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The water required to irrigate greenbelts being established around Iranian cities is a major cause of concern in a country with insufficient supplies. Alternative methods of afforestation which do not require irrigation must be found. One such method is to concentrate water received by a watershed without vegetation on a smaller area where trees are planted. This can be accomplished by making portions of the surface of the watershed area impervious to water through application of asphalt. This principle was tested by constructing two m wide terraces on contour lines at five m intervals resulting in a watershed to spreading area ratio of 1.5. A special formulation of asphalt was sprayed onto the surface of the microwatersheds at the rate of one liter/m^2 in December 1969. Seedlings of Robinia pseudacacia L., Cupressus arizonica G., and Fraxinus rotundifolia Mill., tree species commonly used in irrigated afforestation projects, were planted in March 1970 on the terraces.

Asphalt treatment did not result in a significant increase in the survival of the tree seedlings because 23.4 mm of rain fell in July 1970. This is a rare event for the Tehran environment. The increases

in the growth of height, crown cover, and stem cross section due to the asphalt treatment during five growing seasons for *Robinia pseudacacia* L. were 61.5, 61.4, and 53.0 percent, respectively; for *Cupressus arizonica* G. these were 14.6, 15.4, and 31.6 percent, respectively; for *Fraxinus rotundifolia* Mill. these were 29.4, 79.2, and 23.9 percent, respectively.

Runoff plots two m wide and ten m long were constructed at the site and sprayed with the asphalt. Runoff from each plot was collected in a container to study its variations as a function of time and rainfall amount and intensity. Calibrated gypsum blocks were placed at depths of 15, 30, 45, and 60 cm in terraces and at depths of 10, 20, and 30 cm between terraces to measure soil water potentials.

A regression equation was developed correlating the runoff coefficient with the age of the asphalt-soil membrane, amount of rainfall, and intensity of rainfall. The coefficient was negatively correlated with the age of the membrane ($r = -0.658^{**}$). As the membrane aged, its efficiency in inducing runoff decreased. Subfreezing temperatures, growth of vegetation, and expanding clays accelerated deterioration of the membrane. Extrapolation of the regression line indicates that the membrane is effective only for five years. The runoff from the asphalt sprayed microwatersheds resulted in high soil water potentials in the spreading basins.

Regression equations were developed correlating growth with precipitation and age of trees. Amount of rainfall received in April and May in any given year was found to determine growth of height and crown cover the following year. Amount of rainfall received in

April through October in any given year was found to determine the growth of stem cross section the following year.

The runoff data and growth equations were used to extrapolate results to microwatershed to spreading area ratios twice and four times as large as used, and to runoff coefficients twice and four times as large as used in the experiment. If the amount of runoff were four times as large as occurred in the experiment the increases of 125 percent in height growth, 109 percent in crown growth, and 109 percent in stem growth for *Robinia pseudacacia* L., and smaller increases for the other two species, could have been obtained.

Application of the developed technique which will result in substantial savings of water, which in some localities will amount to 5000 m^3/ha/year, or enough water to supply the needs of 50 persons, is highly recommended. By decreasing the width of terraces to about 1.3 m and by increasing the width of microwatersheds to about 8 m, higher watershed to spreading area ratios are obtained assuring better survival and substantial increases in growth.

A thorough review of the literature and observations made during the five year experimental period indicate that asphalt spraying for the purpose of establishing trees under the system discussed in this thesis will not be hazardous to plants and animals.

Soil Surface Application of Asphalt in
Afforestation in Semi-Arid Zones of Iran

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SCOPE OF THE PROBLEM

Many modern cities, with their millions of inhabitants, cars which burn fossil fuel, and factories, suffer from air pollution caused by carbon monoxide, carbon dioxide, and other noxious gases and atmospheric particulates. To help supply these cities with oxygen and remove CO_2 by the process of photosynthesis, some environmentalists have supported the establishment of city parks and greenbelts. These might also help to remove dust from the air. Gerakis (1974) refuted this practice on the basis of calculations he made for a hypothetical situation in Athens, Greece, which showed that the amount of oxygen produced by the plants was virtually equal to the amount needed for the oxidation of the plant biomass produced. But he recognized the role and importance of city parks and greenbelts in improving the microclimate, healing scarred land, and in removal of particulates from the polluted air by providing large settling areas in the form of leaves as suggested by Waggoner (1972).

Awareness of the degradation of environmental quality, the potential for removal of some of the air pollutants by plants, along with the favorable economic condition of the country, prompted the urgent desire to establish greenbelts around Iranian cities and towns. The city of Tehran, with its 3.6 million people, was assigned high priority for the establishment of such a greenbelt. The projected area of the belt, on the basis of the oxygen production potential of plants (Gerakis, 1974), is 18,000 ha or 50 m^2 per inhabitant.

Tehran, in common with most of Iran, receives very little precipitation. The range in annual precipitation measured over 50 years is from 91.4 to 560.1 mm (Appendix Table 1), with an average of 232 mm, of which 81 percent occurs between November and May (Hashemi, 1969). Much of the growing season which extends from early April to late September is practically dry (Appendix Table 2). It is obvious, therefore, that the establishment of a greenbelt around Tehran depends on the provision of an adequate supply of water.

Not much information is available on the consumptive use of water by forest trees. The amount of water transpired by European forests ranges from 50 mm/year for Scotch pine (Pinus sylvestris L.) to 200 mm/year for beech (Fagus spp.) and Norway spruce (Picea abies L.) (Moller, 1947). Had Moller specified the climates under which these levels of transpiration occur, these figures would have been more meaningful. Kozlowski (1958) noted that the estimated transpiration of forest trees in the southern United States is 8,000 gal/acre/day, or about 7.4 mm of water. A conservative estimate of the annual evapotranspiration demand of a middle aged stand of mixed forest located at Tehran (35°41' north) is about 600 mm. For such a forest to thrive in the climate of Tehran, some means of supplementing natural precipitation is required.

Irrigation of the so called "drought enduring species" currently occupies the attention of the responsible authorities of the Tehran Water Board. It is estimated that the rate of water consumption of the city at present is 274 million cubic meters (m^3)/year. This figure is alarmingly close to the available storage capacity of the two reservoirs now supplying the capital. The domestic consumption of water by 2.5 million of Tehran's 3.6 million people was 246.5 million m^3 during the year 2530 (1971-1972) (Anon. 1972).. Approximately 26 million m^3 of water were used for irrigation of 5200 ha of greenbelt then in existence around Tehran. To irrigate the projected greenbelt of 18,000 ha would require about 90 million m^3/year. Assuming the per capita water consumption of the inhabitants of Tehran to remain constant at 100 m^3/year, the city's population to remain constnat, and no new demands to the water system to be made, an irrigated greenbelt of the required size could only be maintained by depriving one-fourth of the city's population of water!

A further assumption made in these considerations is that there will be no drastic changes in the amount of precipitation received by the watersheds which supply Tehran with water. The occurrence of drought is omnipresent and this calamity might strike in any part of the world. In case of water shortage, the irrigated greenbelts would be the first to suffer because of the priority of people over trees.

To save the water for domestic consumption and to decrease the probability of mass mortality of trees during a drought event, an effective means of harvesting and conserving water must be found.

The sealing of the soil surface on parts of sloping lands and the conservation of the runoff in the soil of basins below these sloping lands is a promising method of water harvesting and use. The use of asphalt as the soil sealant is a logical choice in an oil producing country. Tehran's water shortage by itself qualifies it as a suitable place for experiments with water harvesting. Other factors make it an even more appropriate site: (i) the Tehran Oil Refinery can supply any grade and quantity of asphalt desired so the transportation costs would be very low, (ii) Tehran's annual precipitation is very close to the nation's average of 250 mm, (iii) its elevation is about the average of the Iranian Plateau, (iv) proximity to the desert makes it an ideal representative of a large portion of Iran, and (v) its proximity to three universities and many technical colleges and industrial complexes makes consultation and site visits practical.

This thesis describes a study which had as its objective an evaluation of the use of asphalt for the purpose of sealing soil to induce runoff. A second objective was the determination of the irrigation requirements of several tree species which might be used for greenbelts around Tehran.

Several new research projects were started two years after the initiation of the study discussed here. These were based on observations made in the present study. The main objectives of these studies were to maximize conservation of water and to optimize its use. Improvements are being made on the physico-chemical properties of asphalt which makes it more suitable for the intended use. Increasing the ratio of microwatershed area to spreading basin area increases the amount of water received by the trees planted on them. Efforts are made to decrease the loss of water due to percolation by providing underground moisture barriers. Fertility trials are also in progress.

INTRODUCTION

A large percentage of the earth's surface suffers from an imbalance between water supply and demand with evaporative demand exceeding natural rainfall. Shantz (1956) estimated this percentage to be about 36. Utilization of parts of this vast land area has been possible only through the importation of water, and the application of ingenious methods of irrigation developed by those in need of this vital commodity.

The ancient Chinese drilled wells as deep as 1500 meters (Tolman, as reported by Davis and DeWiest, 1966, p. 5). The industrious Persians constructed Qanats (aqueducts) more than 3,000 years ago. Through this system they were able to bring water stored in the soils of alluvial fans to lower lying arid plains. It is estimated that 75 percent of the water used in Iran is carried through 350,000 kilometers (km) of aqueducts which also double as drainage lines for a large volume of soil to supply many farms on the Central Plateau (Bybordi, 1974).

To use a limited resource to its best advantage has been the main goal of man's endeavor in his search for water. Many approaches have been taken in conserving water and some are worth closer examination. Lambert et al. (1971) were able to conserve seven cm of water during one summer by removing weeds from a seven year old, red pine, plantation. The saving amounted to one-third of that summer's rainfall. Timmons (1962) estimated that saltcedar (Tamarix pentandra Pall.) uses seven feet (213.3 cm) of water annually in Safford, Arizona. The possibility of saving most of this water by removing the saltcedar was encouraging. The saving of about 200,000 acre-ft (2.467×10^8 m^3) of water was achieved between 1951 and 1956 on a 35 mile (56.3 km) stretch of the Rio Grande in New Mexico by eradicating the adjacent phreatophytes.

Changes of plant communities have been tried and improved water yields have been achieved under certain conditions. An increase in runoff of 1.4 inches (in) (3.5 cm) in Arizona (Rich, 1972), 10 in (25.4 cm) in West Virginia, 10 to 14 in (25.4 to 35.5 cm) in New Hampshire, and 18 in (45.7 cm) in western Oregon (Storey and Reigner, 1970) has been observed for forested watersheds after improved cutting. Johnston (1970) observed that evapotranspiration losses from bare, herbaceous, and aspen-herbaceous plots were: 11.28 in (28.6 cm), 15.27 in (38.7 cm), and 21.00 in (53.3 cm), respectively. He estimated that 6.0 in (15.2 cm) of water could be saved by the removal of deep rooted aspen and the conversion to herbaceous plants. Although this mode of thinking has gained popularity among some hydrologists, not all of them are firm believers in it. Grover et al. (1970) enumerated many prerequisites for achieving an increase of a few inches in the runoff by the conversion of brush-oak type vegetation to grass-oak type. Important drawbacks of clear cutting and conversion of plant communities limit application of these practices. Mass movement following clear cutting in southeastern Alaska (Swanston, 1974) and following brush to grass conversion in southern California (Rice et al., 1969; Rice and Foggin III, 1971) has been attributed to the loss of mechanical support due to the deterioration of root systems.

Snow manipulation by the modification of its surface properties, although yet impractical on a large basis, has shown promise. Smith and Halverson (1970) reported a reduction ranging from 85 to 100 percent in evaporation from a snowpack by the application of a monomolecular layer of octa- and hexadecanol to its surface. Megahan et al. (1967) accelerated snowmelt by a factor of 2.8 for one day through the reduction of albedo by the application of carbon black to the snow surface.

Reduction of evaporation from free water surfaces by film forming heavy alcohols has been tried. Frasier and Myers (1968) reported a 28 percent reduction in evaporation by the application of 10 pounds of dispersed alkanol per acre (11.2 kg/ha) of reservoir per month. Cooley and Myers (1973) were able to reduce evaporation up to 87 percent by light colored floating objects. The cost of water saved was $3.84 per 1000 liters.

The most important factor in the water balance, the plant, has been in focus for a long time. It had been theorized that since about 99 percent of the water consumed by the vegetation is transpired a small reduction in the transpiration rate could amount to a considerable saving in water. To achieve this Waggoner and Hewlett (1965) sprayed the trees with the glyceryl half-ester of decenyl succinic acid in order to physiologically decrease the rate of transpiration. However, they did not measure a statistically significant increase in the streamflow from a forested watershed after doing so. The application of high alcohols to form a monomolecular film on leaves for reduction of evaporation was also of little benefit. Although hexadecanol decreased evapotranspiration by 60 percent, the material reduced photosynthesis and growth as well. The reduction in the rate of photosynthesis was actually more than the reduction in transpiration (Gale et al., 1967). Even if the difficulties in reducing transpiration were surmountable, the increased leaf temperature would have posed a new dilemma. The cooling action of transpiration is vital to the well being of leaves when the heat load on them is large. Thermal death of leaves is likely to occur when their temperature rises too high (Gates, 1968).

Tapping unused sources of water may also solve some of the water shortage problems. Saline water is being used in agriculture and forestry with much success and irrigation with sea water is not a far-fetched proposal (Boyko, 1968). Even the "occult precipitation" is under investigation. *Pinus halepensis* Mill., *P. bruttia* T., and *Cupressus horizontalis* Mill. have been grown successfully in Beersheba, Israel, by dew harvested with plastic sheetings (Gindel, 1973, p. 49-60).

"Arid" Zones Defined

Numerous definitions have been given for the term "arid," and some researchers have tried to quantify it by the use of climatological data. The simplest quantification was proposed by DeMartonne, as reported by Walton (1969, p. 10), who defined an aridity index, AI, as:

$$AI = \frac{P}{10+T} \qquad (1)$$

where P is the mean annual rainfall (mm), and T is the mean annual temperature (°C). An aridity index <5 defines true deserts (e.g. Death Valley, Calif.), and AI = 10 is the upper limit of the dry steppe, where irrigation is definitely needed for agriculture. The aridity index for Tehran, according to Walton (1969, p. 10) is 9.5, while Dehsara (1973) presented the range of 6.3 to 7.7. Both values classify Tehran's climate somewhere between true desert and dry steppe.

The problem of arid zones is not only that the total amount of precipitation is generally low but its distribution is erratic and undependable. Strong convection currents sometimes develop in the air above the hot land, or desert mountains, rapidly forming clouds which burst up in thunderstorms and torrential rains (Simons, 1967, p. 14). These climatological events are usually followed by overland flows which develop into violent floods. The precious water in these discharges is of limited usefulness unless it can be impounded (Baily, 1956).

Water Spreading: An Old Practice

Water spreading, also called flood spreading, is the process of collecting runoff from a large area and concentrating it on a small area, where it can be used more effectively for the growth of agricultural crops. Water spreading projects have been in use for a long time, but few records have been maintained. Hubbell and Gardner (1944) studied the effects of water spreading on rangelands in New Mexico. They spread runoff water from three watersheds ranging in size from 1032 ha to 1441 ha onto flood plains ranging in size from 61 ha to

182 ha. The authors reported a net decrease in the density of vegetation and a net increase in the forage production. Apparently, sediment deposits had covered some of the plants. Hubbard and Smoliak (1953) reported the production of 3,770 lb/acre (4222.4 kg/ha) of forage as compared to 110 lb/acre (123.2 kg/ha) for the control, due to water spreading in an area with a mean annual rainfall of 11.18 inches (28.3 cm). Branson (1956) spread the runoff from a 1,060 acre (429.3 ha) watershed over a 275 acre (111.3 ha) tract in Alzada, Montana. The thickness of the soil mantle was about 20 ft (6.1 m). He not only observed higher yields on the spreader area, but desirable species competed favorably with big sagebrush (Artemisia tridentata Nutt.) and pricklypear cactus (Opuntia polyacantha Haw.). The main nutrients N, P, and Ca were higher in plants from the treated area as compared to those from the control area.

Two of the most successful water spreading projects are underway on the Shivta and Avdat farms of the Negev Desert of Israel. The Negev is a true desert with a mean annual rainfall of 86 mm, and total rainfall range from 28 to 168 mm during a ten year period. Runoff from the hillsides is directed to terraced valley fields and subdivided into small units (Evenari et al., 1968). The amount of water collected from the hillsides averages 150 to 200 m^3/ha/yr. Each ha of cultivated land receives the runoff produced by 20 to 30 ha of hillside catchment area.

Shanan et al. (1970) attributed the high water yield of these desert watersheds to the crust forming characteristic of the loessial soils of the area. These soils, when wetted, become practically impermeable and cause a high degree of runoff. Shanan et al. (1970)

observed the following relationships:

$$R_a = K_a(P_a - D_a) \tag{2}$$

$$R_d = K_d(P_d - D_d) \tag{3}$$

where R is the runoff (mm), K is the runoff coefficient, P is the rainfall (mm), D is the priming rainfall (mm), a indicates annual values, and d indicates daily values. They established the following values: $K_a = 0.70$ and $D_a = 29$, with a correlation coefficient $r = 0.98$. $K_d = 0.28$ to 0.39 for low rainfall years, $K_d = 0.75$ to 0.96 for high rainfall years, and $D_d = 1.2$ to 2.2.

The minimum amount of precipitation required is therefore 29 mm to insure annual runoff and about 2.0 mm to insure daily runoff. The runoff coefficients, K_a and K_d, are functional only after the priming rainfalls, D_a and D_d, have occurred.

Using data for six years which included 124 daily records, they observed:

$$R_d = 0.78(P_d - 2.0) \text{ with } r = .95 \tag{4}$$

which means, that the first 2.0 mm of rainfall is used to recharge the surface few mm of soil and to form the crust. From then on 78 percent of the rainfall becomes runoff. The value of K was inversely related to the size of the catchment.

The runoff is conserved in a three m deep soil which holds 17 to 20 percent water at 1/3 atm and 7 to 10 percent at 15 atm. With a bulk density of about 1.4 g/cm^3, the soil mantle holds 300 to 350 mm of water or 3,000 to 3,500 m^3/ha in the root zone (Tadmor et al., 1970).

To help increase runoff ancient farmers collected surface stones in mounds. Recent studies by Lamb, Jr. and Chapman (1943), Grant and Struchtemeyer (1959), and Epstein et al. (1966) have established that removing stones ranging from 4.76 to 52 mm in diameter decreases infiltration and increases the amount of runoff.

Many fruit trees including figs, pomegranates, grapes, peaches, apricots, almonds, and carobs, and range plants have been grown successfully in the project area with impressive results. Alfalfa with dry matter yields of 7.8 tons/ha/yr has been the superior species. It is important to note that most of the plants survived 22 months of drought in 1962 through 1963 when only 25.6 mm of rainfall was available for the period (Tadmor et al., 1970).

Evenari et al. (1971, p. 220-228) also reported on the establishment of "negarins" or micro-catchments ranging in size from 15.6 m^2 to 1000 m^2 on a 1.5 percent slope. "Neger" is the Hebrew word for runoff. It was observed that the 500 m^2 catchments had the highest percentage of runoff on an area basis. The lower ratio of runoff from the smaller "negarins" was attributed to border effects while the decreased yield from large micro-catchments was due to seepage losses during overland flow (Hillel and Rawitz, 1968). Trees planted in the lowest portion of these micro-catchments performed very well. Kemper (Anon. 1964) realized that using micro-catchments on agricultural lands may be more efficient than fallowing. He suggested a ratio of 2/1 to 4/1 for the watershed to catchment area. However, this procedure is effective only with high rainfall.

Water Harvesting: A New Approach

Theory

Runoff is mainly determined by soil infiltrability which is modified, among other things, by surface cover, slope, physical and chemical properties of the soil, soil water retention characteristics, presence or absence of water table, and air and soil temperatures.

Runoff yield under arid conditions amounts to less than ten percent of the total annual rainfall (Rawitz and Hillel, 1971). The remainder which infiltrates into the ground may be considered a complete loss since it soon evaporates either directly or through the leaves of native vegetation which is of no substantial value.

The volume of runoff is a function of precipitation characteristics including amount, intensity, and distribution and soil properties including surface conditions and infiltrability. If the precipitation that falls on the soil could be kept from infiltrating into the soil and collected, then it could be redistributed to provide an adequate supply of water for intensive use on a smaller area. This concept is called "water harvesting" (Fink and Myers, 1968).

Deep, medium textured soils with few limitations for agricultural use are the best reservoirs for the runoff water and its use in farming. Deep rooted, perennial, drought resistant crops or trees which occupy and extract water from large volumes of soil are the most suitable plant species because they can survive in the prolonged, rainless periods common in desert environments (Rawitz and Hillel, 1973). Terraces on contour lines could be used to establish the desired ratio of catchment area to spreading area. It should be possible to design a layout which would produce the optimum use of the limited rainfall by (i) considering the soil water holding capacity of the root zone, (ii) modifying the soil surface of the catchment area through the application of water repellent materials, (iii) adjusting the catchment to spreading area ratio according to the runoff coefficient of the modified soil surface, and (iv) selecting the most suitable plant species.

Soil Water Repellency

The occurrence of water repellent soils has been reported from many parts of the world. Scholl (1971) observed in a juniper (*Juniperous osteosperma* Torr.) stand in Utah, that the resistance to wetting of the surface soil increased from completely wettable in open areas to highly non-wettable in litter under the juniper canopy. Resistance to wetting decreased with depth in the soil profile and increased with increasing organic matter content. Krammes and DeBano (1965) identified hydrophobic soils under chamise (*Adenostoma fasciculatum* Hook.) plants in southern California. Savage et al. (1969a) reported that a humic acid isolated from a *Stachybotrys atra* culture caused water repellency in sand and soil. The Al^{3+} and Fe^{3+}

salts of this humic acid rendered the sand and the soil practically impermeable to water. In a later study (1969b) they observed that two fungi, *Aspergillus sydowi* and *Penicillium nigricans* caused limited water repellency in the sand. However, they claimed that the products of many other fungal species produced water repellency when heated briefly at temperatures between 200 to 400 C. Savage et al. (1972) later identified the hydrophobic material to be aliphatic hydrocarbon groups.

Fire induced water repellency was first hypothesized by Krammes and DeBano (1965). They realized that high amounts of runoff and debris yield in southern California were caused by rainfall on soils rendered non-wettable after brush fires. They later confirmed their hypothesis (DeBano and Krammes, 1966).

The mechanism by which fire induces water repellency was studied by DeBano et al. (1970). They observed that the hydrophobic substances in the surface layers of litter vaporize, move downward, and condense onto soil particles about 2.5 cm below the soil surface. As the percentage of silt and clay decreases, the thickness of the water repellent layer increases. They attributed this phenomenon to large differences in specific surface areas of the soils. DeBano (1971) also reported that the rate of infiltration in a tube packed with a soil which had been made water repellent by heat treatment and placed horizontally was 25 times slower than that of the control.

The drastic reduction in infiltration rate could also have been attributed to a decrease in the cross sectional area of pores through which infiltrating water should pass. However, calculations made by

DeBano (1971) based on capillary rise with ethanol which has a surface tension of 22 dynes/cm at 20 C, proved that burning decreased the average pore radius by only 2.3×10^{-2} mm, which DeBano claimed to be a relatively small and insignificant change for a soil with 62.7 percent of the sand grains having diameters <1 mm. Therefore, another factor must have been responsible for this phenomenon.

Fink and Myers (1968) made a detailed study of hydrophobic materials and used the following relationship, better known as the capillary rise equation, to elucidate the water repellency phenomenon:

$$h_w = \frac{2\gamma \cos \theta_w}{\rho g r} \tag{5}$$

where h_w is the breakthrough pressure or air entry value in cm of water, γ is the surface tension of water, θ_w is the angle of contact between water and soil (wetting angle), ρ is the density of water, g is the acceleration due to gravity, and r is the effective pore radius. For $\theta_w < 90°$, capillary forces draw water into the porous material and for $\theta_w > 90°$, positive pressure must be applied to force water into the capillaries. It should be realized that this criterion for separating a wettable from a non-wettable soil, the value of θ_w proposed by Fink and Myers, is based on the theory that soil pores behave as capillary tubes, which is only a good, practical approximation.

The reduction in infiltration rate in the burned, water repellent soil was attributed to the increase in the wetting angle at soil-water interfaces. DeBano (1971) reported that the value of θ_w was 58° for the wettable soil and 80° for the non-wettable soil.

Considering the variables in Equation (5), it is obvious that, under natural conditions, only the effective pore radius, r, and/or the wetting angle, θ_w, can be changed effectively to achieve increased runoff. The decrease in r is achieved, among other methods, by compaction (Hillel and Rawitz, 1968), or by dispersion of clay particles through the application of a monovalent ion to the soil surface. Kemper and Noonan (1970) increased the runoff from 140 to 220 percent over a control by the addition of 224 to 896 kg/ha of NaCl. Maximum runoff was obtained when the sand fraction was between 50 and 80 percent. Dispersion of clay particles by Na^+ ions caused sealing of the surface. The authors did not report on the salt content of the runoff water. Dutt and McCreary (1975) observed 52.6 percent runoff from 14.23 in (36.1 cm) of rainfall in Arizona following the application to the soil surface of five tons of sodium chloride per acre (12.3 ton/ha). The salt content of the runoff water was 610 ppm following the treatment but decreased to 210 ppm after two years. Covering the soil surface with a layer of expanding clay is another means of decreasing infiltration rate. The method is attractive where clay and labor are readily available. The increase in θ_w, and hence the decrease in cos θ_w, is obtained, very economically, by the application of hydrophobic materials to the soil surface.

Treatment of a silt loam with 1.5 percent by dry weight asphalt emulsion changed the contact angle from the original 58° to 88° (Hartmann et al., 1976). These authors further claimed that a sandy soil used in the experiment became so water repellent after asphalt treatment that it was impossible to measure its contact angle. Myers and Frasier (1969) sprayed soils ranging in texture from sandy loam to loam with sodium rosinate, dialkyl quaternary ammonium chloride, sodium stearate (Na soap) and potassium stearate (K soap), each in combination with $AlCl_3$ or $CuSO_4$, fatty amine acetate, and sodium methyl silanolate, to make the soil hydrophobic and to increase the runoff. Sodium methyl silanolate applied at the rate of 500 lb per acre (560 kg/ha), as a three percent solution in water, proved to be very effective as well as economically feasible under the experimental conditions in Arizona. The first year's efficiency of rainfall capture was 94 percent. However, erosion caused the second year's efficiency to decrease to 76 percent.

Asphalt: A Suitable Water Repellent

Physical and Chemical Properties

Asphalt or bitumen is a complex thermoplastic mixture of high molecular weight hydrocarbons with small amounts of sulfur, nitrogen, and oxygen compounds, prepared from the residue left over after distillation of petroleum. Asphalt consists mainly of saturated compounds, aromatic compounds, and asphaltenes (Gleason et al., 1969). This material has been applied successfully in the stabilization of soils especially in warm dry climates where the soil water content is relatively low (Gillott, 1968, p. 150-153).

The viscosity of asphalt at ambient temperatures is high which makes it difficult to use. Therefore, its viscosity should be reduced by heat treatment or the combination of heat treatment and other methods. Two of the most widely used techniques are cutback and emulsification. In cutbacks, a solvent such as kerosene, naphtha, or fuel oil is added to the asphalt to increase its fluidity (Dickson, 1966). In emulsification, asphalt is dispersed in water in the form of colloidal particles (Gillott, 1968, p. 150-153). The use of cutback asphalt for soil stabilization is favored due to its ease of application and extent of its physico-chemical properties. MC_2, or medium curing asphalt, which contains about 38 percent solvent is a widely used soil stabilizer. It forms a rather flexible mix with the soil after volatilization of its solvent (Katti et al., 1960; Gagle, 1965).

Stability of a cohesive soil is to a great extent a function of its water content. Water, with its unique physico-chemical characteristics, induces cohesion in the soil when present at low concentrations while it behaves as a lubricant at water contents approaching the plastic limit. Specific surface area and type and amount of exchangeable ions determine the affinity of a soil for water. The basic difficulty in stabilizing a cohesive soil is maintaining its water-induced cohesion while preventing excessive water uptake (Winterkorn and Reich, 1962). Apparently, some asphalts are able to satisfy these two criteria.

Many theories have been advanced to explain the behavior of asphalt when used for soil stabilization. Those of Endersby (1942) have gained the most support. According to his "intimate mix" theory, granular particles are individually coated and cemented together, with a resultant increase in strength. According to the "plug" theory, asphalt tends to waterproof fine grained soils by plugging their voids, thus making the access of water to clay minerals more difficult.

Endersby also noted that the longer it takes for a given amount of water to enter the soil, the less structural damage it produces. And the longer the water remains in the soil, the stronger its stripping action on the asphalt will be.

Winterkorn and Eckert (1940) investigated the physico-chemical factors involved in the stabilization of soil by asphalt and arrived at the following conclusions: i) as the amount of clay, silica to sesquioxide ratio, and base exchange capacity increase, the asphalt requirement increases, ii) the higher the valence of exchangeable cations, the easier the stabilization can be achieved, iii) the stabilization of well drained and well aerated soils is much easier than those which have been developed under poor drainage conditions. While the organic matter developed in well drained soils is neutral to basic and tends to be hydrophobic, that formed under reducing conditions is acidic and possibly hydrophilic, iv) while sodium is definitely detrimental to the soil-asphalt system, potassium might be either beneficial or detrimental depending on the clay species, v) relatively moist soils can be stabilized more readily than air dry soils.

Having these conclusions in mind, Winterkorn et al. (1945) hypothesized in a follow up study that the stabilization process of soil by asphalt is of polar nature. Polar or polarized molecules present in asphalt are adsorbed on the exchange sites of clay particles. They tested this hypothesis by the addition of polar substances, like two percent of aniline-furfural, to asphalt and observed substantial increases in its stabilizing properties. They concluded that only a small fraction of asphalt constituents are actively involved in stabilization while the bulk of it acts as a relatively inert carrier. This conclusion lends support to a previous finding (Winterkorn and Eckart, 1940) that the asphaltene content of a bitumen was correlated with its stabilizing performance.

The behavior of certain polar molecules in asphalt-soil water repellency was further examined by Winterkorn and Reich (1962). They observed that treatment with organic amines tends to control the water affinity of clays by replacing some of the hydrophilic ions with amines which have a cationically active amino group "head" and a water repellent "body." When cation exchange takes place in this system, the amino "heads" force the cations already on the clay surface out and their water repellent "bodies," extending away from the surface, prevent wetting thus interfering with osmotic swelling possible in these soils. For these reactions to take place soil should be wet enough to induce native cations to separate from the clay surfaces and go into solution. Winterkorn and Reich further suggested that the system should be acid so that the amines have close associations with organic or inorganic acids, or acid-salt complexes. They further contended that it would be advantageous for the released ions to form insoluble salts with acids. In a recent paper Clementz (1976), while concurring with the polar nature of asphaltene adsorption, presented evidence that water is a deterrent to the adsorption of asphaltenes on clay particles. This is because the asphaltenes are not soluble in water, therefore they cannot easily penetrate adsorbed water layers to approach the surface. Only in certain situations when the adsorption energy is strong enough and the adsorbed water film is only a few layers thick can adsorption take place.

Soil water content as a factor in asphalt stabilization was also examined by Katti et al. (1960) who had observed that water facilitates uniform distribution of asphalt throughout the soil mass during mixing. They further noted that the amount of water required for thorough distribution of cutback asphalts increases as the amount of fine material in the soil increases. However, if the water content is higher than certain threshold limits a surface sealing of soil and asphalt occurs.

