.30	0.25	N.D.
Shale wet							
1	106.84	29.69	24.63	13.42	6.25	1.97	1.72
2	69.15	19.01	27.81	7.13	1.79	1.54	0.87
3	41.29	18.27	17.49	9.06	1.79	0.87	0.70

[1]Not detectable.

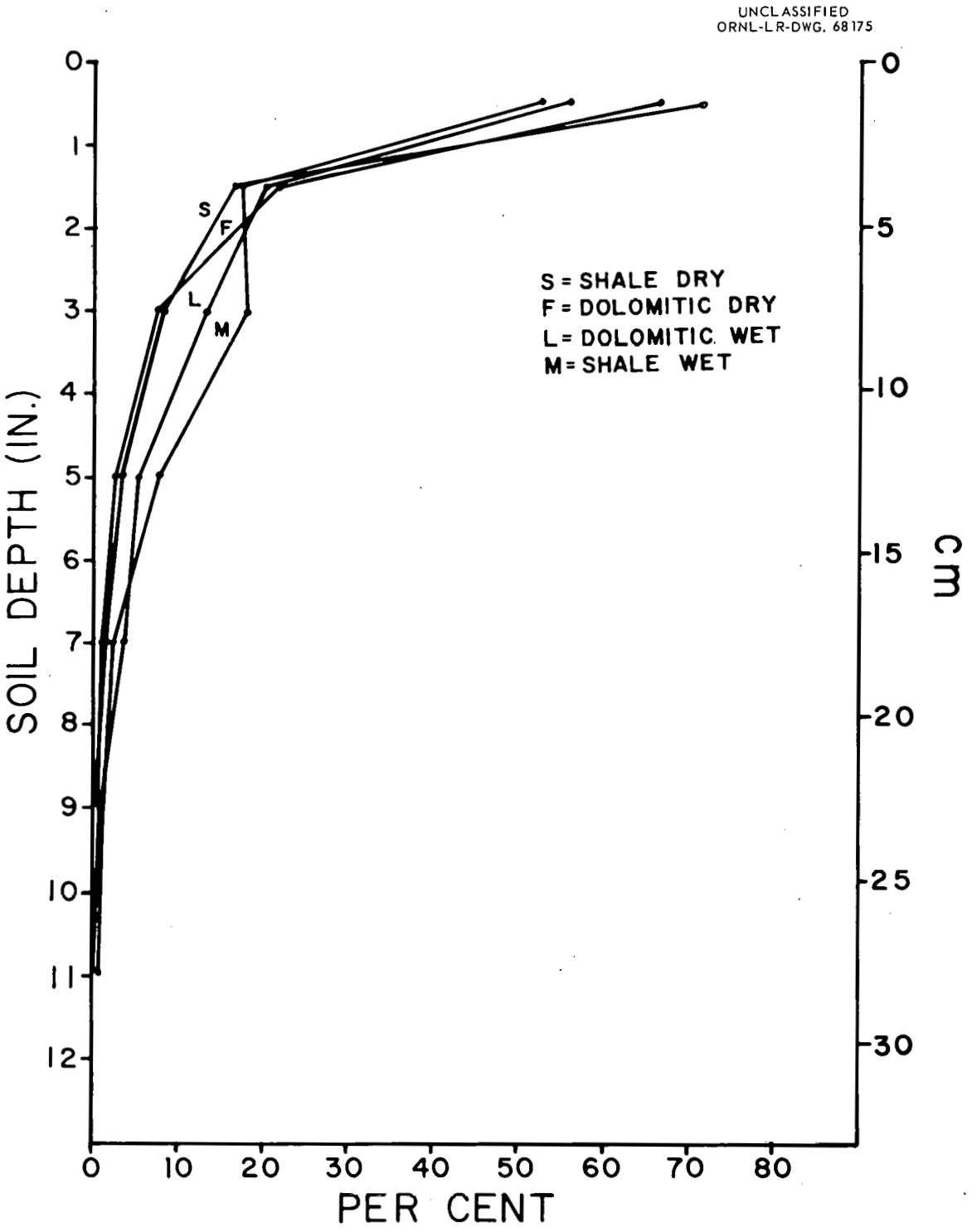

Fig. 21. Average Per Cent of Total Soil Cs^{134} in 0 to 12 Inches Depth of Four Soils.

Table XXV

Analyses of Variance

Per Cent of Cs^{134} in 0-12 Inches of Soil, End 1961 Growing Season

Source	Degrees of Freedom	SS	MS	F Calculated	F.05	F.01
		Per Cent in 0-1 In. Layer				
A. Moisture**	1	626.11	626.11	23.01	5.12	10.56
B. Geology	1	2.11	2.11	0.07	241.00	
C. Interaction	1	47.85	47.95	1.94	5.32	
D. Subtotal	3	676.07	225.36			
E. Within	8	197.03	24.62			
F. Total	11	873.10	79.37			
G. Residual	9	244.88	27.21			
		Per Cent in 1-2 In. Layer				
A.	1	0.28	0.28	0.01	241.00	
B.	1	58.08	58.08	3.20	5.12	
C.	1	2.86	2.86	0.14	239.00	
D.	3	61.22	20.41			
E.	8	160.40	20.05			
F.	11	221.62	20.15			
G.	9	163.26	18.14			
		Per Cent in 2-4 In. Layer				
A.**	1	183.31	183.31	11.34	5.12	10.56
B.	1	22.22	22.22	1.37	5.12	
C.	1	28.35	28.35	1.94	5.32	
D.	3	233.88	77.96			
E.	8	117.11	14.64			
F.	11	350.99	31.91			
G.	9	145.46	16.16			
		Per Cent in 4-12 In. Layer				
A.**	1	127.66	127.66	12.99	5.12	10.56
B.	1	3.04	3.04	0.31	241.00	
C.	1	2.05	2.05	0.19	239.00	
D.	3	132.75	44.25			
E.	8	86.42	10.80			
F.	11	219.17	19.92			
G.	9	88.47	9.83			

**Significant at the 1% level.

Table XXVI

Average Percentages of Cesium-134 Found in Soil Depth Layers on All Sites, September, 1960, and November, 1961.

Soil Depth (Inches)	Per Cent of Total Soil Cs^{134}		Cumulative Per Cent	
	September 1960	November 1961	September 1960	November 1961
0 to 1	59.2 ± 5.5	61.6 ± 2.4	59.2	61.6
1 to 2	23.9 ± 3.1	19.0 ± 1.4	83.1	80.6
2 to 4	16.9 ± 3.1	11.7 ± 1.4	100.0	92.3
4 to 6		4.7 ± 0.8		97.0
6 to 8		2.2 ± 0.4		99.2
8 to 10		0.5 ± 0.1		99.7
10 to 12		0.3 ± 0.1		100.0

inoculated trees was found to be related to size of tree crown. Relatively large quantities were found around tree trunks and most of the total quantities observed were located under crown perimeters. Tables XXVII through XXX give total microcuries of Cs^{134} found around each tree by soil depth and radial distance from trunk. Figures 22 through 25 depict the mean horizontal and vertical distribution under trees on each site. Tree to tree variations in this horizontal pattern were not great, probably because tree crowns were of similar size. For all trees an average of 19.0 ± 1.0 per cent of the total soil radiocesium was found within a radial distance of 0.8 foot from the trunk. Transfers of rather large quantities of radiocesium from trees to soil by rain water flowing down tree trunks must have caused this high soil concentration. This 19 per cent of total activity was in an area which was only 0.8 per cent of the total area sampled. By contrast, the outermost sampling zone (6.9 to 9.2 feet radial distance), which was not under tree crowns, made up 43.5 per cent of the total area sampled, but contained only 0.8 ± 0.3 per cent of the total soil radiocesium.

Figure 26 shows the average site distribution of radiocesium around inoculated trees. The site similarities can be observed in this figure. The smaller trees on the shale wet site had a smaller percentage of total radiocesium in the area 5.1 to 9.2 feet from trunks. The two zones at 0.8 to 2.3 and 2.3 to 3.6 radial feet from trunks tended to have similar percentages of the total activity (32.4 ± 2.0 and 32.4 ± 2.3 per cent, respectively), although their respective areas were 5.5 and 9.5 per cent of the total area sampled. The 3.6 to 5.1 feet zone was just outside

Table XXVII

Microcuries of Cs^{134} Around Inoculated Trees on Dolomitic Dry Site

Tree	Soil Depth (Inches)	Radius of Circle Around Trunk (Feet) 0.82	0.82 - 2.32	2.32 - 3.67	3.67 - 5.18	5.18 - 6.95	6.95 - 9.25
1	0 - 1	28.04	132.29	123.78	50.79	9.22	1.83
	1 - 2	40.45	37.89	30.26	5.49	4.36	0.54
	2 - 4	17.19	12.78	14.17	3.51	1.73	1.45
	4 - 6	4.69	5.40	1.29	0.81	0.16	0.11
	6 - 8	5.44	2.86	0.75	0.38	0.16	N.D.[1]
	8 - 10	.91	0.16	0.11	0.11	N.D.	N.D.
	10 - 12	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
2	0 - 1	42.78	61.67	83.01	33.45	7.78	0.87
	1 - 2	10.14	23.50	18.21	3.17	1.16	0.29
	2 - 4	3.01	5.68	10.62	3.23	0.16	0.03
	4 - 6	2.84	2.06	2.90	0.35	0.19	N.D.
	6 - 8	0.74	2.39	2.03	0	0.03	N.D.
	8 - 10	0.16	0.32	0.04	0.06	N.D.	N.D.
	10 - 12	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
3	0 - 1	53.80	116.25	123.91	43.67	32.55	6.06
	1 - 2	48.91	41.21	42.92	14.18	5.12	0.71
	2 - 4	12.95	14.77	6.12	0.53	0.29	0.18
	4 - 6	5.18	5.06	6.65	0.65	0.35	N.D.
	6 - 8	1.76	4.24	0.06	N.D.	N.D.	N.D.
	8 - 10	0.13	0.39	N.D.	N.D.	N.D.	N.D.
	10 - 12	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.

[1]Not detectable.

