ROOTING CHARACTERISTICS OF *EUCALYPTUS GLOBULUS* LABILL. AND *BUDDLEIA NITIDA* BENTHAM ON IRAZU VOLCANO. CARTAGO, COSTA RICA

by

Robert B. Peck

Inter-American Institute of Agricultural Sciences of the O.A.S.

Training and Research Center

Turrialba, Costa Rica

October, 1969

ROOTING CHARACTERISTICS OF *EUCALYPTUS GLOBULUS* LABILL., AND *BUDDLEIA NITIDA* BENTHAM ON IRAZU VOLCANO CARTAGO, COSTA RICA

Thesis

Submitted to the Graduate School Council in partial fulfillment of the requirements of the degree of

MAGISTER SCIENTIAE

at the

Inter-American Institute of Agricultural Sciences of the OAS

APPROVED: ______________________ Principal Advisor
Kenton Miller, Ph. D.

______________________ Committee
C. J. Campbell, M.S.

______________________ Committee
T. A. McKenzie, M.F.

______________________ Committee
Elemer Bornemisza, Ph. D.

September, 1969

ACKNOWLEDGEMENT

The writer would like to acknowledge the valuable suggestions of Dr. C. V. Plath, Land-use Economist, Food and Agricultural Organization of the United Nations assigned to the Inter-American Institute of Agricultural Sciences, and for the cooperation of Paulino Gutierrez, Agronomist in charge of the Reforestation Project on the Upper Reventado Watershed, Defensa Civil, Cartago, Costa Rica.

The financial assistance of a scholarship provided by the Training and Research Center of the Inter-American Institute of Agricultural Sciences of the O.A.S. and it's Director Ing. Fernando Suárez de Castro was greatly appreciated.

Special mention should be made to the committee members Drs. Kenton Miller and Elemer Bornemisza and Professors Thomas McKenzie and Jean Campbell, for their cooperation and guidance.

VITA

Name: Robert B. Peck

Date and Place of Birth: July 7, 1943; Washington, D. C., U.S.A.

Education:

	Name and Location	Dates	Degree
High School	Onteora Central Boiceville, New York	1957- 1961	
College	Paul Smiths College Paul Smiths, New York	1961- 1963	A.A.S.
	University of Montana School of Forestry Missoula, Montana	1963- 1966	B.S.F.
Graduate Work	Inter-American Institute of Agricultural Sciences of the O.A.S. Turrialba, Costa Rica	1968- 1969	M. S.

Employment Experience

Employer	Dates	Position
New York State Forest Pest Control Service Kingston, New York	Summer of 1961 and 1962	Ribies Eradication Crew
U. S. Forest Service Big Prairie R. D., Hungry Horse, Montana	Summer of 1963	Look-out Observer and Trail Crew
U. S. Forest Service Bonners Ferry, Idaho	Summer of 1964	Forest Technician
U. S. Forest Service Moscow, Idaho	Summer of 1965	Research Assistant Forest Pathologist
Peace Corps Volunteer Inter-American Institute of Agric. Sciences Turrialba, Costa Rica	1966 - 1968	Assistant Silviculturist

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

Volcano Irazú erupted in 1963. The prevailing easterly winds distributed lithic ash west of the volcano where, after approximately two years of continuing eruptions, accumulations on the upper watershed of the Reventado River exceeded 50 cm depth. These deposits of ash and cinder had the dual effect on the upper watershed, of 1) destroying the vegetation that had formerly protected the watershed, and 2) forming, once wetted, thin concrete-like sheets which led to excessive runoff rates and uncontrollable erosion on the upper slopes of the Reventado watershed. In areas where penetrations did occur, the water flowed beneath the layer of ash, causing slippage and landslides resulting in avalanches of mud falling into the channel bottom of streams.

A series of such avalanches, starting in December of 1963, caused extensive damages to properties located several miles downstream on the alluvial fan of the Reventado River west of the main business center of the city of Cartago. Since 1963, expenditures covering both reconstruction and the prevention of further flood damages have amounted to more than ten million dollars (44).

The Civil Defense[a], created to handle the emergency situation, decided to try to control the avalanches by working at their source: the upper watershed of the Reventado River. A reforestation project, coordinated with diversion ditching, was proposed to stabilize the steep slopes and prevent additional mud flows.

---

[a] A semi-autonomous organization of the Costa Rican Government.

Today, some three years after the creation of the Civil Defense, the immediate goal of reducing the avalanches has been accomplished by the reforestation and diversion ditching. But the question still remains as to which of the two species used for reforestation will stabilize the slopes from excessive surface erosion and land sluffing, and also serve as a future source of raw material for the local population.

The needs of the local population living on the upper reaches of the volcano can be shown by the following comparison: In 1910 during the Calvert (11) visits to the Volcano Irazú area, references were made to the tall oak forest lying above 8,500 feet (2,850 meters) elevation which was then the lower limit of the forest which encompassed the entire upper watershed. But by 1963, a review of aerial photographs shows that only 20 percent of the upper watershed remained under forest cover. Demands made on the forest resources coincided with a change in land use. As the forests were felled for raw material to be used for firewood, fence posts and lumber, pastures were extended where terrain permitted.

Continued demand for firewood and fence posts results in a condition in which the forest is still being harvested for these products.

This condition tends to support the assumption that species selection for reforestation project could meet both the short term goals and also provide a source of future raw material.

By selecting proper species, plantations could be made to satisfy the immediate goals of reforestation for watershed stabilization, as well as serving as suitable material for the future demand of the local population.

In this study, the rooting characteristics of two species *Eucalyptus globulus* Labill, and *Buddleia nitida* Bentham, which were selected by the Civil Defense, have been studied to provide a more knowledgeable basis for species selection for future watershed reforestation. In order to evaluate the suitability of a species to be used for reforestation, several characteristics may be considered:

A. The species' ability to meet the immediate needs of restoring the hydrologic balance in the watershed by stabilizing steep slopes, preventing mud flows, and increasing infiltration.

B. The species' ability to meet the long-term needs of the local economy. Bushy species would not be favored when there is a demand for firewood or lumber.

C. Fast-growing species should be selected for planting so that the immediate and long-term needs of the economy will be met in as short a time period as possible.

II. REVIEW OF THE LITERATURE

Much has been published about the influential role of vegetative cover in the management of watersheds. Three representative watersheds in which the existing vegetation had been destroyed are:

1) The Reventado watershed destroyed by the eruption of Irazú Volcano.
2) The Davis County watershed (18) destroyed due to severe fire and overgrazing.
3) The Coweeta Watershed #3 (65) destroyed by forest grazing.

In these cases reviewed, removal of the protective cover resulted in catastrophic flooding, and when reforested, the excessive runoff was rapidly diminished by increasing the interception and evapotranspiration. The accumulation of a litter layer and growing root system also influenced the stabilization of the watersheds.

A. INTERCEPTION

Interception, which deals with the amount of moisture caught and stored on the leaves and stems of vegetation, can amount to a considerable percentage of total rainfall. Reviewing more than 50 regional studies dealing with interception in the eastern United States, Helvey and Patric (34) found that in Coweeta, a region typical of the majority of those studied, annual interception amounted to 10 inches (254 mm) or 13 percent of gross rainfall. Mohr and Van Baren (50), reviewing interception in tropical forests, found that an average interception rate of 4 mm per shower, and 160 days of rain per year, gave him an annual interception figure of 640 mm, or more than 23 percent of gross rainfall. Nye (52), working in African tropical forests, found an average interception value of approximately 2 mm per shower, or 16 percent of the annual rainfall. This represents a figure somewhat less than that reported by Mohr.

While these studies indicate that a relatively large percentage of rainfall is lost through interception, the losses have little effect on the prevention of flooding. Hoover (38) points out that interception loss is of doubtful value in reducing flood peaks from rains greater than 2 inches (50 mm). During those small storms of little flood-producing potential, interception removes a relatively high proportion of the precipitation from runoff; but only a small proportion of the runoff is removed by interception during major flood-producing storms.

Grasses and herbs, as well as trees and shrubs, intercept surprisingly large amounts of rainfall. Clark (16) recorded the maximum rainfall interception of prairie grasses, weeds, and some agricultural crops, and found that interception per storm ranged from 0.5 to 2.8 mm for green plants. Kittredge (40) reported that undisturbed grass species intercepted 25.9 percent of the annual rainfall of 32.52 inches (826 mm).

B. EVAPOTRANSPIRATION

Forest trees through the process of evapotranspiration remove soil water which would otherwise add to stream-flow and ground water recharge (49, 63). Annual use of water by forests has been estimated to range from 3 inches (76 mm) in boreal forests to 125 inches (3175 mm) in tropical forests (15). In the United States, Chow (15) reported that evapotranspiration by forest vegetation may range from 10 to 55 inches (254 mm to 1397 mm) within a year.

As plants withdraw water from the soil, storage space is created for future rainfalls (49, 55, 63). Gardner (28) reported that shallow layers of the soil profile are depleted of water first. Similarly, Black (7) observed in humid areas of the world, that rainfall is used preferentially insofar as it replenishes that water deficit created by the concentration of roots in the surface layer of soil. Metz and Douglass (49), and Thames *et al.* (63) found that evapotranspiration by forest trees depletes soil moisture more rapidly and to a greater depth than non-forested, grass-covered sites. The forested condition creates a maximum storage space for recharge by subsequent rains.

Recent studies have indicated that climate determines some of the differences in evapotranspiration rates between forested areas and grass-covered areas. An example of the influence of climate is the greater rooting depth for species growing in regions having distinct wet and dry seasons. In humid regions, where shallow-rooted grasses may use as much water as do forest trees, water use may be decreased by selecting grasses that mature early (21).

There is some evidence that evapotranspiration increases with stand height in humid regions, a condition possibly due to greater utilization of radiant energy, advective heat, and increased air turbulence (21).

Studies by Gates (30) have indicated that winds exceeding 3 miles per hour (5 km per hour) remove the boundry layer of saturated water around leaves and accelerate the evapotranspiration process. Records by Allee (3) of wind movement within a tropical forest in Panama have indicated that the winds averaged less than 1 mile per hour (1.7 km per hour) in the lower crown area. These measurements would indicate that the wind velocity within the lower crown region of some tropical forests is not sufficient to increase the evapotranspiration process by removing the boundary layer.

C. LITTER LAYER

Duley (23) observed that rain falling on bare soils forms a thin, compact layer at the soil's surface which rapidly reduces the infiltration rate. This layer apparently results when the beating of the rain drops breaks the soil down into individual particles, allowing the water on the soil surface to act as a medium within which the small particles group around large ones, forming a relatively impervious seal. Under forest conditions, the accumulated litter nullifies the kinetic energy of falling rain, preventing any disturbance of soil particles. Raindrops, having a diameter exceeding 2 mm are considered rare (31), but under forest cover, Ovington {as reported by Gieger (31)} found that raindrops falling from the trees may have diameters exceeding 6 mm. Chapman (12), and Laws (43) have shown that if these drops fall from heights exceeding 25 feet (7.8 meters), they have reached their terminal velocity, and their striking force will exceed that of unobstructed rain. Therefore, the litter layer serves as a protective layer by reducing physical erosion.

The important role played by the accumulation of litter on the soil surface is not limited to its modifying effect on raindrops.