Application in Water Harvesting

The use of asphalt for water harvesting is relatively new. In 1958 a rainfall catchment in Hawaii was sprayed with asphalt at rates of 8.5 to 34 lb/yd^2 (4.6 to 18.4 kg/m^2) to form a "membrane" of varying thickness with a mean of about 0.5 in (12.7 mm) at a cost of \$2.70 per square yard (\$3.23/m^2). The runoff coefficient of this catchment was 93 percent in 1959 and 78 percent in 1961. Apparently, cracking of the asphalt membrane and growth of vegetation through it decreased its performance (Chinn, 1965). Myers et al. (1967) sprayed different formulations of cutbacks and emulsions on soils ranging in texture from sand to clay loam in Arizona and made many interesting observations. Best results were obtained when an asphalt compound was sprayed and mixed with the soil to form a strong and porous pavement followed by the application of a second asphalt compound to seal the surface against infiltration of water and to protect the base against oxidation. The runoff coefficient was close to 100 percent when the seal was maintained. The pavements were in good condition 1.5 to 3 years after being installed. In the case of a clay loam soil containing 36 percent clay with a specific surface area of 235 m^2/g the pavement, which had been formed on rain moistened soil, disintegrated after four months. In a new trial on the same soil asphalt was sprayed on the disked and rolled dry soil and then covered with 1.5 mil (0.38 mm) black polyethylene film. Seventeen months later, the polyethylene covered pavement was in good condition while the bare pavement had disintegrated after only 12 months of exposure. Myers and coworkers emphasized that the durability and performance of asphalt-soil pavement cannot be reliably predicted by laboratory tests. Field investigations are essential to these types of studies. The cost of the asphalt pavement was $\$0.73/yd^2$ ($\$0.87/m^2$), based on prices and wages in Phoenix, Arizona, in 1965.

Heavy fuel oil, another petroleum product, has also been used for water harvesting. Hillel and Rawitz (1968) obtained runoff coefficients ranging from 81 to 85 percent in Gilat, Israel, in experiments where they sprayed the compacted dry surface of 2.8 x 2.0 m runoff plots with 0.3 liter/m^2 heavy fuel oil. The runoff coefficient of the compacted surface (control) decreased from 71 percent in the first year to 44 percent in the second year. However, when fuel oil was applied at the rate of 0.2 liter/m^2 on larger plots, in whose lowest parts almond trees were growing, to induce higher runoff and therefore increase the yield, no significant difference was obtained in the production of almonds. In fact, in several instances the control plots produced higher yields than sprayed plots (Rawitz and Hillel, 1973).

Heavy fuel oil diluted with power kerosene in the ratio of three to one sprayed onto a smooth sandy soil surface at the rate of 0.95 liter/m^2 produced a soil surface seal with a runoff coefficient of about 31 percent in the first year and 15 percent in the second year after application in Western Australia (Laing and Prout, 1975). They noted that a smoothed and compacted blanket of clay, eight cm thick, was the most practical and economical method for water harvesting in that area.

To overcome the ineffectiveness of asphalt on some clay soils, especially those with expanding clay species found in Arizona, Cluff (1973, 1975) developed a method in which a base of cationic emulsified asphalt is sprayed onto the smoothed soil surface at the rate of 0.25 gal/yd^2 (1.13 liter/m^2). A polyethylene sheeting 4 mil (1.01 mm) thick then covers the asphalt onto which a coating of asphalt is sprayed, which is immediately covered with 1/8 to 3/8 in (3.2 to 9.5 mm) chips, presumably wood chips. The whole system is then covered with 20 to 30 lb/yd^2 (10.8 to 16.2 kg/m^2) of gravel. The asphalt, chips, and gravel which cover the polyethylene sheeting protect it against oxidation by ultraviolet radiation and wind damage. The efficiency of this system in inducing runoff is about 95 percent. The cost is about $2000/acre ($4942/ha). With a life expectancy of 10 to 15 years, the cost of water is 59 cents/gal (15.6 cents/liter) in 18 in (45.7 cm) rainfall areas during the first 15 years, decreasing to 14.7 cents/gal (3.9 cents/liter) during the next ten years.

Soil: The Best Reservoir

The use of soil as a reservoir for water has always intrigued man. About 50 percent of the soil volume can be used to store water when impermeable barriers are used to prevent vertical and lateral movement. Dixey (1956) believed that the construction of subsurface dams in arid areas should be examined. The stored water would be conserved well because the rate of evaporation from the dry soil surface is low. Rapid drying of soil surface layers in arid climates has a mulching effect which prevents further evaporation of soil water (Nikiforoff, 1937). Cohen et al. (1968) reported that the evaporation from the soil surface in the Negev Desert was only 1.93 cm for a full year. It should be realized that this is not in contradiction with the statement made earlier regarding the high rate of water consumption in arid climates through evapotranspiration of the limited amount of precipitation which wets only a few surface cm of soils. In this case the soil profile is wet to much lower depths and the rapid drying affects only the upper few cm.

Construction of level pans and terraces to facilitate infiltration and storage of water was given new momentum by the results of recent studies. Mickelson (1966) observed that soil moisture stored over a seven month period in a level pan, which had been constructed in a broad natural waterway to intercept runoff from the contributing watershed, was equal to the amount stored in an unleveled fallow plot over a 21 month period. He obtained a 100 percent increase in yield of sorghum with the level pan system. The effectiveness of Zingg conservation bench terraces, which employ level contour benches and terrace ridges to control erosion and spread runoff water over leveled benches, has been demonstrated in areas with about 600 mm of rainfall (Zingg and Hauser, 1959; Hauser and Cox, 1962).

The idea of using soil as a water reservoir may be misleading. It should be realized that each soil has a typical moisture characteristic curve which cannot be changed easily. This property, in combination with soil depth, controls the amount of water that can be stored and made available for the growing crops (Hursh and Fletcher, 1942). The presence of slowly permeable layers parallel to the soil surface in steep terrain could cause overloading of the soil mantle and trigger slumps.

POTENTIAL HAZARDS OF ENVIRONMENTAL POLLUTION BY ASPHALT APPLICATION

Although man has been using petroleum and oil products for millenia, only recently has he become aware of their possible drawbacks. Events such as the Santa Barbara oil spill, in which the blowout from an oil well off the coast of southern California caused extensive contamination of offshore waters and sea coast (Anon., 1970), or the Torrey Canyon mishap which resulted in release of 60,000 tons of crude oil causing widespread destruction of marine and wildlife resources in southeast England (Anon., 1968), have made him conscious of the dramatic impact that oil can have on the environment. Petroleum products are used in everyday life, from jetliner fuels to paving asphalts. Physical contact between oil products and living things are common. Therefore, seemingly contradictory facts and rumors regarding the potential dangers of petroleum products also exist.

Some researchers claim that petroleum oil is toxic to the lowest level of the food chain, namely the plankton. Oil, in combination with low O_2 concentrations, has an adverse effect on the aquatic biome (Tarzwell, 1971). Others present data suggesting that some of the oil products stimulate growth in single cell organisms, such as certain algae (Krauss et al., 1973). It is proposed by some that 3,4-benzpyrene, a petroleum oil derivative, is a carcinogen, while others provide evidence to the contrary and indicate additional substances may be involved. The "killing" of soil by crude oil is suggested by a few, while beneficial effects have been claimed by others (Carr, 1919).

To gain a better understanding of the pollution potential of asphalts and some of the oil derivatives which are added to them as solvents, a brief summary of petroleum chemistry, biological degradation of oil products, and finally their effects on soil, water, plants, animals, and men are presented.

Chemistry of Petroleum Oil

Although a thorough understanding of the chemistry of petroleum products is essential in the study of their biochemical activities, only a few pertinent points are mentioned here. Crude oil, depending on its point of origin, consists of saturated and unsaturated hydrocarbons, and certain impurities. Three main groups are recognized as the main hydrocarbons in crudes (Baker, 1970):

1. Alkanes (paraffins). Saturated chain compounds, e.g., hexane.
2. Cycloalkanes (naphthenes). Saturated cyclic compounds, e.g., cyclohexane.
3. Aromatics. Compounds containing benzene rings.

Other hydrocarbon groups of less importance include:

1. Alkenes (olefines). Unsaturated chain compounds which are _not_ present in the crude oil and are formed in the refining processes.
2. Naphthenic acids. Alicyclic compounds with carboxylic acid groups.

Additional elements and compounds which could be classified as "impurities" are: sulfur occurring as free S, H_2S, organic S, for example, thioalcohols, nitrogen, and oxygen compounds. Well-known derivatives of petroleum include the following (Baker, 1970):

1. Petrol (gasoline). Straight and branched chain alkanes and aromatics, S and alkenes are removed.
2. Kerosene. S and aromatics are removed.
3. Diesel oil. A refined kerosene with a high boiling point or refined gas oil with a low boiling point.
4. Fuel oil. A residual oil, or distillate, or a blend of these.
5. Alkenes and aromatics. Products produced by the cracking and refining processes.
6. Pesticidal and fungicidal spray oil. These contain a high proportion of saturated hydrocarbons. When unsaturated compounds are used there is less risk of toxicity to plants.
7. Herbicidal oil. Aromatic compounds which are phytotoxic.

Degradation of Petroleum and its Products

Decomposition of oil constituents is achieved by physical processes, chemical processes, and biological processes. Since in the asphalt-soil system, as well as in the entire biosphere, microbial degradation is the safeguard against universal pollution only this phase of decomposition is discussed here.

Crude oil and oil products can be attacked by one or more groups of microbes. Ellis, Jr. and Adams, Jr. (1961) observed that there are more than 100 species of bacteria, yeasts, and fungi which oxidize hydrocarbons. Traxler (1964) noted that there are at least ten genera of bacteria and seven genera of molds which use bitumen as a source of energy. However, each of these microorganisms is selective and consumes only specific kinds of crude oil or petroleum products.

Byrom and Beastall (1971) conducted selectivity tests and found that crude oils from California, Louisiana, Oklahoma, Pennsylvania, and Texas varied in their response to microbial decomposition. The average weight loss of the oil substrates due to microbial decomposition was 45.3 percent while the range was from 0.78 to 98.8 percent.

Hydrocarbon oxidizing bacteria and fungi tolerate relatively large variations in their environment. Traxler (1964) reported that the bitumen oxidizing bacteria and fungi are of three types, namely, obligate aerobes, obligate anaerobes, and facultative anaerobes which can live under varying O_2 concentration or in the complete absence of it. Ellis, Jr. and Adams, Jr. (1961) suggested that all hydrocarbon consuming microorganisms in soil, except _Methanon-bacterium omelianskii_, are aerobic. They also reported that some withstand up to 150,000 psi (10546.5 kg/cm^2) of pressure, are active from 0 to 85 C, need small amounts of O_2, and are effective over a pH range of five to nine. They also noted that certain heavy metals, H_2S, and oxidase inhibitors prevent microbial oxidation of hydrocarbons. The microorganisms also need mineral salts and a N source in the form of NO_3^- or NH_4^+ in their diet.

The biodegradation of petroleum oil products depends on the molecular weight and configuration of the molecule. Also, due to their varied biological requirements, the organisms attack different products and the end results are not the same. Harris (1966) observed that actinomycetes are more effective in utilization of asphalt. Higher populations of these are found around coated pipes than of bacteria. Traxler (1964) showed that Bacillus No. 14 attacks asphalt 6A. Flavobacterium No. 16, however, attacks all bitumens, including bitumen G, which is not oxidized by Bacillus No. 14. Ellis, Jr. and Adams, Jr. (1961) were of the opinion that as the oil molecules become heavier and more viscous, they become less susceptible to microbial attack. Kerosene to lubricating oils (10 to 16 carbon molecules) are most readily attacked. Pseudomonas fluorescens attack saturated hydrocarbons containing 12 or more C, whereas Methanomonas methanica grows on C_1- and C_3- saturated hydrocarbons (Traxler, 1964). He (1966) also observed that Mycobacterium ranae utilizes both aromatic and saturated hydrocarbons. McKenna and Heath (1976) noted that the aliphatic and alicyclic hydrocarbons of oils are attacked more readily by microorganisms than are aromatic fractions.

Potentially hazardous polynuclear aromatic hydrocarbons (PNAs) which are abundant in natural soils and waters are also added to the biosphere by oil spills and coal conversion processes. McKenna and Heath (1976) published data suggesting that the microorganisms which degrade some of these potentially carcinogenic PNAs protect the higher organisms by removing these chemicals from the environment. The observation that Flavobacterium sp. metabolized more than half of the present 3,4-benzpyrene--a known carcinogen--when phenanthrene (a three ring compound) had been added to the substrate is especially worth mentioning.

The by-products of microbial decomposition are varied. Schwendinger (1968) reported that *Cellulomonas* sp. produced CO_2 and other volatile end products when N and P were added to Port Berga crude. ZoBell (1969) noticed the formation of H_2O, CO_2, microbial cell substance or biomass, and a great variety of other products, many of which have not yet been identified. He also demonstrated that several strains of *Achromobacter* and *Pseudomonas* could grow on a variety of petroleum derived substrates, including toluene, benzene, catechol, benzyl alcohol, and cresol produced acetic and pyruvic acids.

After reviewing numerous reports, ZoBell (1969) developed several conclusions relating to microbial degradation of petroleum and petroleum products of which those pertinent to the discussion at hand are cited here:

(i) Lack of available N and P might be factors limiting the growth activities of certain oil oxidizing microorganisms. It may be advantageous to enrich oil polluted waters with N and P to increase rates of degradation.

(ii) Lipids, organic acids, esters, alcohols, ketones, polysaccharides, and microbial proteins result from the microbial decomposition of petroleum.

(iii) Temperature, O_2 supply, chemical composition of oil, dispersion of hydrocarbons in the medium, abundance, and kinds of microorganisms influence the rate of oxidation.

Effects of Petroleum Products on Soil

Not all the effects of oil on the environment are detrimental. Researchers have found beneficial effects as well. In a classical study, Carr (1919) examined the "killing" of soil by crude oil. He added from 0.12 to 4.0 percent oil, on a dry weight basis, to a mixture of sand and peat. After the addition of soybean bacteria to the mixture, soybeans were planted. Although Carr did not specify the bacterial species, they presumably were nitrogen fixing bacteria. Contrary to the expectation, Carr observed that growth rate of soybeans was significantly improved by the addition of crude oil. The most effective application was 0.75 percent which increased yield 271 percent over the control. Additions of up to 1.5 percent crude oil did not have any deleterious effect on growth or yield of soybeans. Apparently, the presence of crude oil stimulated N-fixation which produced the increase in yield. However, Murphy (1929) obtained contradictory results. He noted that 0.4 percent crude oil applied to the soil surface decreased NO_3 content about 50 percent, and one percent practically checked nitrate formation. Later studies by Baker (1971b) and Ellis, Jr. and Adams, Jr. (1961) substantiated Carr's findings. Giddens (1976) reported that application of spent motor oil to soil at rates of up to 31, 111 liters/ha did not decrease growth and yield of peanuts, cotton, soybeans, and corn, especially when fertilized with N. However, he observed a significant reduction in the growth of sorghum and weeds. It was concluded that the main problem resulting from the application of high rates of spent motor oil to the soil was the immobilization of nutrients, primarily that of nitrogen.

The observations made by Murphy (1929) and Giddens (1976) regarding the immobilization of N following application of crude and motor oil to soil, are easily explainable on the grounds that heavy hydrocarbons contain large numbers of C and very little N in their structure. They create an imbalance in the C:N ratio in soils. Lubricating oils which contain 20 to 70 carbons (Mahncke, 1966) act as highly carbonaceous crop residues when added to soils. Efficient growth of oil oxidizing bacteria require a C:N ratio of about ten. If the ratio is greater, e.g., 100:1, the utilization of C will be retarded (Jobson et al., 1974). Since microorganisms incorporate some of the soil nutrients in their biomass in the processes of degradation of oil, deficiency of some elements in the soil should be expected. Jobson et al. (1974) stimulated bacterial numbers and utilization of *n*-alkanes by fertilizer application.

Contamination of soil by petroleum oil products has been the subject of much controversy. In general the beneficial effects, as far as soil and plants are concerned, far outweight any negative effects. Plice (1948) demonstrated that aromatics can readily enter the seed coat and kill the germ. He also cited evidence that the number of microorganisms increases rapidly after treating the soil with oil, finding nine million/g in a control as compared to 94 to 110 million/g in oil treated samples. Plice concluded that the decrease in redox potential due to the addition of oil and the increased activity of microorganisms favor N-fixation which results in the increase of organic matter as well. Ellis, Jr. and Adams, Jr. (1961) supported this hypothesis with similar results and reported an increase in the chemically reduced substances e.g., Fe^{2+}, Mn^{2+}. They also observed that Methanon-bacterium omelianskii fixes N, although inefficiently.

Ellis, Jr. and Adams, Jr. (1961) studied the effects of petroleum oil gases on soils and microorganisms. In addition to effects indicated for liquid oils, these gases decreased pH in alkaline soils and increased it in acid soils, thus buffering the soil toward neutrality. This change in pH increased the availability of P. They also attributed part of the increase in P to the reducing conditions provided by gases which in turn made iron phosphate more soluble.

An interesting result, although not substnatiated by other studies was obtained by Ellis, Jr. and Adams, Jr. (1961). A gas saturated soil was found to have a higher percentage of micropores, lower bulk density, and a markedly higher water retention capacity than the control.

Pollution of Groundwater by Oil Components

The ever-increasing consumption of petroleum products has made the failures and fractures of pipelines, underground and aboveground tanks, and oil tankers an ever-present reality and therefore the contamination of deeper soil strata and, in some cases, water resources, a possibility.

Petroleum oil products that are solid at ambient temperature will hardly penetrate the soil. Light components which are fairly soluble in water evaporate by aeration, whereas heavy components which are barely soluble cause no problem. Offensive components are of intermediate molecular weight, soluble in water, and persistent during aeration of water. These components may be present in diesel oil, light fuel oil, and crudes.

During percolation a small amount of oil, about 15 percent of the volume of soil pores, stays in the pores as "immobile saturation" and the rest continues to move downward (Dietz, 1971). For example, if one m^3 of oil is poured onto one m^2 of sand with a porosity of 35 percent, 52.5 liters remain in the pores per meter of percolation and the rest passes through. Oil can under these conditions contaminate 19 m of sand calculated as follows:

$$\frac{1 \ m^3/m^2}{0.35m^3 x 0.15} = \frac{1 \ m}{0.0525} = 19 \ m.$$

Thus, the last drop of oil will theoretically reach the depth of 19 m. He further proposed that when there is a water table within the 19 m depth, the oil forms a "pancake" over it, rather than mixing with the groundwater.

The less viscous the liquid the more penetrating it is, hence the distance traveled is also a function of viscosity. Ineson and Packham (1967) reported that the infiltration rate of gasoline into similar types of porous materials was ten times that for water.

When the immiscible hydrocarbons reach the groundwater and form the "pancake," they continue to move with the potential gradient existing within the groundwater system, preferentially along the upper surface of the water body (Ineson, 1971). The lateral movement of petroleum oil products over the water table is also a function of the geology of the strata in which it moves. Ineson and Packham (1967) noted that some phenolic constituents of oil traveled six kilometers and kerosenes up to several kilometers through Triassic sandstone in central England. They also reported that petroleum oil tends to penetrate damp and wet soils to a greater extent than dry soils. However, in saturated soils penetration is to a large degree impeded.

Oxidation of some of the oil products takes place even at great depths. Dietz (1971) claimed that rainwater, rich in O_2, passes through the "pancake" while diluting it. The dissolved O_2 is used by aerobic microorganisms to oxidize the oil component. He also noted that if hydrogen acceptors (sulphates, nitrates) are present, anaerobic oxidation takes place as well.

Groundwater contaminated with oil interferes with filtering operations in plants processing water for human consumption. Interferences with coagulation, sandbeds, ion exchange beds, flocculation, sedimentation, and backwashing have been discussed by Ineson and Packham (1967). The oil polluted water also requires more chlorine, carbon, or oxidizing agents. The phenolic constituents of petroleum oil intensify the odor of the water when it is treated with chlorine. However, taste and odor of the contaminated water could be moderated if it is treated with activated carbon, chlorine dioxide, potassium permanganate, or ozone (Ineson, 1971).

Toxicity of Oil Products to Plants

The injurious effects of oil products were known even before their worldwide use. Richet, as reported by Currier (1951), noted as early as 1893 that the toxicity of petroleum compounds is inversely proportional to their solubilities in water. Tucker (1936) later observed that the relative toxicity of various petroleum products to foliage was roughly proportional to the amount of unsaturated hydrocarbons present in the oil. Tucker further suggested that hydrocarbons are not toxic to foliage until they are oxidized to oil soluble, asphaltogenic, acids. He indicated that sunlight activates oxidation to a marked degree and the rate of formation of the toxic acids becomes so large that they cannot be tolerated by the foliage. Although Tucker did not specify the mode of activation of oxidation by sunlight, he presumably had in mind the UV region which helps ionization.

The degree of toxicity of different petroleum products and their mode of action have been the main theme of many studies. Currier (1951) proved that toxicity increases along the series of benzene, toluene, xylene, and trimethylbenzene, thus substantiating Richet's finding. An increase in the number of methyl groups apparently promotes penetration into plants. Benzene, toluene, and xylene cause acute injury, while polycyclic aromatics result in chronic injury to plants. Baker (1970) indicated that the toxicity increases from paraffins to naphthenes and from olefins to aromatics. Within each series the smaller molecules are more toxic than the larger ones. Octanes and decanes are extremely toxic, dodecane and higher paraffins are nontoxic, and 12 C atom olefins and aromatics are toxic.

Apparently, the molecular weight and length and shape of petroleum oil molecules control their relative toxicities. Baker (1970) pointed out that compounds with high boiling points have large molecules which cannot penetrate plant tissue easily. Volatile oils evaporate before being able to affect plants. Low boiling point herbicides are selective, high boiling ones are nonselective. Those compounds with a boiling point within the range of 150 to 275 C, such as naphtha and kerosene, are the most toxic to plants. In a later study, Baker (1971c) reported a direct relationship between the activity of herbicides and their aromatic compound content. An inverse relationship was also established between viscosity and surface tension of the petroleum products and their toxicity to plants. Taking into account these physical properties, Baker (1971c) concluded that fresh oil is toxic while residue is relatively nontoxic at any concentration.

The effect of petroleum products on whole plants and on individual cells has been studied in detail. Baker (1970, 1971d) noted that oils wet the plant surface easily and penetrate mostly through the stomata. A heavy cuticle prevents penetration through the epidermis. However, highly toxic products penetrate the plant at the point of contact.

Hydrocarbons dissolve in the plasma membrane and open it by displacing the fatty molecules. The cell sap then leaks into the intercellular space and darkens the leaf. This process causes loss of turgor and produces the odor of macerated tissue (Baker, 1970, 1971d). Nelson-Smith (1971) was of the same opinion except that he suggested that death of cells occurred by wilting. He also noted that disruption of chlorophyll and discharge of pigments usually occurs following contact with oil products. Krauss et al. (1973) reported that some oil products, such as mixed sour oil, stimulated the growth of two species of algae. However, naphthalene at concentrations of three ppm blocked photosynthesis and uptake of nutrients in an algal species.

Petroleum oil products which penetrate the plant move from roots to leaves and vice versa. This movement is through the vascular system as well as through the intercellular spaces. Petroleum oil compounds, either on the surface or within the plant, can cause numerous physical, as well as biochemical changes, some of which are listed below (Baker, 1970, 1971d):

(i) Transpiration rate drops drastically by the plugging of stomata. A decrease of 80 percent has been noticed in parsnip.

(ii) Respiration may be reduced or stopped by the very toxic oxidized oils and aromatics; however, it may be increased by nonherbicidal oils. Oxygen uptake is increased in some cases due to uncoupling of electron transport from phosphorylation.

(iii) Translocation is hindered by obstruction of phloem and xylem vessels with oil, change of interfacial tensions within the protoplasm, or changes in the structure and molecular orientation of the transport pathway within the protoplasm by dissolving in its lipoid phase.

(iv) Photosynthesis is reduced due to changes in separate functions mentioned above in addition to disorders such as reduction in absorption of those wave lengths needed in photosynthesis, destruction of chlorophyll and cell injury which lower the photosynthetic activities, and accumulation of photosynthates in the leaf due to the inhibition of translocation.

(v) Mitochondrial membranes may be broken up and the tricarboxylic acid cycle and oxidative phosphorylation are interfered with.

Effects of Environmental Conditions, Stages of Growth and Species Differences in Petroleum Oil Toxicity to Plants

Environmental conditions profoundly influence the toxicity of oil. Currier (1951) found that spraying green plants with oil in bright sunlight resulted in destruction of chlorophyll and bleaching of dead portions of the treated leaves. Baker (1971a) suggested that the higher toxicity of oils during hot, sunny, days is caused by the decrease in viscosity and the resultant increase in penetrability. Sunny weather also increases the formation of toxic acids and peroxides in the oil. These findings are in accordance with those of Tucker (1936). Stomatal opening is further responsible for the higher toxicity during daylight conditions. Baker (1970) observed that little or no injury occurs to plants sprayed with oil in the dark. Apparently, the opening of stomata during the day facilitates penetration. Humidity affects toxicity in certain species. A high humidity favors oil penetration because the stomata are usually open under this condition. Drought conditions probably favor the formation of toxic acids in the oil. However, in some, such as apple, both humidity and drought cause an increase in toxicity.

Nelson-Smith (1971) reported that aromatic compounds, rich in xylene, killed submerged plants while they had little effect on those with aerial leaves. The temperature of the environment for high phytotoxicity is very exacting. For aquatic weeds it has been found to be 21 C (Baker, 1971c). Thus, several conditions are required to optimize the penetrability and toxicity of less potent petroleum products. Those which penetrate easily and are highly toxic, such as n-decane, cause plant damage independently of environmental conditions.

Stage of growth is also an important factor determining plant reaction to petroleum oil products. Annuals are most severely damaged by summer spraying. Marked reduction of flowering occurs if oil is applied when flower buds are developing. Oil treated flowers rarely produce seeds. Seeds treated with oil do not germinate in the spring (Baker, 1971a). Murphy (1929) found that petroleum oil physically inhibited imbibition and O_2 uptake, which in turn prevented seed germination.

The toxicity of petroleum products is not the same in all plant species or even in different parts of a single species. The selectivity of petroleum oil products in their herbicidal effects were demonstrated by Lachman (1944) who found that beet and turnip plants were destroyed by oil while carrots or parsnips did not show any adverse effects. He concluded that members of the Umbelliferae family are tolerant of petroleum oil. This finding was later supported by studies of Cowell (1971) who reported that of all the salt marsh plants tested, only Oenanthe lachenalii C. survived. The resistance of conifers to injury by light petroleum oil spray has made the use of oil as a herbicide in coniferous plantations practical (Baker, 1970). She also reported that roots of barley and carrot are more resistance than their leaves to the oil. Baker hypothesized that, since roots absorb polar compounds and leaves nonpolar compounds, petroleum oil products affect leaves easier.

An interesting case is the resistance of bulrush (*Scirpus lacustris* L.) to phenol which is a possible end product of microbial degradation of oil (Shay, Jr., 1972). Although phenol is toxic to fish at 50 mg per liter of water, bulrush can tolerate concentrations up to 1000 mg/liter. The plants utilize phenol. It is emitted through the plant to the atmosphere or converted to a non-phenolic product through oxidation and breakage of the phenolic ring. The possibility of using this plant to absorb petroleum oil products from water thereby decreasing its pollution is encouraging.

Toxicity of Petroleum Oil Products to Animals

Petroleum oil products are toxic to many animals and their effects include physical, physiological, and behavioral aspects.

Byrom and Beastall (1971) noted that birds covered with crude oil die through exposure to cold due to the lack of insulation which their plumage normally provides. They also die of toxicity and starvation. Tarzwell (1971) observed that fish die of anoxia and suffocation due to the formation of a film of crude oil over gill filaments.

The main detrimental effect of oil to living things, however, is physiological toxicity. Tarzwell (1971) suggested that oil is toxic to a variety of plankton organisms. This toxicity works in synergism with low O_2 concentrations. The harmful effect of oil thus causes serious repercussions at higher levels of the food chain.

Bugbee and Walter (1973) cited evidence that gasoline pollution of a small stream in South Dakota resulted in eradication of fish, mayflies, and stoneflies over a distance of 3.2 km. They noted, however, that midge (Orthocladius) proved to be resistant. Mackie et al. (1972) pointed out that spilled diesel oil in a stream caused tainting of trout flesh caught 10 to 30 days after the spill. The tainted fish, when eaten by man causes nausea and vomiting (Martin, 1971).

The toxicity of different petroleum products varies with type of animal and environmental conditions. Barnet and Kontogiannis (1975) reported on the critical levels of toxicity (CLT) of oil products to tidepool copepod (Tigris californicus). These were 87 ppm for diesel oil, 83 ppm for kerosene, 80-200 ppm for gasoline, and 225-450 ppm for benzene. They concluded that the slower evaporating crude oil fractions are the most damaging to the copepod. Larger animals have a higher resistance to the toxicity of the oil products. To kill 50 percent of a rabbit population 28.35 grams of kerosene per kilogram of live weight is required (Ineson and Packham, 1967). For a human child, death may occur when 35 grams of kerosene is consumed (Martin, 1971).

The mechanism of toxicity to ducklings (Anas platyrhynchos) was recently described by Crocker et al. (1974). When ducklings are transferred from freshwater to seawater, the rate of transport of Na^+ and water across the intestinal mucosa increases, otherwise dehydration causes their death. Two-tenths ml of crude oil given to a duckling transferred from freshwater to seawater prevented the increase in mucosal water and Na^+ uptake. Even those ducklings which had developed the characteristic after living on seawater lost their adaptability after a single administration of 0.2 ml of crude oil. It was postulated that the high mortality rate among sea birds in waters contaminated with petroleum oil is attributable to dehydration resulting from the described mechanism.

In addition to physiological toxicity of petroleum products change in behavior has been observed in certain animals treated with petroleum oil. Atema and Stein (1974) described effects of crude oil on the feeding habits of lobster (Homarus americanus). Ten ppm crude oil in seawater doubled the period between noticing food and going after it. They suggested that the oil impaired the chemosensory system of the lobster and hypothesized that petroleum oil contamination depressed appetite and chemical excitability. Rice (1973) noted that pink salmon fry tolerated 88 ppm of Prudhoe Bay oil in freshwater and 213 ppm in seawater for a period of 96 hours in June. The toxic level of oil in seawater in August decreased to 110 ppm. Rice also found that older fry were more susceptible to oil toxicity than younger ones in seawater. The older ones were also more sensitive in their detection and avoidance of oil. The avoidance suggests that oil pollution could change migration behavior of pink salmon fry and cause unforeseen alterations in their way of living.

Carcinogenic Properties of Petroleum Oil

Direct poisoning of petroleum oil products to man is rare. Although Davis (1967) puts toxicity due to oil contamination of water below that of phenol and above that of aromatics from coal gas, man is seldom poisoned by consumption of petroleum polluted water or food. The reason is that its presence is detected by smell at concentrations ranging from 0.00005 mg/liter for gasoline to one to two mg/liter for refined petroleum (Ineson and Packham, 1967).

Carcinogenic properties of some of the oil derivatives have caused concern. The French discovered 3,4-benzpyrene, a proven carcinogen, in Mediterranean sediments in concentrations of five ppm at the 8 to 13 cm depths and 0.016 ppm at the 200 cm depth (Holcomb, 1969). Although Holcomb claimed that this material is also formed by algae in the soil, he conceded that problems could occur when 3,4-benzpyrene enters the food chain. Martin (1971) reported that this chemical is also produced in plants, formed as a result of pyrolysis of organic matter and is therefore present in coal smoke, gasoline, and diesel fume, and even in smoked foods.

When the presence of 3,4-benzpyrene in tars was established, a team of doctors from the American Medical Association conducted a survey to determine the effects of asphalt on those who work with it (Baylor and Weaver, 1968). They concluded that petroleum asphalt workers show no greater incidence of disease than non-asphalt workers in similar environments.

The petroleum industry admits that coal tar pitches are carcinogenic, but maintains that petroleum asphalts are not (Wallcave et al., 1971). In an extensive study, benzene solutions of eight petroleum asphalts and two coal-tar pitches of known aromatic hydrocarbon content were tested for tumorigenic activity on mouse skin. The incidence of skin tumor in the asphalt treated mice was low with six tumor bearing animals, including one with carcinoma, out of 218 autopsied. The coal-tar pitch treated mice exhibited a very high tumor incidence with 53 tumor bearing animals out of 58 autopsied, of which over one-third were classified as carcinomas (Wallcave et al., 1971). Comparing the results with that of the control, the researchers concluded that the solvent, not the asphalt, had been responsible for the six tumors in the animals treated with asphalt. They also pointed out that the bynzpyrene concentration of the coal-tar pitches was as high as 10,000 ppm, while that of the asphalt was 0.1 to 2.5 ppm. Wallcave and coworkers concluded that there was no relationship between the polynuclear aromatic content of the asphalts and their tumorigenic properties.