Table XXVIII

Microcuries of Cs^{134} Around Inoculated Trees on Dolomitic Wet Site

Tree	Soil Depth (Inches)	Radius of Circle Around Trunk (Feet) 0.82	0.82 - 2.32	2.32 - 3.67	3.67 - 5.18	5.18 - 6.95	6.95 - 9.25
1	0 - 1	59.71	130.94	107.89	79.89	10.38	4.06
	1 - 2	12.92	54.58	40.84	14.18	5.09	1.31
	2 - 4	29.91	22.14	14.78	4.95	5.98	0.82
	4 - 6	8.66	20.65	11.89	4.51	1.37	0.55
	6 - 8	2.68	12.41	8.56	2.75	0.62	0.27
	8 - 10	1.92	3.50	2.96	1.11	0.07	0.06
	10 - 12	0.03	0.96	0.69	0.39	0.05	0.01
2	0 - 1	24.26	31.18	31.61	33.16	2.12	0.37
	1 - 2	13.25	12.29	6.95	6.45	0.52	0.07
	2 - 4	13.54	11.17	14.83	9.37	1.37	0.10
	4 - 6	4.22	5.10	3.80	5.43	0.92	0.05
	6 - 8	3.00	4.57	2.39	2.63	0.65	0.07
	8 - 10	0.47	0.31	0.49	1.06	0.32	0.02
	10 - 12	0.44	0.24	0.37	0.53	0.17	N.D.[1]
3	0 - 1	35.89	123.40	137.34	57.08	18.23	3.79
	1 - 2	14.44	72.32	50.28	15.61	12.60	0.79
	2 - 4	12.97	19.58	8.63	4.16	2.63	0.42
	4 - 6	1.77	1.41	2.20	0.49	0.24	0.13
	6 - 8	4.95	4.71	2.45	0.73	0.19	N.D.
	8 - 10	0.79	0.49	0.01	0.06	N.D.	N.D.
	10 - 12	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.

[1] Not detectable.

Table XXIX

Microcuries of Cs^{134} Around Inoculated Trees on Shale Dry Site

Tree	Soil Depth (Inches)	Radius of Circle Around Trunk (Feet) 0.82	0.82 - 2.32	2.32 - 3.67	3.67 - 5.18	5.18 - 6.95	6.95 - 9.25
1	0 - 1	26.18	56.91	52.75	12.31	4.28	1.19
	1 - 2	7.78	13.23	16.47	2.09	0.87	0.26
	2 - 4	1.95	6.04	8.18	0.50	0.32	0.15
	4 - 6	0.59	0.77	1.56	0.17	0.02	N.D.[1]
	6 - 8	0.59	0.93	0.99	0.05	N.D.	N.D.
	8 - 10	0.06	0.09	0.02	N.D.	N.D.	N.D.
	10 - 12	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
2	0 - 1	43.14	73.21	125.73	83.72	9.91	3.21
	1 - 2	4.77	12.76	23.68	9.37	1.56	0.32
	2 - 4	5.55	4.27	27.13	2.58	0.27	0.04
	4 - 6	0.51	4.68	12.85	0.23	0.05	N.D.
	6 - 8	0.41	3.12	4.31	0.05	0.09	N.D.
	8 - 10	0.59	0.33	0.46	N.D.	N.D.	N.D.
	10 - 12	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
3	0 - 1	34.66	50.16	52.64	42.40	8.67	3.13
	1 - 2	5.76	13.30	14.77	17.21	2.11	0.25
	2 - 4	1.03	5.16	4.85	7.29	0.78	0.05
	4 - 6	0.44	3.38	3.53	3.71	0.25	0.05
	6 - 8	0.25	0.36	0.28	0.30	0.11	N.D.
	8 - 10	N.D.	0.02	0.04	0.14	0.05	N.D.
	10 - 12	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.

[1] Not detectable.

Table XXX

Microcuries of Cs^{134} Around Inoculated Trees on Shale Wet Site

Tree	Soil Depth (Inches)	Radius of Circle Around Trunk (Feet)					
		0.82	0.82 - 2.32	2.32 - 3.67	3.67 - 5.18	5.18 - 6.95	6.95 - 9.25
1	0 - 1	9.83	25.32	32.12	34.89	3.54	1.14
	1 - 2	3.91	7.84	9.63	6.03	0.99	1.29
	2 - 4	4.19	6.83	6.79	5.83	0.55	0.44
	4 - 6	1.54	4.26	3.07	4.25	0.13	0.17
	6 - 8	0.64	1.63	2.82	1.07	0.05	0.04
	8 - 10	0.53	0.59	0.55	0.28	0.02	N.D.[1]
	10 - 12	0.32	0.49	0.64	0.24	0.03	N.D.
2	0 - 1	5.05	27.31	19.75	16.34	0.51	0.19
	1 - 2	3.87	6.86	4.94	3.09	0.18	0.07
	2 - 4	2.23	9.35	10.23	5.83	0.15	0.02
	4 - 6	1.36	2.47	2.07	1.19	0.04	N.D.
	6 - 8	0.39	0.31	0.84	0.25	N.D.	N.D.
	8 - 10	0.14	0.43	0.79	0.18	N.D.	N.D.
	10 - 12	0.03	0.29	0.48	0.07	N.D.	N.D.
3	0 - 1	1.90	10.14	20.70	8.44	0.09	0.02
	1 - 2	1.14	6.10	9.22	1.78	0.03	N.D.
	2 - 4	1.96	6.29	8.82	0.42	N.D.	N.D.
	4 - 6	0.38	4.64	3.95	0.09	N.D.	N.D.
	6 - 8	0.06	0.69	1.00	0.04	N.D.	N.D.
	8 - 10	0.04	0.17	0.65	0.01	N.D.	N.D.
	10 - 12	0.03	0.12	0.55	N.D.	N.D.	N.D.

[1] Not detectable.

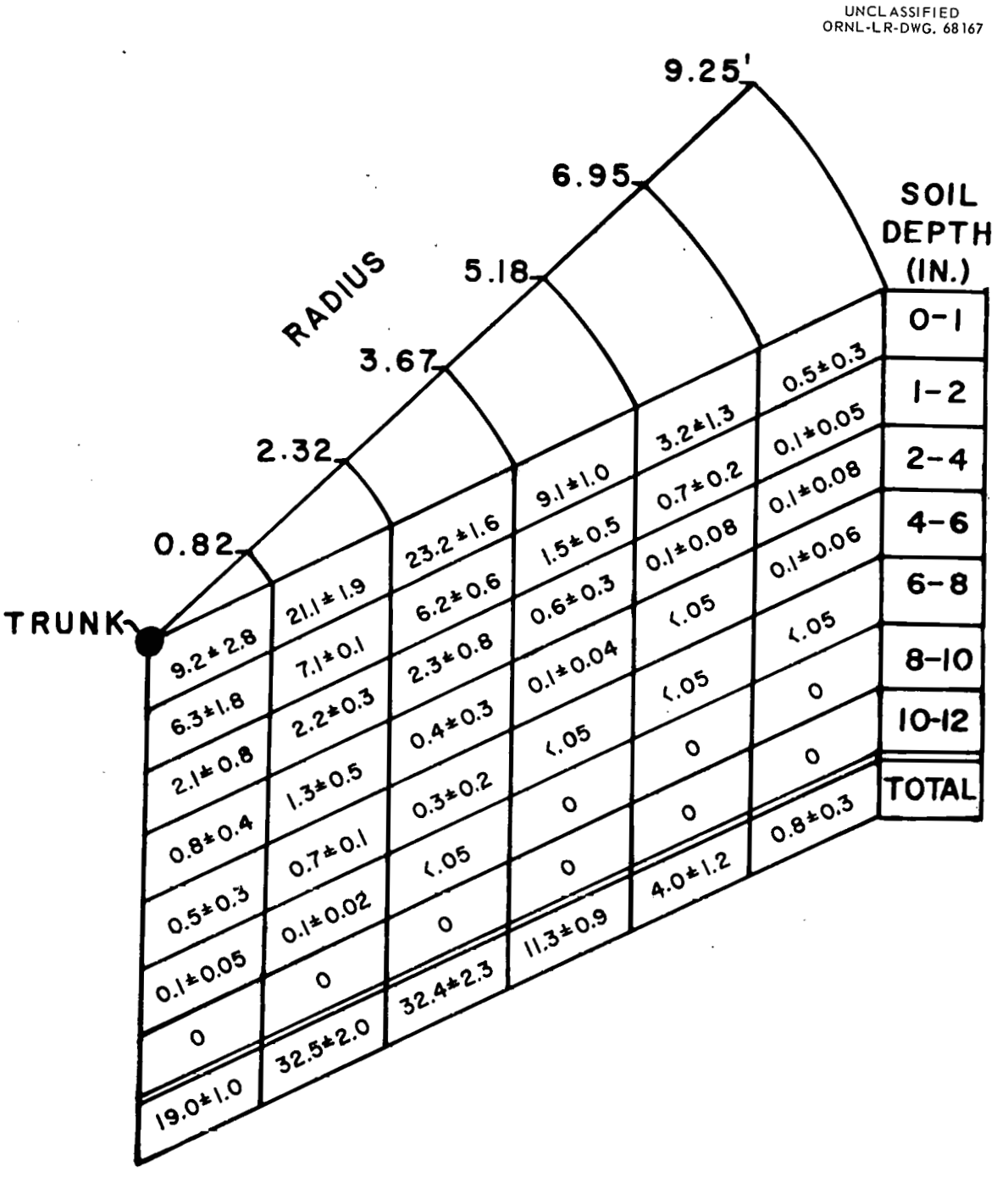

Fig. 22. Mean Distribution of Cs^{134} in Soil Around Three Trees on Dolomitic Dry Site. (Per cent of total soil activity ± one standard error).