Lowdermilk (46) found that litter maintained the percolating capacity for a given soil profile at a maximum, thereby causing a desirable effect of reducing surface runoff. In addition he observed that the litter layer acted as a filter, preventing the macropores in the soil from clogging by removal of the colloidal and clay particles from suspension.

D. ROOT SYSTEMS

The various aspects of the influence of rooting systems on the soil has been reported by many authors.

The extension of tree rooting systems, as indicated by early studies of Holch (36), and Weaver and Kramer (70), are governed by genetic characteristics as well as by environmental factors. Hoffman and Sckublatis (35) demonstrated that the height of the water table influences plant growth nearly as much as does rooting distribution. Veihmeyer and Hendrickson (67) showed the influence of soil layering in preventing even root distribution throughout the soil profile. Exploring further this subject of root distribution, Gardner (29) found that the physical properties of the soil determined the water availability, which in turn determines rooting distribution. As Black (7) indicated, root growth only occurs when soil moisture tensions are sufficiently low enough to permit the absorption of water required for cell elongation.

Large physignomic differences occur among the rooting systems of tree species, which may be attributed to genetic factors (41). Of interest, are both the total number of roots and the rooting form. Kozlowski and Scholtes (42) reported a 4-month-old *Robinia pseudoaca-*

cia seedling grown without competition that had over 7,000 roots, while a seedling of *Pinus taeda* of the same age had only 419 roots. The total length of the root system for the *Robina* seedling was 1,068 feet (328.6 meters) while for *Pinus*, only 5.3 feet (1.8 meters). Another difference is that some species develop deep tap-roots (59), while others have wide spreading lateral roots that send down vertical suckers (54) or "sinkers".

Cheyney (13, 14) observed that new roots grow where there is least resistance, such as in old channels left by decomposed roots. These same channels also serve as hydraulic pathways for rapid penetration and movement of water (37). It has been observed that a channel 0.1 inch (2.54 mm) in diameter will carry one million times as much water as the disconnected soil pores of equal volume (40). In a study conducted by Gaiser (27), more than 4,000 vertical root channels per acre were found in a temperate zone hardwood forest. In the process of root decomposition, organic constituents are added to the soil, helping to cement soil particles into aggregates (69). Developing root systems also help maintain the soil structure by wedging soil particles apart in some places and crowding them together in others. The small soil particles become aggregated into larger ones, their permanence being established by a surrounding colloidal film of humified root materials (71). Evidence for the time needed to develop and accumulate organic matter may be gathered from the study by Hardy (33) of volcanic ash deposits on the Caribbean island of St. Vincent. He reported a 2.1 percent (21 tons) organic matter content in the first six inches (152.4mm) of ash after an accumulation period of 33 years. From soil analysis conducted 17 years prior to Hardy's study, it is shown that 17 tons of organic matter per acre had accumulated (53). This high rate of organic matter accumulation can only be expected of soils well below the equilibrium level described by Nye and Greenland (53). The equilibrium level is the content of humus carbon accumulated in a soil that has fallowed for a long time.

E. SPECIES DESCRIPTION

1. *Eucalyptus globulus* Labill 1799

E. globulus (Myrtaceae) is a tall tree growing up to 100 meters high, having a straight trunk of up to two-thirds of its total height (24) and a narrow crown that is non-deciduous. When grown in closed stands, it is self-pruning (58). Natural regeneration from seed trees and sprouting have both been reported by Cozzo (17) although the latter method is most commonly used in the management of the species. Pulgar Vidal (58) reports *E. globulus* as having a deep extensive root system which anchors the tree and protects it from windfall. Abellán-Mora (1) cited *E. globulus* as being noted for its high transpiration rate, although no comparative figures were reported.

Native to Tasmania, *E. globulus* has been widely planted throughout the world under many different climatical conditions and elevational ranges. Its light yellow-brown wood has an open texture and commonly has interlocked grain. It has a density of 69 lb/cu ft when green or 56 lb/cu ft at 12 percent humidity (32).

The timber of *E. globulus* (56) is used commercially, as are its leaves, which are distilled for their oil content. In Argentina, E.

globulus wood is reportedly used with success for parquet flooring, and in Chile, extensive plantations (44,561 ha) supply firewood, charcoal, pit props, and lumber. In Ecuador, *E. globulus* is the major source of timber and firewood. Tests have shown that the pulping qualities of *E. globulus* are suitable for the sulphate and soda process. In fact, a pulp and paper mill near Lisbon, Portugal has been manufacturing paper since 1911. Cineole oil extracted from the leaves of *E. globulus* has medicinal value when used as an antiseptic such as in soap or gargles.

A search of available literature and correspondence with the Forest Research Institute in Canberra, Australia, failed to reveal any detailed rooting studies for *E. globulus*.

2. *Buddleia nitida* Bentham 1846

B. nitida (loganiaceae) was identified by Standley (60) as *B. alpina* Oerst. 1853, a supposed endemic to Costa Rica. More recently Norman (51) in 1964 synonymized *B. alpina* with *B. nitida*, retaining the earlier name. However, the species is still widely known in Costa Rica as *B. alpina*. According to Norman, *B. nitida* is one of 20 Buddleias growing on the North American continent and has wide distribution. It is found growing as far north as Chiapas, Mexico. Its southern limit is the upper slopes of Volcano Chiriquí in Northern Panama.

The species is found between 2,500 and 3,700 meters above sea level on the upper slopes of most of the volcanoes of Central America. *B. nitida* is a dioecious shrub, having a height of 4 to 10 meters and a dense, rounded crown. In Costa Rica it is commonly known as salvia. On volcanoes Turrialba and Irazú, *B. nitida* is a dominant species.

Although B. *nitida* is used for fence posts and firewood, it is not highly prIzed for either. Acosta (2) reports that structural properties of B. *nitida* are not technically suitable for commercial purposes. Therefore, its primary benefit is its crown cover, which intercepts rain, and its rooting structure. Comparative benefits between this speoies and E. *globulus* will be discussed as a basic part of this study.

III. DESCRIPTION OF THE AREA AND METHODOLOGY

A. DESCRIPTION OF THE AREA OF STUDY

1. Location

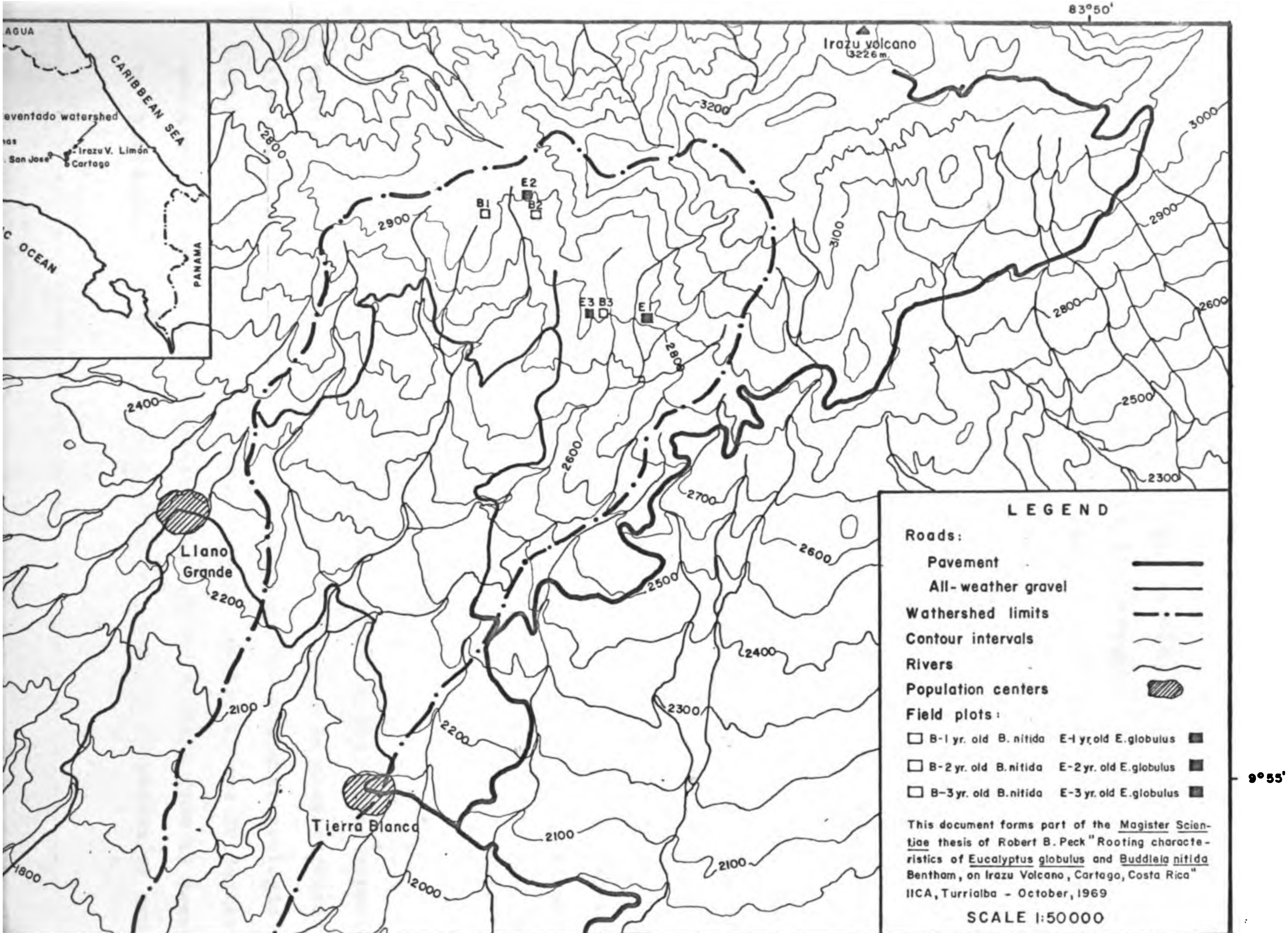
The study area is located in the upper Reventado watershed on the southwestern slope of the Volcano Irazú in the Province of Cartago, Costa Rica (Fig. 1). The watershed includes approximately 800 hectares, situated between 2,700 and 3,000 meters above sea level, and comprises two basins formed by the tributary rivers Retes and Reventado. Originating in the Central Mountain Range, this drainage system joins with the Reventazón River system, which eventually empties into the Atlantic Ocean.

2. Climate

The watershed lies near the Continental Divide, and is influenced by storms originating in both the Atlantic and Pacific coastal areas. It also receives additional precipitation from relatively small convection storms (44).

Two distinct seasons dominate the climate of the Reventado watershed. A long wet season, extending from May to December, is characterized by brief storms of high-intensity rains. Average monthly rainfall during this period exceeds 160 mm. The dry season, spanning the remaining four months, is characterized by less than 50 mm of rainfall monthly. The mean annual rainfall in the basin is 2,200 mm. This is lower than that of surrounding areas, indicating that the high ridges to the west and north might somewhat shelter the basin from the Pacific and Atlantic storms (44). Snow has never been reported to have

ʼO, COSTA RICA UPPER REVENTADO WATERSHED STUDY AREA



The upper Reventado watershed, Cartago, Costa Rica. Locating the field plots studied fallen in the basin under study.