Plant Growth Stimulation by Petroleum Products

From the time Carr (1919) reported an increase in the yield of soybeans, due to the presence of petroleum products until more recently, improved nitrogen metabolism was assumed to have been responsible for the observed results. Yet the reasons for the cited yield increase are not well understood. In studying the effect of petroleum oil pollution on *Puccinellia maritima* Parl. and *Festuca rubra* L., Baker (1971b) showed that the oil was responsible for a better than 100 percent increase in the yield of the former and a significant increase in the growth of the latter species. The two plants also appeared darker green than the control. The response of *Agrostis stolonifera* L. to oil supplied at the rate of 450 cm^3/m^2/month for a 12 month period was similar to one supplied with 243 ppm N. Baker thus concluded that the darker green color suggests a possible increase in N uptake. The possibility of nutrient release from soil organisms killed by oil was also proposed as a mechanism for causing the darker green coloration.

Researchers have also postulated that some microorganisms might be able to synthesize plant regulating hormones from petroleum oil substrates. Taking note of Russian studies, Baker (1971b) tried naphthenic acid, also called "petroleum auxin," but contrary to the reported results did not observe any improvement in crop yield, root production, or chlorophyll and protein N content in the tested species. Nelson-Smith (1971) suggested that since flowering is inhibited by the application of naphthenic acid, more nutrients are available for vegetative growth.

However, not all of the researchers are skeptics! In a discussion session following the presentation of a paper by Baker (1971d), Dr. Syratt observed:

> "Where oil occurs naturally, as in bituminous shales and sands, there is an observable growth stimulation where plants are in contact with bituminous horizons. _Psoralea bituminosa_ L. on natural shales, _Medicago sativa_ L. on spent shale tips, _Trifolium repens_ L. at Dunkirk on oiled sand, all show growth stimulation...they all belong to the family _Papilionaceae_ (Pea family). _Robinia pseudacacia_ L. grows in intimate contact with high concentrations of bituminous material in bituminous sand..."

In the same discussion, M. Gatellier, as referenced by Baker (1971d), mentioned that the production of gibberellic acids (GAs) by microorganisms grown on petroleum fractions had been achieved in the U.S.A. and Japan.

Moore[1] is of the opinion that if acetone, the building block of

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[1] Personal communication. T. C. Moore, Department of Botany and Plant Pathology, Oregon State University, Corvallis.

the GAs, could by synthesized by the microorganism grown on oil, it may be possible to hypothesize that some form of GA is produced by the decomposition processes. ZoBell (1969) reported that acetone is produced by the microbial degradation of oil. Since acetone is produced, it is possible that the GAs could be formed by the microbes which live on petroleum oil. Thus, the increases in growth and yield could in some cases be attributed to the growth regulating hormones such as gibberellic acids.

Asphalt: Its Pollution Potential

Asphalt is a nontoxic compound as far as the present state of knowledge is concerned (Gleason et al., 1969). Known biodegradation products are nontoxic. However, not all of these have been identified. Some of the aromatics used as solvents in asphalt might produce carcinogens. If this is the case, the solvents could be changed when the carcinogens are identified. That asphalt is not toxic is mostly due to its insolubility in water.

Although some of the toxic oil products may be consumed by planktons and algae and accumulate at the higher levels of the food chain, this is not the case with asphalt, especially when sprayed onto the soil surface in dry environments. The solvents used in preparation of the cutbacks are mostly aromatic compounds. These are potentially toxic materials, but they volatilize rapidly when exposed to air at ambient temperatures (Krauss and Hutchinson, 1975).

The possibility of unvolatilized aromatics or degradation products of asphalt reaching surface or underground waters is very remote under the present system of application. The terrace system under investigation has been proven to be effective in controlling surface runoff from very intense short duration rainfall, as well as long duration rainfalls, for the past six years. The amount of precipitation is barely enough, even when using the water harvesting system, to wet the soil of the spreader area to a depth of more than three m. The probability of contamination of ground water, which is very deep in arid environments, is therefore remote.

The runoff water in this project is used by trees and no assessment has been made of its potential for human consumption. However, in similar experiments no ill effects were observed when cattle (Myers et al., 1967) and sheep (Laing and Prout, 1975) drank runoff water from asphalt and fuel oil treated catchments.

MATERIALS AND METHODS

Description of the Experiment

To apply the principles of water harvesting to afforestation using a material which is readily available in Iran - namely asphalt - and to demonstrate the feasibility of this method to responsible authorities, an experiment was designed with the following points in mind:

(i) Terraces following contour lines serve as reservoirs for water captured on uphill microwatersheds sprayed with asphalt. The terraces can then be used for the growth of suitable tree species (Figure 1).

(ii) The sloping soil surfaces between the terraces serve as microwatersheds, particularly when sprayed with asphalt. Runoff water from these asphalt treated surfaces is concentrated in adjoining terraces to be used by the trees. Survival and growth of trees relative to untreated areas or control plots indicate the benefits to be achieved by this method.

(iii) Small plots should be used to assess quantitatively the performance of the asphalt treated soil surface in inducing runoff. The process of aging of the asphalt and its effect on runoff induction must be measured accurately.

(iv) Soil water potential is the most important factor for the determination of the growth rate of plants in arid lands. This parameter measured in the root zone

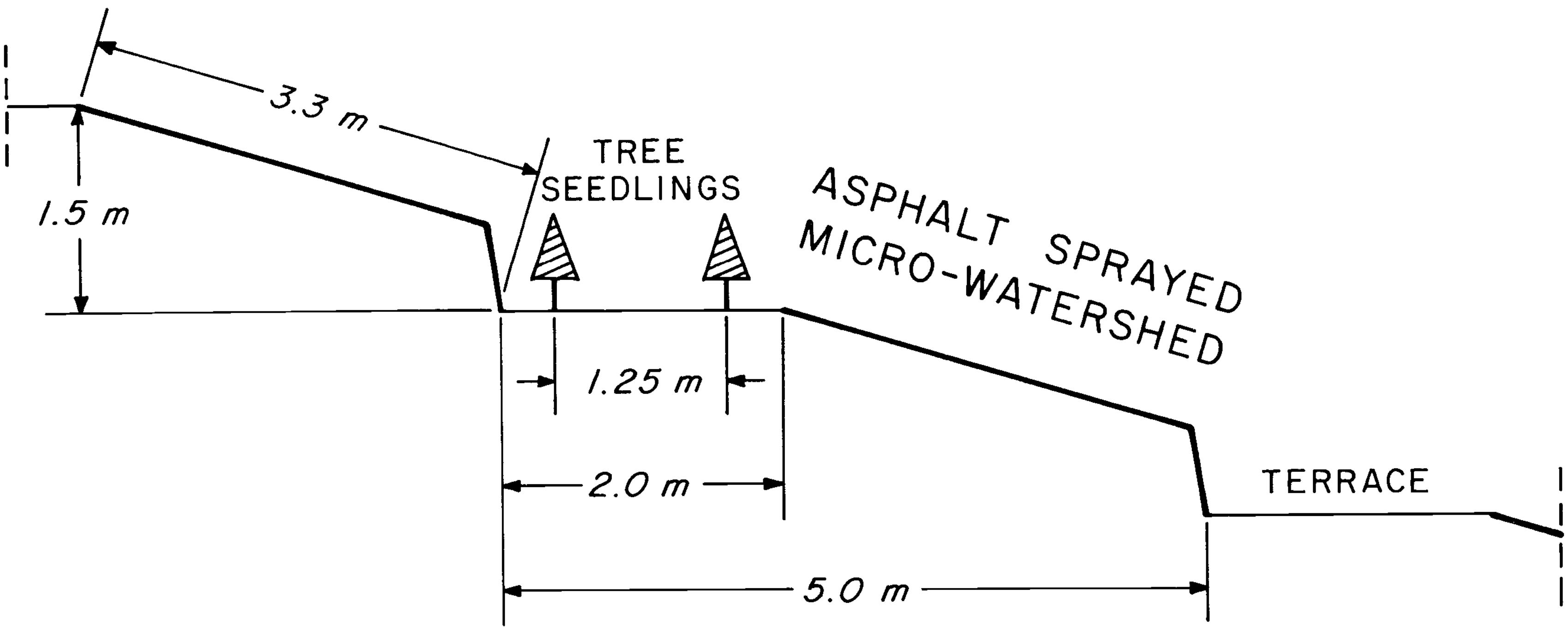

Figure 1. Schematic diagram of the asphalt treated micro-watersheds, terraces, and tree seedlings of the experimental site.

is therefore an indirect measure of the effectiveness of the asphalt treatment and its relationship to tree growth.

(v) The survival and growth of tree species may be correlated with the amount of runoff produced by the asphalt cover and with the soil water potential. Predictive equations should be obtained which can be used as the basis for recommendations for method of application in similar environments in Iran and elsewhere in the world.

Location

A five ha piece of land was selected in the Qootchak Afforestation Project District (15 km NE of Tehran) which has a total area of 10,000 ha. The soil map along with visual observations made in the District attested to the uniformity of the soil of the area. Therefore, the applicability of the results of the experiment to large areas was assured. Description of a representative profile along with particle size distributions and chemical analyses of the soils of the experimental site are presented in Appendix Tables 3, 4, and 5.

To eliminate effects of exposure in the study, the experiment was conducted on plots with southern (S), southeastern (SE), northeastern (NE) and northern (N) exposures.

Land Preparation

The experimental site was fenced with steel posts and rabbit-proof galvanized steel netting to control the movement of animals.

Two meter wide terraces, which followed the contours, were constructed with a bulldozer in such a way that the distance between the consecutive terrace shoulders was about five m (Figure 2). The terrace surface was then ripped to a depth of at least 50 cm using a ripper hitched behind a bulldozer. The ripping was done to facilitate the infiltration of water and for easier root penetration.

The Statistical Design

Each of the four terraced exposures was a block of a split-plot design. Each block was divided into two main plots running up and down the slope. One of these was selected randomly and sprayed with asphalt. The other main plot of each block remained as the control plot. In each main plot five subplots running up and down the slope were selected. The width of each subplot was nine m and its length depended on location on the slope. Three rows of pits spaced three m apart were dug on the terrace floors of each subplot (Figure 2). The rows were parallel to the subplot length. The distance between the pits in each row was 1.25 m on all terraces. One tree species was assigned randomly to each of the five subplots. The remaining area on each plot was planted to grapevine, judas tree, white mulberry, and wild pear. These species did not enter into the design of the experiment.

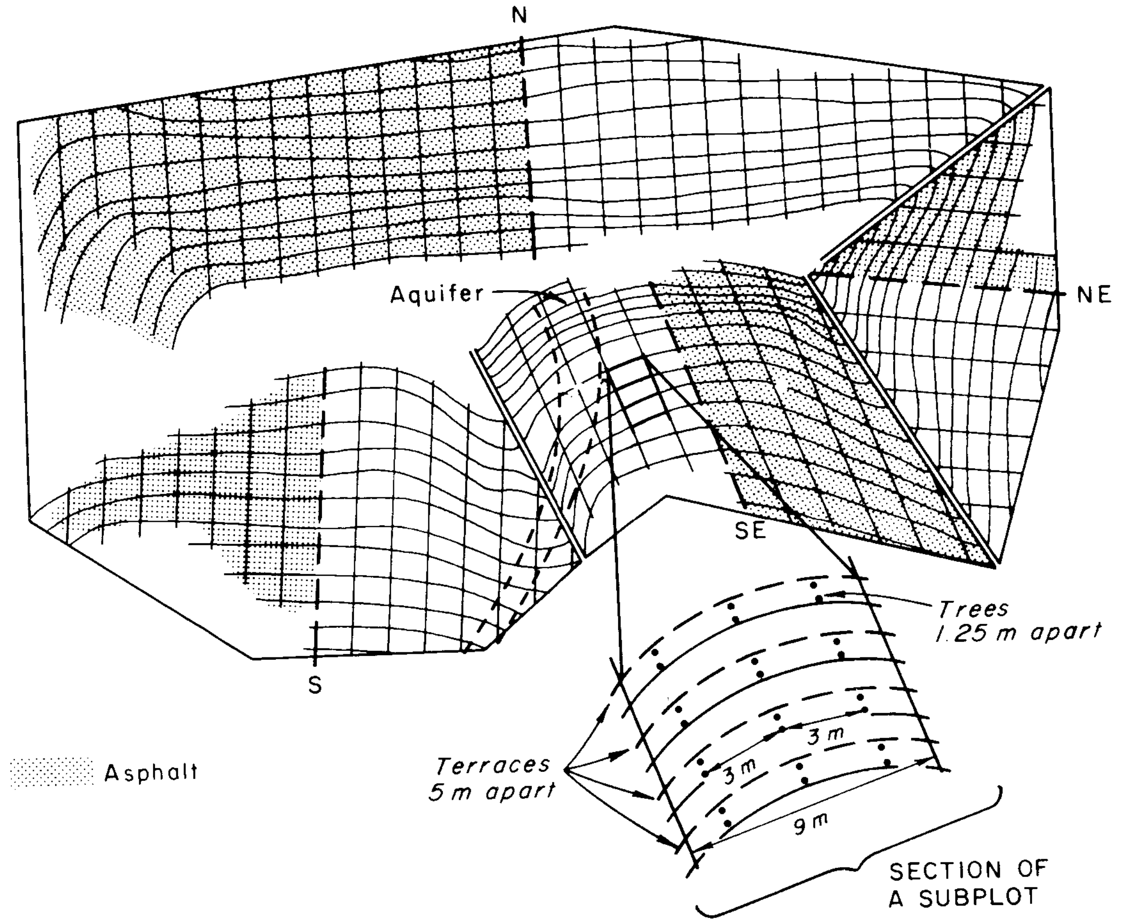

Figure 2. General layout of the experimental site. Contours signify the positions of 2 m wide terraces. Mainplots are either asphalt sprayed or control; subplots are laid out up and down the slopes. Three rows of trees are planted in each subplot, two trees in each row per terrace.

To facilitate the presentation, the terms "treated plots" and "treated trees" are defined as the asphalt sprayed plots and the trees planted on those plots. The terms "control plots" and "control trees" are defined as the plots on which no asphalt was sprayed and the trees planted on those plots.

Application of Asphalt to the Soil Surface

Asphalt was provided and sprayed by the Petroleum Mulches Project of the Ministry of Agriculture and Natural Resources. Although the formulation for the asphalt was not revealed by the project engineer due to administrative regulations, the base seemed to be medium curing asphalt (MC_2) with solid and liquid additives which modified its physico-chemical properties to suit the site and enhance the performance.

Asphalt was sprayed on the microwatersheds between the terraces at the rate of one liter/m^2 of soil surface in December 1969. The terraces were not treated (Figure 1). Truck-mounted tank and pumping facilities were used to distribute the asphalt through a system of hoses. Laborers carried the hoses with the applicator nozzles to the required sites and sprayed the asphalt.

The temperature of the asphalt was 60 C and the nozzle pressure 21.0 kg/cm^2. These specifications were provided by the Petroleum Mulches Project's field engineer. At this rate, temperature, and pressure the asphalt penetrated to depths ranging from three to 15 mm, with an average depth of five mm, making the soil surface nearly impermeable to water. Nonuniformity of the thickness of the asphalt-soil layer was caused by differences in slope, depressions in soil surface, and natural variations which are characteristic of any soil.

Planting

Tree seedlings were planted in hand dug pits in the terraces. The dimensions of the pits were 50 x 50 cm. Ten kg of cattle manure were mixed with the soil of each pit at the time of planting. One year old seedlings of Arizona cypress (*Cupressus arizonica* G.) grown in containers and bare rooted one year old seedlings of black locust (*Robinia pseudacacia* L.), ash (*Fraxinus rotundifolia* Mill.)[2], and hackberry (*Celtis caucasica* Hohen.) were planted on the assigned subplots of the treated and control plots of each block. Cuttings of fig (*Ficus carica* L.) were planted in 100 x 100 cm pits, with two cuttings per pit. Forty kg of cattle manure were mixed with the soil of each pit at the time of planting.

Planting was started on February 22, 1970, after the soil was thawed out, and continued through March 7, 1970. It is a common practice to irrigate seedlings following planting to prevent dehydration of roots as well as providing better contact between the disturbed soil of the pit and that of terrace. This was not necessary here because 47.8 mm of precipitation fell from March 9 to March 18.

Measurements

Height growth and soil water potential were measured to assess the

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[2] *Fraxinus rotundifolia* Miller equals: *F. parvifolia*, *F. oxycarpa*, *F. oxyphylla*, *F. syriaca* (Rechinger, 1968).

effect of asphalt treatment on the growth of the trees. Tree height is the most sensitive growth parameter for measuring site productivity. Soil water is generally accepted as the most important growth factor (Zahner, 1968). However, visual observation during the second year of the project indicated differences in crown cover and girth of the saplings between the treated and control plots. Therefore, measurements of the horizontal projection of crown diameter and stem diameter at 20 cm height were also obtained starting in April 1972.

Calibrated gypsum blocks were placed at depths of 15, 30, and 60 cm in the middle of the black locust subplot of each main plot to measure soil water potential. It was later realized that the blocks had been placed close to the saplings so that the acquired data measured the water consumption of the saplings, and not the water potential of the soil of the main plots. It was therefore necessary to install new blocks. Since the sprayed asphalt had deteriorated somewhat by that time and disturbance of the surface would have occurred, the new installation of gypsum blocks would not have measured values of soil water potential as they would have existed in a newly applied treatment. Therefore, new plots were prepared at an adjacent location.

To measure the efficiency of the asphalt cover in inducing surface runoff eight runoff plots were installed in September 1971 and sprayed with asphalt in December 1971.

The data from these runoff plots were to be used for the development of a regression equation correlating percent runoff with rainfall amount and intensity and age of the asphalt cover. A second regression equation correlating soil water potential with runoff and a third equation correlating growth with soil water potential were also desired.

The development of equations correlating amount of rainfall, age of the asphalt cover, and growth of trees was the principle goal of this project.

Soil Water Potential

Soil water potential was measured with calibrated gypsum blocks once each week throughout the life of the project except when snow cover hindered the measurement. These blocks were placed at 15, 30, 45, and 60 cm depths in the center of the treated and control plots located midway between the crest and toe of the experimental hill on S and N exposures. The gypsum blocks were installed equidistance between two tree rows. Calibrations of soil water potential versus conductivity of the blocks were obtained in the laboratory (Figure 3). Meter readings were converted to soil water content and soil water potentials using soil water characteristic curves obtained previously (Figure 4).

Surface Runoff

Eight 2 x 10 m runoff plots with the 10 m long side parallel to the slope were used to measure the efficiency of asphalt in inducing surface runoff. Steel borders, 50 cm high, were installed around each plot to define the catchment area and improve the accuracy of the runoff measurements. Four plots were sprayed in December 1971 with

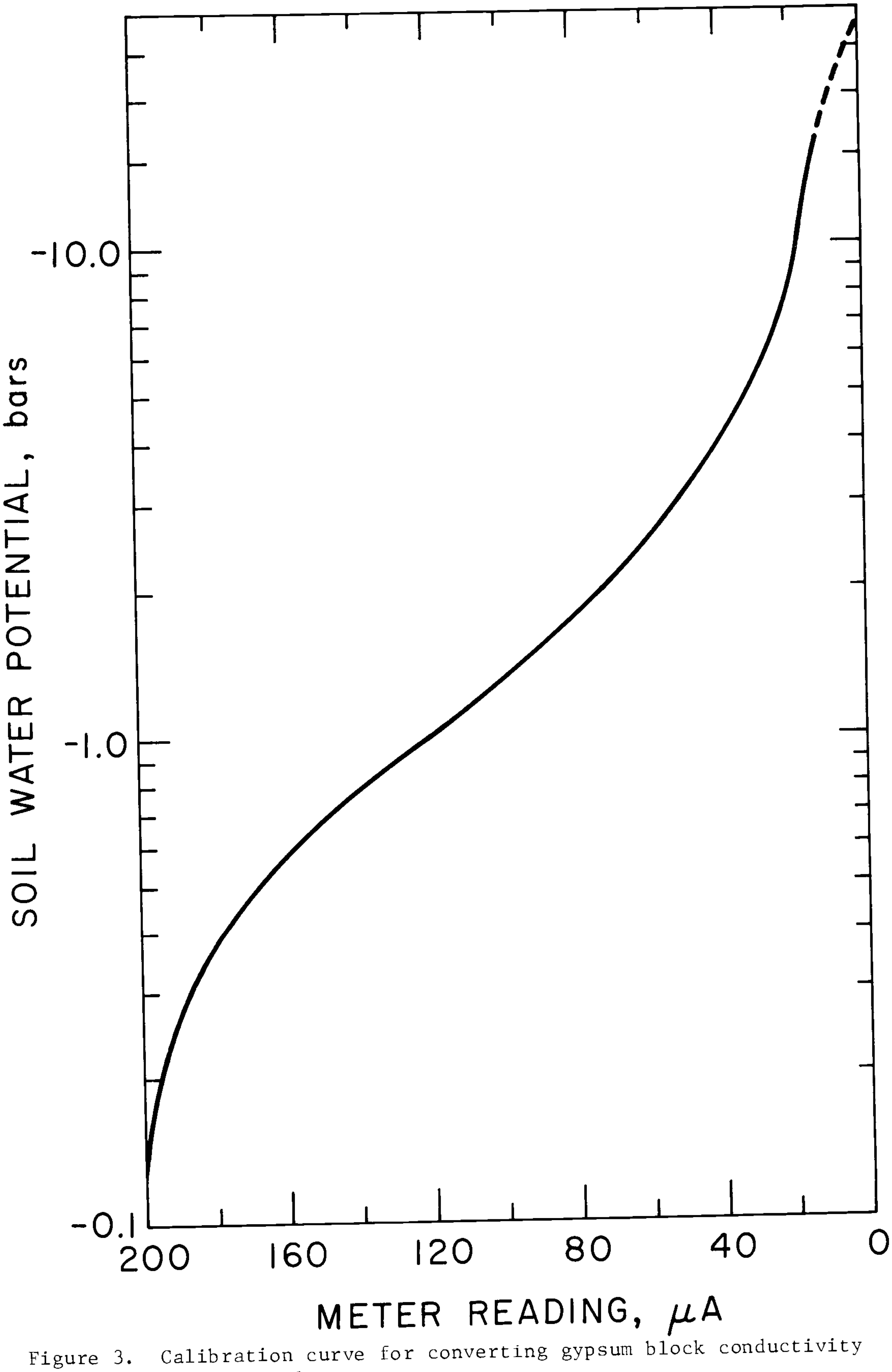

Figure 3. Calibration curve for converting gypsum block conductivity to soil water potential.

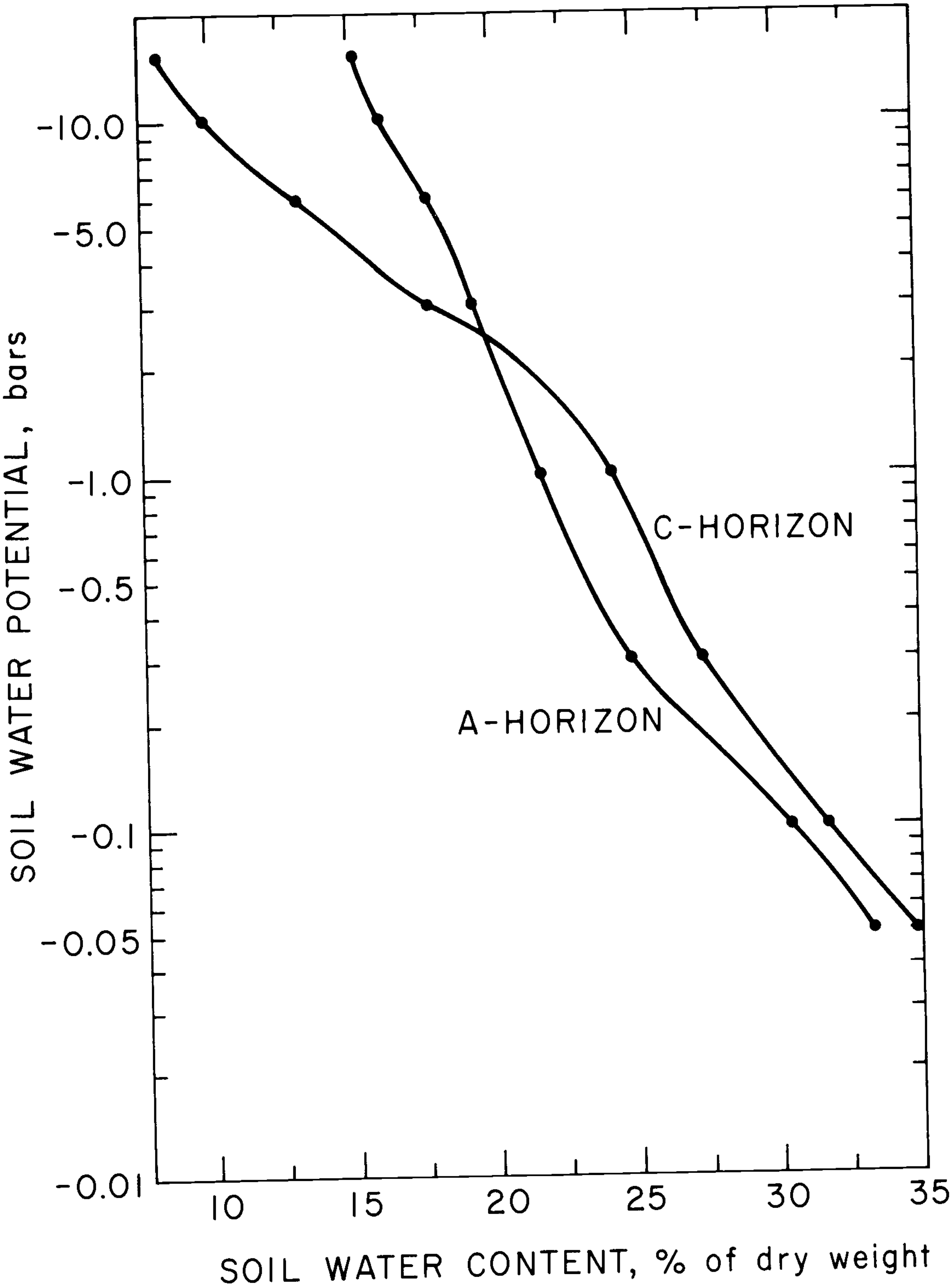

Figure 4. Soil water characteristic curves for the A and C horizons of the experimental site.

asphalt similar to that used previously at the same specifications of rate, temperature, and pressure.

Four plots were left as control (Figure 5). However, since one of the control plots was sprayed with asphalt of a different formulation and one of the treated plots proved to be extremely leaky three replications instead of four were used in the statistical analyses.

The runoff from each plot was collected in a 200 liter barrel located at the lower end of the plot and connected to the lowest point on the plot by a 7.5 cm ID steel pipe. Each barrel was covered with a close fitting lid to prevent precipitation from falling into the barrel and to prevent evaporation of the collected runoff water. A calibrated stick was used to obtain the amount of runoff in each barrel in liters. The runoff was measured after each rainstorm or twice daily during continuous rainfall events, and daily during snow melting periods.

A recording rain gauge with a speed of 12 mm/hour was used to measure the amount and intensity of rain.

Calibrated gypsum blocks were placed at depths of 10, 20, and 30 cm in the lower end of runoff plots, 20 cm from the wall. Ease of installation and measurement prompted installation of the blocks at the lower end of each plot. Measurements were made weekly and converted to soil water potential as described earlier. Soil water potentials measured at the same depth under the asphalt cover and on the control plots simulate conditions between two consecutive terraces on the sloping microwatersheds. The measured potentials under the asphalt cover also indicate the change in the permeability of the membrane as it ages.

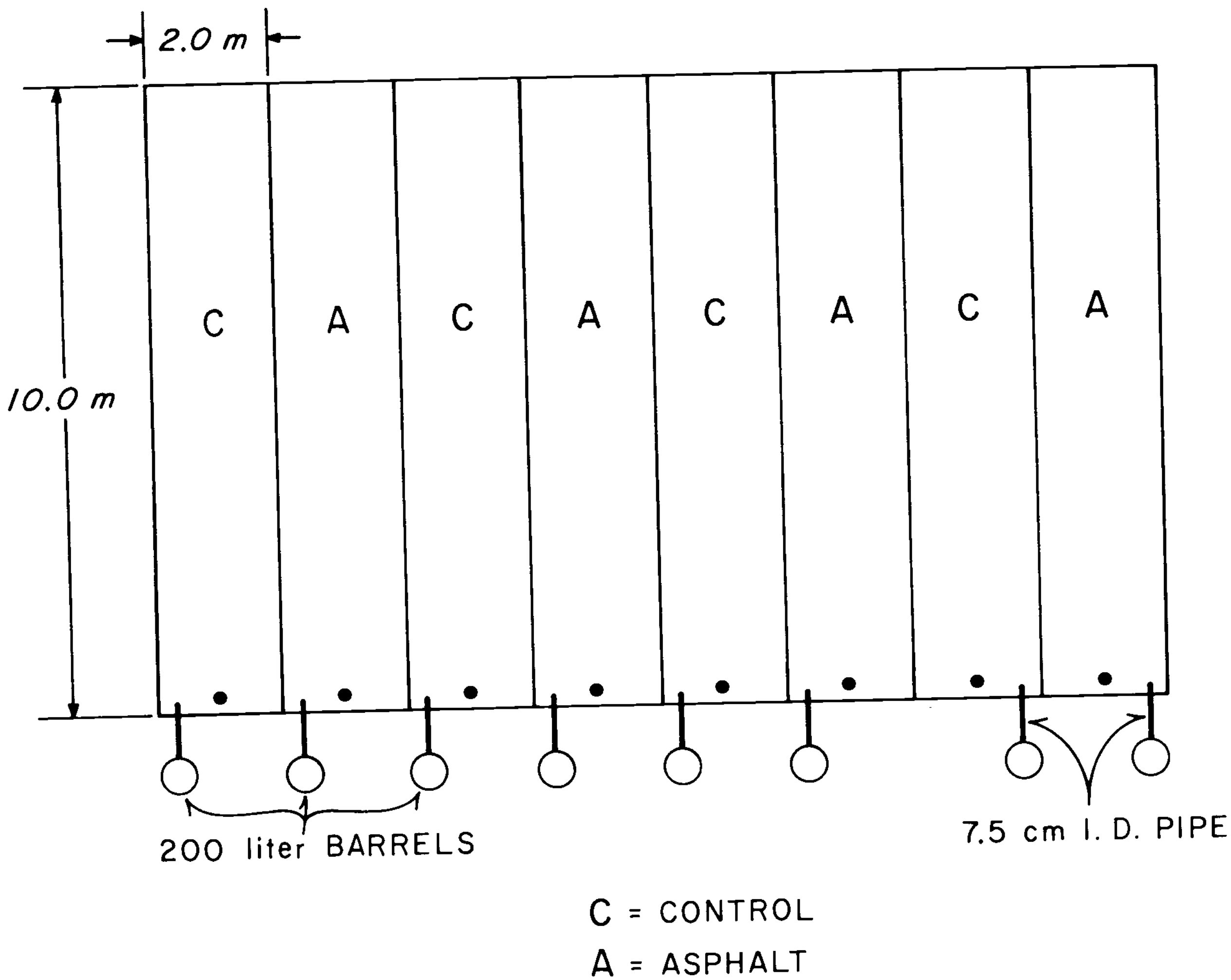

Figure 5. Schematic diagram of runoff plots for the measurement of the efficiency of asphalt in inducing surface runoff. Solid circles indicate the positions of gypsum moisture blocks installed at depths of 10, 20, and 30 cm.

The size, shape, and geology of runoff plots were not the cause of concern as regards to the applicability of the results to the practical situation as was discussed by Amerman and McGuinness (1967). These plots with a surface area of 20 m^2 were about twice as large as the area of microwatershed contributing runoff to a unit terrace which is two m wide, three m long and contains two tree seedlings 1.25 m apart. The amount of precipitation and the geology of the site did not lead to transient flow (underflow). In most instances the amount of precipitation was such that only the upper centimeters of soil were wetted. The shape of the watersheds, which were rectangles two m wide and ten m long, did not pose problems. Identical results, not reported here, were obtained from plots five m wide and four m long.

Growth

The height of each seedling was obtained to the closest cm by measuring from the collar which is at the soil-air interface to the highest point at planting time, and yearly thereafter in April. Crown diameter to the closest cm, and stem diameter to the closest mm, were measured starting in April 1972. Using the measured diameters the corresponding areas were calculated assuming that both crown cover and stem cross section form circles in their horizontal projection.