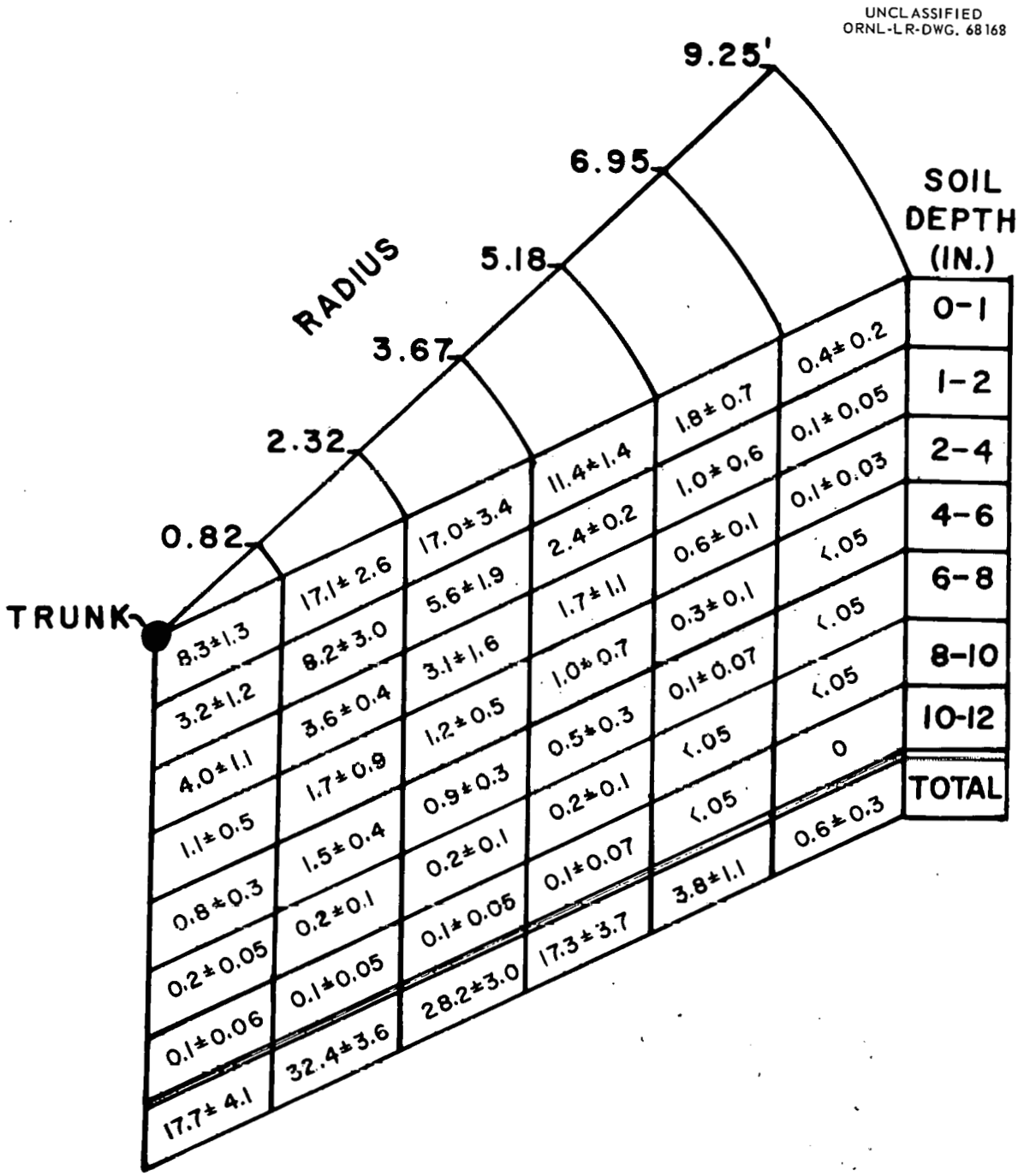

Fig. 23. Mean Distribution of Cs^{134} in Soil Around Three Trees on Dolomitic Wet Site. (Per cent of total soil activity ± one standard error).

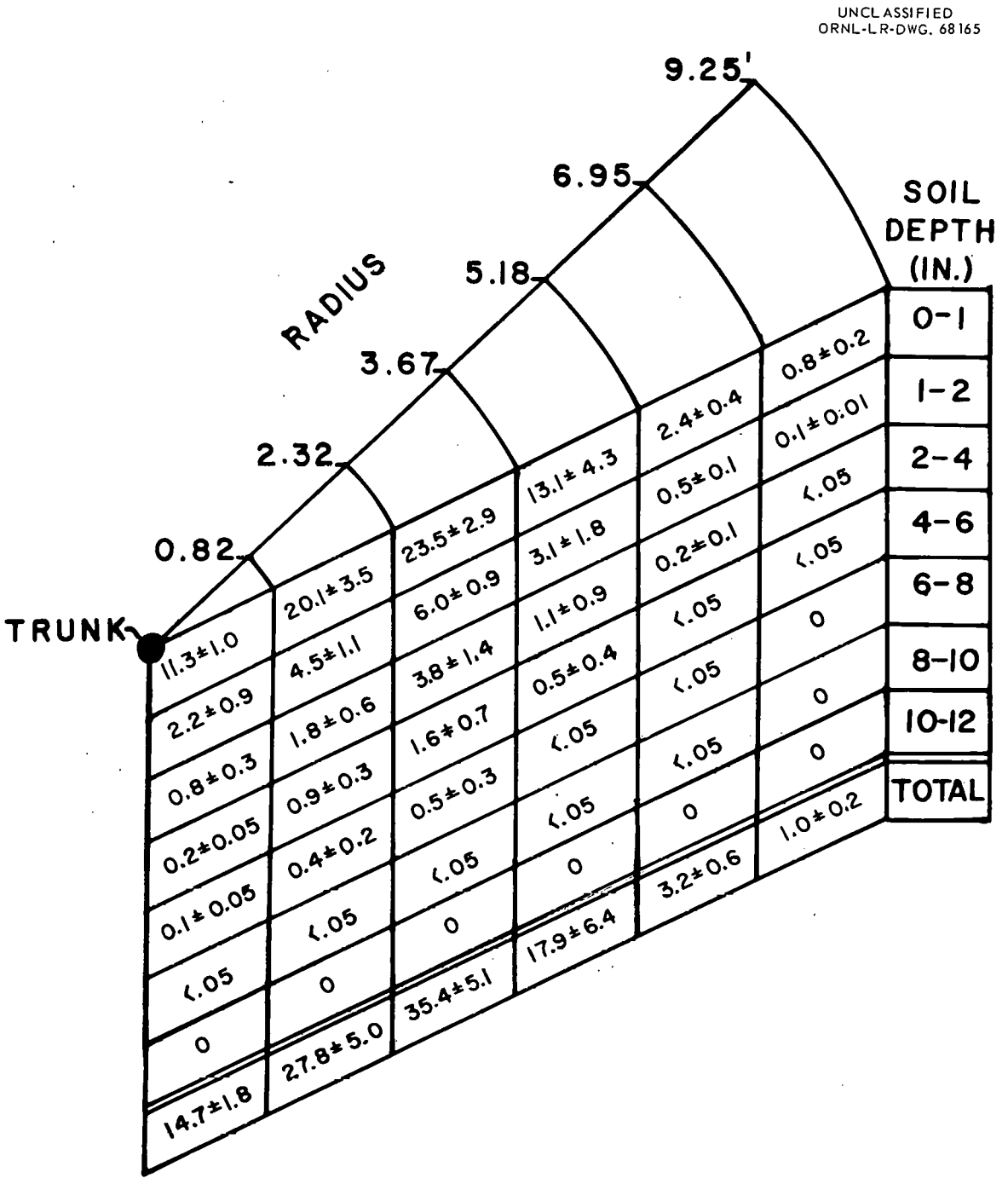

Fig. 24. Mean Distribution of Cs^{134} in Soil Around Three Trees on Shale Dry Site. (Per cent of total soil activity ± one standard error).

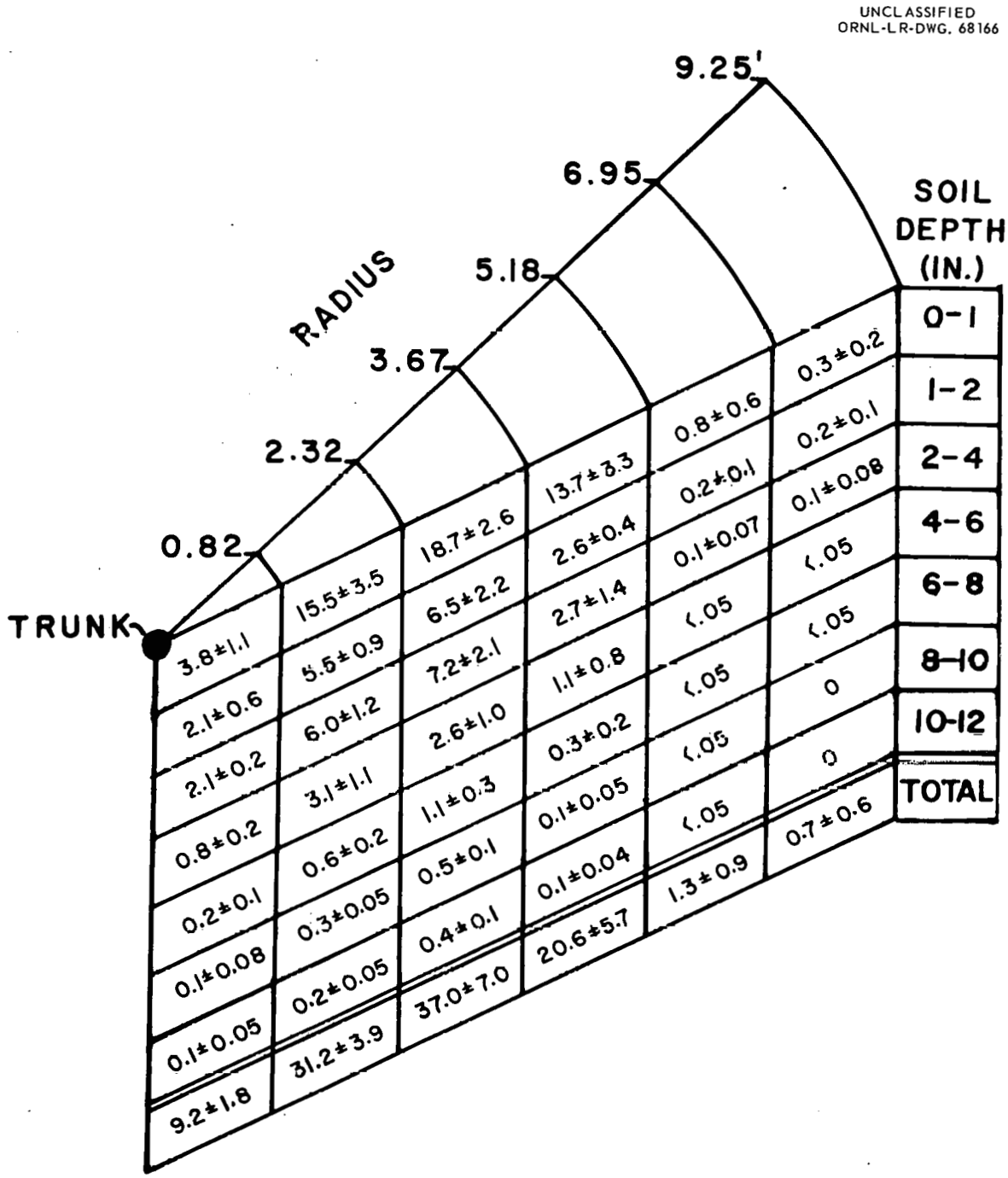

Fig. 25. Mean Distribution of Cs^{134} in Soil Around Three Trees on Shale Wet Site. (Per cent of total soil activity ± one standard error).