Mean annual temperature for the Reventado watershed were derived empirically from a station at the Sanatorium Durán, located southeast of the study area at an elevation of 2,337 meters. The mean annual temperature at the Sanatorium is 14.7 degrees centigrade, with an average monthly fluctuation of less than one degree centigrade from this value (44). Using the dry adiabatic lapse rate of a 0.7 C degree change per 100 meters change in elevation (49), the mean annual temperature for the area is estimated to be between 10 and 12 degrees centigrade.

During the month of May, 1969, when field work for this study was conducted, frost was observed at all elevations within the study area.

Wind direction varies with the seasonal migration of the Intertropical Convergence Zone (ITC) (8, 44, 64). The prevailing easterly trade winds which converge from the northeast and southeast (8) were responsible for the distribution of the volcanic ash to the west of the volcano by aeolian sorting.

3. Topography

The study area comprises two adjoining basins on the upper, southwestern slope of the Volcano Irazú. The land is characterized by steep slopes, a dendriform drainage pattern, and unstable geologic conditions. The basins, whose slopes average between 17 and 20 degrees, are bordered by yet steeper slopes which range locally from 45 degree to vertical. These steeper slopes, which may be convex or concave in form, characterize approximately 80 percent (45) of the study area. The axes of the basins run northeast-southwest and parallel the prevailing wind patterns.

The Reventado and Retes Rivers and their tributaries flow through deeply incised canyons. The average gradients of the riverbeds are between 17 and 20 percent (44). Tributary stream banks in the area, from 5 to 30 meters high, are the scenes of frequent small, active slides. Variation in riverbed hardness gives rise to numerous waterfalls and cascades. Additional erosion is created at the confluence of the two streams by undercutting both sides of the wedge formation.

4. Soil and Ash Description

Soil profiles of the study area exposed by excavation of root systems exhibited individual horizons of unequal depths, belonged to the same soil series. Table 1 indicates a generalized soil profile, typical of the area.

Table 1. REPRESENTATIVE SOIL PROFILE
UPPER REVENTADO WATERSHED
CARTAGO, COSTA RICA
1969

Munsell soil color	Texture	Horizon	Thickness	Description
Gray-1--YR/1 Dry	Sand		20-40 cm	Lithic ash of basaltic andesite composition from the 1963 - 65 eruption.
Dark grayish-brown 10YR-4/2 Dry	Sandy loam	A	15-20 cm	Friable, non-adhesive non-plastic, porous, acid pH.
	Cinder		2-5 cm	Particle size ranges up to 10 cm.
Grayish-brown 10-YR-5/2 Dry	Clay	B	+100 cm	Amorphous clay

The soil classification studies made for the Central Valley of Costa Rica by Vargas and Torres (66) and Dondoli and Torres (22), include descriptions of volcanic soils, but do not specifically describe the soil profiles found within the study area. The Coronado series of soils, first described by Vargas and Torres (66), and later redescribed by Mannix (47), best approximates the soil series found in the area of study. However, due perhaps to the close proximity of the study area to the volcano, a layer of coarse cinder was found at depths of 40 cm to 60 cm (Table 1) which was not mentioned in the reviewed literature for Costa Rica. These cinders have a relatively low decomposition rate due in part to their large particle size. Birrell (6) reported this type of cinder formation to be a common occurrence.

Specific investigation in the study by Mannix (48) concentrated on the chemical and physical characteristics of the 1963-65 ash deposits. Bornemisza and Morales (9) studied the chemical properties of the newly deposited ash as well as its ability to support plant growth under greenhouse conditions. Their findings indicated that fresh volcanic ash from the 1963-1965 eruption cannot support the growth of tomato plants (*Lycopersicon esculentum*) without the addition of nitrogen.

In 1965, Mannix (48) reported ash deposits of up to 160 cm in depth at 1 km distance from the volcano. The depth of initial ash deposits were rapidly altered by both water and wind erosion (68). From 1963 through 1966, ash deposits contributed to an estimated 3,100,000 cubic meters of sediment which were swept downstream and deposited in the alluvial fan to the west of Cartago (44). This amount of ash is approximately 51 percent of the sediment load found in the alluvial fan.

Mannix (48) classified the ash by a distribution of particle sizes and found the sand-sized particles to be most predominant (Table 2).

Table 2. PARTICLE SIZE DISTRIBUTION OF VOLCANIC ASH FROM THE 1963-1965 ERUPTION OF IRAZU VOLCANO UPPER REVENTADO WATERSHED CARTAGO, COSTA RICA 1969

Fraction	Range of Percentages
sand size	73.1 to 86.2
silt size	11.2 to 25.6
clay size	1.1 to 4.7

Source: Mannix, J. F. Estudios preliminares para la recuperación agrícola de los suelos de cenizas recientes del volcán Irazú. San José, Costa Rica, Ministerio de Agricultura y Ganadería, 1965. 8 p.

In spite of the low content of clay or colloidal size particles, the recently deposited ash tended to form a thin, hard, and comparatively smooth crust that was virtually impervious to rainfall. A possible explanation for this formation was given by White, and reported by Waldren (69), as being due to the presence of halogens. Halogens, brought to the surface by capillary action, are precipitated by evaporation in the upper few millimeters of the ash to form a crust 10 to 15 mm thick. Without a renewed source of halogens, the volatility and solubility of these salts would insure that the crust probably could not be maintained for any great length of time. Bornemisza and Morales (9) reported the formation of a crust-like layer of ash, not only under field conditions on the Irazú volcano, but also in pots in which plants were grown in green house experiments. The hardened crust, formed after watering for 8 weeks in the greenhouse, had a hardness of 2.0 kg/ cm^2 when measured with a penetrometer. Bornemisza[a] attributed the formation of this crust to chemical cementation caused by the presence of soluble silicates rather than being formed by halogens as White proposed.

The recently deposited ash had an average pH of 4.4 (48) and has been found to be highly corrosive and toxic to plants and metallic materials (68). However, tree species and grasses planted in 1966 by the reforestation project did indeed grow as the data presented in this thesis will indicate. The average bulk density of the ash was about 1.276 grams per cm^3 (44).

Infiltration of precipitation into the soil at the height of the flooding problems on the Reventado River in 1964, was determined by Leed, Hill and Jewett, Inc. (44) to be 4 mm per unit area per hour. They further found that with the watershed vegetation fully recovered, soil infiltration and interception by vegetation would reach 11 mm per unit per hour. No data were given on antecedent soil-water conditions.

Studies by Birrell (6), Swindale (62) and Forsythe *et al.* (25) have reported high natural moisture content of soils derived from volcanic ash. The amorphous nature of the particles results in large surface areas which give them such properties as high water-holding capacity, high organic matter, high porosities and low bulk densities (62).

---

[a] Personal Communication with Elemer Bornemisza, Ph.D., Professor of Soils, IICA, Turrialba.

5. Land Use

Prior to the eruptions of the volcano in 1963, Waldon (68) reported a luxuriant growth of vegetation on the slopes, mainly consisting of shrubs, which were probably B. *nitida*, (locally known as salvia), but interspersed with open, extensively used pasture areas. These pastures were of improved grasses, predominantly kikuyu (*Pennisetum clandestinum*), and supported several dairy farms which had been in operation even previous to Calvert's (11) visit in 1910. In 1956, aerial photographs showed that pastures which included low brush and shrubs covered approximately 80 percent of the watershed area (39). This indicates a considerable shift in land use since 1910 when Calvert visited the "Laguna del Derrumbe" and reported the area to have been forested by oaks.

Using a land classification system developed by Plath (57), based on potential land use, the study area is classified as Area IV (lands not suitable for intensive agricultural production). According to this classification system, the upper watershed of the Reventado River should be permanently covered with vegetation to protect lower elevation lands dedicated to intensive agricultural and urban uses(57).

Present land use has changed under the direction of the Civil Defense from extensive dairy farming toward forest plantations. The plantations consist primarily of two species, E. *globulus* and B. *nitida*.

Table 3. NUMBER OF TREES PLANTED PER YEAR BY THE REFORESTATION PROJECT UPPER REVENTADO WATHERSHED CASTAGO, COSTA RICA 1969

Species	1966	1967	1968	3 year total
Eucalyptus spp.	63,657	26,485	24,579	
B. *nitida*	4,496	51,822	24,620	
other	6,400	27,644	44,880	
Total	74,553	105,915	94,079	274,583

Since the start of the reforestation project in 1965, the Costa Rican government has purchased 800 ha. in the upper Reventado watershed. Construction of 17 kilometers of all-weather roads has improved accessibility into the area. These roads meet the short-term requirements of the reforestation project, and moreover, provide public access to the area for recreational purposes. Public use of recreational facilities in 1968 was demonstrated by Boza (10) at Poas Volcano National Park, Costa Rica, indicating a high number of visitors during that year. In view of the increasing demand for recreational facilities, it is the expressed intention of the Civil Defense administration in charge of these lands to transfer them to the national park system in the near future. Such action will expand the size of the Irazú Volcano National Park.

B. PLANTING PROCEDURE

The two species considered in this study, *B. nitida* and *E. globulus*, were planted in 1966, 1967 and 1968 by the Civil Defense for reforestation. The planting stock came from various nurseries operated by other national institutions (ICE[a], ITCO[b]). Cylindrical asbestos pots, 15 cm by 5 cm in diameter, were utilized for the first six months of plant growth in the nursery. The plants were approximately 50 to 70 cm in height when they were transplanted into the field.

Procedures for field planting varied with the depth of the ash. Where ash accumulation was less than 25 cm, cube-like holes of approximately 25 cm by 25 cm were dug deep enough to permit the bottom of

[a] Instituto Costarricense de Electricidad
[b] Instituto de Tierras y Colonización

the soil block containing the roots to come into contact with the "A" horizon of the soil buried under the ash layer. The remaining space surrounding the root mat was then filled with soil from the "A" horizon of adjacent areas. This procedure often meant that the plant's stem was buried to a depth of 10-15 cm above the normal root collar.

Where ash accumulation was greater than 25 cm, cube-shaped holes of approximately 40 cm by 40 cm were dug to a depth of 40 cm. These holes were then filled around the root ball of the tree with soil from the "A" horizon which often had to be trucked in over distances exceeding one km. Plants were placed in the ground such that their root collars were at the soil surface.

Although it was the general policy of the reforestation project to remove the asbestos pots before planting, it was found that of the 30 plants examined, only 14 of the pots had been removed.

Another policy of the Civil Defense administration was to place fertilizer (NPK, 10-30-10) at the bottom of the hole. This was then covered by approximately 5 cm of soil before plants were placed in the ground. Certain irregularities were also noticed in this procedure. In several cases, residues of fertilizer were found directly beneath the potted plant. In other cases, the fertilizer had been placed beside the plant, rather than beneath it. Since this fertilizer residue was not found under all the plants examined, it is not certain whether fertilizer was actually applied in all cases.

The trees studied were classified according to the year of their plantation:

One-year-old--planted during the 1968 planting season.

Two-year-old--planted during the 1967 planting season.

Three-year-old--planted during the 1966 planting season.

C. SAMPLING PROCEDURE

Civil Defense reforested the sub-watersheds according to priorities for avalanche control. Therefore, all trees of each age-class were found on separate sites. The sampling procedure used in this study was designed to select randomly five plants from each age-class of both species. For each tree age-class population, five representative sites free from the influence of drainage ditches were selected. Within each site five trees were selected for their good form and vigor and assigned numbers.Then the tree to be excavated was randomly selected by drawing from correspondingly numbered slips of paper.