Most of the seedlings of black locust, hackberry, and ash and cuttings of fig did not have crowns when they were planted and crowns of Arizona cypress were very small. The stem diameters at the time of planting were equal in both treated and control plots.

Seedling Survival

Survival of planted seedlings was determined after the first growing season and yearly thereafter, usually in September. The criteria for mortality were lack of leaves and brittleness of the main stem. Since animals were excluded from the area by a fence, the mortality data indicate true physiological death.

Seedlings which died during the experimental period were deleted from the final data tabulation, and statistical analyses were performed using the remaining trees (Appendix Table 6). For example, 36 seedlings were initially planted on a given plot. Three died during the first year, two died in the second year, one died in the third year, and no deaths occurred in the fourth and fifth years. The six dead trees were then deleted from the data of the first year and the analyses were carried out on the 30 remaining trees. Also deleted from the analyses were Ficus carica L. and Celtis caucasica Hohen. due to their high rate of mortality. Ficus carica L. did not tolerate the low winter temperatures and the seedlings of Celtis caucasica Hohen. apparently were of low quality.

RESULTS AND DISCUSSION

The following chapters contain analyses of the effects of the runoff produced by the asphalt treatment on growth of the planted tree species including such variables as survival rate, height growth, crown cover, and stem cross section. The main factors contributing to growth, namely runoff volume from the asphalt sprayed areas and the resultant soil water potentials are also presented.

Survival

Survival of the three tree species during a period of 4.5 years after planting is presented in Table 1. A statistical analysis of the observations is shown in Table 2. Although the treated species generally show higher survival rates than the control tree, these differences are not statistically significant.

Pooling the seedlings from both treatments, survival of *Robinia pseudacacia* L. was higher than that of *Cupressus arizonica* G. at the ten percent level of significance. Differences in survival between *Robinia pseudacacia* L. and *Fraxinus rotundifolia* Mill., and between *Fraxinus rotundifolia* Mill. and *Cupressus arizonica* G. were not significant.

Differences in survival of the tree species on the control plots were not significant, but the treated *Robinia pseudacacia* L. and *Fraxinus rotundifolia* Mill. showed higher survival than the treated *Cupressus arizonica* G. at the ten percent level of significance.

Table 1. Survival in percent of the tree species used in the experiment, 4.5 years after planting.

Species	Treatment	Exposure				Average
		S	SE	NE	N	
		%	%	%	%	%
Robinia pseudacacia L.	asphalt	95.0	96.0	92.8	96.3	95.0
	control	95.0	89.4	79.8	92.8	89.2
Cupressus arizonica G.	asphalt	82.5	86.2	80.0	66.6	78.8
	control	96.4	82.1	75.0	63.5	79.2
Fraxinus rotundifolia Mill.	asphalt	78.7	92.8	93.5	98.8	90.9
	control	92.1	64.0	84.7	84.4	81.3

Table 2. Analysis of variance for survival of the three tree species used in the experiment, 4.5 years after planting.

Source of variation	df	SS	MS	Observed F	Required F 10%	5%	1%
Replications (Reps)	3	145.5167	48.5056	0.34	5.39	9.28	29.46
Treatments (Trs)	1	150.0000	150.0000	1.05	5.54	10.13	34.12
Reps x Trs (Error a)	3	427.4633	142.4878				
Species (Sps)	2	687.9808	343.9904	4.06*	2.81	3.88	6.93
Sps x Trs	2	103.3075	51.6537	0.61	"	"	"
Sps x Reps	6	814.4958					
Sps x Reps x Trs (Error b)	6	200.8492	84.6128				
Total	23	2529.6133					

* Significant at the 5% level.

The difference between the survival of the first two species was not significant.

Height Growth

Height growth data for each of the five growing seasons by species, treatment, and exposure along with the initial heights, cumulative heights, and final heights are presented in Tables 3 through 5 and Figures 6 through 8. Tables 6 through 11 show the analyses of variance of the height growth data and Table 12 summarizes the levels of significance by species and treatment for each of the five years and for the duration of the experiment.

The asphalt treatment resulted in increased height growth for each of the three species during each year except for *Fraxinus rotundifolia* Mill. in 1973. The difference was significant at the five percent level in 1970, at the one percent level in 1971, at the 20 percent level in 1972 and 1973, not significant in 1974, but significant at the five percent level for the entire period.

On the species level, the cumulative growth of the treated *Robinia pseudacacia* L. and *Fraxinus rotundifolia* Mill. was greater than that of their controls at the one and the five percent level of significance, respectively. The increase in growth due to treatment was significant at the 20 percent level for *Cupressus arizonica* G.

The highest growth rate on the asphalt treated plots occurred on the S exposure for all of the three species. The next highest rate of growth occurred on the SE exposure. Northeastern and N exposures had nearly identical rates of growth. The same trend did not occur on

Table 3. Initial height, yearly height growth, cumulative height growth, and final height in cm of *Robinia pseudacacia* L. planted in four exposures in the experiment for the period 1970-1974.

	Exposure				
	S	SE	NE	N	Average
	cm				
Asphalt					
Initial height	99.4	116.8	119.8	104.6	110.1
1970	18.5	24.3	20.3	29.6	23.1
1971	66.4	64.5	48.9	45.0	56.2
1972	70.6	38.7	24.9	32.3	41.6
1973	46.7	40.1	39.6	30.6	39.2
1974	29.7	22.3	13.7	23.7	22.3
1970-1974	231.9	189.9	147.4	161.2	182.6
Final height	331.3	306.7	267.2	265.8	292.7
Control					
Initial height	101.2	114.2	122.7	107.6	111.4
1970	14.4	14.2	10.0	20.1	14.6
1971	31.7	27.3	23.9	28.3	27.8
1972	23.5	35.1	16.9	26.3	25.4
1973	28.4	38.8	20.9	19.5	26.9
1974	14.7	21.6	15.6	21.1	18.2
1970-1974	112.7	137.0	87.3	115.3	113.0
Final height	213.9	251.2	210.0	222.9	224.5

Table 4. Initial height, yearly height growth, cumulative height growth, and final height in cm of Cupressus arizonica G. planted in four exposures in the experiment for the period 1970-1974.

	Exposure				
	S	SE	NE	N	Average
	cm				
Asphalt					
Initial height	18.8	18.0	22.6	20.0	19.8
1970	26.0	35.1	26.4	23.6	27.7
1971	43.5	49.7	34.3	29.4	39.2
1972	35.2	23.2	20.1	22.9	25.3
1973	40.2	34.4	27.6	32.2	33.6
1974	30.3	24.7	17.7	19.8	23.1
1970-1974	175.2	167.1	126.1	127.9	149.0
Final height	194.0	185.1	148.7	147.9	168.9
Control					
Initial height	17.0	18.3	23.0	22.1	20.1
1970	27.8	32.6	24.4	15.7	25.1
1971	33.8	45.1	29.4	21.4	32.4
1972	26.9	28.1	14.7	15.1	21.2
1973	31.0	35.9	24.5	37.5	32.2
1974	18.3	21.4	24.5	12.5	19.1
1970-1974	137.8	163.1	117.5	102.2	130.1
Final height	154.8	181.4	140.5	124.3	150.3

Table 5. Initial height, yearly height growth, cumulative height growth, and final height in cm of *Fraxinus rotundifolia* Mill. planted in four exposures in the experiment for the period 1970-1974.

	Exposure				
	S	SE	NE	N	Average
	cm				
Asphalt					
Initial height	83.8	79.8	86.3	82.5	83.1
1970	13.4	12.9	8.2	13.1	11.9
1971	43.7	38.8	40.1	36.8	39.8
1972	48.6	43.8	36.4	39.4	42.0
1973	32.4	31.3	13.1	6.6	20.8
1974	24.8	18.2	11.7	16.3	17.7
1970-1974	162.9	145.0	109.5	112.2	132.4
Final height	246.7	224.8	195.8	194.7	215.5
Control					
Initial height	82.6	78.9	81.9	88.8	83.0
1970	8.6	11.2	4.5	8.0	8.0
1971	28.6	32.5	26.7	19.8	26.9
1972	38.1	50.9	14.9	20.9	31.2
1973	32.3	28.3	14.7	10.1	21.3
1974	18.1	19.3	11.5	10.3	14.8
1970-1974	125.7	142.2	72.3	69.1	102.3
Final height	208.3	221.1	154.2	157.9	185.3

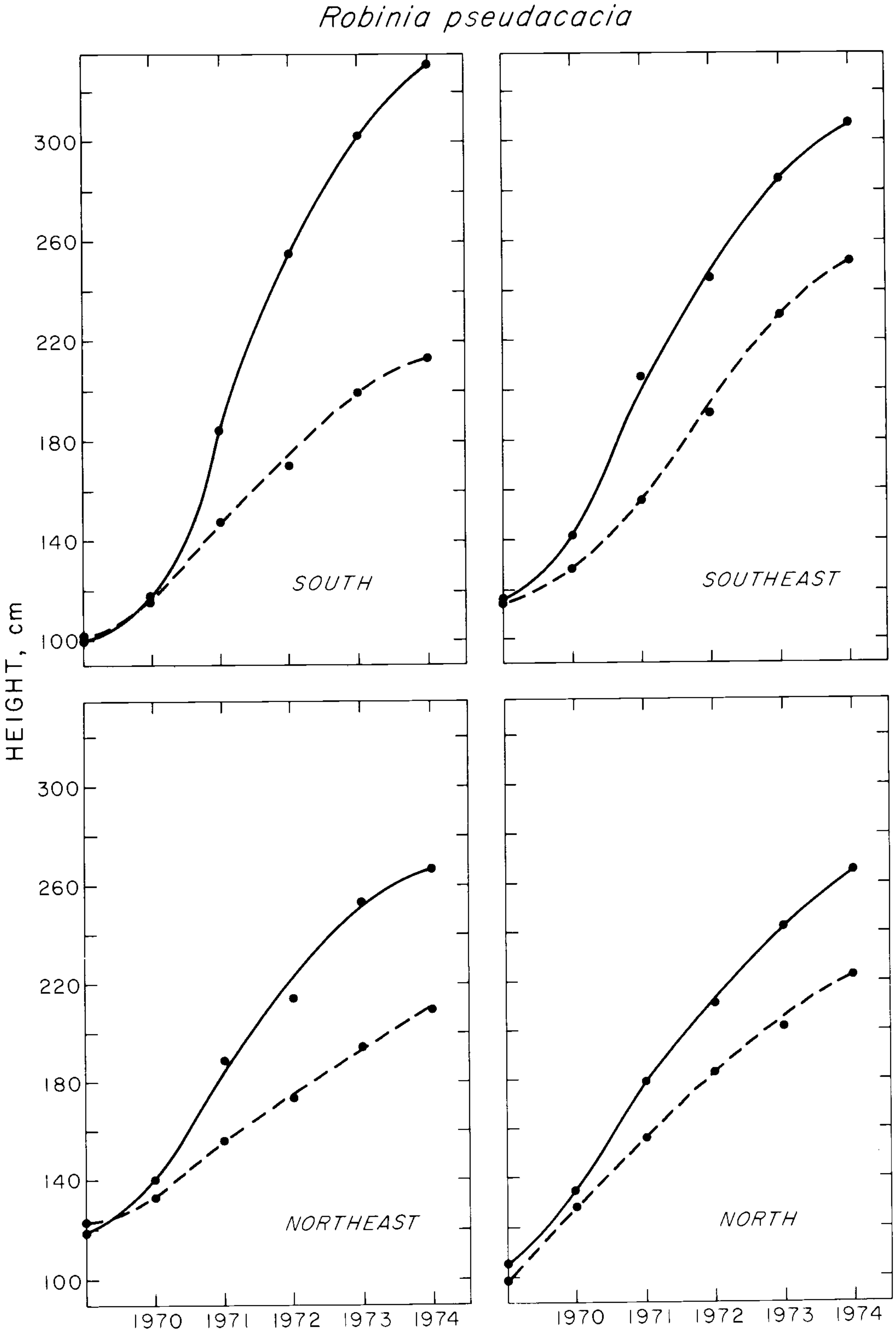

Figure 6. Initial height and growth of Robinia pseudacacia L. during the 1970-1974 period for indicated exposures. Solid lines indicate plants on the asphalt treated plots, broken lines indicate plants on the control plots.

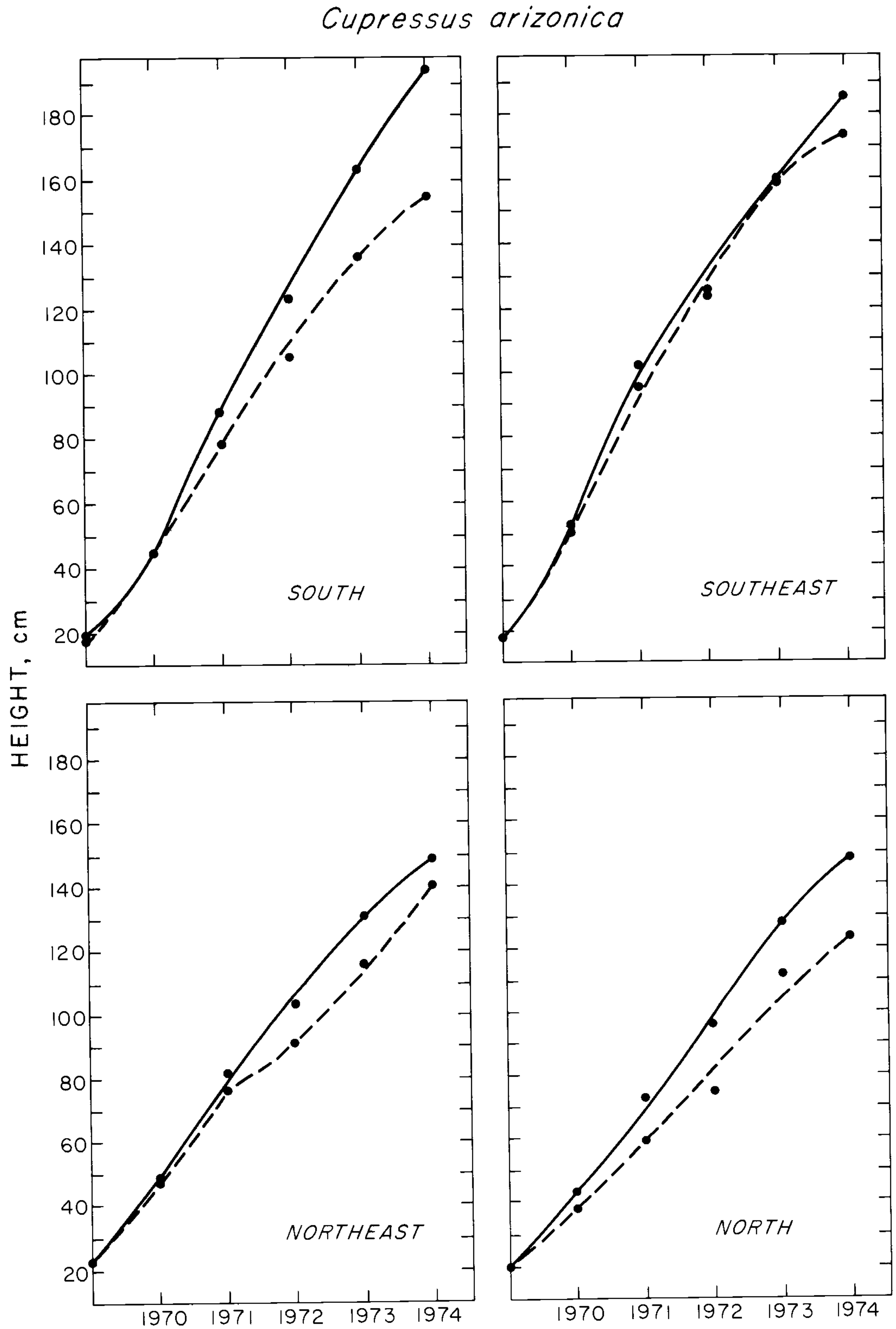

Figure 7. Initial height and growth of Cupressus arizonica G. during the 1970-1974 period for indicated exposures. Solid lines indicate plants on the asphalt treated plots, broken lines indicate plants on the control plots.

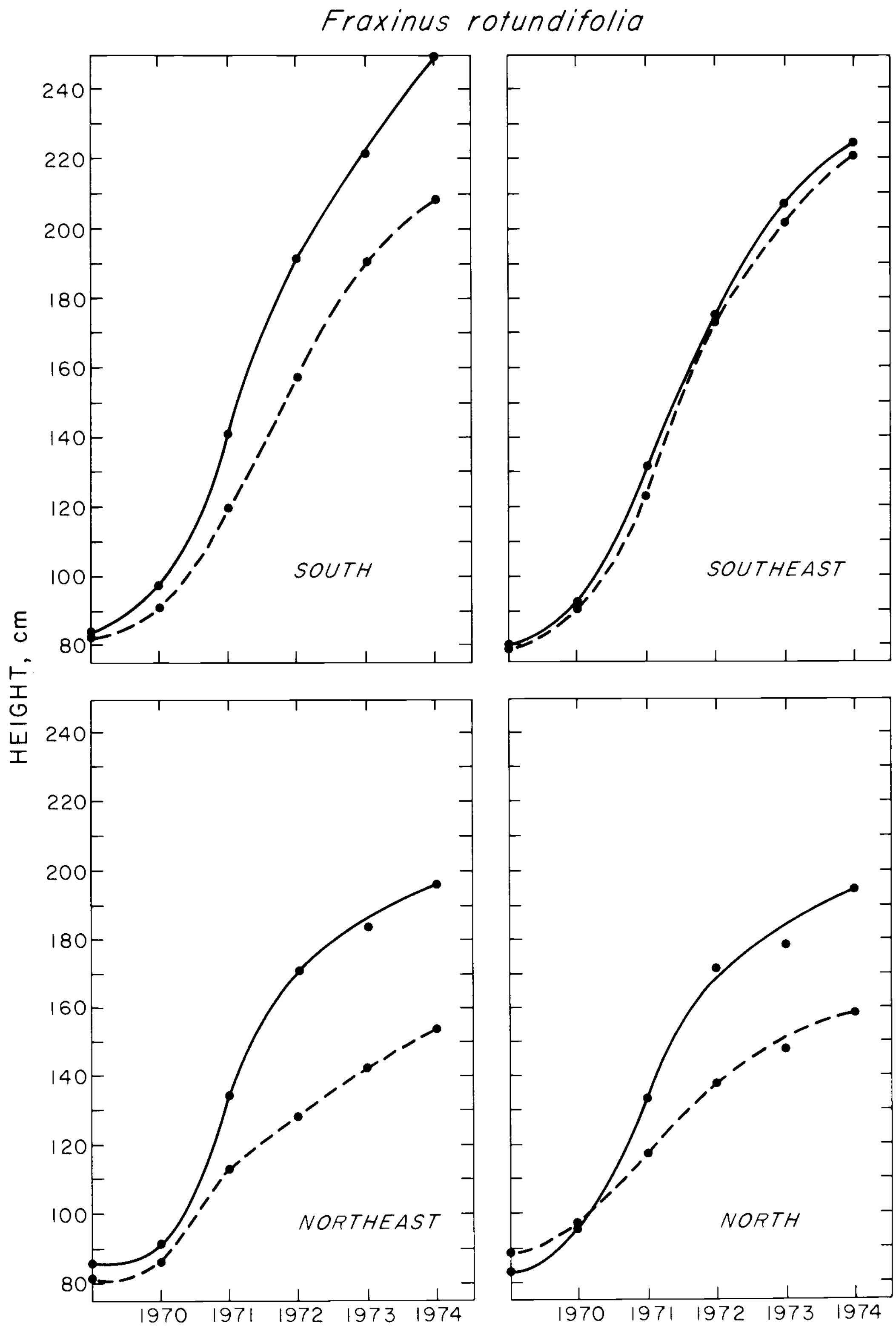

Figure 8. Initial height and growth of Fraxinus rotundifolia Mill. during the 1970-1974 period for indicated exposures. Solid lines indicate plants on the asphalt treated plots, broken lines indicate plants on the control plots.

Table 6. Analysis of variance for height growth during 1970 of the three tree species used in the experiment.

Source of variation	df	SS	MS	Observed F	Required F 10%	5%	1%
Replications (Reps)	3	112.3546	37.4515	5.61	5.39	9.28	29.46
Treatments (Trs)	1	149.5004	149.5004	22.39*	5.54	10.13	34.12
Reps x Trs (Error a)	3	20.0246	6.6749				
Species (Sps)	2	1086.7158	543.3579	24.92**	2.81	3.88	6.93
Sps x Trs	2	38.3058	19.1529	0.87	"	"	"
Sps x Reps	6	241.0842	21.7998				
Sps x Reps x Trs (Error b)	6	20.5142					
Total	23	1668.4996					

* Significant at the 5% level.

** Significant at the 1% level.

Table 7. Analysis of variance for height growth during 1971 of the three tree species used in the experiment.

Source of variation	df	SS	MS	Observed F	Required F 10%	5%	1%
Replications (Reps)	3	667.3400	222.4467	20.64*	5.39	9.28	29.46
Treatments (Trs)	1	1545.6150	1545.6150	143.44**	5.54	10.13	34.12
Reps x Trs (Error a)	3	32.3250	10.7750				
Species (Sps)	2	316.0633	158.0317	5.66*	2.81	3.88	6.93
Sps x Trs	2	495.3900	247.6950	8.87**	"	"	"
Sps x Reps	6	192.6000	27.9116				
Sps x Reps x Trs (Error b)	6	142.3400					
Total	23	3391.6733					

* Significant at the 5% level.

** Significant at the 1% level.

Table 8. Analysis of variance for height growth during 1972 of the three tree species used in the experiment.

Source of variation	df	SS	MS	Observed F	Required F 10%	5%	1%
Replications (Reps)	3	1433.2346	477.7449	3.08	5.39	9.28	29.46
Treatments (Trs)	1	647.9204	647.9204	4.18	5.54	10.13	34.12
Reps x Trs (Error a)	3	464.5246	154.8415				
Species (Sps)	2	781.5308	390.7654	6.94**	2.81	3.88	6.93
Sps x Trs	2	145.2308	72.6154	1.29	"	"	"
Sps x Reps	6	192.8992					
Sps x Reps x Trs (Error b)	6	482.0392	56.2448				
Total	23	4147.3796					

** Significant at the 1% level.

Table 9. Analysis of variance for height growth during 1973 of the three tree species used in the experiment.

Source of variation	df	SS	MS	Observed F	Required F 10%	5%	1%
Replications (Reps)	3	852.5212	284.1737	10.58*	5.39	9.28	29.46
Treatments (Trs)	1	116.6004	116.6004	4.34	5.54	10.13	34.12
Reps x Trs (Error a)	3	80.5546	26.8515				
Species (Sps)	2	754.5658	377.2829	9.79**	2.81	3.88	6.93
Sps x Trs	2	192.7258	96.3629	2.50	"	"	"
Sps x Reps	6	373.0375					
Sps x Reps x Trs (Error b)	6	89.0642	38.5084				
Total	23	2459.0695					

* Significant at the 5% level.

** Significant at the 1% level.

Table 10. Analysis of variance for height growth during 1974 of the three tree species used in the experiment.

Source of variation	df	SS	MS	Observed F	Required F		
					10%	5%	1%
Replications (Reps)	3	188.6717	62.8906	1.14	5.39	9.28	29.46
Treatments (Trs)	1	80.6667	80.6667	1.47	5.54	10.13	34.12
Reps x Trs (Error a)	3	164.1933	54.7311				
Species (Sps)	2	108.5033	54.2517	4.62*	2.81	3.88	6.93
Sps x Trs	2	1.5633	0.7817	0.06	"	"	"
Sps x Reps	6	100.9533	11.7283				
Sps x Reps x Trs (Error b)	6	39.7867					
Total	23	689.3383					

* Significant at the 5% level.

Table 11. Analysis of variance for height growth during 1970-1974 of the three tree species used in the experiment.

Source of variation	df	SS	MS	Observed F	Required F 10%	Required F 5%	Required F 1%
Replications (Reps)	3	12327.4646	4109.1549	7.95	5.39	9.28	29.46
Treatments (Trs)	1	9365.4504	9365.4504	18.12*	5.54	10.13	34.12
Reps x Trs (Error a)	3	1550.1212	516.7071				
Species (Sps)	2	3977.1700	1988.5850	13.42**	2.81	3.88	6.93
Sps x Trs	2	2827.3233	1413.6617	9.54**	"	"	"
Sps x Reps	6	766.1967	148.1172				
Sps x Reps x Trs (Error b)	6	1011.2100					
Total	23	31824.9362					

* Significant at the 5% level.

** Significant at the 1% level.

Table 12. Levels of significance for increase in height growth due to asphalt treatment for the period 1970-1974.

Species	Year					
	1970	1971	1972	1973	1974	1970-74
All species	x	xx	--	--	NS	x
Robinia pseudacacia L.	x	xxx	x	x	NS	xx
Cupressus arizonica G.	NS	+	NS	NS	NS	--
Fraxinus rotundifolia Mill.	NS	xx	--	NS	NS	x

xxx Greater than control at the 0.1% level of significance.

xx Greater than control at the 1% level of significance.

x Greater than control at the 5% level of significance.

\+ Greater than control at the 10% level of significance.

-- Greater than control at the 20% level of significance.

NS Not significant.

the control plots where the highest growth rates always occurred on the SE exposure.

The height growth of both Robinia pseudacacia L. and Cupressus arizonica G. was higher than that of Fraxinus rotundifolia Mill. at the one percent level of significance for the entire period, and in both treatments. There was no significant difference in height growth between Robinia pseudacacia L. and Cupressus arizonica G. The height growth of the treated Robinia pseudacacia L. was 69 cm or 61.5 percent greater than that of the control which was the highest increase of the experiment. The height growth of the treated Cupressus arizonica G. was 19 cm or 14.6 percent greater than that of the control which was the lowest increase of the experiment. The height growth of the treated Fraxinus rotundifolia Mill. was 30 cm or 29.4 percent greater than that of the control which was intermediate between the other two species.

Crown Growth

Growth data for the crown cover during the five growing seasons and total growth are presented in Table 13 and Figures 9 through 11 for all species, treatments, and exposures. Tables 14 through 18 show the analyses of variance and Table 19 summarizes the levels of significance by species and treatment for the years 1970-1971, 1972, 1973, and 1974 and for the entire period.

The initial crown cover was considered to be zero for all of the three species. Robinia pseudacacia L. and Fraxinus rotundifolia Mill. seedlings did not have measurable crowns at the time of planting, and

Table 13. Annual and cumulative increase of crown area in m^2 of the three tree species planted in four exposures in the experiment for the period 1970-1974.

Species	Treat-ment	Expo-sure	Year 1970-71	1972	1973	1974	1970-74
			m^2				
Robinia pseudacacia L.	asphalt	S	1.32	1.49	1.45	0.68	4.94
		SE	1.20	0.97	1.01	0.93	4.11
		NE	1.02	0.63	0.98	0.57	3.20
		N	0.95	0.81	0.62	0.70	3.08
		mean	1.12	0.98	1.02	0.72	3.83
	control	S	0.55	0.74	0.50	0.38	2.17
		SE	0.53	0.96	0.84	0.67	3.00
		NE	0.58	0.72	0.60	0.25	2.15
		N	0.48	0.65	0.90	0.15	2.18
		mean	0.53	0.76	0.71	0.36	2.38
Cupressus arizonica G.	asphalt	S	0.42	0.58	0.28	0.40	1.68
		SE	0.45	0.56	0.12	0.52	1.65
		NE	0.32	0.40	0.18	0.26	1.16
		N	0.20	0.23	0.23	0.27	0.93
		mean	0.35	0.44	0.20	0.36	1.36
	control	S	0.33	0.41	0.12	0.25	1.11
		SE	0.43	0.47	0.24	0.50	1.64
		NE	0.28	0.28	0.16	0.43	1.15
		N	0.12	0.27	0.22	0.19	0.80
		mean	0.29	0.36	0.19	0.34	1.18
Fraxinus rotundifolia Mill.	asphalt	S	0.13	0.40	0.31	0.30	1.14
		SE	0.15	0.36	0.27	0.42	1.20
		NE	0.15	0.29	0.19	0.18	0.81
		N	0.10	0.31	0.21	0.10	0.72
		mean	0.13	0.34	0.25	0.25	0.97
	control	S	0.06	0.21	0.29	0.14	0.70
		SE	0.08	0.29	0.26	0.20	0.83
		NE	0.05	0.10	0.06	0.07	0.28
		N	0.05	0.10	0.10	0.10	0.35
		mean	0.06	0.18	0.18	0.13	0.54

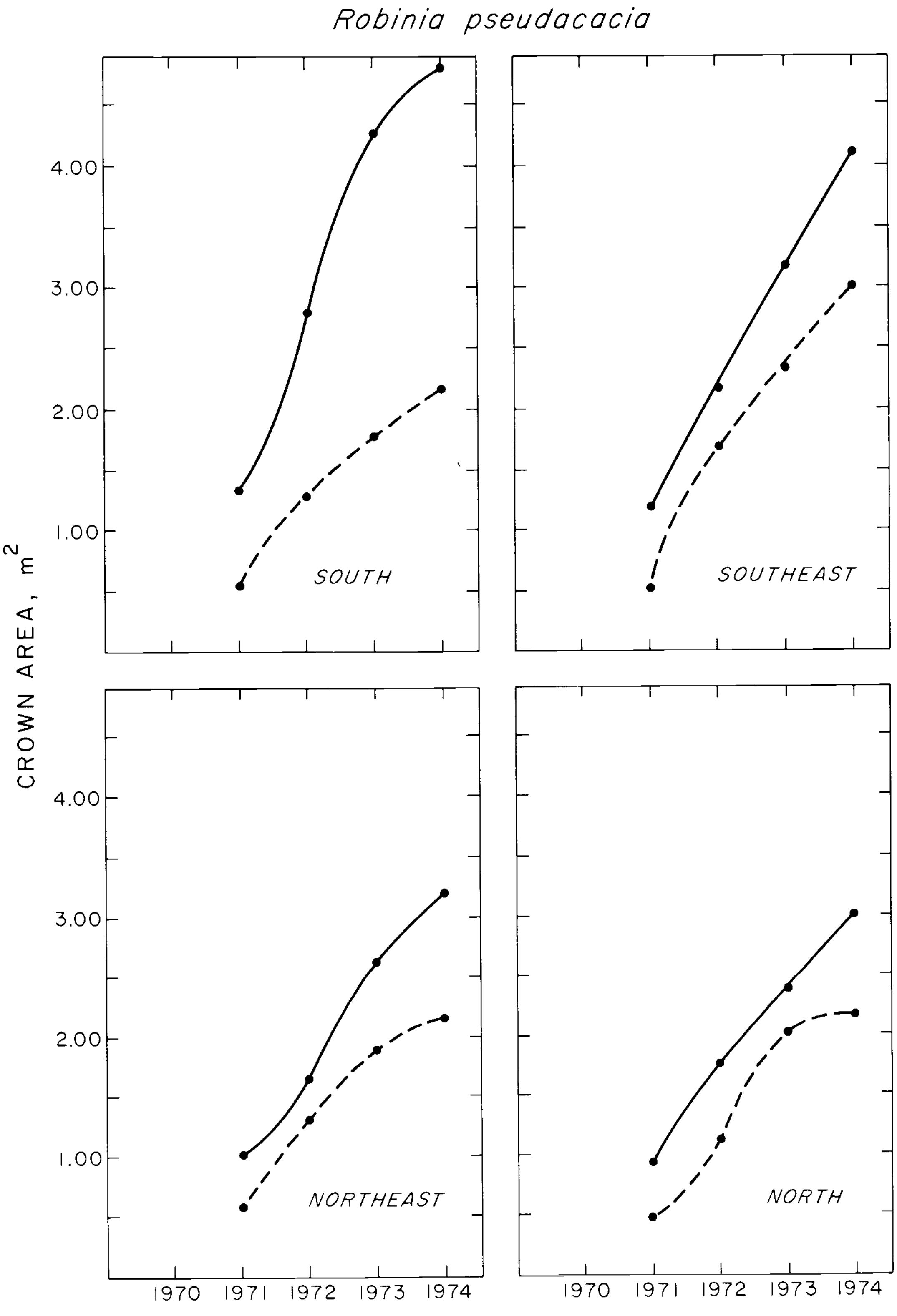

Figure 9. Growth of crown cover for <u>Robinia pseudacacia</u> L. during the 1970-1974 period for indicated exposures. Solid lines indicate plants on the asphalt treated plots, broken lines indicate plants on the control plots.