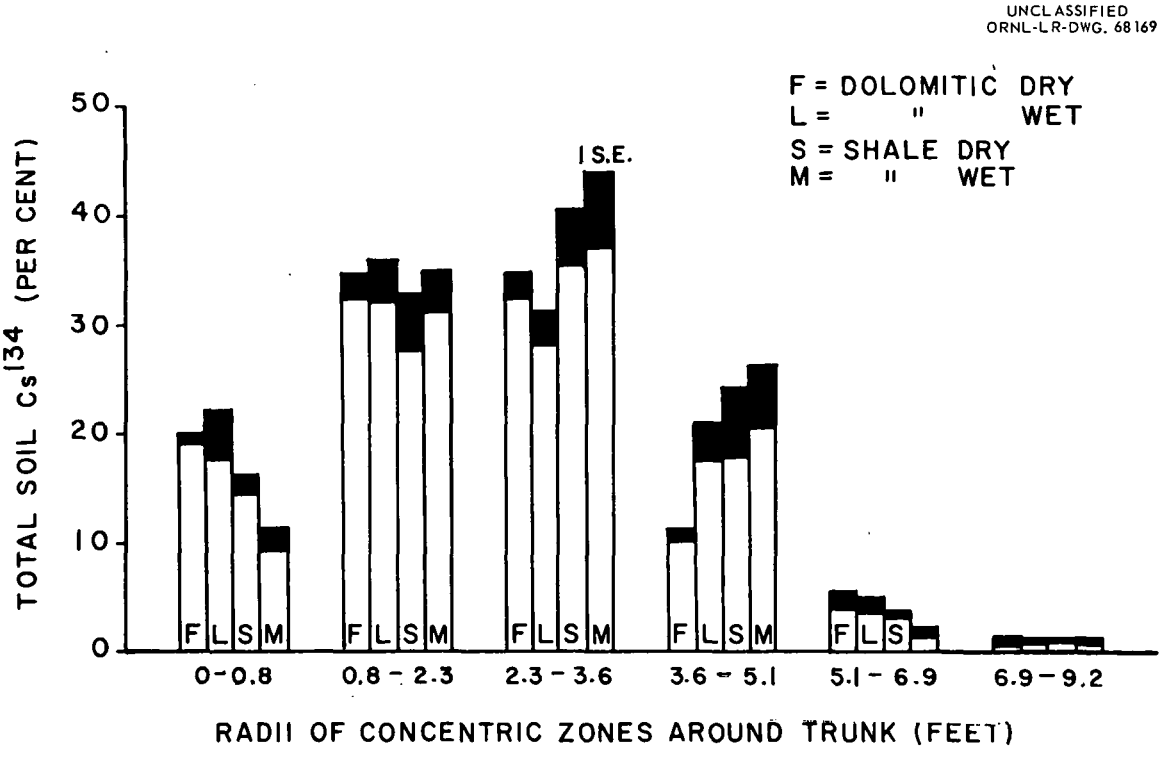

Fig. 26. Horizontal Distribution of Soil Cs^{134} Around Inoculated Trees, End of 1961 Growing Season.

the average crown perimeter, and it contained 11.2 ± 0.9 per cent of total observed activity and 15.6 per cent of the total area.

The average quantity of soil radiocesium per ft^2 and cumulative percentages by radial distance from trunks are shown in Figure 27. About 80 per cent of the soil total was found underneath the crowns with an additional 15 per cent located approximately within 2 feet outside of crown perimeters. The remaining 5 per cent was located from 2 to 6 feet outside of crown perimeters. Thus, radiocesium had fanned out around inoculated trees in a circle of almost 20 feet in diameter.

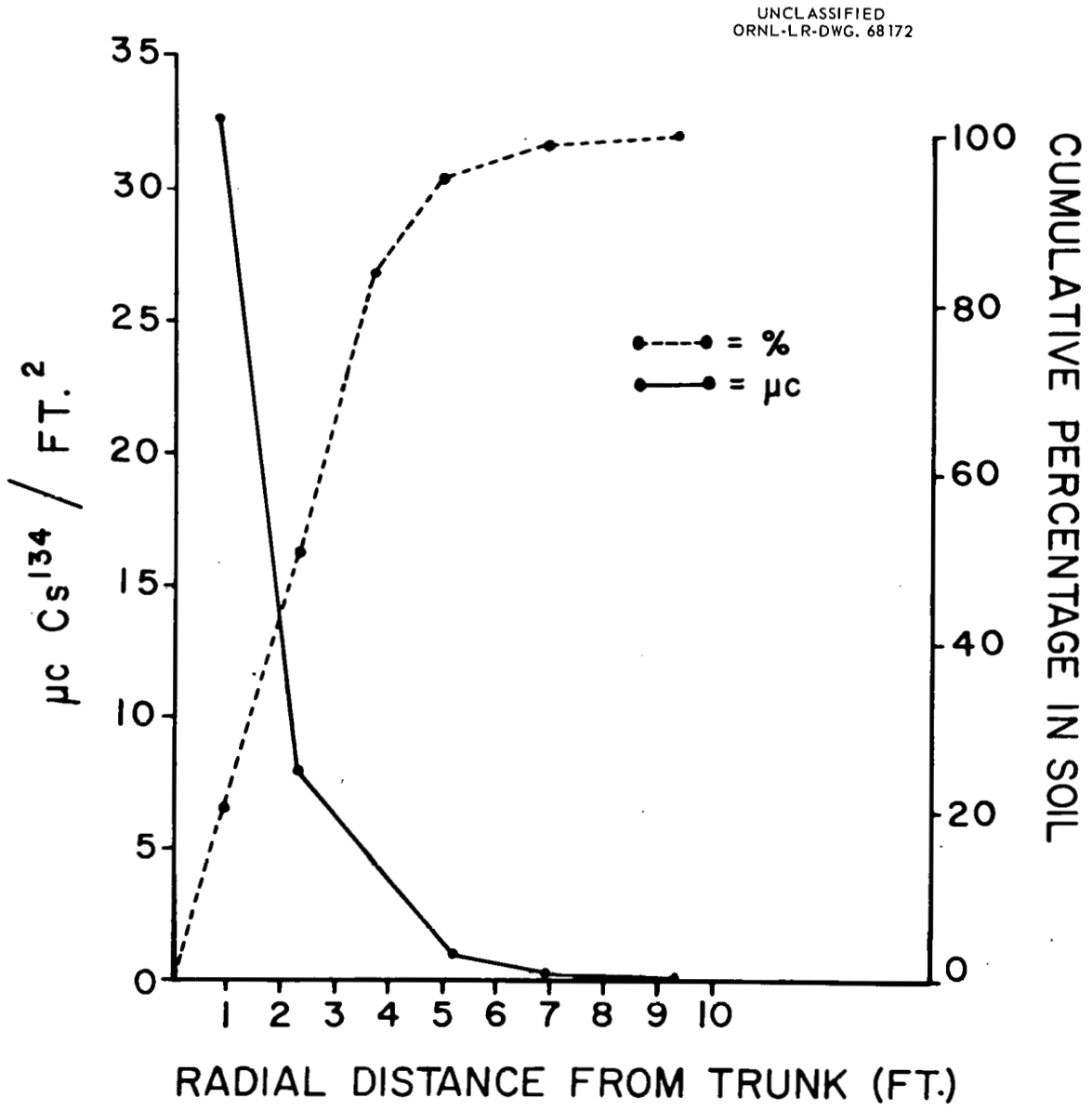

Fig. 27. Average Soil Concentration of Cs^{134} Per Unit Area and Cumulative Percentages Around Inoculated Trees.

IX. TOTAL TREE HARVESTS

A. Mensuration

Four trees harvested at the end of the 1961 growing season served as checks on both estimations of leaf number used in calculating total cesium-134 in leaves and estimations of quantities of cesium-134 in tree wood. Measured branch diameters of inoculated trees were applied to the regression equation of Rothacher, Blow, and Potts (1954) for estimates of leaf number used in this study. This equation is:

$$\text{Log } N = 0.787 + 1.972 \text{ (Log } X)$$

where N is number of leaves and X is branch diameter in tenths of inches.

Regressions of leaf number on branch diameter for the harvested trees gave the following equations:

Dolomitic dry site, tree number three:

$$\text{Log } N = 0.797 + 1.868 \text{ (Log } X)$$

$$r = .932 \quad S_b = .076$$

Dolomitic wet site, tree number three:

$$\text{Log } N = 0.789 + 1.854 \text{ (Log } X)$$

$$r = .972 \quad S_b = .049$$

Shale dry site, tree number three:

$$\text{Log } N = 0.771 + 1.830 \text{ (Log } X)$$

$$r = .826 \quad S_b = .119$$

Shale wet site, tree number two:

$$\text{Log } N = 0.773 + 1.682 \text{ (Log } X)$$

$$r = .710 \quad S_b = .184$$

The common regression for all four trees is:

$$\text{Log } N = 0.777 + 1.810 \text{ (Log } X)$$

$$r = .875 \quad S_b = .052$$

Figure 28 shows the common regression for all four trees of leaf number on branch diameter. The observed common regression equation seems close enough to that of Rothacher, et al. (1954) to warrant use of the latter in this study. Table XXXI gives size of inoculated trees with estimated and actual number of leaves on harvested trees. The net per cent error between estimates and actual counts indicates that the former were 5.3 per cent high.

The oven dry weights of components of harvested trees are given in Table XXXII. The leaves contained 9.0 ± 0.2 per cent of the total tree weight; branches, 12.5 ± 0.5; trunk, 48.0 ± 2.6; roots, 30. 4 ± 2.9; and buds and galls, 0.06 ± 0.02 per cent.

Dry weights of branches by 0.1 inch diameter size classes are given in Table XXXIII. Branches in the 0 to 0.1 inch class contained 14.5 ± 2.7 per cent of the total branch weight; 0.11 to 0.20 inch, 23.1 ± 2.0; 0.21 to 0.30 inch, 24.9 ± 2.5; 0.31 to 0.40 inch, 14.9 ± 1.7; 0.41 to 0.50 inch, 13. 6 ± 1.1; and over 0.51 inch, 9.0 ± 3.5 per cent.