The root systems were excavated in a manner governed by the looseness of the volcanic ash and sandy loam in the "A" soil horizon. Using a small hand pick, the roots were followed out away from the trunk of the tree (Fig. 2). As each root was uncovered, its position in plan view was recorded on millimetric paper at a 1:40 scale. A vertical profile was also recorded at right angles to the slope using the same scale. As each root was uncovered, it was detached to facilitate further excavation.

D. MEASUREMENTS

Tree measurements taken in the field were recorded on a prepared field work sheet (see Appendix 1). All measurements were recorded in centimeters and limited to:

1. Total height of the tree
2. The diameter of the tree at breast height
3. The diameter of the tree at ground level
4. The crown diameter recorded at the widest point
5. Distance from the ground level to the first branches.

Of these measurements taken, it was found that further limitations due to the growth form of B. *nitida* were imposed. Measurements at breast height for diameter were impractical due to the bushy nature of the species, which has a multiple stem without any well-defined central leader. Also the measurements for the distance from the ground level to the first branches were not considered when it was found that branches started right at ground level and were easily confused with the multiple leaders.

Measurements of rooting radius diameter and depth were taken directly from the field sketches of the rooting systems in plan view. These values represent the mean length of the lateral (radial) roots, averaged from the readings taken at the cardinal axes.

Rooting volume is defined as the irregular cone which subtends the deepest root at the apex with the longest radial roots. As a simple measure of this, cross sectional areas were calculated from the field sketches in vertical profile (Fig. 5, and Appendix 1) using the area formed by the two lines drawn from the deepest tap root or other vertical root, through the tip of the longest radial roots to the soil surface. Measurements of the oven dry weight of the root systems and tree crowns, were derived from the collection of their respective parts at the time of excavation.

The samples of the roots and stems were cut up into small lengths, and placed in paper bags (25 lb size) for drying. Stems and roots that exceeded one inch in diameter were split into smaller diameters. Oven-dry weight was obtained by drying the plant material in a forced-air drying oven set at 110°C. Samples were initially dried for 20 hours, after which time their weight was determined. This sequence of oven-drying and weighing was repeated at intervals of ten hours until a constant oven-dry weight was achieved.

E. DATA ANALYSIS

A modified *t* test (26) was used to compare the chosen parameters of the two species in order to evaluate the variation of each value from its respective mean. Application of the *t* test was restricted to the two-year-old age-class for the following reasons:

1. Only the two-year-old trees of both species were found on sites which appeared to be consistent throughout the entire area in terms of slope, soil profile and other physical characteristics.
2. The one-year-old and three-year-old trees of both species occurred on sites which did not exhibit consistent physical characteristic within their boundaries.
3. The variation of physical characteristics among the three sites was not readily adaptable for statistical analysis.

IV. RESULTS AND DISCUSSION

A. RESULTS

Observations on the rooting characteristics of the trees sampled on the Reventado watershed were broken into two categories. The first category deals with rooting characteristics which are apparently genetically controlled, and consequently the observations are subdivided according to species' differences. The second category deals with environment. This second category had apparently an equal effect on both species.

1. Observed Characteristics - Apparently Genetically Influenced

E. globulus	*B. nitida*
a. The arrangement and extent of main lateral roots were uneven (Fig. 3). The ratio of the rooting radius to the crown radius for two-year-olds was 3:1.	a. The arrangement and extent of lateral roots were uneven (Fig. 3). The ratio of the rooting radius to crown radius for two-year-olds was 1.5:1.
b. Of the trees sampled, all exhibited roots, although they did not develop to a great depth (Figs. 4 and 5).	b. Of the trees sampled, none exhibited a tap root, but directly below the trunk a number of vertically descending roots started dividing near the ground level (Fig. 5). This type of rooting system was reported also by Stephens (62) for one of the *Albizzia* in Africa.
c. Sinker roots generally originated from the lower layer of lateral roots observed.	c. Sinker roots always developed where the root came into contact with buried tree branches or wooden stakes. Occasionally, they also formed when there were no visible obstacles present.

d. The growing tips of lateral roots did not fork or branch (Fig. 6). These growing tips were frequently found in the recent layer of volcanic ash, probably because of its high-waterholding capacity and low bulk density.	d. The growing tips of lateral roots were multiple (Fig. 7). These growing tips were also frequently found in the recent layer of volcanic ash.
e. The relationship between rooting systems and slope varied. One condition observed, which was in accordance with the findings of Curtis (17) and Berndt (5), was the concentration or extension of the root systems the downhill slope. A second condition was the concentration of lateral roots perpendicular to the slope.	e. The relationship between rooting systems and slope varied. The concentration or extension of the root systems on the downhill slope was observed but there did not seem to be the concentration of lateral roots perpendicular to the slope.
f. Lateral roots generally forked into no more than three side branches	f. Lateral roots generally branched into 5 to 7 branches which often clustered like a comb (Fig. 3).

2. Observed Characteristics - Apparently Environmentally Influenced

Those characteristics which were apparently influenced by environmental factors appear similar in both species. For that reason they have been aggregated as follows:

a. Lateral roots were generally found growing in distinct layers. One layer of lateral roots extended from the root collar zone[a] to a depth from the surface of approximately 25 cm. This layer of roots was present regardless of whether or not there was a ground cover of kikuyu grass.

A lower layer of lateral roots extended out from the tap root(s). They grew at varying depths, but nearly always extended out from that portion of the tap root which had grown after the time of planting and which was in the "A" soil horizon. These

[a] The root collar zone starts just below the soil surface, and may include roots growing out of the stem. The stem was often partially buried due to the practice of planting the trees in the "A" soil horizon.

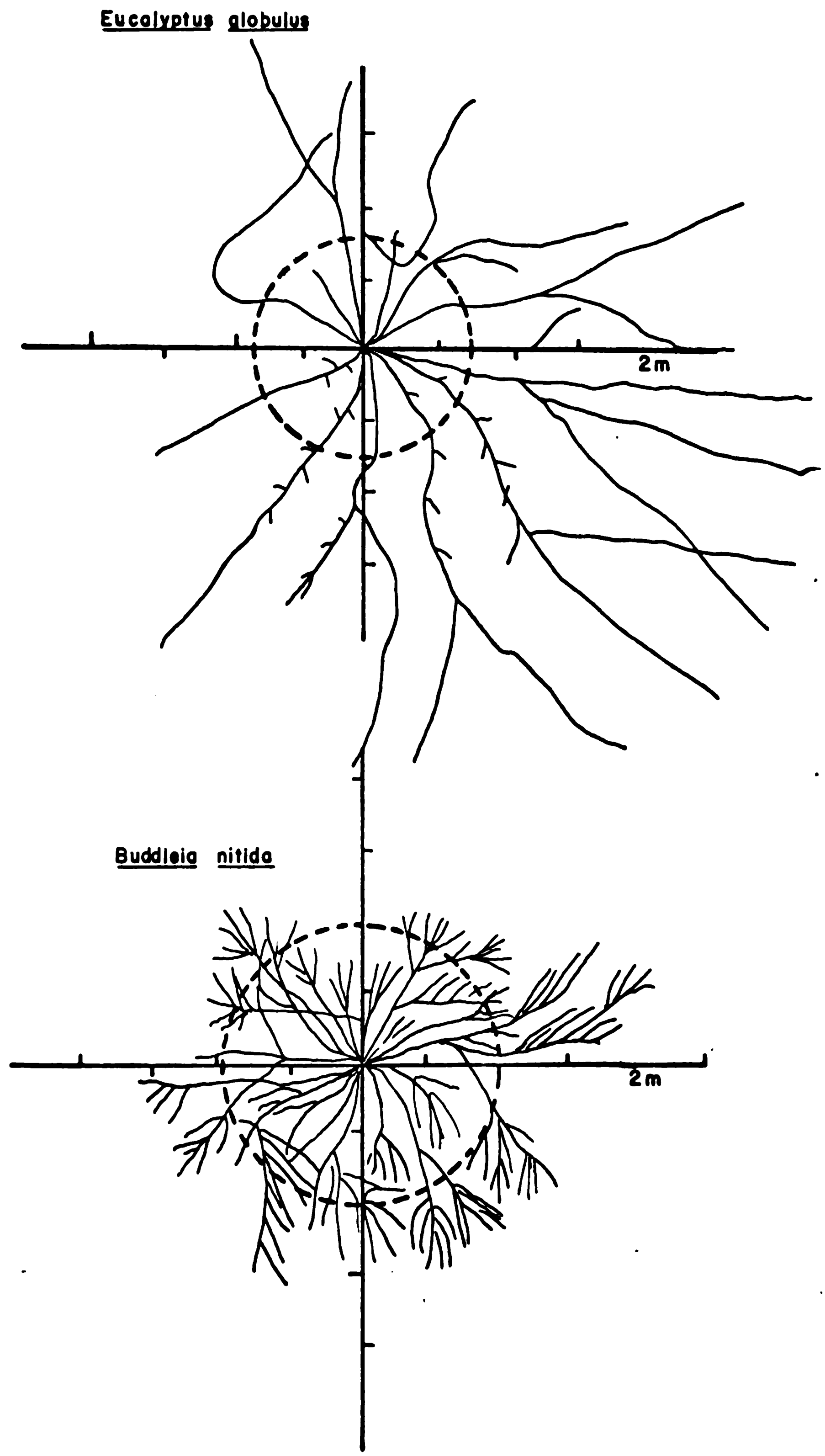


Figure 3 Diagramatic plan velwe of a representative root system for two years old plants.
Crown area is designated by dash lines. Slope direction is indicated by arrow direction.