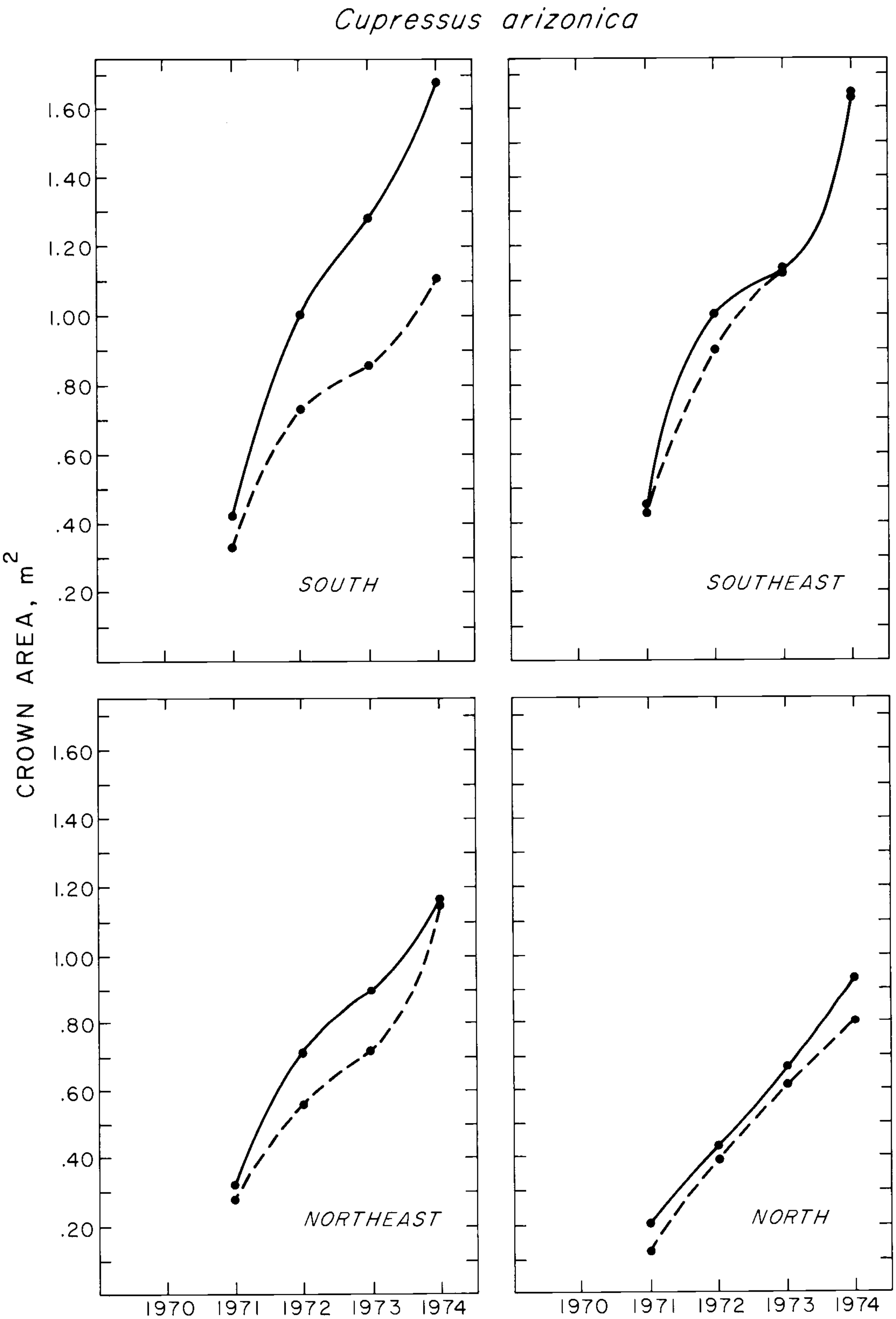

Figure 10. Growth of crown cover for Cupressus arizonica G. during the 1970-1974 period for indicated exposures. Solid lines indicate plants on the asphalt treated plots, broken lines indicate plants on the control plots.

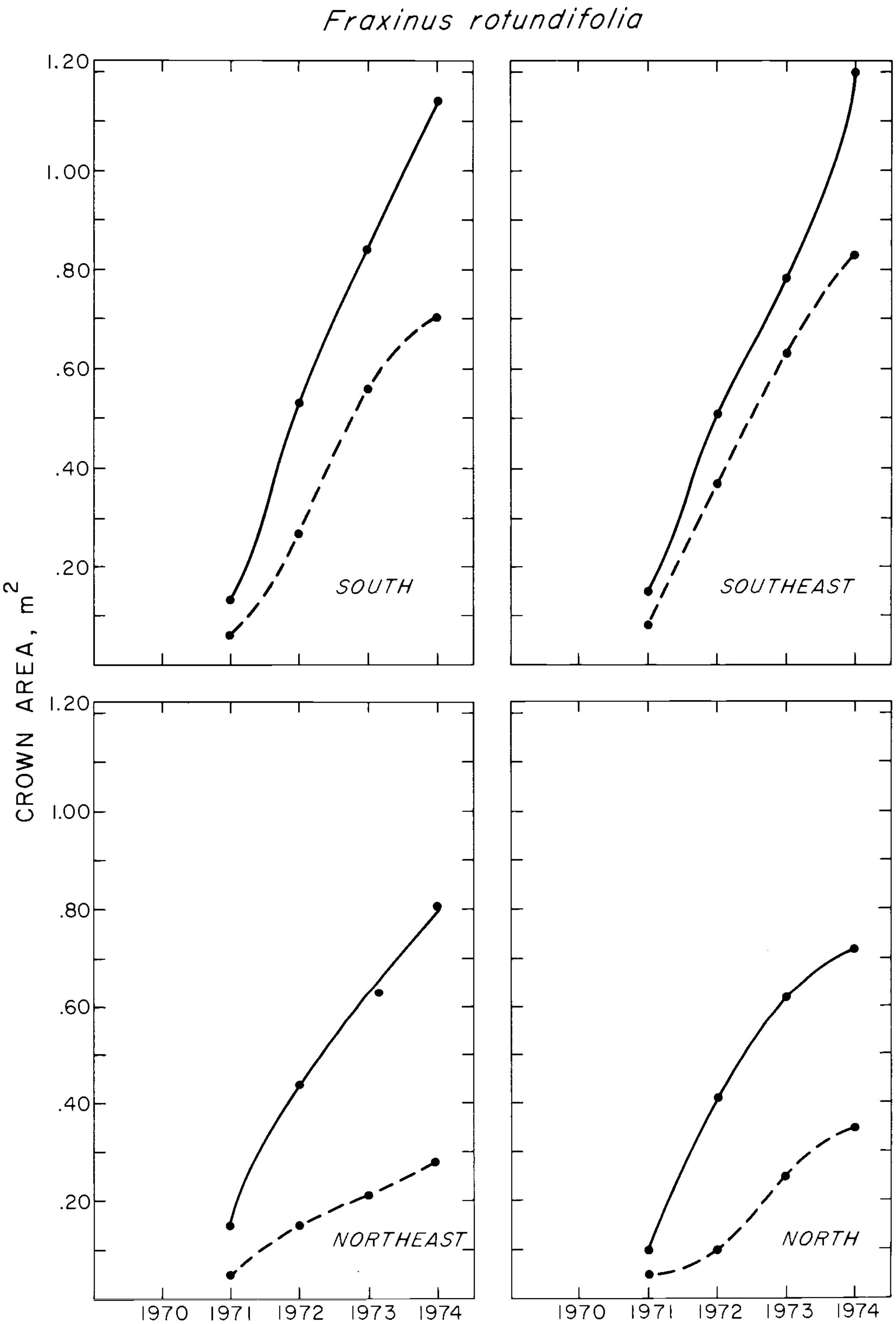

Figure 11. Growth of crown cover for Fraxinus rotundifolia Mill. during the 1970-1974 period for indicated exposures. Solid lines indicate plants on the asphalt treated plots, broken lines indicate plants on the control plots.

Table 14. Analysis of variance for crown area growth during 1970-1971 of the three tree species used in the experiment.

Source of variation	df	SS	MS	Observed F	Required F 10%	Required F 5%	Required F 1%
Replications (Reps)	3	0.0968	0.0323	7.34	5.39	9.28	29.46
Treatments (Trs)	1	0.3432	0.3432	78.00**	5.54	10.13	34.12
Reps x Trs (Error a)	3	0.0133	0.0044				
Species (Sps)	2	2.2564	1.1282	191.22**	2.81	3.88	6.93
Sps x Trs	2	0.3642	0.1821	30.86**	"	"	"
Sps x Reps	6	0.0444					
Sps x Reps x Trs (Error b)	6	0.0268	0.0059				
Total	23	3.1451					

** Significant at the 1% level.

Table 15. Analysis of variance for crown area growth during 1972 of the three tree species used in the experiment.

Source of variation	df	SS	MS	Observed F	Required F 10%	5%	1%
Replications (Reps)	3	0.2968	0.0989	3.06	5.39	9.28	29.46
Treatments (Trs)	1	0.1395	0.1395	4.31	5.54	10.13	34.12
Reps x Trs (Error a)	3	0.0968	0.0323				
Species (Sps)	2	1.6509	0.8254	46.39**	2.81	3.88	6.93
Sps x Trs	2	0.0155	0.0077	0.43	"	"	"
Sps x Reps	6	0.0801	0.0177				
Sps x Reps x Trs (Error b)	6	0.1334					
Total	23	2.4130					

** Significant at the 1% level.

Table 16. Analysis of variance for crown area growth during 1973 of the three tree species used in the experiment.

Source of variation	df	SS	MS	Observed F	Required F 10%	Required F 5%	Required F 1%
Replications (Reps)	3	0.0688	0.0229	0.42	5.39	9.28	29.46
Treatments (Trs)	1	0.1014	0.1014	1.86	5.54	10.13	34.12
Reps x Trs (Error a)	3	0.1631	0.0544				
Species (Sps)	2	2.3244	1.1622	47.24**	2.81	3.88	6.93
Sps x Trs	2	0.0944	0.0472	1.91	"	"	"
Sps x Reps	6	0.0422	0.0246				
Sps x Reps x Trs (Error b)	6	0.2532					
Total	23	3.0474					

** Significant at the 1% level.

Table 17. Analysis of variance for crown area growth during 1974 of the three tree species used in the experiment.

Source of variation	df	SS	MS	Observed F	Required F 10%	5%	1%
Replications (Reps)	3	0.2915	0.0972	20.25*	5.39	9.28	29.46
Treatments (Trs)	1	0.1667	0.1667	34.72**	5.54	10.13	34.12
Reps x Trs (Error a)	3	0.0144	0.0048				
Species (Sps)	2	0.4979	0.2489	32.11**	2.81	3.88	6.93
Sps x Trs	2	0.1198	0.0599	7.72**	"	"	"
Sps x Reps	6	0.0406	0.0077				
Sps x Reps x Trs (Error b)	6	0.0525					
Total	23	1.1834					

* Significant at the 5% level.

** Significant at the 1% level.

Table 18. Analysis of variance for crown area growth during 1970-1974 of the three tree species used in the experiment.

Source of variation	df	SS	MS	Observed F	Required F 10%	5%	1%
Replications (Reps)	3	2.3364	0.7788	3.55	5.39	9.28	29.46
Treatments (Trs)	1	2.8428	2.8428	12.98*	5.54	10.13	34.12
Reps x Trs (Error a)	3	0.6566	0.2189				
Species (Sps)	2	24.4397	12.2198	153.63**	2.81	3.88	6.93
Sps x Trs	2	1.8361	0.9181	11.54**	"	"	"
Sps x Reps	6	0.3361	0.0795				
Sps x Reps x Trs (Error b)	6	0.6184					
Total	23	33.0661					

* Significant at the 5% level.

** Significant at the 1% level.

Table 19. Levels of significance for increase in crown area growth due to asphalt treatment for the period 1970-1974.

	Year				
Species	1970-71	1972	1973	1974	1970-74
All species	xx	--	NS	xx	x
Robinia pseudacacia L.	xxx	+	+	xxx	xx
Cupressus arizonica G.	NS	NS	NS	NS	NS
Fraxinus rotundifolia Mill.	--	--	NS	+	--

xxx Greater than control at the 0.1% level of significance.

xx Greater than control at the 1% level of significance.

x Greater than control at the 5% level of significance.

\+ Greater than control at the 10% level of significance.

-- Greater than control at the 20% level of significance.

NS Not significant.

those of Cupressus arizonica G. seedlings were very small, having an area of less than 50 cm^2. The first measurement included growth of the crown cover for the period 1970-1971. The asphalt treatment increased the growth of crown cover for nearly all combinations of experimental variables. The only exceptions were Robinia pseudacacia L. planted on the N exposure in 1973 and Cupressus arizonica G. planted on the NE exposure in 1974.

The differences in growth between the treated and control plants were highly significant during 1970-1971 and during 1974, significant at the 20 percent level during 1972, and not significant during 1973. The increase in total growth achieved for the duration of the entire experiment was significant at the five percent level. The cumulative crown growth was 3.10 m^2 for Robinia pseudacacia L., 1.26 m^2 for Cupressus arizonica G., and 0.75 m^2 for Fraxinus rotundifolia Mill. The difference between Robinia pseudacacia L. and the other two species was significant at the 0.1 percent level. The difference between Fraxinus rotundifolia Mill. and Cupressus arizonica G. was significant at the one percent level.

The highest growth rate on asphalt treated plots always occurred on S exposure, followed by SE, NE, and N exposures. On the control plots the highest rate of growth occurred on the SE exposure, followed by S, NE and N exposures

The crown growth of the treated Robinia pseudacacia L. was 1.45 m^2 or 61.4 percent greater than that of the control which was the highest increase of the experiment. The crown growth of the treated Cupressus arizonica G. was 0.18 m^2 or 15.4 percent greater than that of the control which was the lowest increase of the experiment. The crown growth of the treated *Fraxinus rotundifolia* Mill. was 0.42 m^2 or 79.2 percent greater than that of the control which was intermediate between the other two species.

Stem Growth

Growth data for the stem cross section at 20 cm height are shown in Table 20 and in Figures 12 through 14 for the five growing seasons by species, treatment, and exposure. Also shown is the cross sectional area at the end of the experimental period. Tables 21 through 25 show the analyses of variance and Table 26 summarizes the levels of significance by species and treatment for the growing seasons 1970-1971, 1972, 1973, 1974 and for the entire period.

The asphalt treatment increased the growth of the stem cross section for every species on every exposure during each year of the experimental period, except on the SE exposure in 1974. The increase in growth on the treated over the control plots was significant at the five percent level for the period 1970-1973, not significant during 1974, but significant at the ten percent level for the entire period. The final cross section of 13.37 cm^2 for *Robinia pseudacacia* L. was higher than that of *Cupressus arizonica* G. which was 9.81 cm^2 and that of *Fraxinus rotundifolia* Mill. which was 8.73 cm^2. This difference was significant at the 0.1 percent level. The difference between *Cupressus arizonica* G. and *Fraxinus rotundifolia* Mill. was significant at the 20 percent level.

Table 20. Increase in stem cross section in cm^2 at the height of 20 cm during the indicated years.

Species	Treat-ment	Expo-sure	Stem cross section growth 1970-71	1972	1973	1974	1970-74
			----------		cm^2	----------	
Robinia pseudacacia L.	asphalt	S	5.72	4.56	6.04	4.98	21.30
		SE	5.42	4.30	3.99	2.25	15.96
		NE	4.00	4.18	3.69	1.13	13.00
		N	4.04	3.84	3.87	2.69	14.44
		mean	4.80	4.22	4.40	2.76	16.18
	control	S	3.14	1.64	3.35	2.27	10.40
		SE	3.29	2.95	3.26	3.24	12.74
		NE	3.23	2.53	3.04	1.03	9.83
		N	2.83	2.23	2.77	1.51	9.34
		mean	3.12	2.34	3.11	2.01	10.58
Cupressus arizonica G.	asphalt	S	1.20	3.55	6.17	4.34	15.26
		SE	2.54	2.93	4.20	4.50	14.17
		NE	1.13	1.58	3.57	2.21	8.49
		N	0.80	1.82	2.32	1.75	6.69
		mean	1.42	2.47	4.07	3.20	11.15
	control	S	1.22	2.01	4.16	2.33	9.72
		SE	1.69	2.64	2.73	5.25	12.31
		NE	1.07	1.36	2.55	1.80	6.78
		N	0.45	1.31	1.80	1.54	5.10
		mean	1.11	1.83	2.81	2.73	8.48
Fraxinus rotundifolia Mill.	asphalt	S	3.52	1.86	4.51	2.85	12.74
		SE	2.98	2.04	4.05	1.27	10.34
		NE	2.60	1.77	3.02	0.90	8.29
		N	2.32	1.79	2.22	0.97	7.30
		mean	2.86	1.87	3.45	1.50	9.67
	control	S	2.77	1.23	4.08	1.70	9.78
		SE	2.60	2.07	3.67	2.17	10.51
		NE	1.93	0.84	2.17	0.65	5.59
		N	1.86	0.97	2.11	0.40	5.34
		mean	2.29	1.28	3.01	1.23	7.81

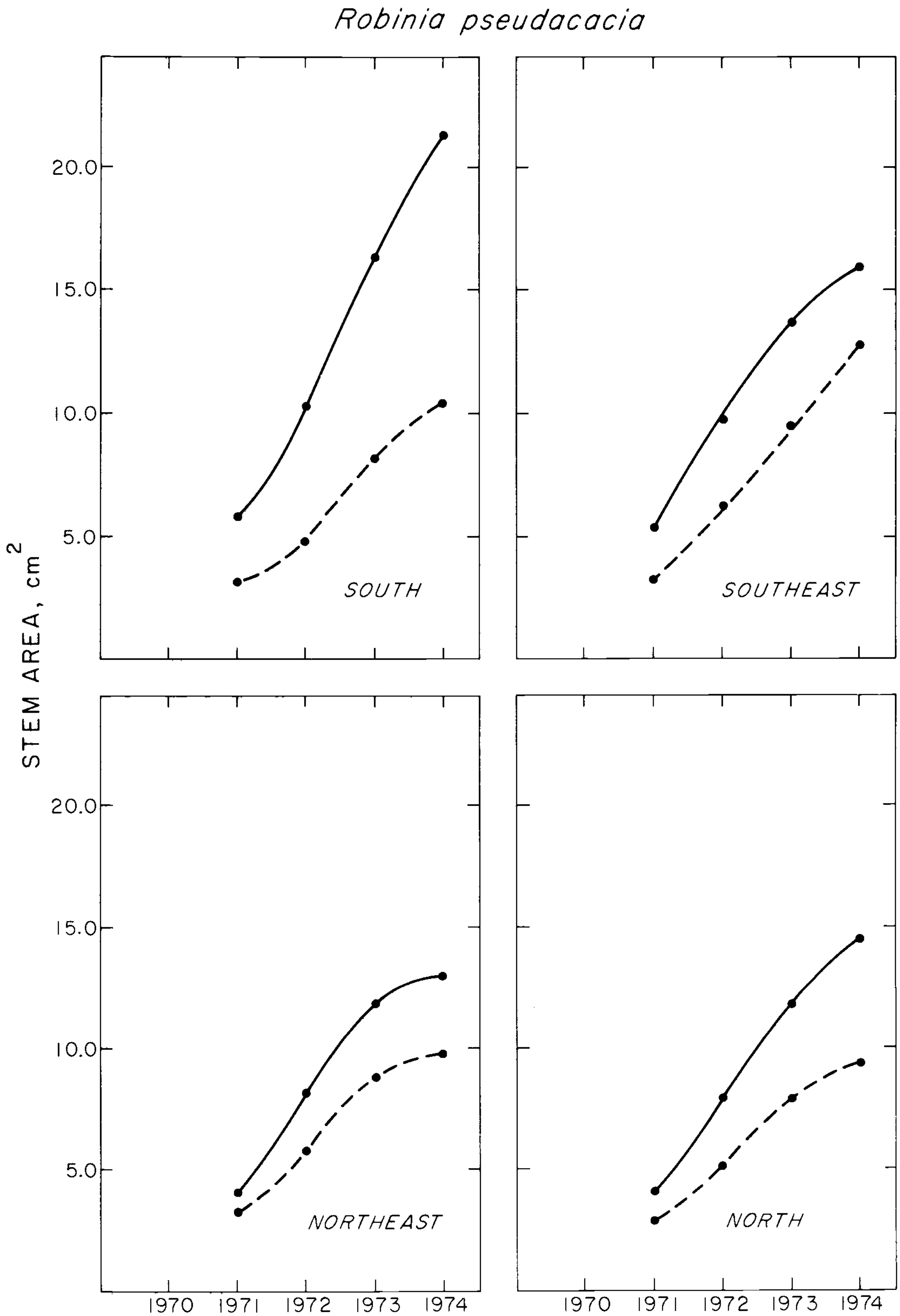

Figure 12. Growth of the stem cross section of Robinia pseudacacia L. during 1970-1974 for indicated exposures. Solid lines indicate plants on the asphalt treated plots, broken lines indicate plants on the control plots.

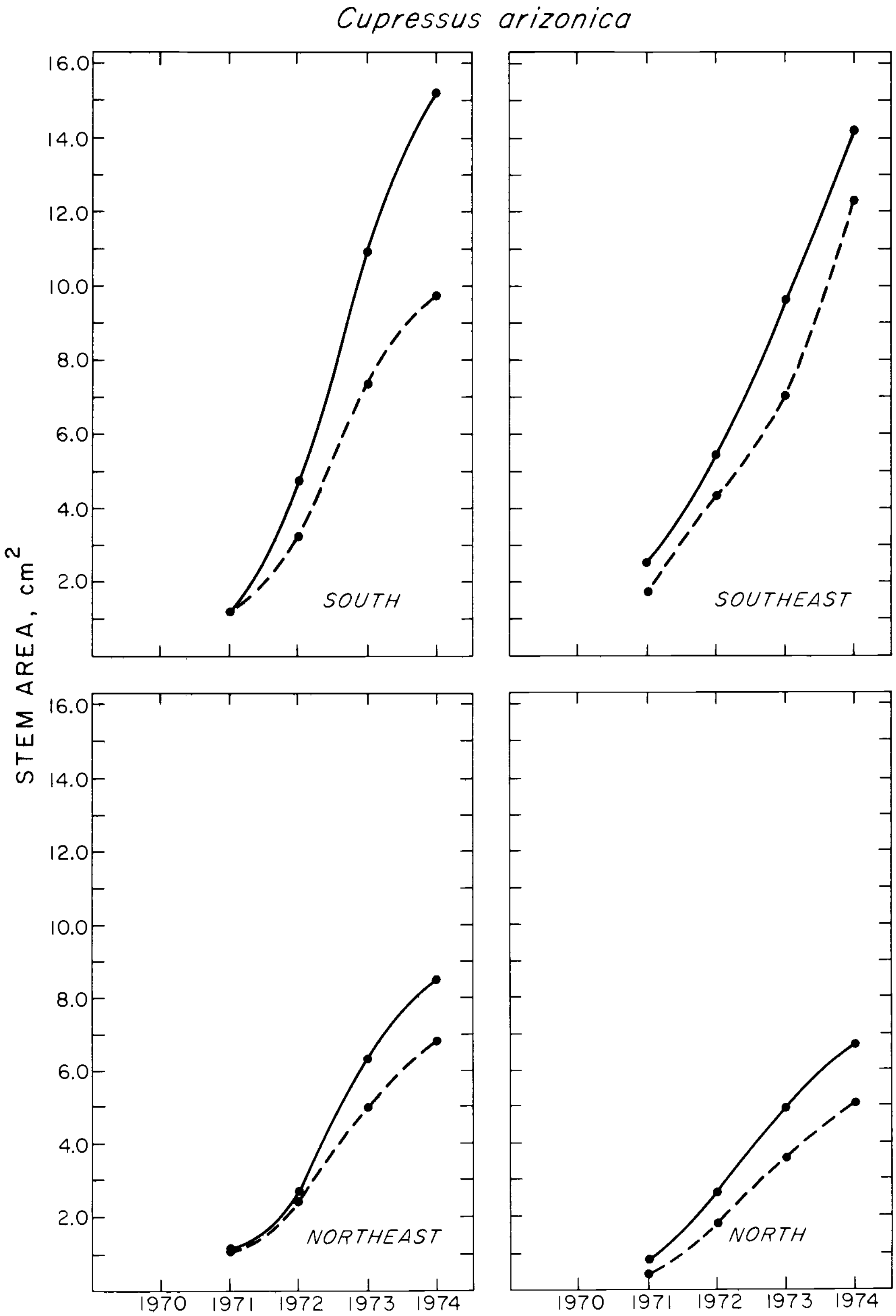

Figure 13. Growth of the stem cross section of Cupressus arizonica G. during 1970-1974 for indicated exposures. Solid lines indicate plants on the asphalt treated plots, broken lines indicate plants on the control plots.

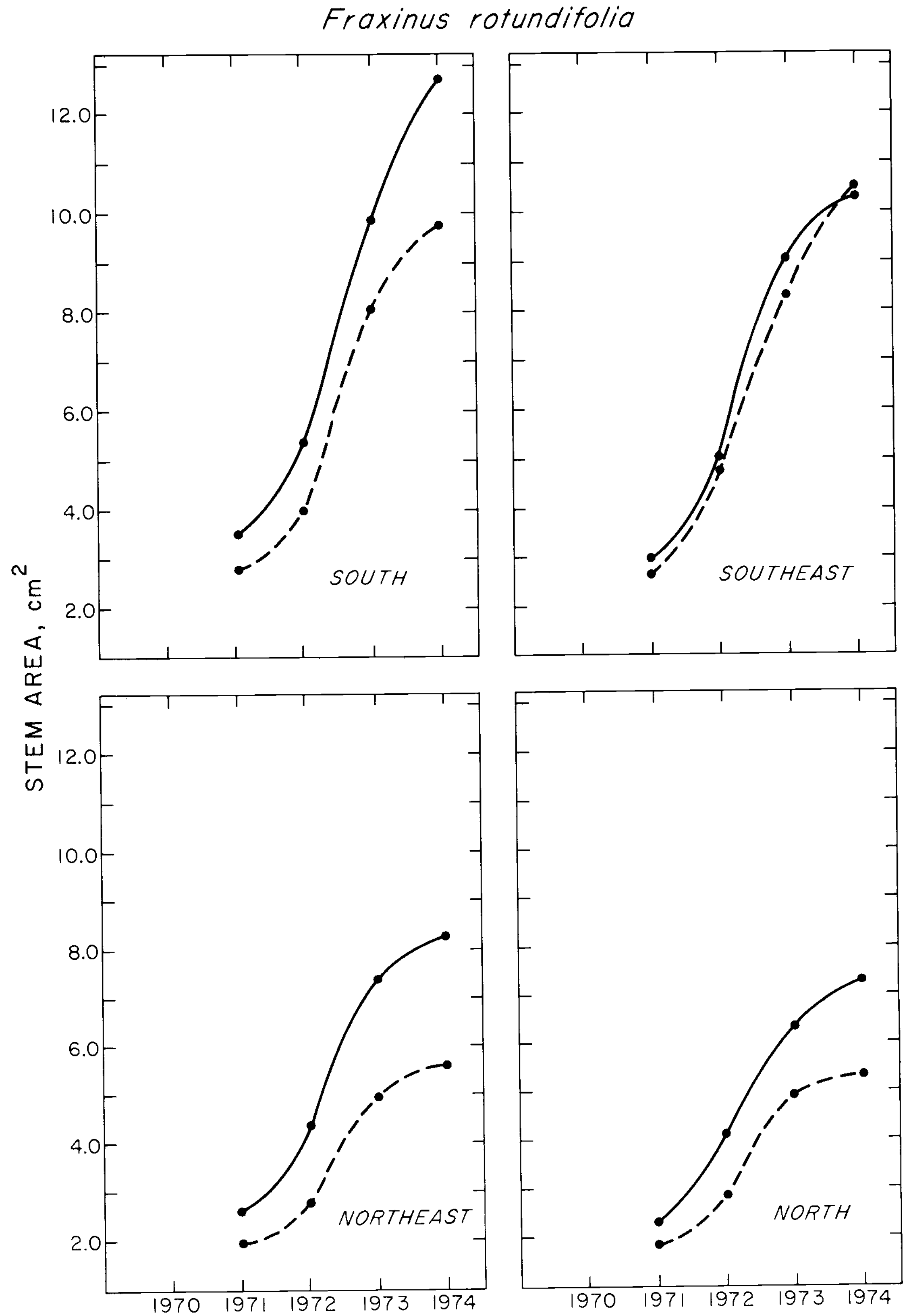

Figure 14. Growth of the stem cross section of Fraxinus rotundifolia Mill. during 1970-1974 for indicated exposures. Solid lines indicate plants on the asphalt treated plots, broken lines indicate plants on the control plots.

Table 21. Analysis of variance for growth of stem cross sections of the three tree species used in the experiment for the period 1970-1971.

Source of variation	df	SS	MS	Observed F	Required F 10%	5%	1%
Replications (Reps)	3	4.3310	1.4437	9.92*	5.39	9.28	29.46
Treatments (Trs)	1	4.3265	4.3265	29.75*	5.54	10.13	34.12
Reps x Trs (Error a)	3	0.4362	0.1454				
Species (Sps)	2	29.0868	14.5434	96.18**	2.81	3.88	6.93
Sps x Trs	2	2.0987	1.0493	6.93**	"	"	"
Sps x Reps	6	0.9416	0.1512				
Sps x Reps x Trs (Error b)	6	0.8720					
Total	23	42.0928					

* Significant at the 5% level.

** Significant at the 1% level.

Table 22. Analysis of variance for growth of stem cross sections of the three tree species used in the experiment for 1972.

Source of variation	df	SS	MS	Observed F	Required F 10%	5%	1%
Replications (Reps)	3	2.9816	0.9939	2.90	5.39	9.28	29.46
Treatments (Trs)	1	6.8267	6.8267	19.96*	5.54	10.13	34.12
Reps x Trs (Error a)	3	1.0258	0.3419				
Species (Sps)	2	11.7939	5.8970	34.16**	2.81	3.88	6.93
Sps x Trs	2	2.2326	1.1163	6.46*	"	"	"
Sps x Reps	6	1.5538	0.1726				
Sps x Reps x Trs (Error b)	6	0.5175					
Total	23	26.9319					

* Significant at the 5% level.

** Significant at the 1% level.

Table 23. Analysis of variance for growth of stem cross sections of the three tree species used in the experiment for 1973.

Source of variation	df	SS	MS	Observed F	Required F 10%	5%	1%
Replications (Reps)	3	16.3045	5.4348	14.92*	5.39	9.28	29.46
Treatments (Trs)	1	5.9601	5.9601	16.36*	5.54	10.13	34.12
Reps x Trs (Error a)	3	1.0927	0.3642				
Species (Sps)	2	1.1067	0.5534	1.96	2.81	3.88	6.93
Sps x Trs	2	0.9227	0.4614	1.63	"	"	"
Sps x Reps	6	2.3662	0.2816				
Sps x Reps x Trs (Error b)	6	1.0131					
Total	23	28.7660					

* Significant at the 5% level.

Table 24. Analysis of variance for growth of stem cross sections of the three tree species used in the experiment for 1974.

Source of variation	df	SS	MS	Observed F	Required F 10%	5%	1%
Replications (Reps)	3	17.7422	5.9141	2.87	5.39	9.28	29.46
Treatments (Trs)	1	1.4751	1.4751	0.71	5.54	10.13	34.12
Reps x Trs (Error a)	3	6.1658	2.0553				
Species (Sps)	2	10.5215	5.2608	10.11**	2.81	3.88	6.93
Sps x Trs	2	0.2348	0.1174	0.22	"	"	"
Sps x Reps	6	5.5879					
Sps x Reps x Trs (Error b)	6	0.6549	0.5203				
Total	23	42.3822					

** Significant at the 1% level.

Table 25. Analysis of variance for growth of stem cross sections of the three tree species used in the experiment for the period 1970-1974.