Dry weight of trunks by diameter classes are given in Table XXXIV. Trunk wood in the 0 to 0.50 inch diameter class contained 1.2 ± 0.4 per cent of total trunk weight; 0.51 to 1.00 inch, 9.4 ± 2.8; 1.01 to 1.50 inches, 22.9 ± 10.9; 1.51 to 2.00 inches, 31.0 ± 6.9; and over 2.01 inches, 35.5 ± 17.1 per cent. More variation between trees was observed in trunk class weights than in size classes of any other tree

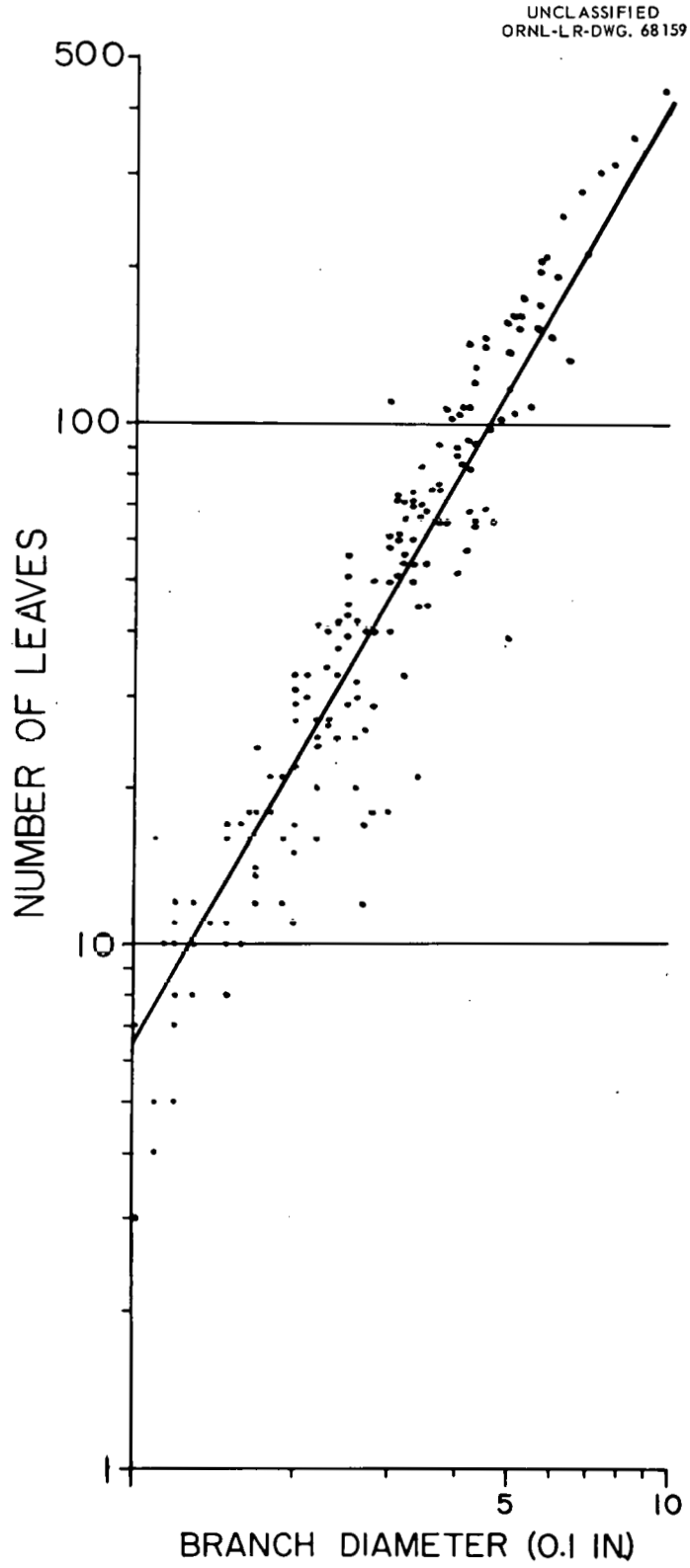

Fig. 28. Regression of Leaf Number on Branch Diameter of Four Harvested White Oak Trees.

Table XXXI

Tree Size and Leaf Number of Inoculated White Oak Trees

Site and Tree	Diameter Breast Height (Inches)	Height of Tree (Feet)	Number of Branches	Estimated Number of Leaves[1]	Actual Number of Leaves	Per Cent Error in Leaf Estimation
Dolomitic dry						
1	1.40	15.7	29	1919		
2	1.47	13.5	37	2272		
3	1.52	13.4	42	2462	2314	+ 6.0
Dolomitic wet						
1	2.10	14.1	71	5133		
2	2.01	17.7	54	2633		
3	1.70	17.3	45	2782	3163	- 12.0
Shale dry						
1	2.55	17.0	72	4350		
2	1.65	17.1	47	2919		
3	1.62	16.7	53	4337	3803	+ 12.3
Shale wet						
1	2.77	14.5	--	5259[2]		
2	1.33	15.2	36	2010	2083	- 1.0
3	0.82	13.1	26	1042		

[1]Estimated from branch diameters (Rothacher, Blow, and Potts, 1954).

[2]Estimated from trunk diameter (Rothacher, Blow, and Potts, 1954).

Table XXXII

Dry Weights (g) of Four White Oak Trees Harvested in September, 1961

Site and Tree	dbh (Inches)	Height (Feet)	Leaves	Branches	Trunk	Roots	Buds	Galls	Total
Dolomitic dry number 3	1.5	13.4	555.36	659.00	2,398.80	2,282.40	--	--	5,895.56
Dolomitic wet number 3	1.7	17.3	895.13	1,278.10	5,010.15	2,689.14	--	--	9,872.52
Shale dry number 3	1.6	16.7	1,057.23	1,628.82	6,322.60	3,279.25	3.38	2.41	12,293.69
Shale wet number 2	1.3	15.2	420.76	601.70	2,338.50	1,374.90	3.76	--	4,739.62

Table XXXIII

Dry Weights (g) of Branches by Diameter Classes in Four Harvested White Oaks

Site and Tree	Size Class (Inches)					
	0 to .10	.11 to .20	.21 to .30	.31 to .40	.41 to .50	.51 +
Dolomitic dry number 3	132.0	126.7	190.5	111.1	82.4	16.3
Dolomitic wet number 3	184.3	301.5	260.6	138.0	228.3	165.4
Shale dry number 3	205.3	445.6	306.5	182.6	216.0	272.7
Shale wet number 2	53.4	147.8	171.5	79.1	99.6	50.3

Table XXXIV

Dry Weights (g) of Trunks by Diameter Classes in Four Harvested White Oaks

Site and Tree	Size Class (Inches)					
	0 to .50	.51 to 1.00	1.01 to 1.50	1.51 to 2.00	2.01 to 2.50	2.51 +
Dolomitic dry number 3	36.3	352.7	583.1	1,093.5	333.2	--
Dolomitic wet number 3	47.9	101.4	319.0	756.7	2,291.3	1,493.8
Shale dry number 3	33.2	213.8	550.4	1,082.1	2,713.5	1,726.6
Shale wet number 2	47.0	331.0	1,203.5	757.0	--	--

component.

Root dry weights by diameter classes are given in Table XXXV. Roots in the 0 to 0.1 inch class contained 1.0 ± 0.2 per cent of the total root weight; 0.11 to 0.30 inch, 6.5 ± 0.9; 0.31 to 0.50 inch, 10.6 ± 1.5; 0.51 to 1.00 inch, 18.2 ± 2.8; 1.01 to 2.00 inches, 18.9 ± 1.9; and over 2.01 inches, 44.7 ± 4.2 per cent.

B. Cesium-134 in Harvested Trees

The distribution and quantities of cesium-134 found in harvested trees are given in Table XXXVI. These results indicate that an average of 18.4 ± 7.2 per cent of total radiocesium in trees was in the leaves, 8.8 ± 1.3 in branches, 49.5 ± 4.4 in trunks, and 23.2 ± 2.1 per cent in roots. The trunks, then, contained about half of the total radiocesium, and about one-fourth was deposited in the roots. Table XXXVII gives ratios of per cent of total radiocesium in the tree to per cent of total tree weight found in components. On this basis, leaves, with a mean ratio of 2.03 ± 0.79, concentrated more radiocesium than any other tree component. The shale wet site tree exhibited a small ratio (0.56) which tended to lower the mean value. The mean ratio for branches was 0.72 ± 0.13, and they had a smaller radiocesium concentration than any of the woody components. Concentration in branches tended to decrease with increasing branch size (Figure 29), and those in the 0 to 0.1 inch diameter class had approximately 1.5 times more radiocesium, on a weight basis, than larger diameter branches.

The mean ratio for trunk wood was 1.02 ± 0.09. This component,

Table XXXV

Dry Weights (g) of Roots by Diameter Classes in Four Harvested White Oaks

Site and Tree	Size Class (Inches)					
	0 to .10	.11 to .30	.31 to .50	.51 to 1.00	1.01 to 2.00	2.01 +
Dolomitic dry number 3	35.6	112.7	235.0	253.4	426.2	1,219.5
Dolomitic wet number 3	19.4	177.5	360.2	490.3	501.0	1,140.7
Shale dry number 3	17.1	286.0	468.1	744.4	526.9	1,236.6
Shale wet number 2	19.5	75.1	111.0	223.3	234.4	711.6

Table XXXVI

Distribution of Cesium-134 in Four Harvested White Oaks, November, 1961

Cs^{134} Activity and Weight of Tree Components	DD3	DW3	SD3	SW2
Leaves				
1. Total dry weight (g)	555.4	895.1	1,057.2	420.7
2. Total Cs^{134} (μc)	167.88	286.88	200.01	77.13
3. Weight as per cent of total tree	9.4	9.1	8.6	8.9
4. Cs^{134} as per cent of total in tree	20.0	34.6	14.1	5.0
Branches				
1.	659.0	1,278.1	1,628.8	601.7
2.	90.56	67.10	77.43	171.37
3.	11.2	12.9	13.2	12.7
4.	10.8	8.1	5.5	11.0
Trunk				
1.	2,398.8	5,010.1	6,322.6	2,338.5
2.	380.83	330.48	775.30	903.97
3.	40.7	50.7	51.4	49.3
4.	45.4	39.9	54.7	58.1
Roots				
1.	2,282.4	2,689.1	3,279.2	1,374.9
2.	199.69	143.18	364.76	402.41
3.	38.7	27.2	26.7	29.0
4.	13.8	17.3	25.7	25.9
Buds				
1.			3.4	3.8
2.			0.17	0.21
3.			0.02	0.08
4.			0.17	0.01
Cynipid Wasp Galls				
1.			2.4	
2.			0.20	
3.			.01	
4.			.01	