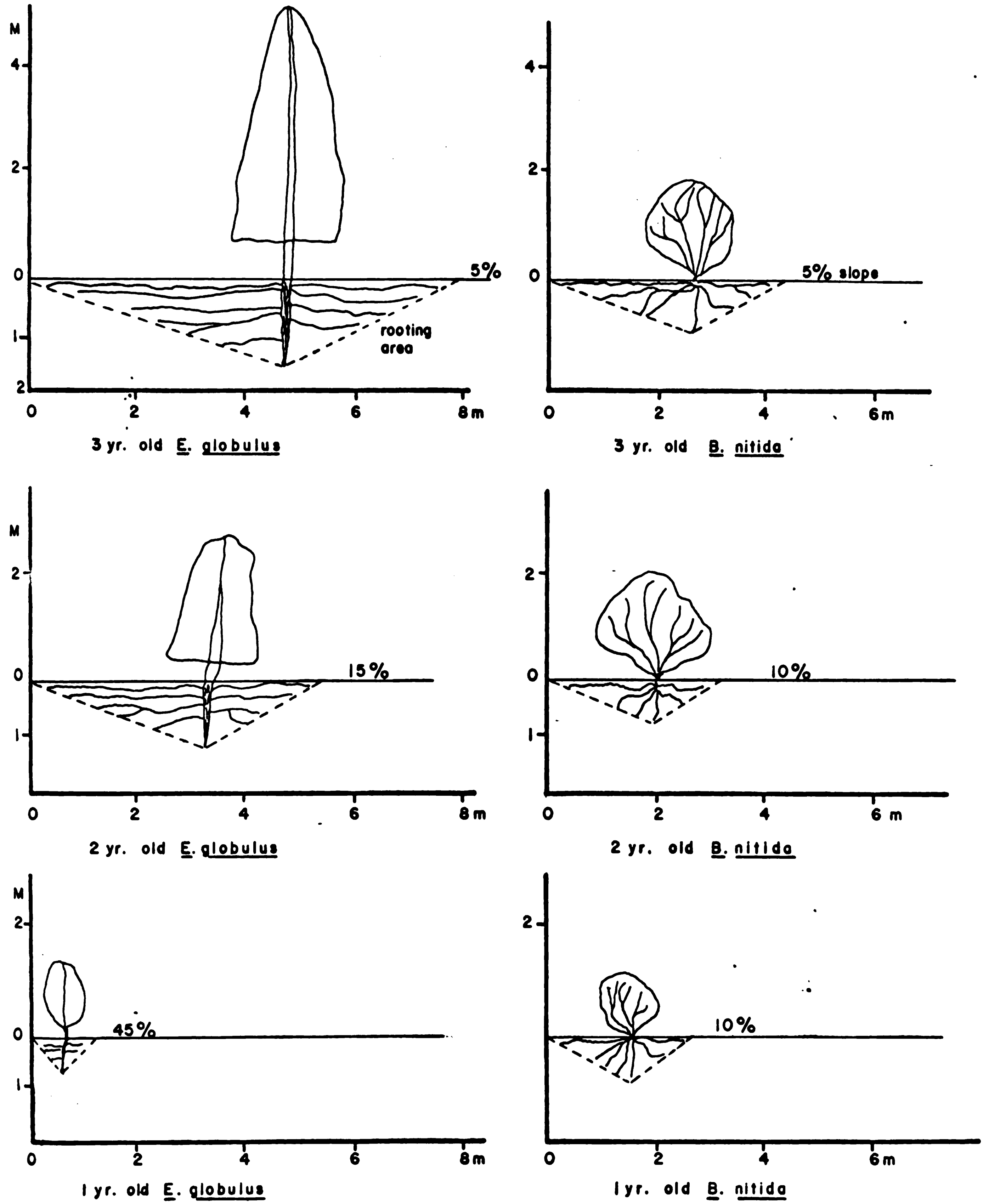


Figure 5 Diagramatic profiles indicating positions of rooting areas as related to positions of crowns. Percent slope is determined by averaging the five tree sites in each age class.

Figure 2. Root excavation of 3-year-old *E. globulus*.

Figure 4. A 3-year-old *E. globulus* tap root.

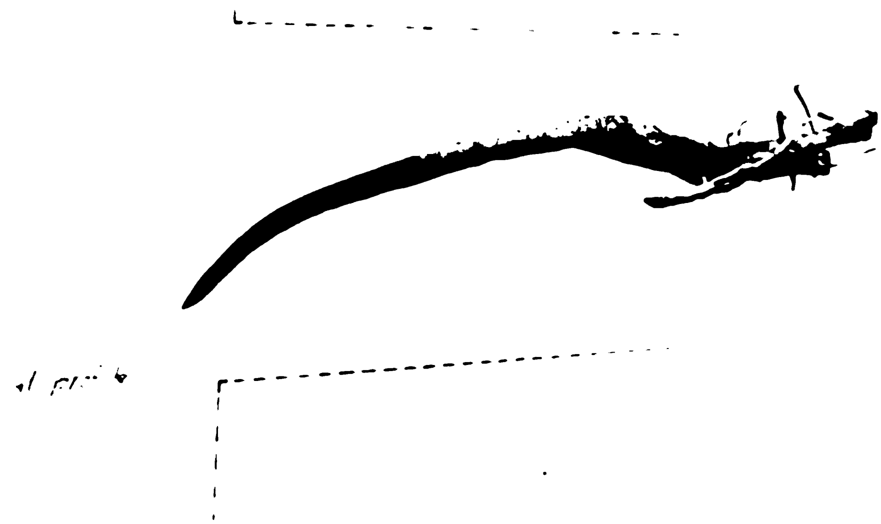


Figure 6. The growing tip of E. *globulus*

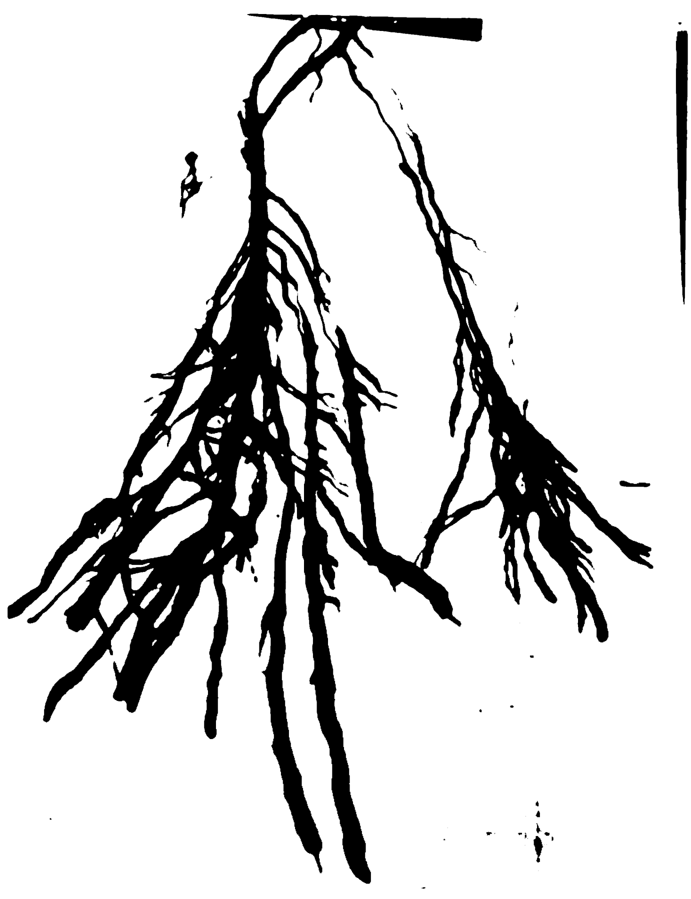


Figure 7. The growing tip roots of B. *nitida*

Figure 8. Roots of *B. nitida* growing in a channel left by a decayed branch.

roots rarely penetrated into deeper soil horizons, although frequently they grew upward into the fresh ash deposits.

b. Extension of roots often occurred where there was little or no competition from neighboring trees. This was especially noticeable in voids created when adjacent trees failed to survive.

c. Direction of main lateral root growth was generally linear, an observation also made by Curtis (19) of roots growing in loose, non-compacted soil. This observation would be in accord with the low bulk density reported for soils of volcanic origin.

d. Rooting systems from neighboring trees seldom came into very close contact with each other, and did not show evidence of competition with each other. However, competition from the dense mat-forming root system of kikuyu grass in the top 10 cm was striking. No roots of the trees were found in this zone, except where kikuyu grass was absent.

e. A schematic presentation of the crown and root distribution is shown in Fig. 5. By indicating the position of the crown above the rooting distribution in relation to slope, it becomes evident that the rooting distribution is greatest on the downhill side of the slope, as summarized by Appendix 2. The percentage of roots on the downhill slope shows very little variation, in spite of the fact that there was variation between sites.

B. SUMMARY OF RESULTS

The summarized results of the field study are presented in Tables 6 and 7 by species and age-classes, and are presented in a comparative form in Figure 9. While Table 6 exhibits obvious differences between the two species in terms of rooting radius, crown diameter, crown height, oven dry stem weight, and oven dry root weight, nevertheless the modified *t* test analysis, presented in Appendix 5, did not establish a statistical significance of these differences. This is probably due, in part, to the small sample size used in the study.

To a large degree, the small differences result from the inherent genetic differences found between the species. *E. globulus* is classified as a tree, while *B. nitida* is more bush-like and develops several leaders.

C. DISCUSSION

Figure 9 and Table 5 indicate that the *B. nitida* planted during 1966 exhibited slower growth than those planted in 1967. While the ash deposits on both sites were similar, the difference of one year between plantings was apparently sufficient time for the occurrence of a favorable change in the soil media.

Although significant differences between the allometric relationships for the two-year-old plants were not established, certain trends appeared. One obvious trend indicated that the plants on different sites were developing differently in their physiognomy relative to each other.

Table 4. AVERAGED[a] MEASUREMENTS FOR RESPONSE VARIABLES AND THE CORRESPONDING ASH DEPTHS, BY SPECIES AND AGE-CLASS UPPER REVENTADO WATERSHED CARTAGO, COSTA RICA 1969

Age class (yr)	Height (m)	Crown dia.[b] (m)	Trunk dia.[c] (cm)	Stem oven dry (kg)	Root oven dry (kg)	Root-ing rad-ius (m)	Root-ing area (m^2)	Volcanic[d] ash depth (cm)
E. globulus								
3	5.1	1.9	7.6	5.3	1.6	4.1	7.9	25
2	2.6	1.7	4.5	1.7	0.7	2.6	3.0	100
1	1.4	0.6	1.3	0.1	0.1	0.7	0.8	15
planting stock	0.5	0.2	0.8	0.04	0.01	0.3		
B. nitida								
3	1.8	1.6	4.0	2.0	1.0	2.1	3.2	100
2	1.9	2.1	6.4	3.9	1.2	1.7	2.3	100
1	1.2	1.0	2.7	0.6	0.2	1.2	1.9	15
planting stock	0.5	0.4	1.0	0.1	0.04	0.3		

[a] Average depth of recent volcanic ash, as calculated from the five trees for each age-class sample.

[b] Trunk diameter is at ground level.

[c] Crown diameter is at widest point.

[d] Average measurements were calculated from field measurements summarized in Appendix 1 and 2.