Source of variation	df	SS	MS	Observed F	Required F 10%	Required F 5%	Required F 1%
Replications (Reps)	3	128.2469	42.7490	6.31	5.39	9.28	29.46
Treatments (Trs)	1	68.4788	68.4788	10.11	5.54	10.13	34.12
Reps x Trs (Error a)	3	20.3124	6.7708				
Species (Sps)	2	94.3355	47.1677	27.29**	2.81	3.88	6.93
Sps x Trs	2	15.4343	7.7171	4.46*	"	"	"
Sps x Reps	6	12.5813	1.7281				
Sps x Reps x Trs (Error b)	6	8.1560					
Total	23	347.5452					

* Significant at the 5% level.

** Significant at the 1% level.

Table 26. Levels of significance for increase in stem cross section due to asphalt treatment for the period 1970-1974.

	Year				
Species	1970-71	1972	1973	1974	1970-74
All species	x	x	x	NS	+
Robinia pseudacacia L.	xx	xx	x	NS	xx
Cupressus arizonica G.	NS	+	x	NS	+
Fraxinus rotundifolia Mill.	+	--	NS	NS	--

xx Greater than control at the 1% level of significance.

x Greater than control at the 5% level of significance.

+ Greater than control at the 10% level of significance.

-- Greater than control at the 20% level of significance.

NS Not significant.

The stem growth of the treated Robinia pseudacacia L. was 5.59 cm^2 or 53.0 percent greater than that of the control which was the highest increase of the experiment. The stem growth of the treated Fraxinus rotundifolia Mill. was 1.86 cm^2 or 23.9 percent greater than that of the control which was the lowest increase of the experiment. The stem growth of Cupressus arizonica G. was 3.04 cm^2 or 31.6 percent greater than that of the control which was intermediate between the other two species.

There was no consistency in the rate of stem growth with respect to exposure in contrast to the rate of height growth and crown growth with respect to exposure. The highest rate of growth on asphalt treated plots usually occurred either on S or on SE exposure. The lowest rate of growth occurred either on NE or on N exposure. The same trend held true for the control plots.

The relatively high growth rates of Cupressus arizonica G. and Fraxinus rotundifolia Mill. on SE control plots, which in some occasions exceeded that of the asphalt treated species (Tables 3 through 5, 13, and 20), prompted the installation of gypsum blocks in a grid system covering two subplots and their continuation downslope. It was observed that a zone of high soil water content (aquifer) starts near the hilltop, transverses diagonally across the ridge between SE and S control plots, and appears as a seepage face on a road cut below the experimental area (Figure 2). Although the extent of this zone was not surveyed, judging from the growth of the trees planted there, the effective width seemed to be 12 to 15 m.

Soil Water Characteristic Curves

Soil water characteristic curves for the dark brown A horizon, "brown soil," and the light gray C horizon, "gray soil," are presented in Figure 4. The sand, silt, and clay size fractions for the brown soil are 17, 40, and 43 percent, respectively, and for the gray soil these are 31, 42, and 27 percent, respectively (Appendix Table 4). These were determined by the pipette method. Both soils hold the same amount of water at -0.05 bars, but differ considerably at -15 bars with respect to water retention characteristics (Figure 4). That the gray soil behaves like a clay soil in the low range of soil water potentials and like a sandy soil in the high range is an anomaly. Since $CaCO_3$ makes up about 65 percent of the weight of the soil, it was hypothesized that the clay size fraction, which is functional in holding water at high potentials, actually consists to a large degree of $CaCO_3$ particles. These particles contribute to the total porosity of the soil but do not behave like layered silicates with respect to affinity for water.

A study was conducted to test this hypothesis so that the soil which makes up most of the root zone might be better understood.

Four 10 g samples of soil which had been passed through a two mm sieve and dried at 105 C for 24 hours were used in this experiment. Calcium carbonate was removed using dilute HCl as recommended by Jackson et al. (1949), iron oxides were removed by the Na -DCB method (Mehra and Jackson, 1960), and organic matter was removed using H_2O_2. The samples were then separated into sand, silt, and clay size fractions following a procedure outlined by Jackson et al. (1949). The $CaCO_3$ contents of the sand, silt, and clay size fractions were found to be 60.2, 71.7, and 64.6 percent, respectively.

The whole soil contains 26.83 percent clay as determined by the pipette analysis so that the $CaCO_3$ content in this fraction on a whole soil basis is 26.83% (clay) x 0.6464% ($CaCO_3$ in clay) = 17.34% $CaCO_3$. The content of clay on a whole soil basis is 26.83% (clay) - 17.34% ($CaCO_3$) = 9.49% silicate clays. The original size fractions classify this soil as "loam" but this newly calculated clay content puts it in the "sand" category, thus supporting the hypothesis advanced earlier.

Runoff

From December 10, 1971 to May 17, 1975 there were 104 occurrences of rainfall and four snow seasons. Of these events, 51 resulted in runoff from asphalt treated plots only, while 28 produced runoff from both the treated and control plots. The runoff coefficient, R, for each precipitation event was calculated according to:

$$R = \frac{V}{I \times A} \tag{6}$$

where V is the volume of runoff in liters, I is the depth of precipitation in mm, and A is 20 m^2 which was the area of each plot. Multiplication of R by I for each event gives the depth of runoff from the plot in mm (Tables 27 and 28).

The runoff coefficients for the treated plots had a very wide range. They were very high immediately after the asphalt treatment

Table 27. Precipitation events and their contribution to runoff from the treated plots from December 1971 to May 1975. Events which did not produce runoff are marked -- and events which caused runoff in both the treated and control plots are marked x. Runoff coefficient and runoff depth for control plots are shown in Table 28.

Year		Precipi- tation		Cumulative precipi- tation	Runoff coeffi- cient	Runoff depth	Cumulative runoff
		mm		mm	%	mm	mm
1971		2.2		2.2	66.28	1.46	1.46
		1.2		3.4	--	--	1.46
		6.6		10.0	74.74	4.93	6.39
1972	x	144.4	snow	154.4	28.45	41.08	47.47
		2.5		156.9	40.00	1.00	48.47
		3.6		160.5	27.31	0.98	49.45
		11.6		172.1	44.68	5.18	54.63
		4.2		176.3	45.24	1.90	56.53
		1.2		177.5	--	--	56.53
		8.0		185.5	48.33	2.41	58.94
	x	14.0		199.5	50.35	7.05	65.99
	x	10.4		209.9	40.38	4.20	70.19
		2.2		212.1	56.06	1.23	71.42
		1.0		213.1	41.66	0.41	71.83
		2.2		215.3	62.12	1.36	73.19
		1.4		216.7	25.00	0.35	73.54
	x	12.0		228.7	26.66	3.20	76.74
	x	15.4		244.1	30.52	4.70	81.44
	x	4.0		248.1	42.25	1.85	83.29
		0.2		248.3	--	--	83.29
		2.0		250.3	54.58	1.09	84.38
		4.0		254.3	56.66	2.26	86.64
		0.2		254.5	--	--	86.64
		0.6		255.1	--	--	86.64
	x	9.4		264.5	45.03	4.23	90.87
		0.6		265.1	--	--	90.87
		1.0		266.1	--	--	90.87
		1.2		267.3	--	--	90.87
	x	5.2		272.5	23.07	1.20	92.07
	x	3.4		275.9	33.08	1.12	93.19
		0.4		276.3	--	--	93.19
		1.4		277.7	--	--	93.19
		2.4		280.1	50.69	1.21	94.40
		0.2		280.3	--	--	94.40
	x	14.4		294.7	40.85	5.88	100.28
		3.0		297.7	52.77	1.58	101.86

continued --

Table 27. Continued.

Year		Precipi-tation		Cumulative precipi-tation	Runoff coeffi-cient	Runoff depth	Cumulative runoff
		mm		mm	%	mm	mm
1972 cont.	x	35.0		332.7	29.43	10.30	112.16
		0.4		333.1	--	--	112.16
		1.2		334.3	39.58	0.47	112.63
	x	70.4		404.7	32.73	22.58	135.21
		9.0		413.7	32.22	2.90	138.11
	x	4.6		418.3	28.98	1.33	139.44
		4.2		422.5	13.09	0.55	139.99
1973	x	130.0	snow	552.5	27.38	35.33	175.32
		18.9		571.4	27.51	5.20	180.52
		2.5		573.9	29.33	0.73	181.25
		4.5		578.4	29.62	1.33	182.58
		2.8		581.2	36.30	1.01	183.59
		5.0		586.2	29.66	1.48	185.07
		5.0		591.2	31.66	1.58	186.65
		8.0		599.2	35.62	2.85	189.50
		4.6		603.8	36.95	1.70	191.20
		3.8		607.6	30.26	1.15	192.35
		6.3		613.9	23.54	1.48	193.83
		25.4		639.3	35.56	9.03	202.86
		7.7		647.0	20.56	1.58	204.44
1974	x	77.1	snow	724.1	11.43	8.71	213.15
		5.5		729.6	18.78	1.03	214.18
		0.5		730.1	--	--	214.18
		19.0		749.1	17.63	3.35	217.53
		10.8		759.9	27.77	3.00	220.53
	x	24.8		784.7	37.63	9.33	229.86
		1.5		786.2	--	--	229.86
		15.0		801.2	33.33	5.00	234.86
		14.6		815.8	28.42	4.15	239.01
		1.0		816.8	--	--	239.01
		2.6		819.4	--	--	239.01
		1.5		820.9	--	--	239.01
		3.2		824.1	62.50	2.00	241.01
		2.6		826.7	--	--	241.01
		1.6		828.3	72.91	1.16	242.17
		2.0		830.3	20.00	0.40	242.57
		9.5		839.8	22.98	2.18	244.75
		1.0		840.8	--	--	244.75
	x	19.0		859.8	24.83	4.30	249.05

continued --

Table 27. Continued.

Year		Precipi- tation		Cumulative precipi- tation	Runoff coeffi- cient	Runoff depth	Cumulative runoff
		mm		mm	%	mm	mm
1974 cont.		5.3		865.1	30.50	1.61	250.66
		4.1		869.2	22.35	0.91	251.57
		2.5		871.7	29.33	0.73	252.30
	x	10.5		882.2	39.84	4.18	256.48
		0.8		883.0	--	--	256.48
	x	5.6		888.6	25.59	1.43	257.91
		3.2		891.8	16.66	0.53	258.44
		0.4		892.2	--	--	258.44
		1.6		893.8	43.22	0.91	259.35
		0.6		894.4	--	--	259.35
		0.2		894.6	--	--	259.35
		0.4		895.0	--	--	259.35
		0.2		895.2	--	--	259.35
	x	17.0		912.2	25.49	4.33	263.68
	x	7.2		919.4	14.58	1.05	264.73
		7.8		927.2	20.08	1.56	266.29
1975	x	252.8	snow	1180.0	4.59	11.60	277.89
		4.4		1184.4	28.40	1.25	279.14
		0.4		1184.8	--	--	279.14
		0.4		1185.2	--	--	279.14
		0.2		1185.4	--	--	279.14
		2.2		1187.6	13.63	0.30	279.44
	x	38.4		1226.0	15.53	5.96	285.40
		2.4		1228.4	15.27	0.36	285.76
		0.4		1228.8	--	--	285.76
		3.6		1232.4	14.80	0.53	286.29
	x	37.4		1269.8	22.72	8.50	294.79
	x	5.8		1275.6	26.72	1.55	296.34
		4.4		1280.0	17.04	0.75	297.09
	x	14.2		1294.2	28.64	4.06	301.15
	x	9.0		1303.2	30.55	2.75	303.90
	x	27.2		1330.4	25.12	6.83	310.73

Table 28. Precipitation events and their contribution to runoff from the control plots from December 1971 to May 1975.

Date		Precipi-tation	Runoff coeffi-cient	Runoff depth	Cumulative runoff
		mm	%	mm	mm
March '72	snow	144.4	8.77	12.67	12.67
5-9-72		14.0	0.95	0.13	12.80
5-10-72		10.4	1.76	0.18	12.98
5-19-72		12.0	3.61	0.43	13.41
5-19-72		15.4	39.61	6.10	19.51
5-20-72		4.0	35.83	1.43	20.94
6-16-72		9.4	12.59	1.18	22.12
8-4-72		5.2	6.41	0.33	22.45
8-5-72		3.4	8.33	0.28	22.73
10-10-72		14.4	23.38	3.36	26.09
11-3-72		35.0	9.95	3.48	29.57
11-29 to 12-1-72		70.4	2.51	1.73	31.30
12-6-72		4.6	3.26	0.15	31.45
March '73	snow	130.0	0.06	0.08	31.53
March '74	snow	77.1	0.41	0.31	31.84
4-5-74		24.8	3.02	0.75	32.59
7-6-74		19.0	2.01	0.38	32.97
7-19-74		10.5	3.65	0.38	33.35
8-26-74		5.6	1.19	0.06	33.41
11-7-74		17.0	0.58	0.10	33.51
11-8-74		7.2	0.46	0.03	33.54
March '75	snow	252.8	0.87	2.20	35.47
4-23-75		38.4	0.73	0.28	36.02
5-6-75		37.4	15.28	5.71	41.73
5-7-75		5.8	19.54	1.13	42.86
5-11-75		14.2	10.45	1.48	44.34
5-12-75		9.0	10.74	0.96	45.30
5-13 to 5-14-75		27.2	21.01	5.71	51.01

had been applied. On one occasion the amount of runoff from plot five exceeded the amount of rainfall as measured by a 1000 cm^2 orifice rain gauge. This is because rain gauges do not sample precipitation properly due to the limitation in the area of their orifices. However, 3.5 years later the same plot had a coefficient of only 47 percent. Cumulative precipitation and runoff from both the treated and control plots measured during the experimental period are presented in Figure 15.

To evaluate the efficiency of the asphalt treatment in inducing runoff the data were divided into four categories according to the runoff coefficients of the control plots. Paired t-tests were conducted for each category. The t values obtained for three categories, including 70 out of the 75 rainfall events, were highly significant (Table 29). The t values were not significant only when the maximum intensity was greater than 100 mm/hour, when the duration of the storm was longer than one hour while the maximum intensity was more than 12 mm/hour, or when the soil was near saturation due to antecedent precipitation and the maximum intensity was nearly 12 mm/hour.

To develop a better understanding of the runoff process the data for 54 rainfall events for which the maximum intensities were available were used and a regression equation was developed correlating the runoff coefficient with the time elapsed since the start of the experiment, and the amount and intensity of rainfall for each event. The runoff coefficients were negatively correlated with the time elapsed since the start of the experiment ($r = -0.65$ with 53 df). The negative correlation of runoff coefficient with the elapsed time is plausible

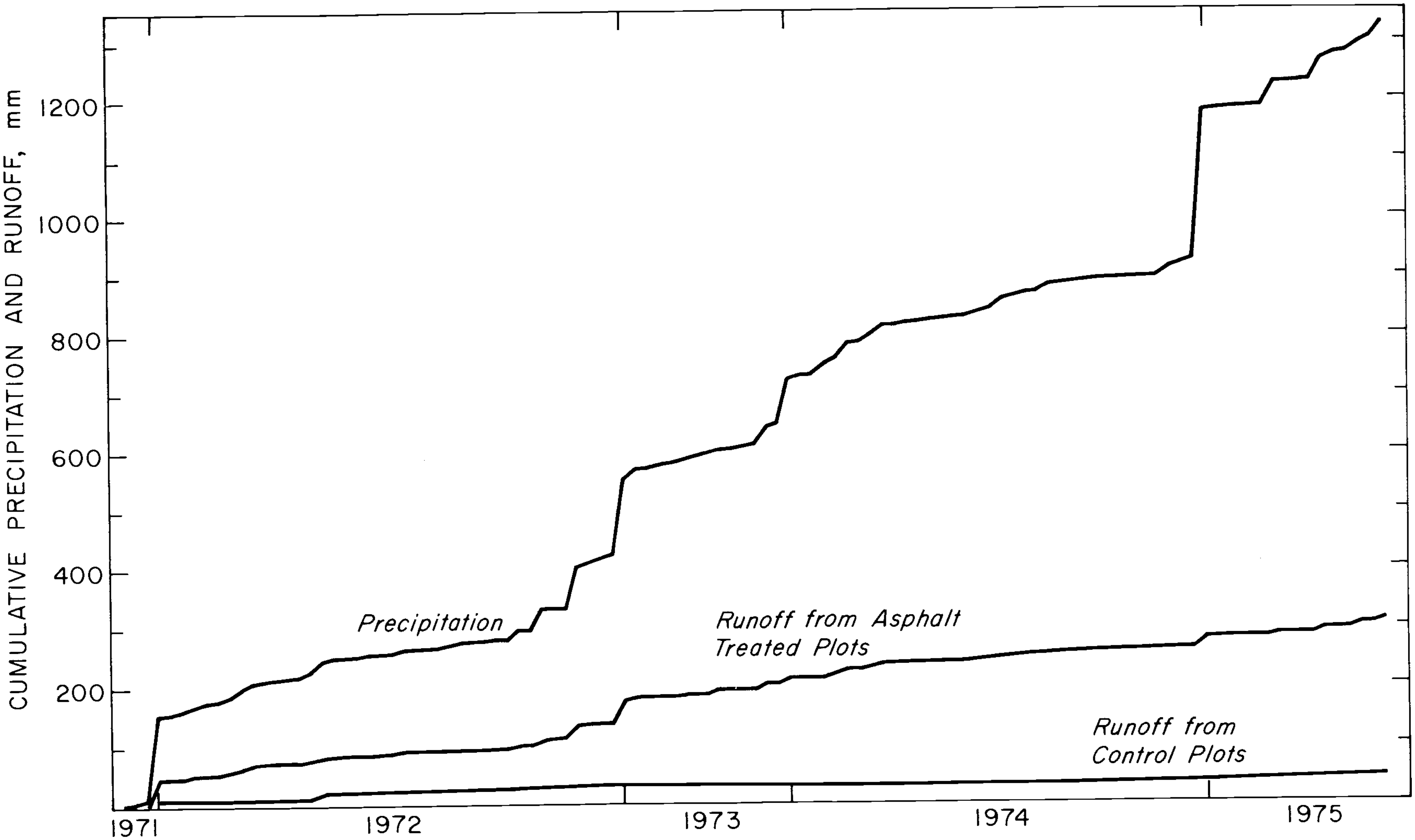

Figure 15. Cumulative precipitation and runoff since installation of the runoff plots in December 1971. Sudden jumps in precipitation reflect the water equivalent of winter snowfall. The number of runoff producing rainfall events was the lowest during 1973.

Table 29. Range in runoff coefficient for the asphalt treated and control plots, degrees of freedom, calculated t and t-table values for the runoff plot data, December 1971 - May 1975.

Range in runoff coefficient				
Asphalt	Control	df	Calculated t	t-table value (0.001)
%	%			
13.09 - 74.74	0	48	15.145***	3.492
14.58 - 50.35	0.46 - 3.65	11	9.463***	4.437
23.07 - 45.03	6.41 - 12.59	5	9.434***	6.859
22.72 - 42.25	15.28 - 39.61	5	1.601	6.859

*** Significant at the 0.1% level.

since as the asphalt layer deteriorates due to weathering, punctured by emerging plants or microbial decomposition, its efficiency in inducing runoff decreases considerably. The least important independent variable was rainfall intensity. It is generally accepted that intense rains cause plugging of soil pores thus inducing surface runoff. Since the asphalt closes the pores, as well as making the surface non-wettable, rainfall intensity apparently cannot surpass the asphalt in inducing runoff, therefore it is of least importance in this regression equation. The best fit regression equation for runoff over the asphalt-soil membrane is:

$$y = 47.974 - .632\ 88x_1 - .1017x_2 \qquad (7)$$

where y is the runoff coefficient (percent), x_1 is the time elapsed since asphalt spraying (months), and x_2 is the amount of rainfall for each event (mm).

This equation was used to calculate the amount of water received during each month by each terrace of the treated area as compared with that received by the control plots. By substituting the elapsed time since asphalt spraying (x_1 in months) and the amount of rainfall (x_2 in mm) in equation 7, the runoff coefficient for each event may be obtained. To simplify the process only monthly runoff coefficients were acquired by using the total monthly rainfall for x_2 (Table 30). Multiplication of monthly coefficients and amount of rainfall gives the depth of runoff from the treated area in mm. This depth when multiplied by 1.5, the ratio of horizontal projection of microwatershed to

Table 30. Monthly precipitation, calculated runoff coefficient, monthly runoff, and total depth of water received by the asphalt treated plants for the period 1970-1974.

Year and month	Elapsed time	Monthly precip-itation	Runoff coeffi-cient	Monthly runoff	1.5 times monthly runoff	Precip-itation plus runoff
	months	mm	%	mm	mm	mm
1970						
March	3	47.8	41.21	19.69	29.53	77.33
April	4	30.0	42.39	12.72	19.08	49.08
May	5	17.6	43.01	7.57	11.35	28.95
July	7	23.4	41.16	9.63	14.44	37.84
Sept.	9	0.4	42.23	0.17	0.25	0.65
Oct.	10	1.2	41.52	0.49	0.73	1.93
Nov.	11	42.8	36.65	15.68	23.52	66.32
Dec.	12	44.6	35.84	15.98	23.97	68.57
		207.8			122.87	330.67
1971						
Jan./Feb.	snow	30.0	27.38	8.22	12.33	42.33
March	15	29.8	35.45	10.56	15.84	45.64
April	16	58.2	31.92	18.57	27.85	86.05
May	17	6.8	36.52	2.48	3.72	10.52
July	19	2.4	35.70	0.85	1.27	3.67
Oct.	22	5.8	33.46	1.94	2.91	8.71
Nov.	23	51.4	28.19	14.49	21.73	73.13
Dec.	24	16.6	31.09	5.16	7.74	24.34
		201.0			93.39	294.39
1972						
Jan./Feb.	snow	40.6	11.43	4.64	6.96	47.56
March	27	91.8	21.55	19.78	29.67	121.47
April	28	23.5	27.86	6.54	9.81	33.31
May	29	82.2	21.26	17.47	26.20	108.40
June	30	13.0	27.66	3.60	5.40	18.40
Aug.	32	13.0	26.39	3.43	5.14	18.14
Oct.	34	17.4	24.68	4.29	6.43	23.83
Nov.	35	87.8	16.89	14.83	22.24	110.04
Dec.	36	56.8	19.41	11.02	16.53	73.33
		426.10			128.38	554.48

continued --

Table 30. Continued.

Year and month	Elapsed time	Monthly precip- itation	Runoff coeffi- cient	Monthly runoff	1.5 times monthly runoff	Precip- itation plus runoff
	months	mm	%	mm	mm	mm
1973						
Jan./Feb.	snow	100.4	4.54	4.56	6.84	107.24
March	39	28.7	20.37	5.84	8.76	37.46
April	40	32.4	19.36	6.27	9.40	41.80
May	41	3.8	21.63	0.82	1.23	5.03
Nov.	47	31.7	15.00	4.75	7.12	38.82
Dec.	48	7.7	16.81	1.30	1.95	9.65
		204.70			35.30	240.00
1974						
Jan./Feb.	snow	68.1	2.00	1.37	2.06	70.16
March	51	20.0	13.66	2.72	4.08	24.08
April	52	85.8	6.33	5.43	8.14	93.94
May	53	7.4	13.67	1.01	1.51	8.91
June	54	11.5	12.62	1.45	2.17	13.67
July	55	42.4	8.85	3.75	5.62	48.02
Aug.	56	6.4	11.88	0.76	1.14	7.54
Sept.	57	6.6	11.22	0.74	1.11	7.71
Nov.	59	32.0	7.37	2.35	3.52	35.52
Dec.	60	89.2	0.92	0.82	1.23	90.43
		369.40			30.58	399.98

spreading basin, yields the depth of runoff water received by the terraces below the catchment areas. Addition of this amount to precipitation on the terraces gives the total amount received by them. For example, in the seventh month since the start of the experiment there was 23.4 mm of precipitation (Table 30). Using equation 7, the calculated runoff coefficient is 0.4116. Therefore, the depth of runoff water over the asphalt was 23.4 x 0.4116 = 9.63 mm, and the depth of harvested water concentrated over the planted terrace was 9.63 x 1.5 = 14.44 mm. Total depth of water received by the terrace was therefore 37.84 mm. Monthly precipitation and runoff depth are shown in Table 30.

Figure 16 presents cumulative precipitation and calculated runoff depth for the period 1970-1974. The distance between the two curves at each point in time is the extra depth of water received due to the asphalt treatment from the start of the experiment up to that date.

The runoff coefficient for snow was very low compared to that of rain, namely 28, 27, 11, and 4 percent for the first, second, third, and fourth year, respectively. This was in part due to the sublimation of snow which approximately amounted to 50 percent of the yearly snowfall. Since the snowfall data for the first winter after asphalt spraying were not available the runoff depth for that year was not calculated. The coefficient for the fifth year was estimated by extrapolation to be two percent.

Examining the calculated runoff values shown in Table 30, it is noted that the average contribution of the treated area was 59 percent of the total precipitation in the first year and decreased to eight

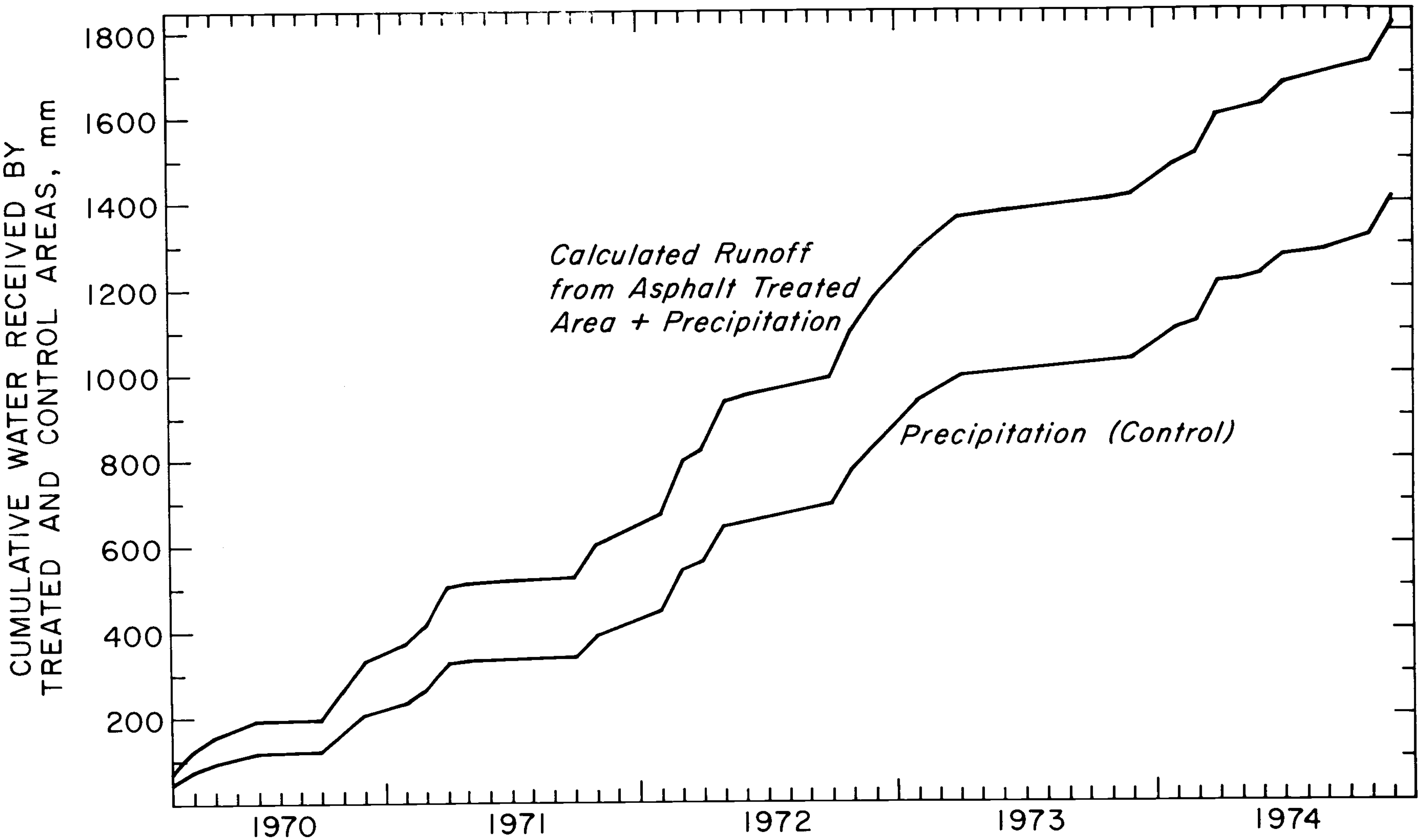

Figure 16. Cumulative precipitation received by the control plots and the calculated total amount of water received by the treated plots during the period 1970-1974.

percent in the fifth year. The yearly contributions of the treated area to the terraces were: 122, 93, 128, 35, and 30 mm for the first, second, third, fourth, and the fifth year, respectively, with a total contribution of 410.52 mm.

Soil Water Potential

Terraces

Soil water potentials measured during 1970 and 1971 had to be discarded due to the close proximity of the gypsum blocks to the tree roots. This was described earlier. The data acquired in the new experimental plot during the growing seasons of the years 1972, 1973, and 1974 at depths of 15, 30, 45 and 60 cm are presented in Figures 17 and 18 for the S and N aspects of the site. Soil water potentials in the asphalt and control treatments were analyzed statistically using paired t-test for each of the three years and each of the two exposures. Table 31 summarizes the calculated t values along with their degrees of freedom and levels of significance.

Soil water potentials were always higher on the asphalt treated plots. The mean potentials for the treated S exposure were -0.47, -7.75 and -2.50 bars during 1972, 1973, and 1974, respectively. The corresponding values on control plots were -7.76, -23.84, and -21.83 bars, respectively. The mean soil water potentials for the treated N aspect were -0.94, -12.83, and -7.78 bars during the years 1972, 1973, and 1974, respectively. The corresponding values for the control were -1.79, -15.86, and -19.38 bars.

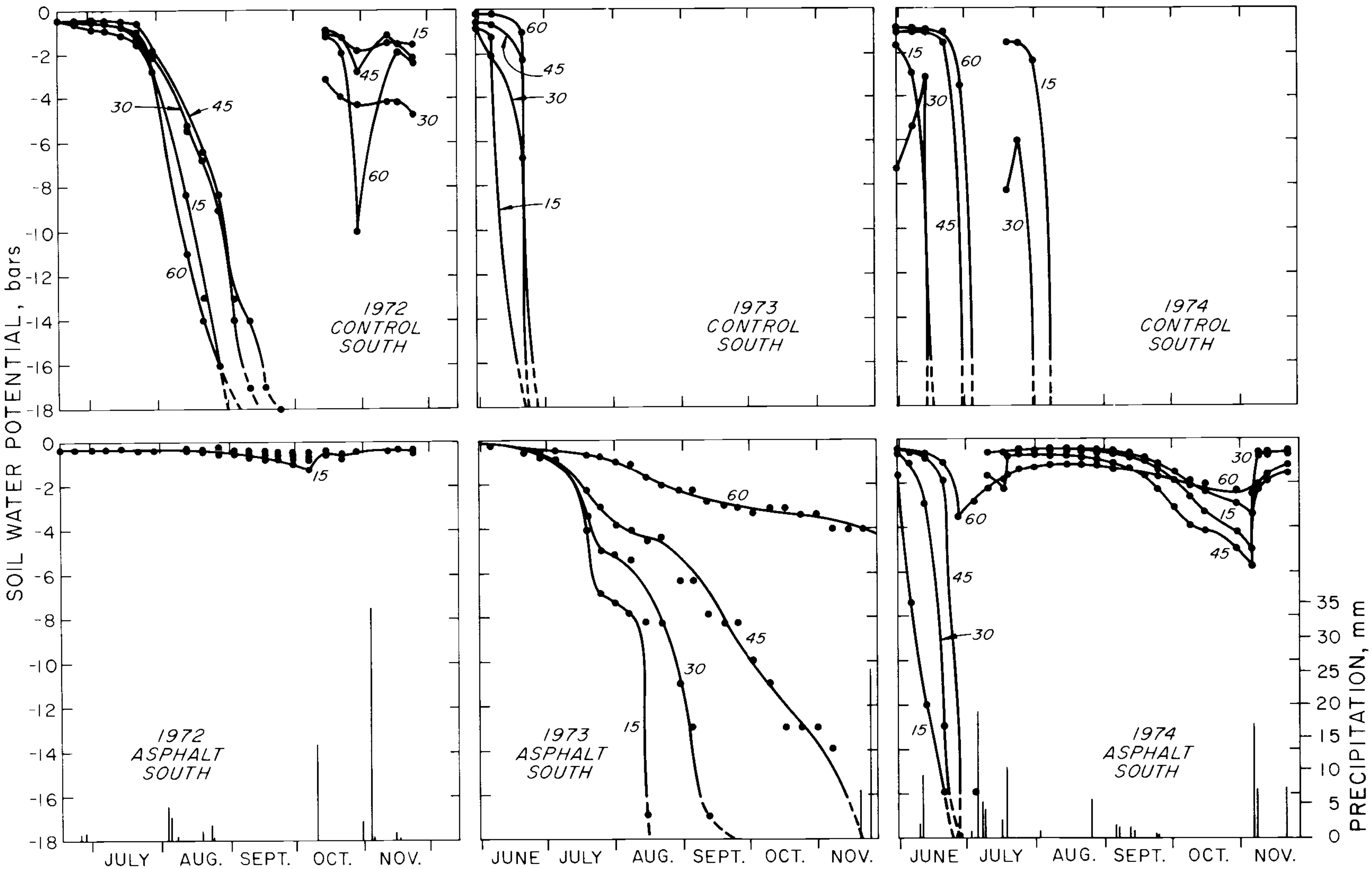

Figure 17. Soil water potential in terraces during the growing seasons of 1972 through 1974 on the asphalt treated and control plots for southern exposure at depths of 15, 30, 45, and 60 cm. Precipitation events and amounts are indicated by vertical bars.