Table XXXVII

Ratios of Cesium-134 to Dry Weight in Four Harvested White Oaks

Site and Tree	Ratio of Per Cent of Total Cs^{134} to Per Cent of Total Dry Weight				
	In Leaves	In Branches	In Trunk	In Roots	In Buds
Dolomitic dry number 3	2.12	0.96	1.06	0.61	--
Dolomitic wet number 3	3.82	0.63	0.79	0.63	
Shale dry number 3	1.64	0.41	1.06	0.96	0.50
Shale wet number 2	0.56	0.87	1.18	0.89	0.12
Mean ± s.e.	2.03 ± 0.79	0.72 ± 0.13	1.02 ± 0.09	0.77 ± 0.09	0.31 ± 0.23

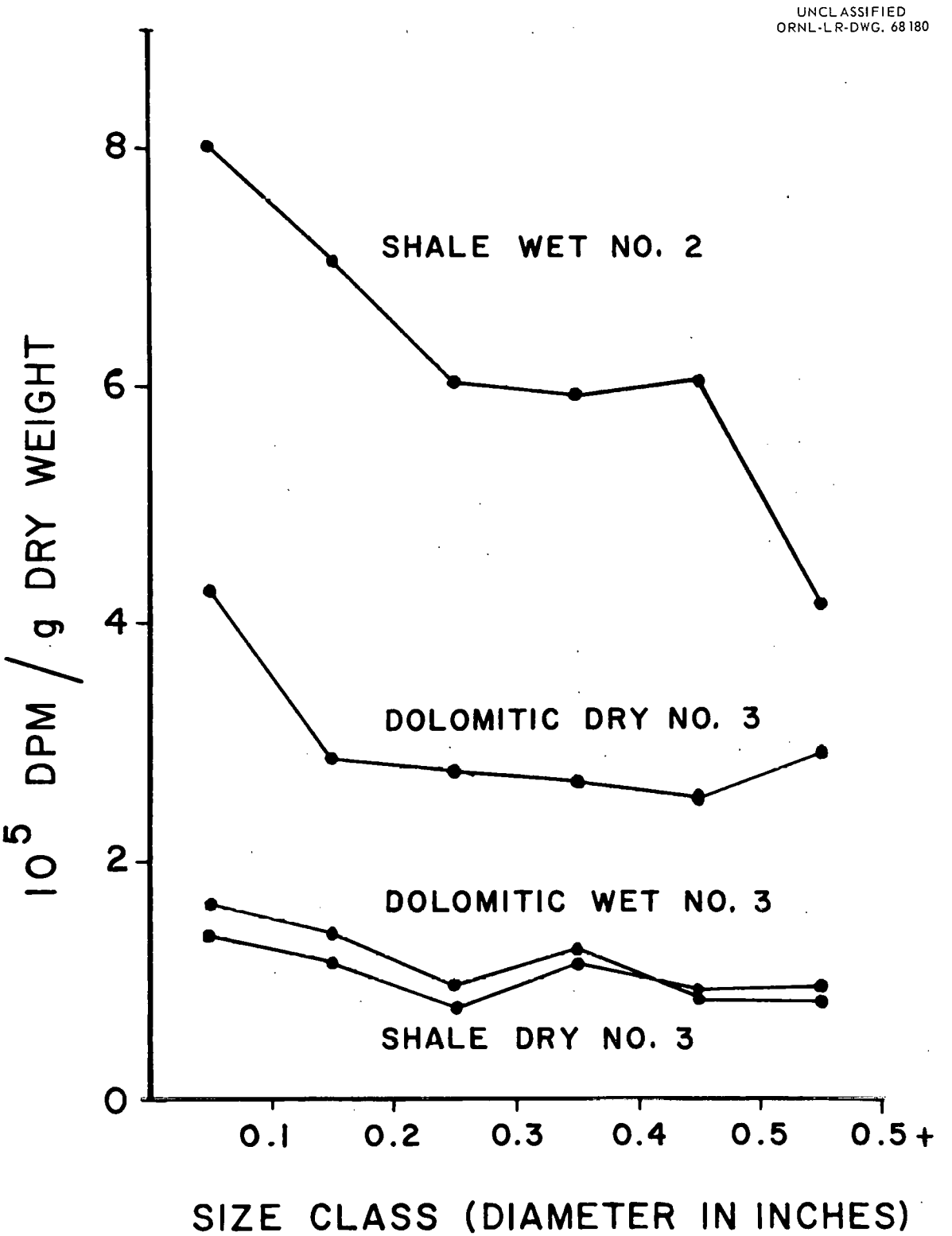

Fig. 29. Cesium-134 Activity and Branch Size.

with almost half of the total tree weight, contained about half of the total radiocesium. Wood samples taken throughout the diameter of trunks all contained Cs^{134} activity. For example, one trunk segment of 2 inches diameter contained the following activity:

depth of sample (inches)	dpm per g x 10^5
0 (outside) to 0.10	3.25
0.11 to 0.20	1.64
0.21 to 0.60	0.73
0.61 to 1.00 (center)	0.73

This distribution of radiocesium throughout trunk wood is not surprising as the feeder tubes driven in the trunks in the initial inoculations were driven deep enough to have released some of the radioisotope into heart wood. Of course, the extreme mobility of this very soluble radioisotope may have permitted an appreciable amount of lateral transfer in woody tissue. Ten samples of bark peeled from fresh trunk segments had a mean ratio of bark Cs^{134} activity to wood activity, on a weight basis, of 2.5 ± 0.3.

Roots contained a slightly higher concentration of radiocesium, on a weight basis, than branches. Unlike the sapling roots described in Chapter VI, the smaller roots contained no more radiocesium, on a weight basis, than larger roots. This might be expected, however, as the former were involved in uptake of Cs^{134} from litter and soil while the latter, presumably, were involved more with downward movement from inoculated trunks.

Total Cs^{134} found in harvested trees came close to estimates of

total tree contents based on subraction of total losses from the original input value (Table XXXVIII). The average quantity in observed trees was 13.3 ± 3.0 per cent lower than estimates, indicating than an average of 255 ± 60 μc was lost or unaccounted for in this study. Some of this loss may be attributed to insects as Rothacher, Blow, and Potts (1954) reported a total of 6 to 7 per cent of the area of oak foliage destroyed by insects during the growing season. Observations of inoculated trees indicated that this estimate of insect damage may be low for several of the trees in this study. Also small quantities of Cs^{134} may have been distributed outside of the 9.2 feet sampling radius.

Table XXXVIII

Estimated and Observed Quantities of Cs^{134} in Trees at End of 1961 Growing Season[1]

Site and Tree	Total Cs^{134} Lost From Tree (μc)	Estimate of Cs^{134} Remaining in Tree (μc)	Total Cs^{134} Found in Harvested Trees (μc)	Per Cent of Original Inoculation Accounted For	Per Cent of Original Inoculation Lost
Dolomitic dry					
1	837.90	1162.10			
2	504.30	1495.70			
3	957.34	1042.66	838.96	89.8	10.2
Dolomitic wet					
1	1008.65	991.35			
2	291.11	1708.89			
3	859.97	1140.03	827.44	79.4	20.6
Shale dry					
1	284.72	1715.28			
2	557.90	1442.10			
3	416.15	1583.85	1417.87	91.7	8.3
Shale wet					
1	275.07	1724.93			
2	165.01	1834.99	1555.09	86.0	14.0
3	118.24	1881.76			
			Mean ± s.e.	86.7 ± 3.0	13.3 ± 3.0

[1]Before 1961 leaf fall.

X. DISCUSSION

A. General Cycle of Cesium

Movements of Cs^{134} during the growing season were rapid and of relatively large magnitude. Translocation of this element in vegetation was much more rapid than that of elements such as Ca or Sr (Glueckauf, 1955; Middleton, 1959), but similar to that of K. Movements of Cs and K seemed to be merely transport phenomena while those of Ca and Sr were interpreted as being involved with exchange mechanisms.

From trunk inoculations, Cs^{134}, like K^{42}, spreads to all parts of the tree crown in the transpiration stream moving, presumably, through xylem. With environmental factors favoring transpiration, radiocesium (with radiopotassium) was found in all parts of a white oak tree crown 1.5 hours after trunk inoculation. Samples were not collected before this time, however, so the initial rate of movement may have been faster. Kuntz and Riker (1955) detected Rb^{86} in crowns of bur oak and pin oak up to 35 feet high at 20 minutes after trunk input. They estimated rate of movement at 1.5 to 3 feet per minute. Downward movement of radiocesium from trunk inoculations also occurred, although at a slower rate than upward movement.

Maximum concentrations of radiocesium in leaves were observed in early June, and they amounted to about 40 per cent of the total input. Leaf concentrations of stable Cs at this time averaged about 35 per cent of average total soil stable Cs, on a weight basis. Yamagata, et al (1959) found a similar value of 40 per cent for Japanese plants and soils in a variety of habitats.

Losses of this element from trees occurred with each rain. Approximately 15 per cent of the maximum leaf content came down in rain water each growing season. By November, 70 per cent of this rain-exported radiocesium had reached the mineral soil, with litter containing 19 per cent and the understory the remainder. Loss from trees by the annual leaf fall was greater, with about one-third of the observed maximum leaf content reaching the ground in litter. The total loss per year resulting from rain exports and leaf fall was approximately 19 per cent of the original input.

Since uptake of radiocesium by plants from soil was low; shown by sapling experiments in this study; and by Nishita, et al. (1959), Pendleton (1960), and Klechkovsky (1957); recycling of these radiocesium losses should be of small quantity. With this assumption, and assuming an annual loss of 20 per cent of the amount remaining, little radiocesium will remain in these trees after 5 or 6 years. The mineral soil will by this time hold most of the depletion from trees.