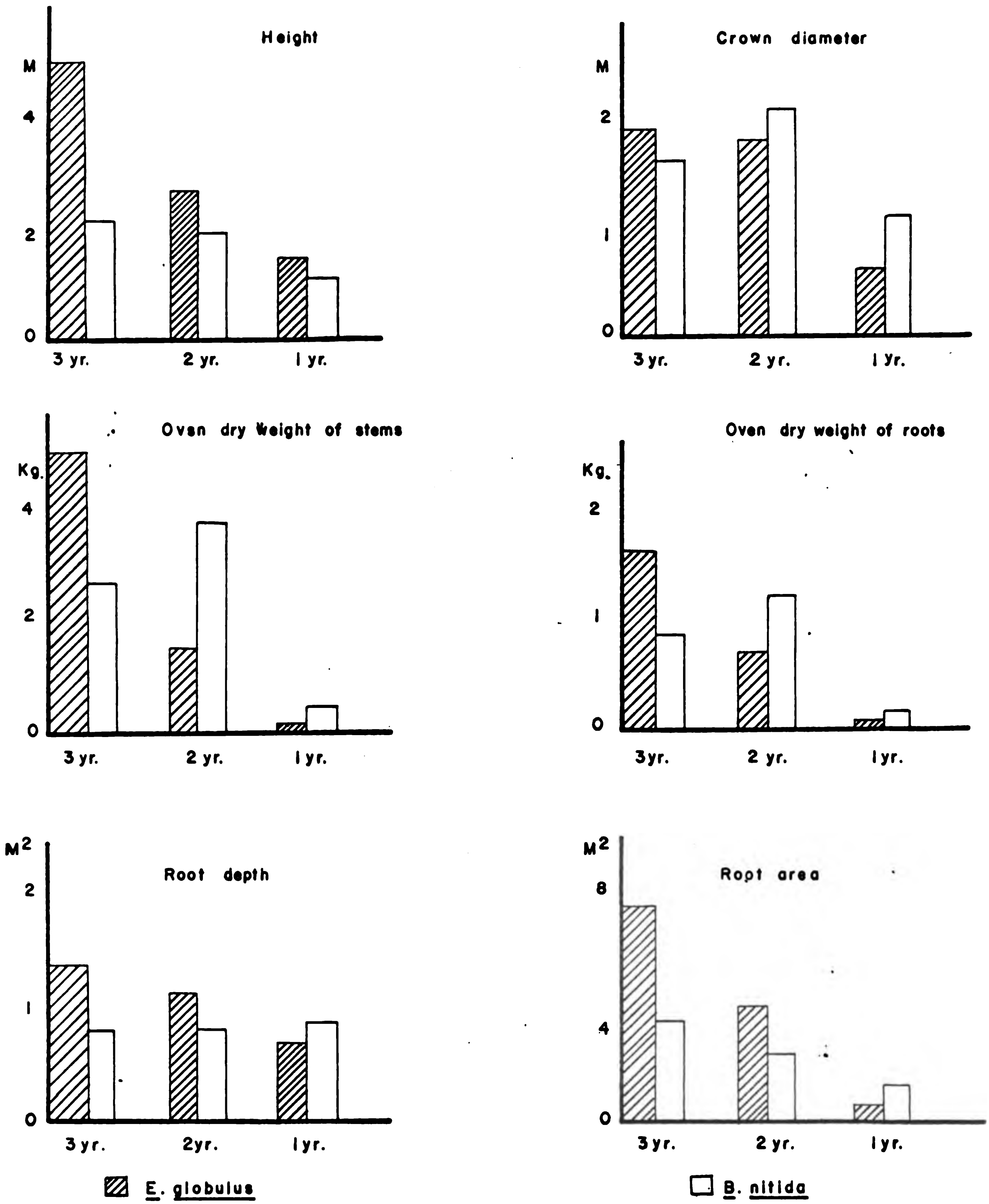


Fig. 9 Six response variables by age class comparing two species.

Table 5. ALLOMETRIC RELATIONSHIPS AMONG SPECIES CHARACTERISTICS BY AGE-CLASSES[a]
UPPER REVENTADO WATERSHED
CARTAGO, COSTA RICA
1969

	Eucalyptus globulus			*Buddleia nitida*		
	Age 1	2	3	Age 1	2	3
Root depth/root radius	1.18	1.59	.36	.80	.55	.40
O. D. root weight/ O. D. stem weight	.53	.44	.38	.32	.33	.52
Crown dia/Root dia.	.42	.40	.24	.47	.65	.32
O. D. root weight/ root area	.08	.39	.21	.11	.61	.32

[a] Differences in allometric relationships between species for two year old trees were tested using a modified *t* test. (See Appendix 6 for list of *t* values).

Root radii continued to increase at a fast rate in both species. Whether or not the tap-root exhibited by the *E. globulus* grows deeper, as lateral root systems begin to compete for the surface soil water, is unknown. Ashton (4) found that in *E. regnans*, a closely related species, a change in the root system occurred in the sapling stage at 8-10 years of age. He found that the tap root dies back and that the sinker roots developed into a heart root system in a hemisphere of 6-8 feet radius beneath the tree.

From the stand point of a particular species' effectiveness in stabilizing a watershed, a larger root system grown in a comparable period of time is preferred. However, this advantage would be lost with the passage of time as root systems from adjoining trees begin to compete.

It would appear that the time period necessary for the final evaluation and selection of species for watershed stabilization work requires a greater span than three years. Characteristics such as early growth may be determined in the first year or two. But whether a species is deeply rooted or not (which is an important characteristics for watershed stabilization work), apparently cannot be judged in such a short period of time.

During the early stages of species selection, when important differences (fast growth and rooting depth) between selected species are not identifiable, other differences such as the future utility of a species should be given consideration. This has an important bearing in species selection if the work is subject to cost/benefit review. All other characteristics between species being considered equal, a species having potential utilization in the local economy would yield higher benefits than a species not having any use other than watershed stabilization.

Pursuing the economic consideration a little further as it pertains directly to the two species being evaluated for selection, differences between species become apparent when characteristics that are not so readily seen when only their adaptability for watershed stabilization are considered.

On the basis of the potential economic value of E. *globulus*,it is the conclusion of this investigation that E. *globulus* is probably the more favorable species to select for reforestation work for future public or private planting under similar ecological conditions as those found in the study area.

The disadvantages that readily come to light for R. *nitida* are:

1. Has little or no economic value.
2. Lacks a central trunk and is not suitable for lumber.
3. Does not display any unique advantage for firewood or fence posts. In fact, its poor form acts as a hindrance.

Advantages tnat seem obvious for E. *globulus* are:

1. Has considerable economic value and diverse forms of utilization.
2. Has a central trunk and has other wood characteristics that makes it acceptable for use as lumber.
3. Can be and is widely used for firewood and fence posts.

Although the present study was designed to determine the relative values of two tree species for watershed stabilization work, this investigator found that planted grasses (particularly kikuyu grass) and natural regeneration of forbs probably contributed significantly to the initial erosion prevention processes and should not be overlooked. It is probable that grasses should always be planted initially because of their rapid growth and soil stabilization characteristics, and that reforestation of watersheds belongs to a second phase of soil stabilization work by nature of the slower relative growth of trees.

SUMMARY

Two species used for reforestation work of Volcano Irazú, Cartago, Costa Rica, after its eruption from 1963 through 1965 were evaluated in terms of:

1. Their capacity to satisfy the immediate goals of reforestation for watershed stabilization work, and

2. Their future utility, in terms of potential use by the local population.

Evaluation of the characteristics of the two species (*Eucalyptus globulus* and *Buddleia nitida*) for satisfying the immediate goal of watershed stabilization was based on a rooting study. Root systems of trees having grown one, two and three years were excavated.

Recognizable differences between rooting forms for the age-classes of the two species studied did not present any distinct advantages for either species.

Rooting depth for both species was essentially the same. Although all of the *E. globulus* exhibited the formation of a tap root, as opposed to the non-centralized root system of *B. nitida*, it did not develop to any great depth.

Radial extension of lateral roots for *E. globulus* was nearly twice that of *B. nitida* for the same period of time. This difference becomes negligible within a very short period of time as root systems from adjoining trees begin to compete. If the rate of growth of lateral roots was an important difference it could be compensated for by adjusting the spacing arrangement.

Evaluation of the potential utility of the two species for use by the local population was based upon form characteristics, and a review of the literature. Recognizable differences between their potential uses are pronounced.

E. *globulus* has a central trunk, and other wood qualities which qualify it as being acceptable for use as lumber. This species is also widely used for firewood and fence posts.

On the other hand, B. *nitida* lacks a central stem making it unsuitable for lumber and does not display any unique advantage for firewood or fence posts.

It is the recommendation of this study that future reforestation projects consider the species ability to meet the immediate as well as long-term needs of the economy, before the final selection as to which species would be planted. According to the findings of this study, it is recommended that E. *globulus* be selected for reforestation projects over B. *nitida* where ecological conditions similar to those of the Reventado watershed prevail.

R E S U M E N

En este trabajo se evaluaron dos especies usadas para trabajos de reforestación en la zona del Volcán Irazú, Cartago, Costa Rica, después de las erupciones de 1963 a 1965, en términos de:

1. Su capacidad para satisfacer las metas inmediatas de reforestación con el fin de estabilizar cuencas hidrográficas.
2. Su utilidad futura, en términos de uso potencial para la población local.

La evaluación de las características de las dos especies (*Eucalyptus globulus* Labill. y *Buddleia nitida* Perst.) para satisfacer las metas inmediatas tendientes a estabilizar cuencas hidrográficas, se basó en un estudio de sus raíces. Para su evaluación se escavaron sistemas de raíces de árboles de uno, dos y tres años de edad.

Las diferencias reconocidas en las raíces de las dos especies estudiadas de edades diferentes, no presentaron ninguna ventaja entre ellas.

La profundidad de las raíces de ambas especies fue esencialmente la misma, aunque todos los F. *globulus* mostraron la formación de una raíz principal, en vez de un sistema de raíces no-centralizado como el presentado por B. *nitida*. El primero no desarrolló gran profundidad.

La extensión radial de raíces laterales que presentó E. *globulus* fue casi el doble que la de B. *nitida*, durante el mismo período de tiempo. Esta diferencia llegará a ser mínima dentro de un corto plazo, cuando los sistemas de raíces de los árboles adyacentes comiencen a competir. Si la tasa de crecimiento de las raíces laterales presentata una diferencia importante, podría compensarse por un ajuste en el espaciamiento de los árboles plantados.

La evaluación de la utilidad potencial de las dos especies, en términos de su uso para la población local, se basó en las características de la forma y por medio de una revisión de la literatura. Las diferencias identificadas dentro de sus usos potenciales son marcados.

E. globulus tiene un tronco central y otras propiedades estructurales, las cuales son requisitos para hacer su uso aceptable como madera. Se utiliza extensivamente para leña y postes para construir cercas. Por otro lado, *B. nitida* no desarrolla un tronco central, y por eso no presenta características para su uso como madera. Tampoco presenta ventajas para leña y postes para cerca.

La recomendación de este estudio es que en los futuros proyectos de reforestación no se consideren solamente las especies capaces de cumplir con las necesidades inmediatas, sino también las económicamente beneficiosas de largo plazo, antes de llevar a cabo la selección final de la especie que va a plantarse. Por los resultados de este estudio se recomienda que *E. globulus* sea seleccionada para proyectos de reforestación en vez de *B. nitida*, en aquellas zonas que presenten las mismas condiciones ecológicas que las descritas en este trabajo.

LITERATURE CITED

1. ABELLAN MORA, E. El eucalipto. Bracelona, España, Mercantil, 1964. 75 p.

2. ACOSTA, I. C. Descripción anatómica, propiedades físicas y algunos usos de 25 maderas de Costa Rica. Master's thesis. Turrialba, Costa Rica, Instituto Interamericano de Ciencias Agrícolas, 1967. 192 p.

3. ALLEE, W. C. Measurement of environmental factors in the tropical rain-forest of Panama. Ecology 7(3):273-302. 1926.

4. ASHTON, D. H. Some aspects of root competition in *E. regnuns*. Forest Research Institute, Canberra, Australia. Unpublished note, 1962. 5 p.

5. BERNDT, H. W. and GIBBONS, R. D. Root distribution of some native trees and understory plants growing on three sites within ponderosa pine watersheds in Colorado. U. S. Forest Service. Station Paper RM37, 1958. 14 p.

6. BIRRELL, K. S. Some properties of volcanic ash soils. Report on the "Meeting on the Classification and Correlation of Soils from Volcanic Ash", World Soil Resources Report No. 14, FAO, Rome, 1965. pp. 74-81.

7. BLACK, C. A. Soil-plant relationships. New York, John Wiley, 1957. 332 p.

8. BLAIR, T. A. and FITE, R. C. Weather elements, Englewood Cliffs, New Jersey, Prentice-Hall, 1957. 414 p.

9. BORNEMISZA, E. and MORALES, J. C. Chemical properties and ion retention of recent volcanic ash. The application of nuclear energy to agriculture. Turrialba, Costa Rica, Instituto Interamericano de Cianscias Agrícolas, Annual REport, U. S. Atomic Energy Commission project, 1965. pp. 49-62.