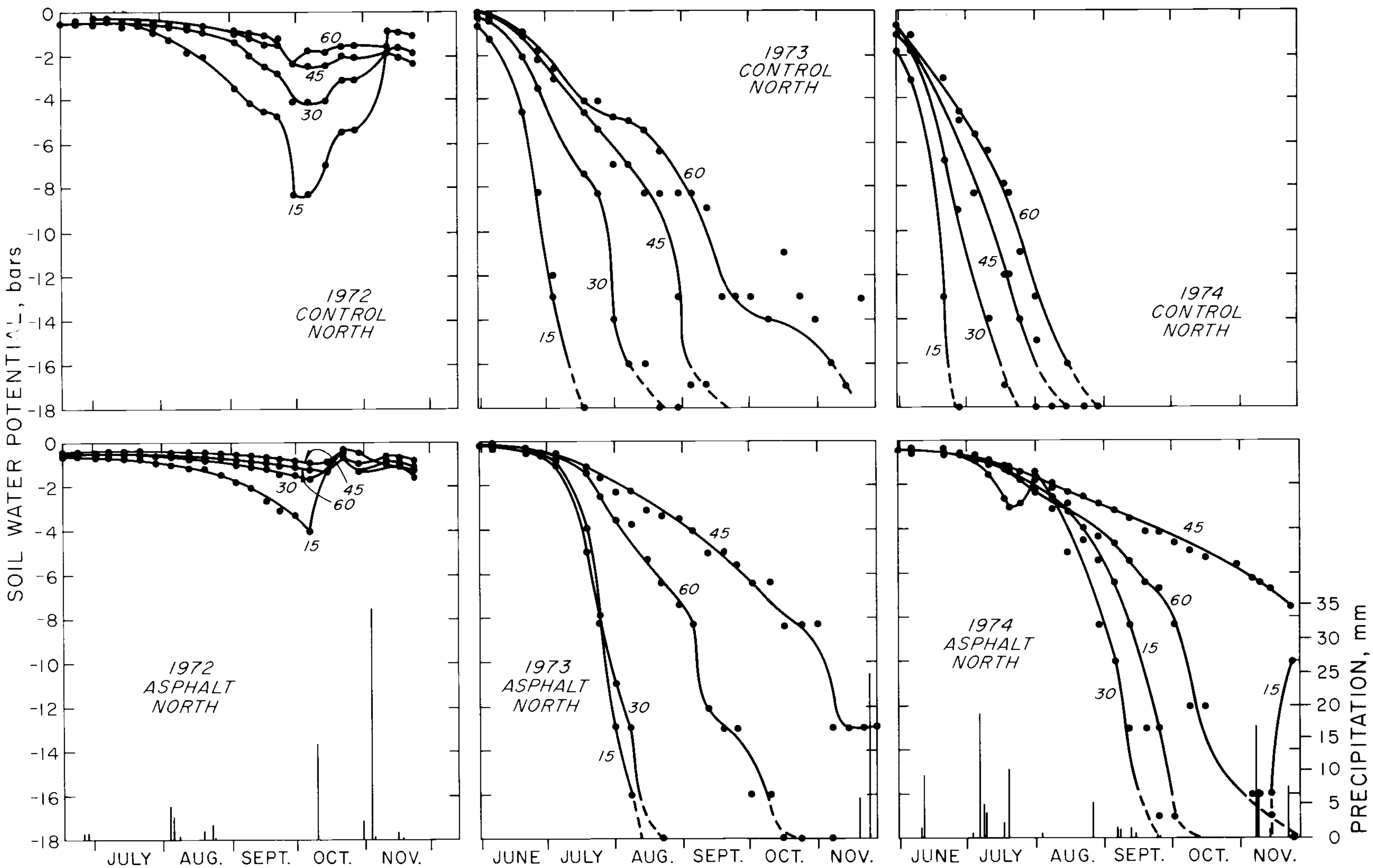

Figure 18. Soil water potential in terraces during the growing seasons of 1972 through 1974 on the asphalt treated and control plots for northern exposure at depths of 15, 30, 45, and 60 cm. Precipitation events and amounts are indicated by vertical bars.

Table 31. Range in mean soil water potential in bars, in terraces for the asphalt treated and control plots of S and N exposures, degrees of freedom, calculated t values, and t-table values for the period 1972-1974.

Year	Expo-sure	Range in soil water potential		df	Calculated t	t-table value (.001)
		Asphalt	Control			
		bars	bars			
1972	S	-0.33 to - 0.77	-0.42 to -21.25	21	4.216***	3.819
	N	-0.54 to - 1.98	-0.38 to - 4.28	20	3.843**	3.850
1973	S	-0.20 to -18.28	-0.60 to -28.0	30	13.220***	3.646
	N	-0.16 to -22.25	-0.39 to -25.0	28	6.807***	3.674
1974	S	-0.67 to -14.63	-2.62 to -27.0	30	12.605***	3.646
	N	-0.45 to -16.80	-1.09 to -25.0	29	15.392***	3.659

*** Significant at the 0.1% level.

** Significant at the 1% level.

Soil water potentials on S and N exposures were not the same during identical periods (Table 32). The potentials of the asphalt covered plots with S exposure were higher than those of asphalt covered plots with N exposure. The potentials of the control plots with N exposure were higher than those of control plots with S exposure. This anomaly prompted the installation of rain gauges on the four principal exposures in the fall of 1973. The total rainfall for June through November of 1974 was 78.2 mm for the S exposure and 66.2 mm for the N exposure. Apparently, the extra runoff inducing rainfall on the S exposure was sufficient to compensate for the lower evapotranspiration from the N exposure. While the S exposure of the control received more water than the N exposure, the higher evapotranspiration rate of that exposure decreased the soil water potential more than on its N counterpart.

Table 32. Mean soil water potential in bars for S and N exposures during 1972-1974.

		Year		
Treatment	Exposure	1972	1973	1974
asphalt	S	-0.47	- 7.75	- 2.50
	N	-0.94	-12.83	- 7.78
control	S	-7.76	-23.84	-21.83
	N	-1.79	-15.86	-19.38

Although these data cannot be used to derive relationships between soil water potential and growth, because the data were not available for the first two years, they may be used in a qualitative manner to show that the asphalt treatment was not only effective during dry periods e.g. 1973, but also during the wet years 1972 and 1974.

The data presented do not adequately describe the soil water regime on the planted area beyond the first year because only a 70 cm deep layer of soil was studied. Additional observations not presented in this thesis indicate that the roots of the three tree species planted in the experiment explored the soil to a depth of about 60 cm during the first growing season but continued their growth to lower depths in the following years.

The soil of the treated terraces was wetted to a greater depth than the soil of the control terraces due to the extra water provided by the asphalt treatment. The following example substantiates this claim.

The total precipitation from December 26, 1971 to March 11, 1972 was 144.4 mm. This amount was received equally by treated and control plots. However, the treated plots received the extra volume of water resulting from 41 mm of runoff from the microwatersheds (Table 27). The ratio of the horizontal projection of the surface areas of the microwatershed to that of the spreading basin is 3.5 m/1.5 m (Figure 19). Using this factor shows that the terraces received 95.6 mm of runoff water. It is assumed that the mean soil water potential at the start of fall was -6.0 bars (October 1972). After the autumn rainfall had replenished the soil water reservoir the

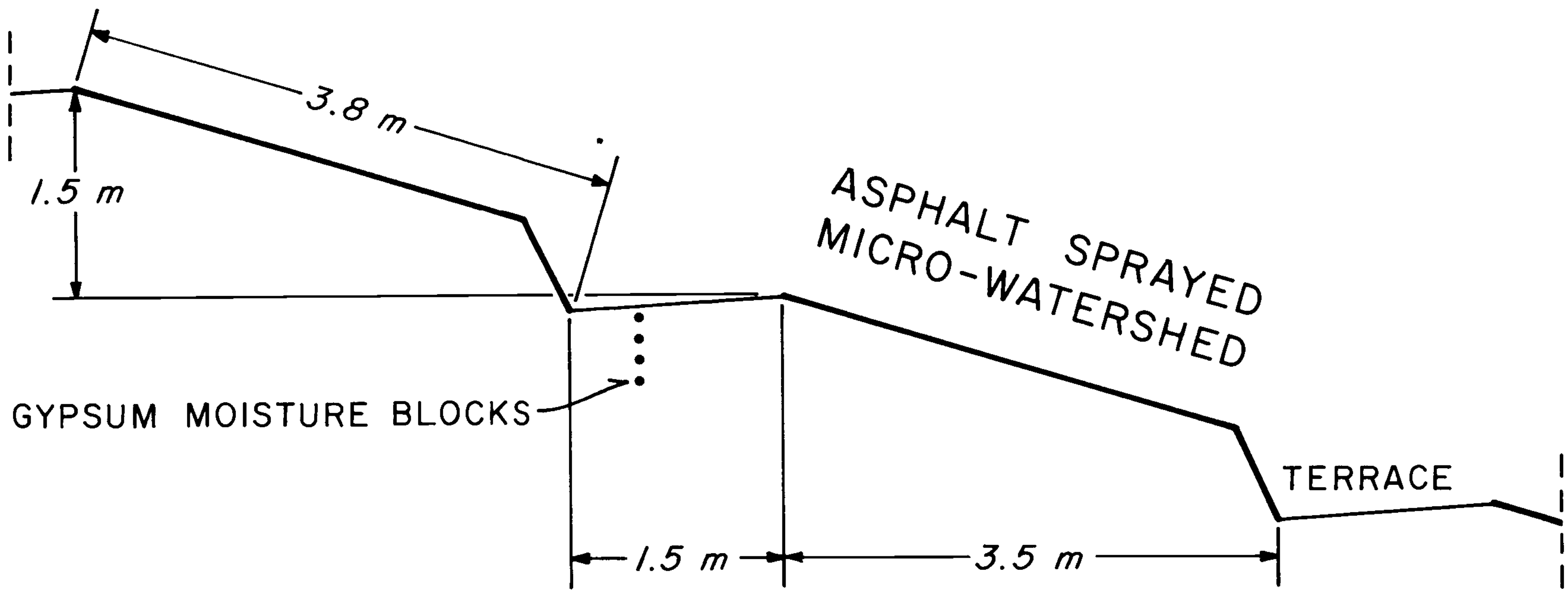

Figure 19. Schematic diagram of the asphalt treated micro-watersheds, terraces, and the position of gypsum moisture blocks in the new experimental site.

potential was -0.33 bars uniformly throughout the profile. The amount of water required to fill the profile was 0.2725 (at -0.33 bars) -0.1305 (at -6.0 bars) = 0.142 gm/gm (Figure 4). With the bulk density of 1.3 gm/cm^3, the volume of water needed to raise the potential to -0.33 bars was 0.142 gm/gm x 1.3 gm/cm^3 x 1.0 cm^3/gm = 0.1846 cm^3/cm^3.

About 12 percent of the soil volume is occupied by stones larger than two mm in diameter. The required amount of water to raise the potential from -6.0 bars to -0.33 bars was therefore 0.1846 x $\frac{100 - 12}{100}$ = 0.1625 cm^3/cm^3, or 1.625 mm of water per cm^2 (Reinhart, 1961). The control plot received 144.4 mm and the treated plots received 144.4 + 95.6 = 240.0 mm of water. The depth of wetted soil for control plots was therefore, 144.4/1.625 = 89 cm, and for the asphalt treated plots 240/1.625 = 148 cm. The soil profile was therefore wetted to a deeper level in the treated plots than control plots, the difference being 148 - 89 = 59 cm. It is important to realize that 95.6 mm of runoff water which was conserved in a layer of woil 59 cm thick not only provided a larger space for root expansion in the treated plots, but also acted as a water reserve during dry periods in the summer when the soil surface was practically dry.

Between Terraces

Soil water potentials measured at depths of 10, 20, and 30 cm at the lower end of runoff plots simulate conditions on sloping micro-watersheds between two consecutive terraces. The data acquired using gypsum blocks are presented in Figure 20. Since the data obtained at the depth of 20 cm were nearly identical with those of 10 cm depth,

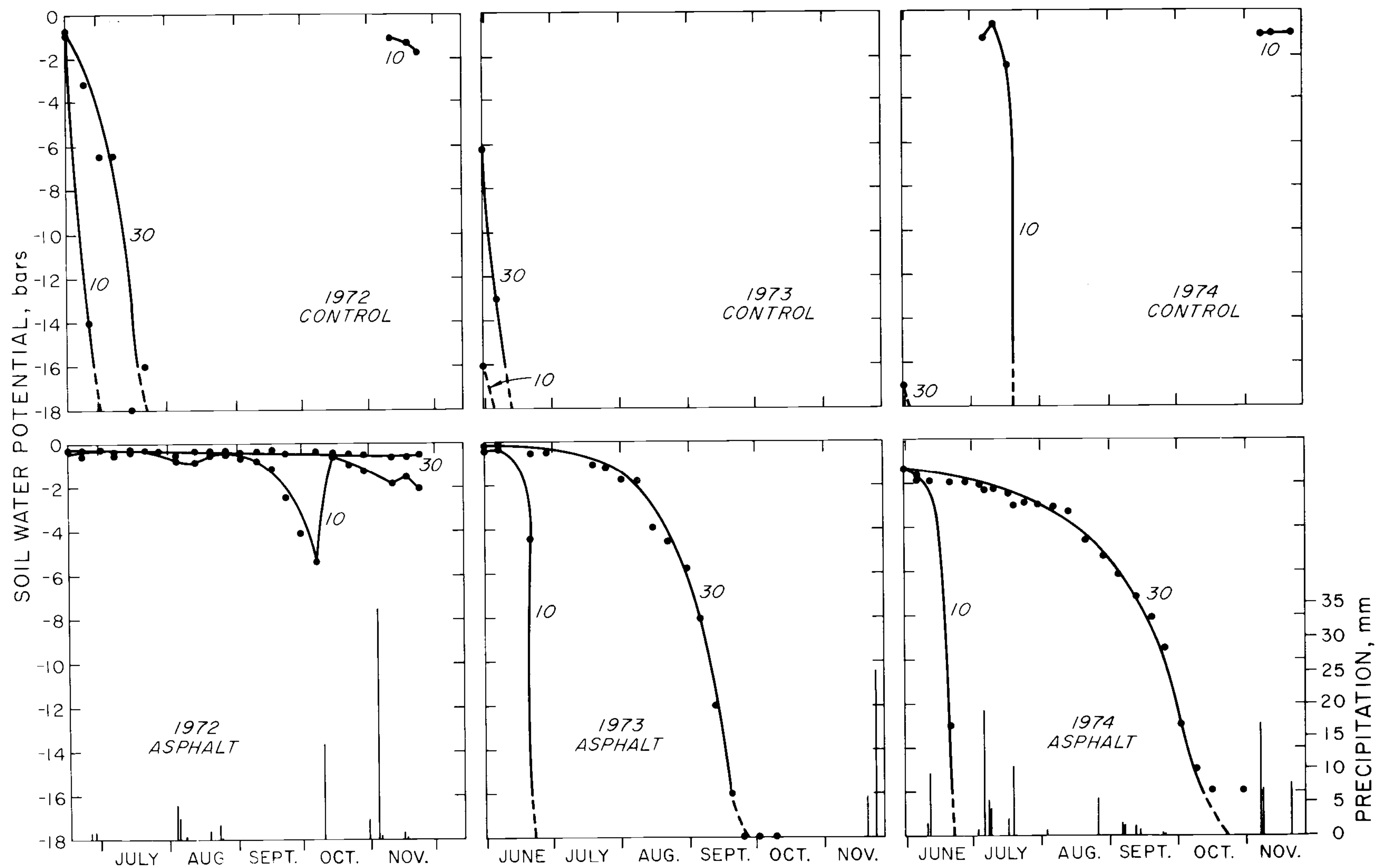

Figure 20. Soil water potential during the growing seasons of 1971-1974 on the asphalt treated and control plots at depths of 10 and 30 cm. Precipitation events and amounts are indicated by the vertical bars.

only the values for the 10 and 30 cm potentials are treated in this section.

Soil water potentials for each of the years 1972, 1973, and 1974 were analyzed statistically using paired t-test. Table 33 summarizes the calculated t values along with their degrees of freedom and levels of significance.

The asphalt treatment resulted in higher soil water potentials in every instance. The mean potentials for the treated plots during the years 1972, 1973, and 1974 were -0.75, -18.52, and -16.64 bars, respectively. The corresponding values on the control plots during the same period were -19.67, -25.02, and -22.31 bars, respectively.

Soil water potential of the treated area was related to the condition of the asphalt-soil membrane. As the membrane deteriorated and its effectiveness as a sealant decreased escape of water vapor through its cracks and pores increased. The potential at 30 cm in 1972 remained close to -0.5 bars during the June through November period. It decreased to -16 bars in September 1973 and to -16 bars in October 1974. Factors such as distribution of rainfall and potential evapotranspiration determine the soil water potential in the absence of the asphalt-soil membrane. The intact membrane functions as a superior mulch, reducing evaporation from the soil surface (Kowsar et al., 1969). Therefore, immediately below the asphalt-soil membrane the potential is mostly controlled by the integrity of the membrane.

Table 33. Range in soil water potential in bars, between terraces for the asphalt treated and control plots, degrees of freedom, calculated t values, and t-table values for the period 1972-1974.

Year	Range in soil water potential: Asphalt	Range in soil water potential: Control	df	Calculated t	t-table value (.001)
	bars	bars			
1972	-0.22 to - 2.88	- 0.29 to -28.0	24	10.214***	3.745
1973	-0.23 to -25.5	-11.95 to -28.0	26	3.981***	3.707
1974	-1.30 to -24.0	-13.55 to -28.0	31	3.236**	3.645

*** Significant at the 0.1% level.

** Significant at the 1% level.

Survival and Precipitation

The first measure of success of a planting project is the survival of seedlings. Many physiological factors and cultural practices play a role in the determination of survival. Water is a vital element in the success of transplanted seedlings in a dry environment. Contrary to the expectations, the extra water received by the trees planted on the asphalt treated plots did not result in a significant increase in their survival rates relative to those of the trees planted on the control plots. Apparently, 47.8 mm of precipitation which fell immediately after the planting season in March, and the timely spring and summer precipitation of the first growing season, were enough to establish the transplanted seedlings.

The survival rates of trees on the treated plots were generally higher than those of the trees planted on the control plots (Table 1). The only exception occurred on the S exposure. The lower survival rate of *Cupressus arizonica* G. and *Fraxinus rotundifolia* Mill. on treated plots with S exposure may seem to contradict the thesis that the increase of surface runoff due to the application of asphalt to the soil surface is beneficial to the establishment of trees in arid climates. The plots of the study site with S exposure have a harsh environment during winter nights. The snow cover melts faster here than on the other exposures, depriving the seedlings of protective cover. This cover is essential for seedling survival particularly during the night. Moreover, the full impact of prevailing S winds which are usually very cold is felt on this exposure. The seedlings on asphalt treated plots should have had a higher chance of survival during the winter, since they were under a lower water stress than the trees on control plots. The probability of death by desiccation should have been lower in them (Zahner, 1968). However, the taller and more succulent seedlings on treated plots were more exposed to the low temperatures. During February 1972 minima of -16 C occurred frequently. The *Cupressus arizonica* G. and *Fraxinus rotundifolia* Mill. trees of the treated plots were on the average 9.5 and 16.8 cm taller than the control trees. It is probable that at the time of winter injury the upper parts of the treated trees were out of snow while the shorter trees on control plots were covered by the snow.

Whether the higher succulency of the trees on treated plots contributed to their mortality is conjectural. The higher water content of the trees on treated plots provides a better condition for cellular rupture due to freezing. But Kramer and Kozlowski (1960, p. 486) refuted the hypothesis that such damage occurs. That the *Robinia pseudacacia* L. on treated plots with S exposure had the same survival rate as those on control plots with S exposure may be due to the cold tolerance of this species which can survive in temperatures as low as -35 C (Fowells, 1965).

Height Growth and Precipitation

The use of tree height as a criterion for measuring site quality is common practice among foresters. It is generally accepted that soil water storage in temperate and arid zones is a key factor in determining site quality (Zahner, 1968). The development and expansion of shoot primordia are impeded by internal water stress. Soil water deficit in any growing season affects both functions for the present and for the coming years (Kozlowski, 1971a, p. 375).

Species respond differently to the distribution of precipitation. Stored carbohydrates rather than the products of current photosynthesis determine the height growth in a given year in many species, especially those which have only one flush of growth per year. In an extensive review of the literature, Kozlowski (1958) concluded that many deciduous tree species start their height growth early in the season and complete much of it long before carbohydrates are produced at the maximum rate by the crown. Height growth in these trees is therefore dependent on the environmental conditions during the previous year, mainly precipitation. However, exceptions do occur.

The annual height increment of yellow-poplar (Liriodendron tulipifera L.) in West Virginia is directly related to the May through June precipitation of the current year (Tryon et al., 1957). Of immediate importance to this study is the claim made by Brown (1973) that the height growth of Robinia pseudacacia L. is determined by the precipitation of the current year. Zahner and Stage (1966) found that low soil water potentials during the period from mid-June through October of the previous year were as much responsible for the reduced height growth of 30 to 40-year-old Pinus resinosa Ait. as the water deficit from May to mid-July of the current growing season. Although height growth in P. resinosa Ait. is predetermined and it makes only one flush of growth each year, the current year's precipitation during shoot growth period affects its elongation. In this respect, P. resinosa Ait. behaves similarly to those species which have three or four flushes of growth every year e.g., loblolly pine, in which the current late season shoot growth is influenced by the current soil water conditions (Zahner, 1962).

Examination of Tables 3 through 5 reveals that the droughty summers of 1971 and 1973 resulted in a decrease in height growth in 1972 and 1974 except for Fraxinus rotundifolia Mill. in 1972. This is in line with Kozlowski's conclusion (1971a, p. 375) regarding the carryover effect of one year's drought on height growth during the following year.

To find a relationship between height growth and precipitation, several attempts were made to correlate the current year's height growth with the depth of precipitation which fell in different periods of either the current or the previous year. Since the growth during the year immediately after transplanting is mainly determined by nursery conditions, the combined growth for 1970 and 1971 was regressed on total precipitation during April and May of 1970. Table 34 presents the total amount of water received during April and May by the treated and control plots, along with the extra depth of water received by the asphalt treated plots. Table 35 presents the cumulative growth for each of the species on treated and control plots along with the increase of treated over control. The increase in height growth of the trees planted on the treated plots due to the increase in the amount of water received by them during April and May of the previous years is shown in Figure 21.

Table 34. Cumulative depth of water received by the treated and control plots for April and May, and the increase on the asphalt treated plots, in cm.

	Year				
Treatment	1970	1971	1972	1973	1974
	- - - - - - - - - - -	- - - - -	cm	- - - - -	- - - - - - - - - - -
asphalt	7.80	17.46	31.61	36.29	46.58
control	4.76	11.26	21.83	25.45	34.77
increase	3.04	6.20	9.78	10.84	11.81
percent increase	63.9	55.1	44.8	42.6	34.0

The best fit for all three tree species, both in the asphalt treatment and control, were found when the cumulative growth of each

Table 35. Cumulative height growth of the three tree species used and the increase in growth of the asphalt treated plants, in cm.

		Year				
Species	Treatment	1970	1971	1972	1973	1974
		cm				
Robinia pseudacacia L.	asphalt	23.1	79.3	121.0	160.2	182.6
	control	14.6	42.4	67.9	94.8	113.0
	increase	8.5	36.9	53.1	65.4	69.6
	percent increase	58.0	86.9	78.2	69.0	61.5
Cupressus arizonica G.	asphalt	27.7	67.0	92.3	125.9	149.0
	control	25.1	57.5	78.7	110.9	130.1
	increase	2.6	9.5	13.6	15.0	18.9
	percent increase	10.6	16.5	17.3	13.5	14.6
Fraxinus rotundifolia Mill.	asphalt	11.9	51.7	93.8	114.6	132.4
	control	8.1	34.9	66.2	87.5	102.3
	increase	3.8	16.8	27.6	27.1	30.1
	percent increase	47.4	48.0	41.8	31.0	29.4

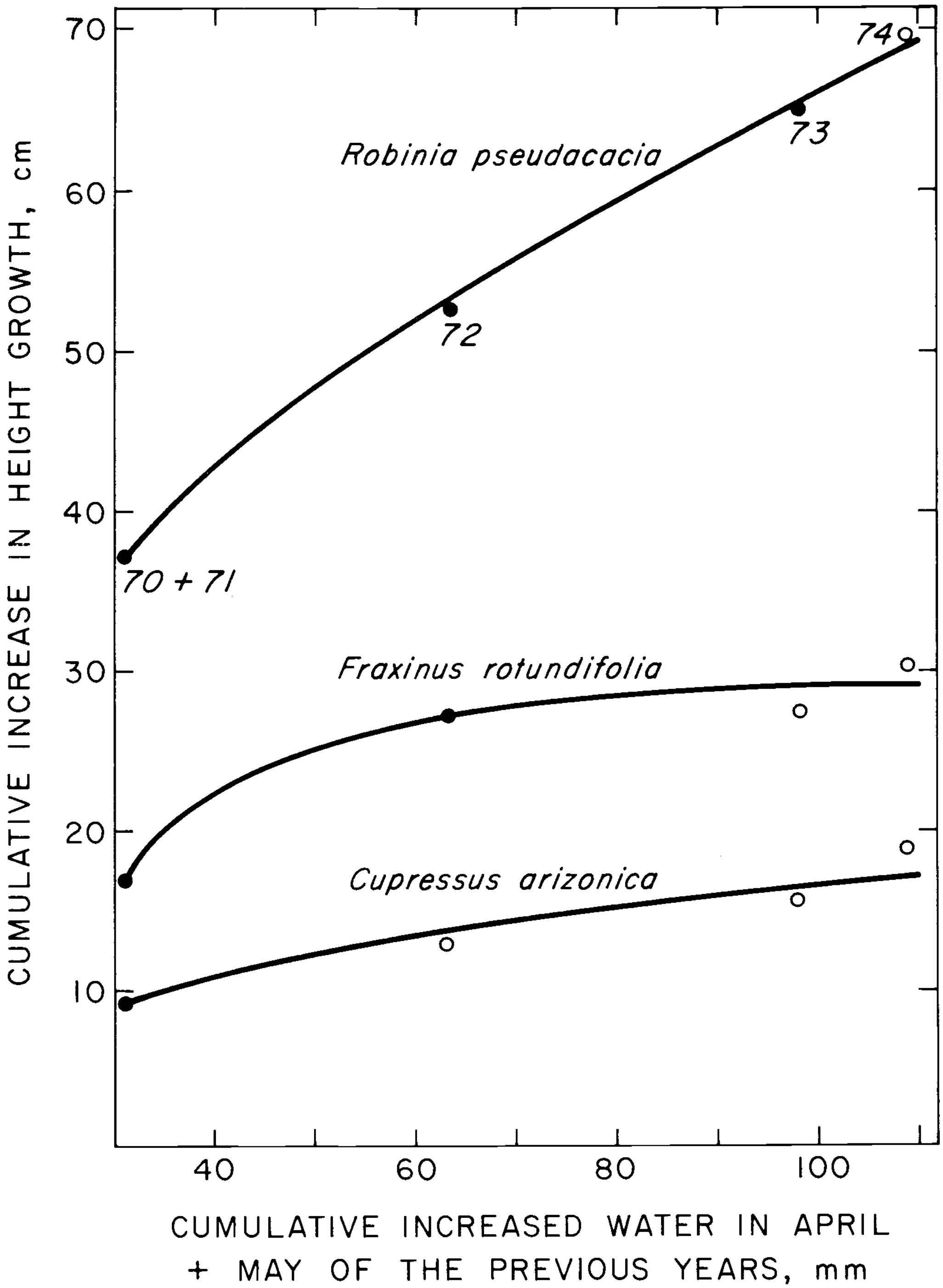

Figure 21. Cumulative increase in height growth of the three tree species as a function of the cumulative extra depth of water received by them due to asphalt treatment during April and May of the previous years. Closed circles indicate values significantly different from those of the control plants measured at the same time. Open circles indicate that results were not statistically different from control plants.

species was regressed on the total rainfall which fell in the previous years during the months of April and May and the time elapsed since the planting date. This observation parallels that of Muelder and Schaefer (1962), who reported that the shoot growth of Pinus ponderosa Dougl. in California was closely related to June and July precipitation of the previous year, but is in contrast with Brown's finding (1973) that the shoot growth of Robinia pseudacacia L. is not predetermined.

The regression equations obtained for each species on treated and control plots are presented in Table 36. That the current year's height growth correlates so well with the precipitation which fell during April and May of the previous year may constitute an anomaly since bud formation usually takes place in the latter part of the growing season. Clemets (1970) observed that the amount of water received by five year old Pinus resinosa Ait. from 23 July to 1 November was the determining factor for height growth of the next growing season. Considering the fact that, except for 2.4 mm of rainfall in July, there was no precipitation during the period from May 29 to October 26, 1971 and that the period from May 1 to November 19, 1973 was rainless, it is concluded that the total April and May precipitation, which recharges the soil water holding capacity to the degree that the trees survive the droughty summers, is responsible for the bud formation later in the season and height growth in the next year.

Table 36. Regression equations correlating cumulative height growth (y in cm) to total April + May precipitation of the previous years (x_2 in cm), and the time elapsed since planting (x_3 in years).

Species	Treatment	Regression equations	r^2
Robinia pseudacacia L.	asphalt	$y=38.467+2.1412x_2+13.562x_3$	.9950**
	control	$y=8.697+1.3196x_2+14.284x_3$	.9986**
Cupressus arizonica G.	asphalt	$y=22.163+.9942x_2+18.078x_3$	.9992**
	control	$y=24.198+1.8075x_2+11.873x_3$	.9989**
Fraxinus rotundifolia Mill.	asphalt	$y=18.947+1.1038x_2+15.284x_3$	.9600**
	control	$y=6.3321+1.2264x_2+13.432x_3$	.9783**

** Significant at the 1% level.

Crown Area Growth and Precipitation

The previous discussion concerning height growth pertains to growth of crown area as well. This is because the crown is composed of shoots which, in contrast to the leader shoots which grow vertically upward resulting in the increase in height growth, grow at different angles relative to the vertical axes of the trees resulting in the enlargement of their horizontal projection. Cumulative crown area was regressed on the cumulative April plus May precipitation of the previous years and the elapsed time since planting date. There was one exception, however. The best fit equation for Cupressus arizonica G. was obtained by regressing cumulative crown growth on cumulative rainfall of April through May of the years in which crown growth took place and the elapsed time since planting.

Table 37 presents the cumulative growth of crown area of the species used in the experiment along with the difference in the growth due to asphalt treatment. The increase in growth of crown area of the trees planted on the treated plots due to the increase in the amount of water received by them during April and May of the previous years is depicted in Figure 22. Table 38 presents the regression equations for crown area growth.

Stem Growth and Precipitation

Stem diameter is so sensitive to changes in soil water conditions that even its diurnal variations due to fluctuations in water availability are measurable (Kramer and Kozlowski, 1960, p. 32). The

Table 37. Cumulative growth of crown area of the three tree species used and the increase in growth of the asphalt treated plants, in m^2.