Approximately 2×10^3 times more stable Cs than radiocesium was involved in tree gains and losses. The amount of stable Cs in the top inch of mineral soil under inoculated trees was 4 to 5×10^6 times greater than the annual addition of radiocesium from trees to this inch of soil. Thus, while the quantities of radiocesium used in this study (2.0 mc per tree) were adequate for following cyclic behavior of this element, they were very small compared to natural levels of Cs. A proposed annual cycle of stable Cs for white oak trees of the size considered in this study is shown in Figure 30. The estimates in this

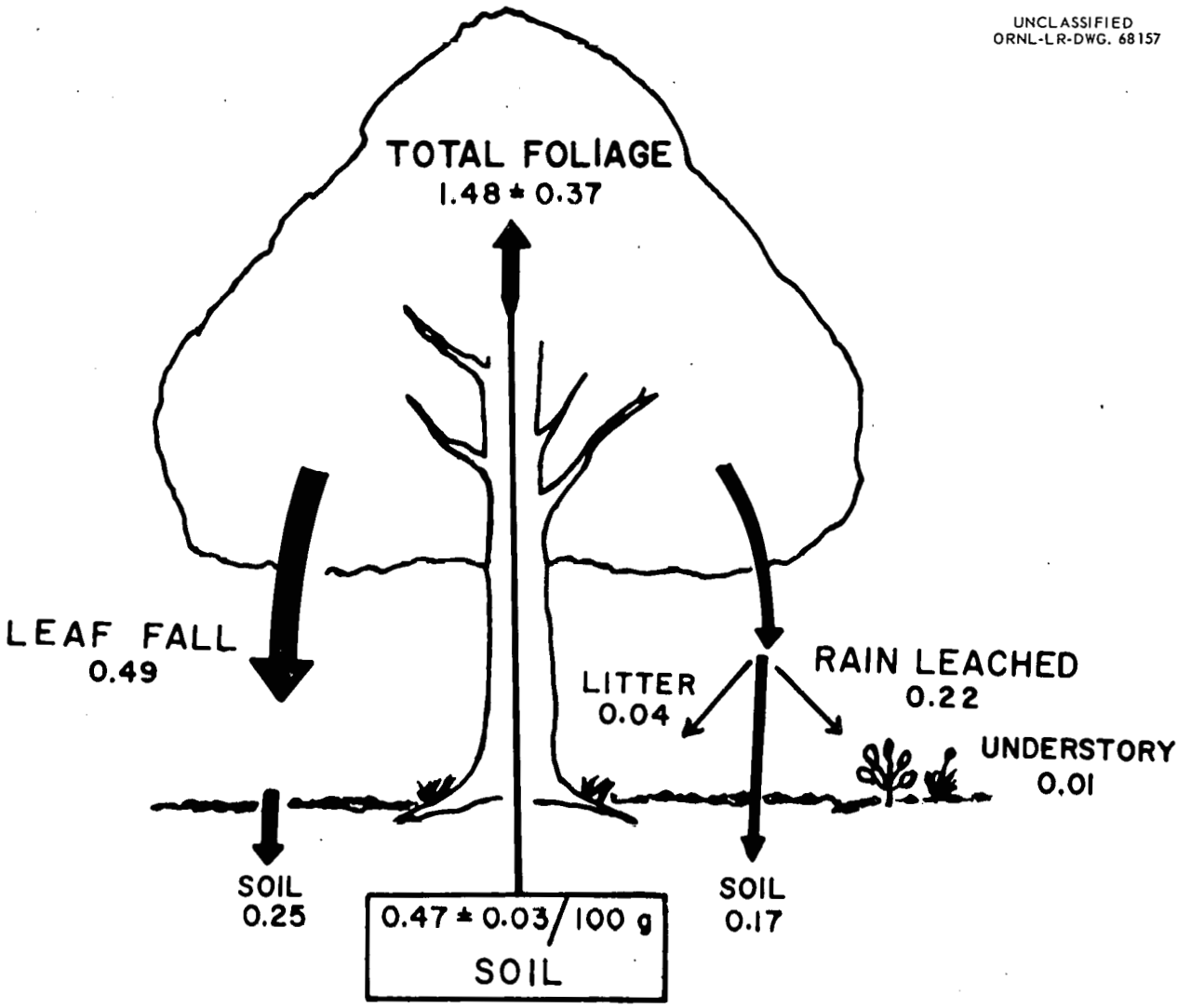

Fig. 30. Inferred Annual Cycle of Stable Cesium in Small White Oak Trees. (Values in mg).

figure were based on observed average percentages of radiocesium involved in various stages of transfer, and stable Cs values obtained by activation analysis. Quantities of natural Cs in stages of this cycle were very small compared to quantities of the macronutrient elements--N, K, Ca, Mg, P, and S. However, the percentage of Cs that was leached from vegetation by rain is probably greater than that to be expected for these elements, with the exception of K.

B. Retention and Movement in System Compartments

Cyclic behavior of Cs^{134} in vegetation indicated that it remained in a highly water soluble form which enabled it to move rapidly in and out of leaves, wood, roots, and litter. Large quantities of radiocesium which were translocated into leaves in the spring, after over-wintering in woody tissue, indicated that even after a year this high solubility remained.

Losses from both litter and living leaves are prompt. Cesium-134 and K^{42} were detected in rain collected under a tree crown 12 hours after trunk inoculation. Leaves of white oak saplings already contained radiocesium when sampled six days after applications of tagged litter to soil. Equally prompt losses from roots were illustrated by the artificial leaching of seedling roots. These rain-induced losses may have been small on a daily basis (in the order of 0.1 μc), but they were large annually. By November, 1961 (one year and seven months after inoculations), estimated radiocesium lost through leaching was 31.5 per cent of the total tree loss. The remaining 68.5 per cent represented losses

through leaf fall.

Radiocesium reaching the litter layer in rain remained there only a short time. At the end of the 1960 growing season, an average of only 16.5 ± 3.0 per cent of the total rain export was found in the litter. At the end of the 1961 growing season, before leaf fall, 25.8 ± 2.3 per cent of the total lost from trees was retained by the litter layer. Olson and Crossley (1962) found a 50 per cent reduction in Cs^{134} in tagged white oak litter in 20 weeks. This litter was in nylon net bags placed in an oak stand in November. The time required for a 50 per cent weight loss was 44 weeks. Over the winter months, then, litter which has fallen from inoculated trees may have about half of its radiocesium transferred to the mineral soil.

Cesium-134 reaching the understory vegetation around inoculated trees probably entered these plants mainly through foliar absorption of rain exports as activity here was greater than that to be expected from uptake from soil. The percentage of total tree loss retained in this compartment was small. In September, 1960, 6.3 ± 1.0 per cent was found in the understory. By November, 1961, 2.4 ± 0.6 per cent of total tree losses resided in this vegetation. The understory plants were also subject to leaching losses of radiocesium from both living and dead plant parts. The rate of return to soil would be especially high in annuals.

Since the passage of radiocesium through vegetation compartments was rapid, and plant uptake percentages were low, the soil became the principal depository and greatest rate-limiting compartment in the system. By the end of the 1960 growing season, 77.2 ± 2.9 per cent of total tree

loss had reached the mineral soil. By November, 1961, the soil retained 71.8 ± 2.1 per cent. Although this radioisotope exhibited downward mobility in soils (a penetration of 4 inches by September, 1960, and 10 to 12 inches by November, 1961), most of it was retained in the top 2 inches. Mobility seems related to soil moisture as the wet site soils had significantly larger percentages of their total radiocesium at depths greater than 2 inches.

A portion of this soil burden was available for plant use. Samples taken 140 days after application of tagged litter to Landisburg silt loam soil showed that 11.0 ± 1.7 per cent of the total radiocesium in the 0 to 2 inch depth was exchangeable when leached with 1 N ammonium acetate (pH 7.0). The presence of organic matter in this depth layer accounted for much of this exchange fraction, and deeper soil layers could be expected to have smaller exchange fractions. Activation analysis of soil leachates also indicated that a small portion (0.027 ± 0.006 μg per g) of the total soil stable Cs was in an exchangeable form.

Although the animal compartment of this system was not studied, there are certain assumptions which might be made concerning the possible relationship of animals to the radiocesium cycle. The estimates of insect damage to oak leaves made by Rothacher, Blow, and Potts (1954) seem reasonable from observation of inoculated trees. If 6 to 7 per cent of the foliage area was killed or eaten by insects during the growing season, an appreciable quantity of radiocesium may have been involved. If half of this foliage damage represented the amount consumed by insects, approximately 10 to 20 μc of Cs^{134} entered the animal compartment. This

is 2 to 4 per cent of the estimated annual loss due to rain and leaf fall. Retention of radiocesium by insects may be of short duration, however, as the biological half-life of this radioisotope in insects is short (Crossley and Pryor, 1960; Crossley and Howden, 1961).

Soil fauna, especially those animals that act upon litter, may have retained minute quantities of radiocesium. The larger animals, such as earthworms or other burrowing species, would come in contact with appreciable amounts of the radioisotope, particularly in the surface soil where retention is greatest.

C. Factors Influencing Cycle

Moisture played a principal role in governing the amount and rate of transfer of radiocesium from one system compartment to another. Leaching losses from living and dead vegetation were largely dependent upon frequency, kind, and amount of rainfall. Mobility of radiocesium in the soil was affected by soil moisture as movement in wet (bottomland) soils was found to be significantly greater than in drier (upland) soils.

Other factors influencing leaching losses from plants are temperature, leaf age and condition, and surface exposure of leaves (Stenlid, 1958). Salts are lost more rapidly at high temperatures due to increased surface wetting of leaves and more rapid dissolving of salts. Old or damaged leaves tend to lose more salts than fresh leaves. This may be due to increased permeability of the cytoplasm or exposure of internal layers by tissue damage. Losses from the upper surface of leaves are greater than from the lower surface, even if there are more stomata on

the under surface (Lausberg, 1935). This is because most of the salts deposited on leaf surfaces by evaporation appear on the upper surface which receives most of the rain.

Both physical and chemical characteristics of the soil profile exert an influence on the retention, mobility, and plant availability of radiocesium. In this study, the physical factors seemed to play a larger role in mobility than the chemical factors (see D. Site Comparisons). Moisture, kind and amount of clay minerals, pH, presence of large pores and root channels, and base status have each been found to influence the behavior of radiocesium in the soil. It is the particular combination of these factors acting at a given time, however, that actually governs the situation. For example, illitic clay minerals have exhibited a great capacity to fix Cs, but a soil which is dominantly illitic in nature may not sorb larger amounts of Cs than a relatively nonillitic soil due to some increase of additional salts in the soil solution of the former (Rhodes, 1957). The amount of total Cs-fixing mineral present is also important, so that an illitic soil may not exhibit a great Cs-fixation capacity because of a low total clay content. The gist of this particular discussion is that before ascribing a great Cs-holding capacity to a soil on the basis of its clay mineralogy, there are other factors to be considered which may be of equal importance.

While chemical factors influence radiocesium accumulation in the soil compartment, they also influence the release to vegetation compartments. Most of these relationships have been discussed in Chapter II.

D. Site Comparisons

Many of the stages involving vegetation gains and losses of radiocesium exhibited more site similarities than differences. Significant site differences were observed in the mobility of this element in soil.