10. BOZA, M. A. Plan de manejo y desarrollo para el Parque Nacional Volcán Poás, Costa Rica. Master's thesis. Turrialba, Costa Rica, Instituto Interamericano de Ciencias Agrícolas, 1968. 305 p.

11. CALVERT, A. S. and CALVERT, P. P. A year of Costa Rican natural history. New York, Macmillan, 1917. 577 p.

12. CHAPMAN, G. Size of raindrops and their striking force at the soil surface in a red pine plantation. Transamerican Geophysical Union 1(4):1-5. 1948.

13. CHEYNEY, E. G. Roots in a square yard of jack pine forest. Journal of Forestry 27:546-49. 1929.

14. ________. The roots of a jack pine tree. Journal of Forestry 30:929-32. 1932.

15. CHOW, V. T. Handbook of applied hydrology. New York, McGraw-Hill, 1964. irr. p.

16. CLARK, O. R. Interception of rainfall by prairie grasses, weeds, and certain crop plants. Ecology Monography 10:243-277. 1940.

17. COZZO, D. Eucalyptus and Eucaliptotecnia. Buenos Aires, Argentina, El Ateneo, 1955. 393 p.

18. CROFT, A. R. A land-use management cycle. Journal of Forestry 44:819-822. 1969.

19. CURTIS, J. D. Roots of a ponderosa pine. U. S. Forest Service. Research Paper INT-9, 1964. 10 p.

20. DICE, L. E. Measures of the amount of ecologic association between species. Ecology 26:299-302. 1945

21. DOUGLAS, J. E. Effects of species and arrangement of forests on evapotranspiration. Coweeta Hydrologic Laboratory, Franklin, N. C. 1965. 32 p.

22. DONDOLI, C. B. and Torres, J. A. Estudio geoagronómico de la región oriental de la Meseta Central. San José, Costa Rica. Ministerio de Agricultura e Industrias, 1954. 180 p.

23. DULEY, F. L. Surface factors affecting the rate of intake of water by soils. Soil Science Society of America, Proceedings 4:60-65. 1939.

24. FORESTRY AND TIMBER BUREAU. Forest trees of Australia. Dept. of National Development. Canberra, Commonwealth of Australia. 1962. 230 p.

25. FORSYTHE, W. M., GAVANDE, S. A. and GONZALEZ, M. A. Propiedades físicas de suelos derivados de cenizas volcánicas, considerando algunos suelos de América Latina. Turrialba, Costa Rica, Instituto Interamericano de Ciencias Agrícolas, 1969. 2 p. (mimeografiado).

26. FREUND, J. E. Mathematical Statistics. New Jersey, Prentice-Hall, 1962. 390 p.

27. GAISER, R. W. Root channels and roots in forest soils. Soil Science Society of America, Proceedings 16:62-65. 1952.

28. GARDNER, W. R. Dynamic aspects of water availability to plants. Soil Science 89:63-73. 1960.

29. ________. Relation of root distribution to water uptake and availability. Agronomy Journal 56:41-45. 1964.

30. GATES, D. M. Energy exchange in the biosphere. Monographs, New York, Harper, 1962. 151 p. (biological)

31. GIEGER, R. The climate near the ground. Rev. Ed. Cambridge, Mass. Harvard University Press, 1965. 611 p.

32. GONDELLES-AMENGUAL, R. El género Eucalyptus en Australia. Ministerio de Agricultura y Cría, Dirección Forestal, Caracas, Venezuela, 1954. 147 p.

33. HARDY, F. Soil erosion in St. Vincent, B.W.I. Tropical Agriculture, Trinidad 16:58-65. 1939.

34. HELVEY, J. D. and PATRIC, J. H. Canopy and litter interception of rainfall of hardwoods of eastern United States. Water Resources Research, Vol. 1, No. 2, 1965. 13 p.

35. HOFFMAN, M. B. and SCKLUBATIS, G. R. The significance of soil variation in raspberry culture. Michigan Agricultural Extension Station. Bulletin no. 177, 1928. 20 p.

36. HOLCH, A. E. Development of roots and shoots of certain deciduous tree seedlings in different forest types, Ecology 12: 259-298. 1931.

37. HOOVER, M. D. Water action and water movement in the forest. *In* Forest Influences, Rome, FAO, 1962. pp. 31-80. (FAO Forestry and Forest Products Study 15)

38. HURSH, C. R. and HOOVER, M. O. Soil profile characteristics pertinent to hydrologic studies in the Southern Appalachians. Soil Science Society of America, Proceedings 6:414-422. 1941.

39. INSTITUTO COSTARRICENSE DE ELECTRICIDAD. Informe sobre el problema del Río Reventado. San José, Costa Rica, 1965. 312 p.

40. KITTREDGE, J. Forest influences. New York, McGraw-Hill, 1948. 399 p.

41. KOZLOWSKI, T. T. Water metabolism in plants, New York, Harper, 1964. 227 p.

42. ________ and SCHOLTES, W. S. Growth of roots and root hairs of pine and hardwood seedlings in the Piedmont. Journal of Forestry 46:750- 54. 1948.

43. LAWS, J. O. Measurements of the fall-velocities of water drops and rain-drops. Transamerican Geophysics Union 3:709-721 1941.

44. LEEDS, HILL AND JEWETT, INC. A master plan for flood control on Rio Reventado and Rio Tiribi, Costa Rica. San Francisco, U. S. Department of State, A.I.D., 1967. 171 p.

45. LIZANO, F. P., GUTIERREZ, R., CRAIG, O. G., DENNIS, C. E. A conservation plan for the stabilization of the upper Reventado watershed. San José, Costa Rica, Civil Defense of Costa Rica, 1965. 56 p.

46. LOWDERMILK, W. C. Influence of forest litter on runoff, percolation, and erosion. Journal of Forestry 28:474-491. 1930.

47. MANNIX, J. F. Redescripción preliminar de suelos volcánicos del Macizo del Irazú. San José, Costa Rica, Ministerio de Agricultura y Ganadería, 1965. 8 p.

48. ________. Estudios preliminares para la recuperación agrícola de los suelos de cenizas recientes del volcán Irazú. San José, Costa Rica, Ministerio de Agricultura y Ganadería, 1965. 19 p.

49. METZ, L. J. and DOUGLAS, J. E. Soil moisture depletion under several piedmont cover types. U. S. Forest Service. Technical Bulletin SE-1207. 1959. 23 p.

50. MOHR, E.C.J. and VAN BAREN, F. A. Tropical soils. Amsterdam, Netherlands, The Royal Tropical Institute, 1954. 498 p.

51. NORMAN, E. M. The genus *Buddleia* in North America. Gentes Herbarum 10(1):47-114. 1967.

52. NYE, P. H. Organic matter and nutrient cycle under moist tropical forest. Plant and Soil 13:333-346. 1961.

53. ________ and GREENLAND, D. J. The soil under shifting cultivation. Harpenden, England, Commonwealth Bureau of Soils, 1960. 156 p.

54. OPPENHEIMER, H. R. UNESCO. Reviews of research, 105, 1960. 98 p.

55. PATRIC, J. H., DOUGLASS, J. E. and HEWLETT, J. D. Soil water absorption by mountain and piedmont forests. Soil Science Society of America, Proceedings 29:303-308. 1965.

56. PENFOLD, A. R. and WILLIS, J. E. The eucalyptus. New York, Interscience 1961. 551 p.

57. PLATH, C. V. and SLUIS, A. VAN DER. Uso potencial de la tierra de Costa Rica, evaluación basada en los recursos físicos. Parte II, Roma, FAO, 1964. 25 p. (FAO no. AT2234).

58. PULGAR, VIDAL J. El eucalipto. Ministerio de Agricultura, Publicación no. 4, Bogotá, Colombia, 1955. 186 p.

59. RABER, O. Water utilization by trees, with special reference to the economic forest species of the North Temperate Zone. U. S. Department of Agriculture. Miscellaneous Publications no. 257, 1937. 98 p.

60. STANDLEY, P. C. Flora of Costa Rica. Chicago, Field Museum Press, 1938. 1571 p.

61. STEPHENS, J.E.M. Tree growth on a seasonally dry swamp in Eastern Uganda. East African Agricultural Journal 20:232-235. 1955.

62. SWINDALE, L. D. The properties of soils derived from Volcanic Ash, Report on the "Meeting on the Classification and Correlation of Soils from Volcanic Ash", World Soil Resources Report no. 14, FAO, Rome, 1965. pp. 82-88.

63. THAMES, J. S. *et al.* Soil moisture regime in some forest and non-forest sites in northern Wisconsin. Soil Science Society of America, Proceedings 19:381-384. 1955.

64. TROJER, J. Algunas characterísticas agroclimatológicas del trópico americano. Lima, Belem do Pará, Reunión Internacional sobre Problemas de la Agricultura en los Trópicos Húmedos de América Latina, 1966. 16 p.

65. UNITED STATES FOREST SERVICE. A guide to the Coweeta Hydrologic Laboratory. Ashville, North Carolina, Southeastern Forest Experimental Station, 1957. 40 p.

66. VARGAS, O. C. y TORRES, J. A. Estudio preliminar de suelos de la región occidental de la Meseta Central. Costa Rica. Ministerio de Agricultura e Industrias, Boletín Técnico no. 22, 1958. 64 p.

67. VEIHMEYER, F. J. and HENDRICKSON, A. H. Soil moisture as an indicator of root distribution in deciduous orchards. Plant Physiology 13:169-177 1938.

68. WALDRON, H. H. Debris flow and erosion control problems caused by the ash eruptions of Irazú Volcano, Costa Rica. U. S. Geological Survey, Bulletin 1241-I. 37 p.

69. WEAVER, J. E. and HARMON, G. W. Quantity of living plant materials in prairie soils in relation to run-off and soil erosion. Nebraska University Conservation Bulletin 8, 1935. 53 p.

70. ________ and KRAMER, J. Root system of *Quercus macrocarpa* in relation to the invasion of prairie. Botanical Gazette 94: 51-85 1932.

71. ________ and NOLL, W. C. Comparison of runoff and erosion in prairie, pasture, and cultivated land. Nebraska University Conservation Bulletin 11 1935. 37 p.