Radiocesium translocated from original inoculations into leaves was significantly less (1 per cent level) in trees on shale sites than in trees on dolomitic sites during the 1960 growing season. Smaller amounts were also translocated during the 1961 growing season, but they were not significantly different at the 5 per cent level from amounts translocated in trees on dolomitic sites. It is felt that this smaller amount of total radiocesium transfer into leaves was due mainly to time of inoculation in the case of the 1960 observations. One shale wet site tree was inoculated June 20th, and the other two in the first week of July. These times may have corresponded to periods in the growing season which were less favorable for translocation or periods of temporary summer dormancy, as described by Kramer and Kozlowski (1960). The smaller tree size and leaf number of two of the shale wet site trees also may have contributed to this smaller amount of transfer.

The amount of available (ammonium acetate extractable) K exerted no observable influence on radiocesium movement from trunk inoculations into leaves in 1960, or from woody tissue into leaves in 1961. The Sequoia and Monongahela (shale) soils contained two times more available K in their profiles than the Fullerton and Landisburg (dolomitic) soils. Two trees (one on Fullerton soil, one on Monongahela) exhibited no significant difference in ratios of K^{42} to Cs^{134} in leaves after trunk

inoculations of these two radioisotopes. Maximum movement of radiocesium into leaves of trees on the Sequoia soil was similar to that of dolomitic soil trees. The higher K levels in shale soils should influence plant uptake, or the recycling of radiocesium, as a result of competition for available ion exchange sites on plant roots.

The percentages of radiocesium leached out by rain, returned to wood, and remaining in leaves at the end of the growing season were remarkably uniform from site to site. Tree to tree variations were larger possibly due to such factors as variation in leaf content and number, canopy coverage over individual trees, and individual physiological differences.

Site differences in distribution and mobility of soil radiocesium were observed in 1960 and 1961. In 1960, the Monongahela and Landisburg (wet) soils had a greater loss of radiocesium from the top inch and significantly (1 per cent level) greater penetration down to 4 inches. In 1961, the wet soils had significantly greater (1 per cent level) losses from the top inch than dry soils and significantly (1 per cent level) greater penetration down to 12 inches. This greater mobility in wet soils may have been largely due to the higher moisture levels maintained in these bottomland positions and to the smaller amounts of total clay in the top 12 inches.

That significant differences in mobility were not observed between illitic (shale) soils and dolomitic soils may have been due to several factors. These soils were acidic in reaction, and Klechkovsky (1957) demonstrated that Cs^{137} is sorbed more stably and in a more

unexchangeable form in base saturated soils. Prout (1959) found radiocesium sorption to be pH dependent in kaolinitic soils. Moreover, the total amount of clay in the Monongahela and Sequoia soils at the 0 to 12 inch depth was less than that in the Fullerton and Landisburg. The higher K levels (total and exchangeable) in the shale soils may have lowered their potential to sorb small amounts of Cs due to K occupancy of fixation and exchange sites on the clay minerals. Mobility of radiocesium in all four soils may have been less than that of many other elements, for 92 per cent of the total soil concentration remained in the top 4 inches after one year and seven months.

Site differences in soil and white oak leaf content of stable Cs were observed. Soil Cs showed a significant (1 per cent level) linear relationship to clay content, with a coefficient of correlation of 0.87. This might be expected, as Vinogradov (1959) gave the crystal lattices of aluminosilicates as the solid phase depository of this trace element in soils. White oaks on the dolomitic soils had almost two times more stable Cs in their leaves than those on the shale soils. With the small sample number, no meaningful statistical comparison could be made, but it is possible that the higher K levels in shale soils contributed to the smaller uptake of Cs.

E. Significance

An attempt has been made to describe some of the movements of Cs^{134} in a forest ecosystem. This information is basic, in that Cs occurs naturally as a trace element in soil and vegetation, and practical, in that it may be applied to radiocesium from waste disposal operations or

nuclear weapons detonations.

While Cs is not essential to plants, it represents one of many elements that are taken up from the soil. Information on the contents of natural Cs in plants is scarce, and the work of Yamagata, et al. (1959) and Bertrand and Bertrand (1949) represents much of our knowledge on this subject. The present study has illustrated the magnitude and rates of some of the transfer stages of this element as they occurred in a relatively simple forest system. It has also illustrated how certain edaphic and environmental factors may affect these stages. Analyses of soil content of natural Cs have been more numerous than plant content analyses (Vinogradov, 1959). With the new analytical techniques available, such as activation analysis and cathode-layer arc spectrography, perhaps new information on this element and others will be provided.

The significance of this study in predicting the behavior of fallout radiocesium, or radiocesium from waste disposal operations, lies in the elucidation of paths of movement from one system compartment to another and the speed at which these transfers were made. Passage of this radioisotope through vegetation is rapid. Fallout Cs^{137} absorbed by tree leaves or taken up from the soil will soon reach the ground through the leaching action of rain and leaf fall. In the case of conifers, in which leaf fall is extended over longer periods of time, rain may be more important than leaf fall in accelerating the return to soil. For herbaceous plants, particularly annuals, this return would be of shorter duration due to the rapid leaching of radiocesium from dead plant parts. Rain can also spread contamination from one plant to another as illustrated

by understory contamination from inoculated trees. Litter from contaminated plants affected radiocesium transfer to other plants as well as to the soil.

The high rate of return to the soil, and subsequent low percentage of uptake by vegetation might tend to minimize the hazard of fallout in natural vegetation. But low-level radioactive waste operations may produce levels of contamination several thousand times higher than fallout levels (Auerbach, et al., 1959). Even with the high rate of return to the soil, trees may still be contaminated for several years at levels well above fallout. It is possible that trees, with their deeper root penetration, can take up atomic wastes buried in the soil or in waste pits and transfer them to other shallow rooted plants which might not have been contaminated otherwise.

Levels of radiocesium used in this study (2.0 mc per tree) resulted in concentrations in vegetation many thousand times greater than fallout levels. But experimental concentrations observed in various cyclic stages were similar to those found in the soil of the White Oak Lake low-level waste disposal area at Oak Ridge (Auerbach, et al., 1959).

The cyclic behavior of Cs^{134} showed some similarities to reported behavior of K, but several important differences were observed. Experiments on simultaneous rates of movement of Cs^{134} and K^{42} in inoculated trees indicated that both elements moved rapidly in and out of white oak leaves. Buds were found to concentrate K^{42}, however, and no such concentration of Cs^{134} was observed. There was an average reduction of leaf radiocesium from observed maximums during both growing seasons of 67.5 ±

4.5 per cent. This is similar to a K reduction in leaves of 72.5 per cent reported by Lutz and Chandler (1946) for several hardwood species. The estimated average growing season loss of radiocesium due to rain leaching (15.1 ± 1.9 per cent) was much smaller than values reported for K loss from tree crowns by Will (1955) and Tamm (1951). Considering the difference between ionic radii of Cs (1.63 Å) and K (1.33 Å), it may be that the former does not follow K movements as closely as would Rb, for example, with a 1.49 Å radius. Total radiocesium downward movement in soils observed in this study may have been less than that of K subjected to the same environmental conditions.

Extremely rapid transfer of Cs^{134} from litter to plants indicated that this same pathway is available to potassium. Such transfers probably occur almost continually in forest systems.

Ratios of available K to available stable Cs (determined by leaching with 1 N ammonium acetate) in the experimental soils averaged 9.4 ± 2.1 x 10^3 for A horizons and 3.3 ± 0.8 x 10^3 for B horizons. This difference between ratios in A and B horizons is attributed to larger available K levels in the A_1 horizons. The average K to stable Cs ratio in white oak leaves was 4.5 + 1.1 x 10^3. This is of the same order of magnitude as the soil ratios of availability. Average total K to total Cs ratios in soils have been given as 2.0 x 10^3 for Japanese soils (Yamagata, et al., 1959) and 2.7 x 10^3 for a world average (Vinogradov, 1959). Although total soil K was not determined in this study, it is probable that the total K to total Cs ratio in these soils would be similar to those reported. The mean soil Cs value observed (4.67 ± 0.35 μg per g soil) is close to the 5 μg per g soil world average given by Vinogradov.

XI. SUMMARY AND CONCLUSIONS

The cycle of Cs^{134} in white oak trees was followed from spring, 1960, to autumn, 1961. Three trees on each of four sites differing in soil type and moisture were each inoculated with 2.0 mc Cs^{134}. Gains and losses of this radioisotope during the growing season were estimated by sampling from inoculated trees, understory, litter, and soil.

Chemical and physical properties of soils (Fullerton and Landisburg on dolomitic dry and wet sites, respectively; and Sequoia and Monongahela on shale dry and wet sites, respectively) were determined.

With rapid translocation into leaves from initial trunk inoculations in the spring, white oak leaves contained 10^5 to 10^6 dpm Cs^{134} per g dry weight by early June. This represented a total transfer of about 40 per cent of the original input. With the first rains following inoculation, loss of radiocesium from leaves began. These losses continued throughout the growing season until September, by which time total loss of 15 per cent of the observed maximum concentration in leaves had occurred. Of this rain-induced loss, 70 per cent reached the mineral soil by September, the remainder being located in litter and understory vegetation.

Radiocesium transferred from trees via annual leaf fall was approximately two times greater than the quantity exported by rain. With subsequent leaching over the winter months, the litter produced by inoculated trees lost about half of its radiocesium to the mineral soil.

Passage of this element through trees, litter, and roots was found to be very rapid. Transfers from litter to vegetation were demonstrated as well as transfers by leaching from living leaves to understory

vegetation.

Downward movement of radiocesium in soils under tagged trees was observed, and soils on wet sites had significantly greater percentages at lower depths down to 12 inches (30 cm). However, 92 per cent of the total soil radiocesium remained in the top 4 inches (10 cm) one year and seven months after tree inoculation. A definite pattern of distribution, presumably related to leaching and stem flow, was found under tagged trees, with 19 per cent of the soil radiocesium occurring near the trunk and 80 per cent confined to the area underneath the crown.

Total annual loss of this radioisotope from inoculated trees was estimated at 19 per cent of the original inoculation. Results from analysis of four trees harvested at the end of the study indicated that estimates of radiocesium remaining in trees one year and seven months post inoculation were 13.3 ± 3.0 per cent high.

Stable Cs determinations for soil horizons and white oak leaves showed that the quantities of Cs^{134} involved in all stages of this experiment were very small compared to natural levels of Cs.

Ascertaining the rates and percentages of Cs^{134} transfer from one forest system compartment to another serves several objectives. It adds to our knowledge of the natural behavior of trace elements which, lacking nutritional significance, nevertheless appear in natural vegetation. It also gives certain bases for predicting behavior of radiocesium which might enter such a system as fallout or as a product of atomic waste disposal operations. Finally, detailed knowledge of the behavior of tracer Cs in natural systems may provide clues to a better understanding of the behavior and role of K, an element of nutritional significance which is related and similar to Cs in certain ways.

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