A P P E N D I X

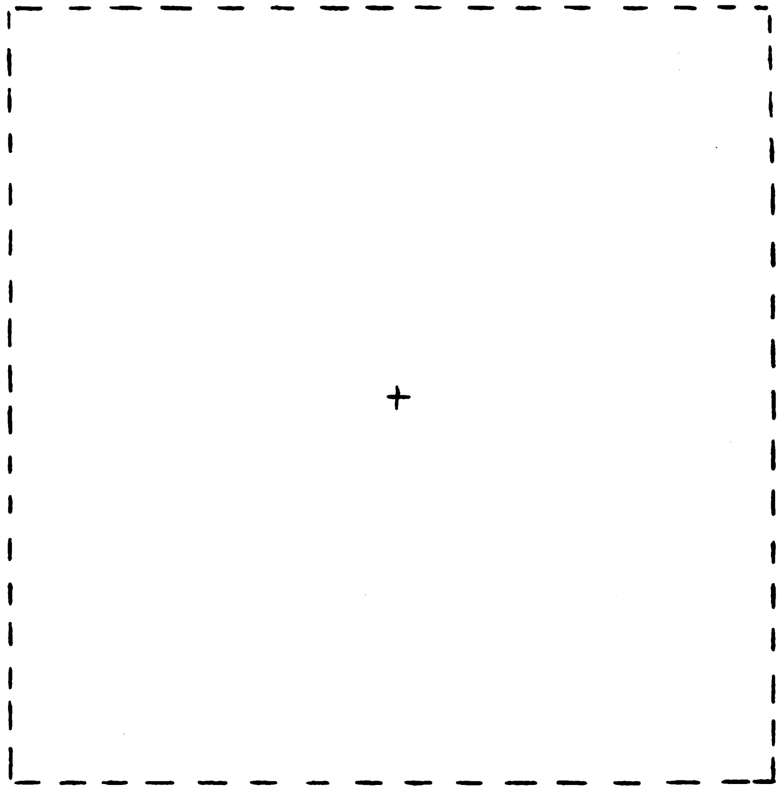
APPENDIX 1

FIELD WORK SHEET

Species Age Tree#

Rooting Schematic

Plan View



Soil Profile

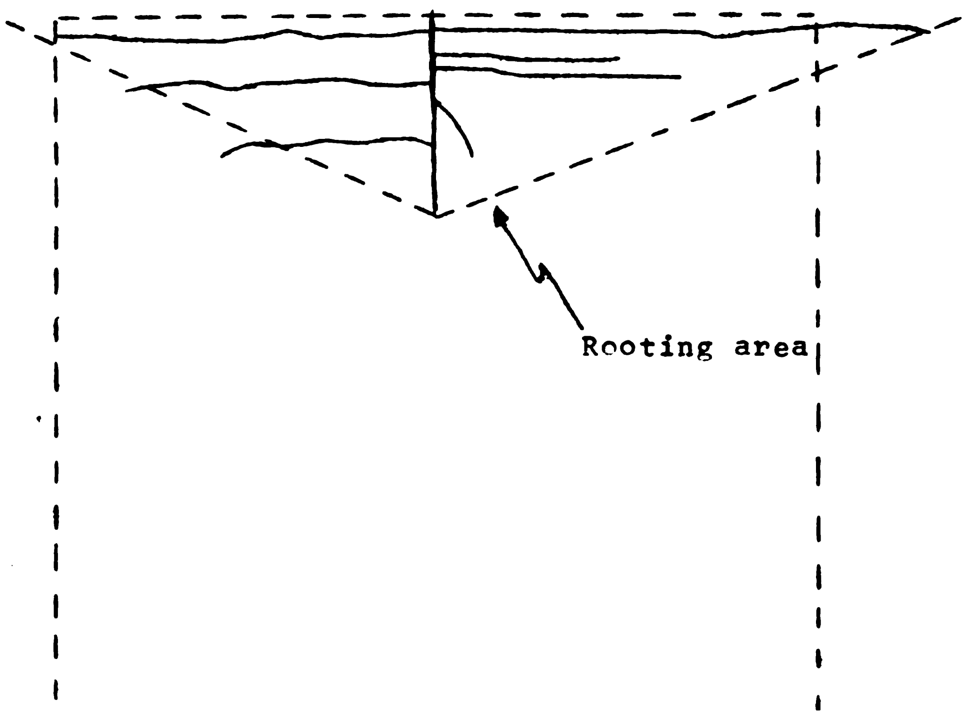
Depth of Ash-
Organic Layer-
Cinder Layer-
Yellow subsoil-

Presence of asbestos planting pot

Other observations:

Vertical Profile
Slope %
Type of ground Cover

Exposure



Appendix 1 (cont.)

Tree form measurements

Total height -

D.B.H. -

D.G.L. -

Cm. to first branch -

Crown diameter -

Total o.d. weight -

Rooting form measurement

Total o.d. weight

APPEMDIX 2

Percentage of rooting system found growing on the donwhill slope, for *Eucalyptus globulus* and *Buddleia nitida*.

E. globulus	Age-Class	% Slope[a]	% Roots on the Downhill Slope[b]
	3-year-old plants	5	62
	2-year-old-plants	15	64
	1-year-old plants	45	59
B. nitida			
	3-year-old plants	5	62
	2-year-old plants	10	59
	1-year-old plants	10	59

[a] Average slope from tree sites sampled.

[b] Average rooting radius from the downhill quadrants from the plan view sketches.

APPENDIX No. 3

Summary sheet of field and laboratory measurements taken on the stems and root systems for *E. globulus*.

Age Class	Tree #	Height (m)	Crown[a] Dia. (m)	Trunk[b] Dia. (cm)	O.D.[c] stem (kg)	O.D.[d] root (kg)	Rooting Radius (m)	Rooting area (m^2)	Root depth
I	1	1.10	0.40	0.01	0.03	.015	0.42	0.61	0.80
	2	1.35	0.60	0.015	0.14	0.145	0.87	0.76	0.70
	3	1.45	0.45	0.015	0.07	0.03	1.00	1.38	0.70
	4	1.30	0.40	0.01	0.03	0.01	0.43	0.45	0.85
	5	1.70	1.10	0.015	0.24	0.09	0.92	0.57	0.50
Average		1.38	0.59	0.013	0.10	0.06	0.73	0.76	
II	1	2.45	1.7	0.045	1.15	0.26	1.21	2.31	1.25
	2	3.00	2.2	0.06	3.51	0.94	3.66	5.80	1.10
	3	2.55	1.6	0.05	1.32	1.18	3.91	0.78	0.25
	4	2.80	1.6	0.04	1.49	0.66	1.91	5.76	1.80
	5	2.40	1.5	0.03	0.85	0.335	2.06	5.29	1.30
Average		2.64	1.72	0.045	1.66	0.677	2.55	3.99	
III	1	3.0	1.0	0.05	1.096	0.535	3.25	6.73	1.30
	2	5.3	1.8	0.08	3.61	1.06	3.65	8.18	0.85
	3	8.6	3.0	0.12	15.70	3.91	5.35	10.40	1.65
	4	4.3	1.8	0.06	2.94	1.26	2.67	4.18	1.95
	5	4.5	1.8	0.07	3.29	1.45	5.59	9.81	1.80
Average		5.1	1.88	0.076	5.325	1.643	4.10	7.86	

[a] Crown diameter is at widest point.
[b] Trunk diameter is measured at ground level.
[c] Oven dry stem weight.
[d] Oven dry root weight.

APPENDIX No. 4

Summary sheet of field and laboratory measurements taken on the stem and root systems for B. *nitida*.

Age-Class	Tree #	Height (m)	Crown[a] dia. (m)	Trunk[b] dia. (cm)	O.D.[c] stem (kg)	O.D.[d] root (kg)	Rooting radius (m)	Rooting area (m^2)	Root depth (m)
I	1	1.2	1.2	0.025	0.55	0.16	0.89	1.96	0.65
	2	1.2	1.0	0.030	0.41	0.16	1.22	1.57	0.90
	3	1.1	0.8	0.030	0.48	0.17	1.18	1.89	1.1
	4	1.0	1.1	0.045	0.76	0.235	1.75	2.72	1.1
	5	1.4	1.1	0.040	0.76	0.20	0.91	0.94	0.9
Average		1.18	1.04	0.027	0.59	0.185	1.19	1.96	
II	1	1.80	2.00	0.07	2.66	1.16	2.06	3.64	0.80
	2	2.30	2.50	0.07	6.56	1.81	1.69	2.14	0.95
	3	2.10	1.70	0.06	2.50	0.57	1·44	2'44	0.80
	4	1.70	2.30	0.06	5.05	1.63	1.85	1.50	0.70
	5	1.70	2.30	0.06	2.50	0.93	1.39	1.57	1.10
Average		1.92	2.13	0.064	3.85	1.22	1.69	2.26	
III	1	1.30	1.20	0.04	0.80	0.64	1.58	1.31	0.70
	2	1.70	1.80	0.05	2.41	1.40	3.04	2.87	0.50
	3	2.10	1.90	0.05	2.78	0.86	2.31	4.25	1.00
	4	2.30	2.00	0.06	3.07	1.54	1.92	5.03	0.90
	5	1.40	1.10	0.04	0.69	0.30	1.44	2.68	0.70
Average		1.76	1.60	0.05	1.95	0.95	2.06	3.25	

[a] Crown diameter is at widest point.
[b] Trunk diameter is measured at ground level.
[c] Oven dry stem weight.
[d] Oven dry root weight.

APPENDIX 5

In the table which follows the values in the first line represent *t* values of the 2-year-old B. *nitida* and E. *globulus*. Given four degrees of freedom, the second line of the table represents the corresponding probability or level of confidence for each value. The procedure for calculating the *t* value and corresponding probability follows the method for small populations established by Freund[a].

TABLES OF *t* VALUES FOR COMPARISON OF CHARACTERISTICS OF 2-YEAR-OLD *Buddleia nitida* and *Eucalyptus glogulus*

	Height	Crown dia	Trunk dia	Stem oven dry	Root oven dry	Rooting radius	Rooting area	Rooting depth
value	2.14	1.86	32.0	1.88	1.45	1.54	1.14	0.92
P $\bar{<}$	0.20	0.40	0.001	0.40	0.60	0.40	0.80	1.00

For example the *t* value and probability for the height measurements were attained as follows:

Height Measurement

E. *globulus*[a]	B. *nitida*[b]	x[c]	x^2
2.45	1.80	0.65	0.42
3.00	2.30	0.70	0.49
2.55	2.10	0.45	0.20
2.80	1.90	1.10	1.21
2.40	1.70	0.70	0.49
		$\Sigma x = 3.60$	$\Sigma x^2 = 2.81$

$\bar{x} = 0.72$

[a] Appendix 3 - Height measurements for 2-year-old plants of E. *globulus*.
[b] Appendix 4 - Height measurements for 2-year-old plants of B. *nitida*.
[c] x values are the differences among height measures of the 2 species.

---

[a] Freund, J. E. Mathematical Statistics. Prentice-Hall, New Jersey,

APPENDIX 5 (cont.)

Using these table values and substituting in the following formulas:

$$t = \frac{(\bar{x} - u_o)\sqrt{n}}{s}$$

where $s = \sqrt{\dfrac{\Sigma x^2 - (\frac{\Sigma x}{n})^2}{n - 1}}$

$u_o = 0$

and degrees of freedon = n - 1

where n = sample size

$$t = \frac{(0.72 - 0)\sqrt{5}}{\sqrt{\dfrac{2.81 - (0.72)^2}{4}}} \qquad \tau = \frac{1.61}{0.24} \qquad = 2.14$$

From a table of τ values using four degrees of freedom the probability of the height measurements exceeding the mean value is 0.20 or 20%, i.e., there is a 1 in 5 probability that the *t* value will be exceeded by chance[a]. Therefore a significant difference was not established for the height measurement.

[a] Maroney, M. J. Facts from figures. Baltimore, Penguin, 1956 492 p.

APPENDIX 6

Table of *t* values for the allometric relationships among species characteristics for 2-year-old *Buddleia nitida* and *Eucalyptus globulus*.

	Root depth / root radius	Root O.D. / stem O.D.	Crown dia. / root dia.	Root O.D. / root area	
value	0.80	0.76	1.56	0.54	
P ≤	1.0	1.0	0.4	1.0	