Species	Treatment	Year 1970-71	1972	1973	1974
		m^2			
Robinia pseudacacia L.	asphalt	1.1225	2.0975	3.1125	3.8325
	control	0.5350	1.3025	2.0125	2.3750
	increase	0.5875	0.7950	1.1000	1.4575
	percent increase	109.9	61.1	54.7	61.4
Cupressus arizonica G.	asphalt	0.3475	0.7900	0.9925	1.3550
	control	0.2900	0.6475	0.8325	1.1750
	increase	0.0575	0.1425	0.1600	0.1800
	percent increase	19.9	22.0	19.3	15.4
Fraxinus rotundifolia Mill.	asphalt	0.1325	0.4725	0.7175	0.9675
	control	0.0600	0.2350	0.4125	0.5400
	increase	0.0725	0.2375	0.3050	0.4275
	percent increase	120.9	101.1	74.0	79.2

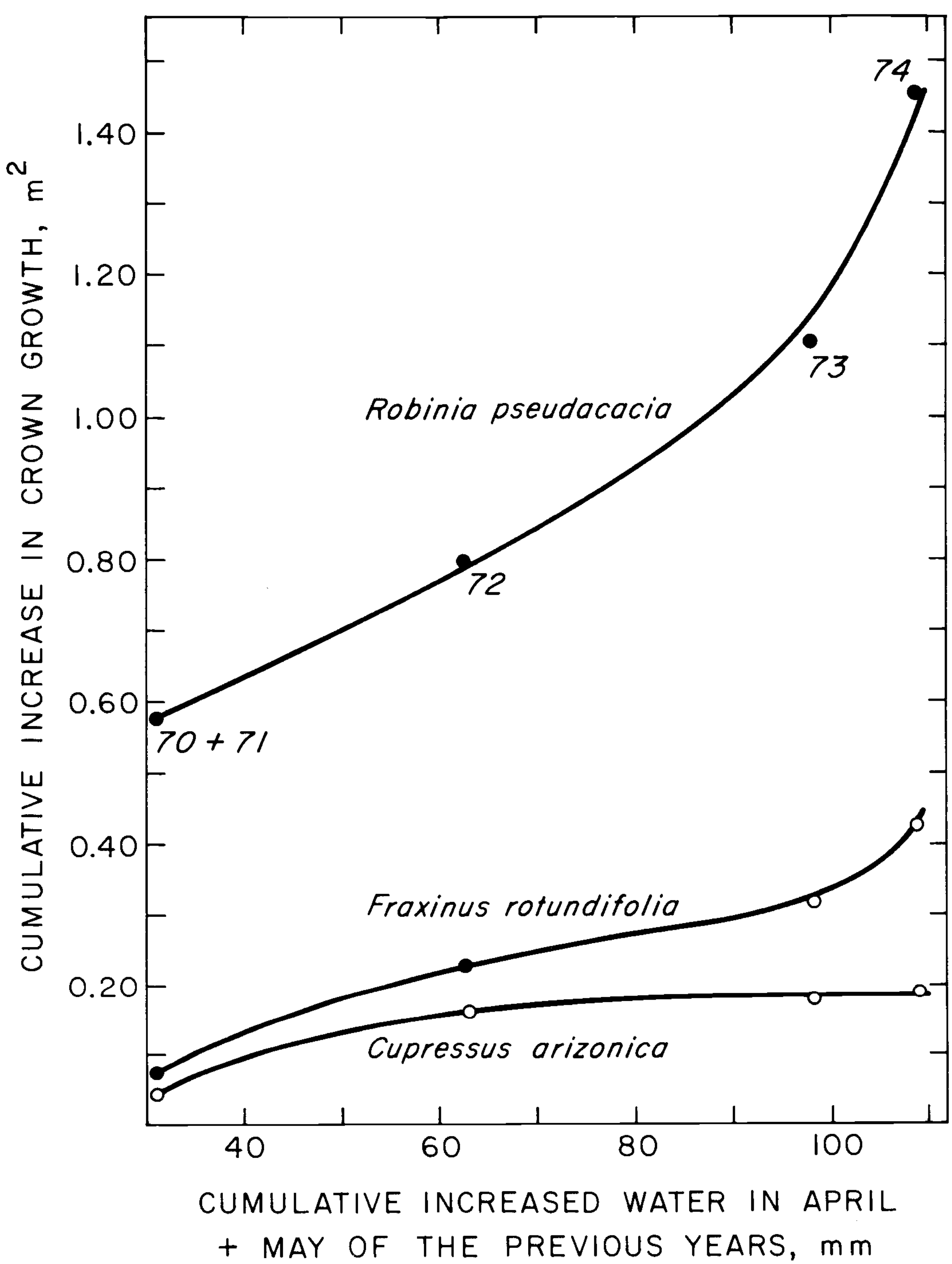

Figure 22. Cumulative increase in crown growth of the three tree species as a function of the cumulative extra depth of water received by them due to asphalt treatment during April and May of the previous years. Closed circles indicate values significantly different from those of the control plants measured at the same time. Open circles indicate that results were not statistically different from control plants.

Table 38. Regression equations correlating cumulative crown growth (y in m^2) to cumulative April + May precipitation of the previous years (x_2 in cm)+, and the time elapsed since planting (x_3 in years).

Species	Treatment	Regression equations	r^2
Robinia pseudacacia L.	asphalt	$y=-.25915+.034586x_2+.56996x_3$	.9993**
	control	$y=-.092321+.055415x_2+.22047x_3$	.9898**
Cupressus arizonica G.	asphalt	$y=-.27685+.025094x_2+.091534x_3$	.9998**
	control	$y=-.19099+.025431x_2+.095427x_3$	.9998**
Fraxinus rotundifolia Mill.	asphalt	$y=-.35751+.0028132x_2+.24705x_3$	.9936**
	control	$y=-.17986+.0077499x_2+.10545x_3$	.9983**

\+ For Cupressus arizonica G. x_2 is the cumulative April + May precipitation of the same years in which crown growth took place.

** Significant at the 1% level.

relationship between soil water content and diameter growth has been established. This phenomenon is so well proven that past weather conditions may be reconstructed by comparing the width of annual rings produced in different years (Fritts, 1966). Comparison of the thickness of early wood and late wood even indicates the relative abundance and distribution of the precipitation during a growing season (Kozlowski, 1971b, p. 164-166). The thinning of crowded stands to increase diameter growth is a common practice among foresters. It is done to make more water, light, and nutrients available for the remaining trees (Youngberg, 1975).

Diameter growth starts later than height growth and continues much longer. Cambial growth depends, to a large degree, on food and growth regulators which are synthesized in leaves. Therefore, the climate of a given season may affect the cambial growth during the following year (Kozlowski, 1971b, p. 119). Observations on the diameter growth of *P. aristata* Engelm., made by Fritts (1966, 1969) in the White Mountains of California, fully support this hypothesis. Moisture conditions of the previous summer and fall, temperature of the winter, and evapotranspiration deficits during April through June, all parameters which precede the beginning of growth, dictate the ring width in this species. Tryon and True (1958) reported that the annual radial growth of *Quercus coccinea* Muenchh. was directly related to the previous year's precipitation. Fritts, as reported by Kozlowski (1971b, p. 119) presented evidence that the environmental conditions of the previous year were as effective, or even more so, than those of the current year on diameter growth of *Fagus grandifolia* Ehrh. Ring width in this species was proportional to the amount of precipitation during August of the previous year. In contrast to these findings, Tryon et al. (1957) established that ring width in yellow-poplar was proportional to the precipitation of May through June of the current year. No relationship was observed between diameter growth and the rainfall of the previous year. These observations notwithstanding, the general consensus among the workers in this field is that diameter growth depends mostly on products of the current photosynthesis, hence it is sensitive to changes in soil water content during the current season (Kozlowski, 1958, 1962).

Duration of diameter growth differs for different genetic, stages of plant life, and environmental conditions. The growing season for _P. aristata_ Engelm. in the cool, White Mountains of California lasts about 45 days (June 26 through August 9). The young trees initiate growth four to seven days earlier and terminate growth as much as 13 days later than the old trees. While the length of the growing season ranges from 35 to 43 days for old trees, it lasts from 47 to 56 days for the young trees (Fritts, 1966, 1969).

As the climate becomes milder the growing season lasts longer. Duration of stem growth in ash (_Fraxinus excelsior_ L.) in Oxford, England, has been reported to be about five months, from early April to late August (Chalk, 1930). In a study of eight species of softwood and eight species of hardwood in Ontario, Canada, Fraser (1962) observed that the diameter growth starts in the latter part of spring and continues until early September. It has been shown that _Pinus taeda_ L. and _P. echinata_ Mill. begin diameter growth about mid-March in southeast Arkansas and continue until October (Bassett, 1964). Moehring and Ralston (1964) observed that the rate of diameter growth in sawtimber P. taeda L. was related to the amount of water available from June through August. They further observed that at the rate of soil water loss of 0.25 cm/day, growth ceased at an average potential of -4.0 bars for the 0 to 122 cm layer. At the rate of water loss of 0.635 cm/day growth stopped at an average potential of -2.0 bars for the 0 to 122 cm layer. In an irrigation experiment with P. taeda L., Zahner (1962) found that irrigated trees continued their growth until early October while control trees stopped growing in the middle of June.

Attempts were made to obtain a correlation between the growth of the stem cross section and precipitation. Table 39 presents cumulative stem cross sections at the 20 cm height for the plants on asphalt treated and control plots and the increase due to the asphalt treatment. Table 40 presents cumulative depth of water received by the treated and control plots for the period April through October and the increase due to the asphalt treatment. The increase in stem cross section growth of the trees planted on the asphalt treated plots due to increase in the amount of water received by them during April through October of the previous years is depicted in Figure 23.

Considering that Robinia pseudacacia L. and Fraxinus rotundifolia Mill. are dormant at the experimental site from late October to early April, the selection of April through October precipitation is reasonable. However the application to Cupressus arizonica G. may seem coincidental. The following explanation may clarify this point.

Table 39. Cumulative growth of stem cross section of the three tree species used and the increase in growth of the asphalt treated plants, in cm^2.

Species	Treatment	Year 1970-71	Year 1972	Year 1973	Year 1974
		cm^2			
Robinia pseudacacia L.	asphalt	4.79	9.01	13.41	16.17
	control	3.12	5.46	8.56	10.57
	increase	1.67	3.55	4.85	5.60
	percent increase	53.6	65.1	56.6	53.0
Cupressus arizonica G.	asphalt	1.41	3.88	7.95	11.15
	control	1.10	2.93	5.74	8.47
	increase	0.31	0.95	2.21	2.68
	percent increase	28.0	32.4	38.4	31.6
Fraxinus rotundifolia Mill.	asphalt	2.85	4.72	8.17	9.66
	control	2.29	3.56	6.57	7.80
	increase	0.56	1.16	1.60	1.86
	percent increase	24.7	32.3	24.3	23.9

In a thorough review of the literature, Tranquillini (1964) concluded that the minimum temperature for net photosynthesis of northern alpine evergreen species lies between -2 to -5 C. The water in the leaves of cold resistant conifers begins to freeze in this temperature range, hence photosynthesis must stop because water is drawn out of the cells by freezing. The net photosynthesis in Pinus aristata Engelm. declines in the subfreezing temperatures of November and stops completely by mid-winter (Fritts, 1966; Schulze et al., 1967).

Table 40. Cumulative depth of water received by the treated and control plots for April through October, and the increase on the asphalt treated plots, in cm.

	Year				
Treatment	1970	1971	1972	1973	1974
			cm		
asphalt	11.84	22.74	42.94	47.63	65.61
control	7.26	14.58	29.49	33.11	49.12
increase	4.58	8.16	13.45	14.52	16.49
percent increase	63.0	56.0	45.7	43.9	33.6

The soil of the experimental site is frozen to a depth of about 40 cm in February and to shallower depths in late December, January and early March. Assuming that Cupressus arizonica G. does not photosynthesize during the winter due to low temperatures, it should respond to November and March precipitation when the higher temperatures facilitate photosynthetic activities. One explanation which is

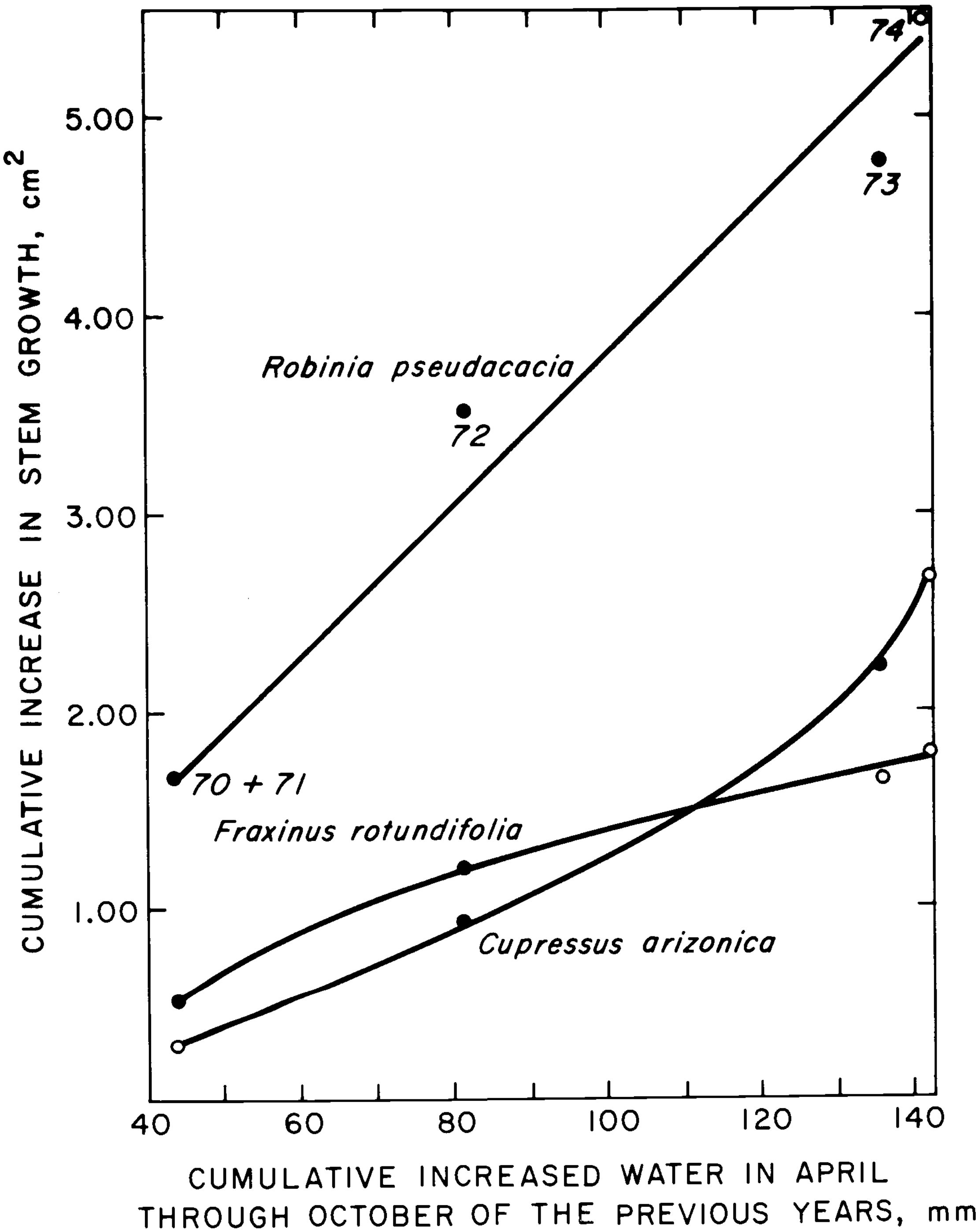

Figure 23. Cumulative increase in stem cross section of the three tree species as a function of the cumulative extra depth of water received by them due to asphalt treatment during April through October of the previous years. Closed circles indicate values significantly different from those of the control plants measured at the same time. Open circles indicate that results were not statistically different from control plants.

conjectural at this point is that the produced photosynthates just balance the energy used in metabolism and do not contribute to the growth.

To compare the viewpoint that the diameter growth is dependent on the current year's precipitation which is the prevailing consensus, with the belief that the previous year's precipitation regulates the diameter growth, two approaches were taken. Cumulative stem cross section was regressed on the cumulative rainfall of April through October of the current year and the elapsed time since planting. The equations obtained using this approach were meaningless, despite the highly significant r's squared. This is because the sign of the precipitation variable in the equations were negative. This means that stem growth is inversely proportional to precipitation which, for a site in a dry environment with adequate drainage, is not logical. When cumulative stem growth was regressed on cumulative rainfall of April through October of the previous years and the elapsed time since planting, meaningful equations were obtained (Table 41).

That the stem growths of the species used here were predetermined is understandable on the basis that the current years precipitation controls both height growth and crown growth of the coming year. Therefore precipitation controls the photosynthesizing area produced in any one growing season, thus affecting the food making potential and ring growth of trees for several years following (Fritts, 1966).

It should be realized that this finding neither supports one viewpoint nor refutes the other. The conclusions arrived at by the authors cited in this section were on the basis of the studies made on pole

Table 41. Regression equations correlating cumulative stem growth (y in cm^2) to cumulative precipitation for the period April through October of the previous years (x_2 in cm), and the time elapsed since planting (x_3 in years).

Species	Treatment	Regression equations	r^2
Robinia pseudacacia L.	asphalt	$y=-1.1496+.11149x_2+2.4316x_3$	.9974**
	control	$y=-.89419+.096797x_2+1.6520x_3$	.9999**
Cupressus arizonica G.	asphalt	$y=-4.9082+.047449x_2+2.7217x_3$	.9938**
	control	$y=-4.0655+.0079143x_2+2.4188x_3$	.9917**
Fraxinus rotundifolia Mill.	asphalt	$y=-.3701+.12259x_2+.82497x_3$	.9982**
	control	$y=-.0072567+.15792x_2+.49513x_3$	.9956**

** Significant at the 1% level.

size or large trees in environments different from those of the Tehran area. Had they conducted their researches on seedlings, and in dry environments, they might have reached the same conclusion as presented here.

To achieve a better understanding of the value of asphalt treatment in increasing growth of the tree species used in the experiment, Figures 21 through 23 were combined and are presented as Figure 24. It is noted that the largest increase in height growth occurred during 1970 and 1971, mainly in 1971 (see also Table 34). This is because the asphalt-soil membrane remained intact during the first growing season and the runoff coefficient was about 42 percent. As the membrane deteriorated and its efficiency in inducing runoff decreased, its contribution to the height growth of the seedlings was reduced.

The height growth of Cupressus arizonica G. benefitted significantly from the extra water provided by the asphalt treatment only during the 1970-1971 period. The extra growth of this species due to runoff was not significant after 1971, although the treated trees always grew better than the control trees. This is apparently a characteristic response of this species which will be discussed later with regard to stem growth. Fraxinus rotundifolia Mill. benefitted from the extra water in 1971 and 1972. The runoff coefficient was about 36 percent during the growing season of 1971. This produced a quantity of water large enough to affect height growth of this species significantly. Robinia pseudacacia L. used the extra water to the best advantage. The increase in height growth of this species over that of the control was significant even in 1973, when Fraxinus rotundifolia

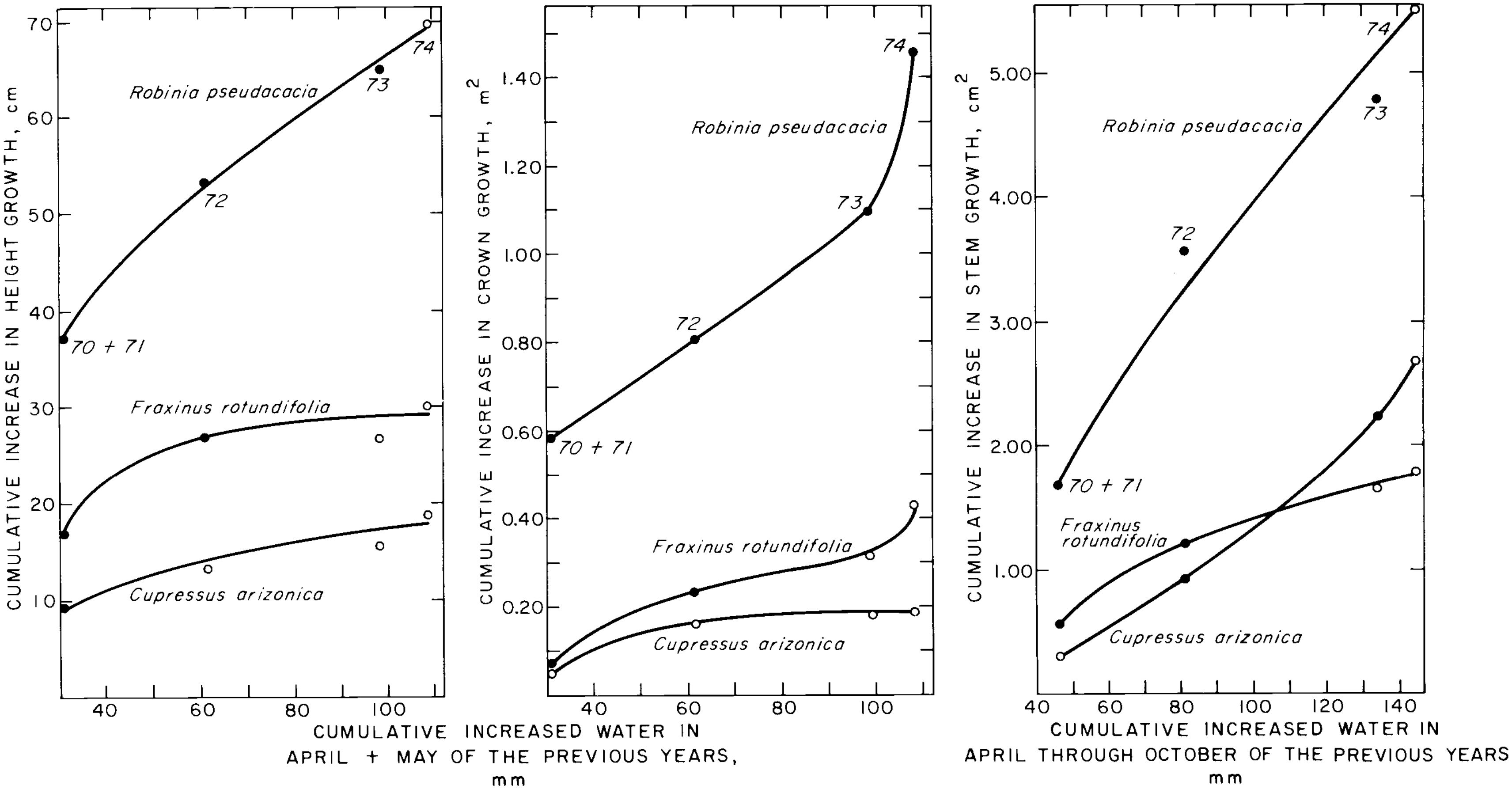

Figure 24. Cumulative increases over controls in the growth of height, crown cover, and stem cross section of Robinia pseudacacia L., Cupressus arizonica G., and Fraxinus rotundifolia Mill. as a function of the cumulative extra water made available in April and May of the previous years due to asphalt treatment for height and crown growth, and from April to October of the previous years for stem growth. Closed circles indicate values significantly different from those of the control plants measured at the same time. Open circles indicate that results were not statistically different from control plants.

Mill. and Cupressus arizonica G. did not show a significant increase over controls.

Total precipitation during April through May in 1973 was 36.2 mm which resulted in 10.63 mm of runoff from the treated area. Apparently, this amount was not enough to cause a significant increase in height growth of Robinia pseudacacia L. planted on the asphalt treated area. Additional precipitation might have produced the extra height growth required to obtain a significant increase for 1974.

The increase in crown growth of the trees planted on the asphalt treated plots over the trees of the control plots followed the same trend as the increase in height growth, with two exceptions. Firstly, the crown growth of the treated Cupressus arizonica G. trees was not significantly different from that of the control trees during any of the five growing seasons. Secondly, the crown growth of the treated Robinia pseudacacia L. trees was significantly higher than that of the control trees, even during the 1974 growing season.

Crown growth is correlated with height growth, therefore the increase was not expected to be significant during 1974. The geometry of the horizontal projection of the crown plays an important role here. The increases in the crown radii were 6.9 and 11.0 cm for Robinia pseudacacia L. trees planted on the control plots and on the asphalt treated plots, respectively. The difference of 4.1 cm is relatively small. However, the 6.9 cm for the control trees were added to the existing radius of 160 cm, while the 11 cm for the treated trees were added to the existing radius of 198 cm. Identical increments added to radii of different length circumscribe different areas. This area is larger when the increment is added to a larger existing radius. As a result the increase in the horizontal projection of the crown of the treated species was higher than that of the control species at the 0.1 percent level of significance for 1974.

The increases in stem growth of the trees due to treatment followed the same trends as were described for height and crown growth. This was to be expected. The photosynthesizing area increases as the crown grows larger so that more metabolites are available to produce wood. However, the asphalt treated Cupressus arizonica G. present an exception. The increase in height growth was significant only during the 1970-1971 period, and the increase in crown growth was not statistically significant during any of the five growing seasons, or for the entire duration of the experiment. However the increase in growth of stem cross section of the treated Cupressus arizonica G. over that of the control was significant at the ten percent level for 1972, and at the five percent level for 1973. During the period 1970 through 1971, the absorbed water and nutrients were used to increase the volume of the needles; therefore, the first significant increase was shown in 1972. The largest amount of runoff for any growing season was 5.29 cm and occurred during 1972. It apparently added so much to the photosynthesizing area that the largest increase in stem cross section of Cupressus arizonica G. occurred in 1973, the driest growing season of the experimental period (Appendix Table 7).

The increase in the growth of the tree species due to extra water received as runoff from asphalt treated plots has been in accordance with expectations. However, the spectacular increase in growth of

Robinia pseudacacia L. on asphalt treated plots relative to that of control plots deserves special attention. The increases were 69 cm for height, 1.45 m^2 for crown area, and 5.6 cm^2 for stem cross section, corresponding to increases of 61.5 percent, 61.4 percent, and 53.0 percent relative to the controls.

The soil of the study site is very poor in nitrogen, containing only 0.09 and 0.03 percent in the A and C horizons, respectively (Appendix Table 5). Nitrogen could become a limiting factor after replenishment of soil water. When there is no N deficiency, the photosynthates are converted mainly to proteins and are available for growth, mainly in the shoots. Where N supply is deficient it is used mainly by the roots, into which the assimilates flow from the leaves. Therefore, root growth proceeds at the expense of the aerial parts (Stocker, 1960). Robinia pseudacacia L., being the only nitrogen fixing species in the experiment, used the available water more beneficially than the other two species. The increased availability of water for the asphalt treated trees facilitated N fixation and its more effective use than on the control species. This fact has been proven statistically as well. The highly significant levels of interaction of species and treatments for height and crown growth (Tables 11 and 18), and the significant level of interaction of species and treatments for stem growth (Table 25) are due to the discussed mechanism.

Another reason which might explain the high growth rate of the treated Robinia pseudacacia L. seedlings is the special characteristic of this species. The mature trees generally cease growth by the end of July, but the seedlings grow well into the autumn (Wareing, 1956), thus the treated trees benefitted more from the summer and fall rainfall than the control trees.

PERFORMANCE OF THE ASPHALT MEMBRANE

Asphalt spraying for the purpose of water harvesting was executed for the first time in Iran with this experiment. Techniques used for sand dune stabilization with petroleum mulch were modified to suit the present requirements. The performance of the asphalt membrane varied according to exposure and soil type. On the dark brown A horizon on the N exposure the membrane remained intact four years after spraying. The membrane was badly cracked on the light gray C horizon with SE exposure after the first winter, which decreased the runoff coefficient. Two causes responsible for this rapid deterioration can be identified. These are low temperatures and expanding clays. These will be discussed separately.

Aging of Asphalt on Different Exposures

The N exposure is covered with snow from late December to mid-March, thus protecting the membrane against low temperatures at night. Minima of -16 C occur frequently. Visual observations indicated that the asphalt membrane under the snow remained flexible. On the other hand, the snow cover melts rapidly on S exposures thus depriving the membrane of an effective insulator against subfreezing temperatures. Cold southerly winds which prevail during the winter intensify the effect of the low ambient temperatures. The daily temperature cycling furthermore produces alternate shrinkage and expansion which produces cracks. The melt water which enters through the cracks freezes during the night and peels the membrane in weak spots.

Aging of Asphalt on Different Soil Types

The asphalt sprayed onto the surface of the dark brown, A horizon lasted much longer than that applied to the exposed, light gray C horizon. Visual observations suggested that, among other things, the presence of expanding clays in the C horizon might have been responsible for the breakdown of the asphalt membrane.

It was mentioned earlier under the discussion of soil water retention characteristic that silicate clays constitute only 9.5 percent of the soil weight of the C horizon. Since the CEC of this soil as determined by the NH_4-acetate method (Schollenberger and Simon, 1945) is 9.4 meq/100 g (Appendix Table 5), one is tempted to conclude that smectite is the sole clay species in this soil.

However, the specific surface area, calculated according to Gardner (1968), does not lend support to this conclusion. Gardner believes that the water content at a potential of -15 bars is well correlated with the surface area of a soil and represents approximately ten molecular layers of water distributed uniformly over the particle surfaces. Taking the average thickness of a molecular layer of water to be 3×10^{-10} m, and the water content of this soil at -15 bars to be 0.0833 cm^3/g, the specific surface of the soil would be 27.76 m^2/g. Assuming that silicate clay particles contribute about 70 percent of the specific area, the specific area of the silicate clay fraction would be:

$$\frac{27.76\ m^2/g\ \text{soil} \times 0.70}{0.095\ g\ \text{clay}/g\ \text{soil}} = 204.5\ m^2/g\ \text{clay}$$

which categorizes it as illite, a non-expanding clay species (Carter et al., 1965).

Experiments were conducted to resolve this anomaly and to shed some light on the difference in performance of asphalt on these two soils.

Procedures

Efforts were made to keep the structure of the clay fractions as close to field conditions as possible during the experiments to be conducted. This is of utmost importance especially as far as the soil-water system is concerned since any constraint imposed on the clay system would change its behavior.[3] To achieve this dispersion in water is recommended.

A sample of each of the two soils was dispersed in distilled water for one minute using a blender. The samples were then separated into sand, silt, and clay size fractions following procedures outlined by Jackson et al. (1949).

Each clay suspension was divided into two equal parts. One part was saturated with Mg^{2+} and the other with K^{+} by washing them three times with one N chloride solutions followed by washing three times with distilled water. From each set of clays two glass slides of Mg^{2+} saturated material and one of K^{+} saturated material were prepared using the Theissen and Harward (1962) paste method. The Mg^{2+}

[3] M. E. Harward, Methods and criteria for clay mineral identification, 7 mimeographed pages. Dept. of Soil Science, Oregon State University, Corvallis.

saturated slides were kept in a 54 percent R.H. atmosphere and the air dried K^+ saturated slides were dried again at 105 C for one hour and kept in a desiccator.

X-ray diffraction patterns were obtained with a Phillips Norelco diffractometer using CuK_α radiation, a Geiger tube as the detector, and a potentiometric recorder with a speed of one degree per minute. The pattern for one of the Mg^{2+} saturated slides of each set was obtained at 54 percent R.H. The same slide was then solvated with glycerol (Brown and Farrow, 1956) and its duplicate with ethylene glycol using the Kunze (1954) method. The patterns for these two solvated slides were then obtained at 54 percent R.H. The pattern for the K^+ saturated slides were obtained with "dry" air (R.H. = 15%) and also at 54 percent R.H. The same slides were then dried at 300 C for two hours and following the recording of patterns at 15 percent R.H. dried again at 550 C for two hours. The diffraction patterns were again obtained at 15 percent R.H. The d spacings were determined from the centers of the peaks at half-peak height.

The patterns obtained for the C horizon soil presented an anomaly (Figure 25-II). It was therefore decided to treat the sample for removal of some of the materials which might interfere with its proper identification.

Calcium carbonate was removed using dilute HCl as proposed by Jackson et al. (1949), iron oxides were removed by Na-DCB method (Mehra and Jackson, 1960), and organic matter was removed using H_2O_2. The "clean" samples were then given the same treatments outlined earlier, and their x-ray diffraction patterns obtained.

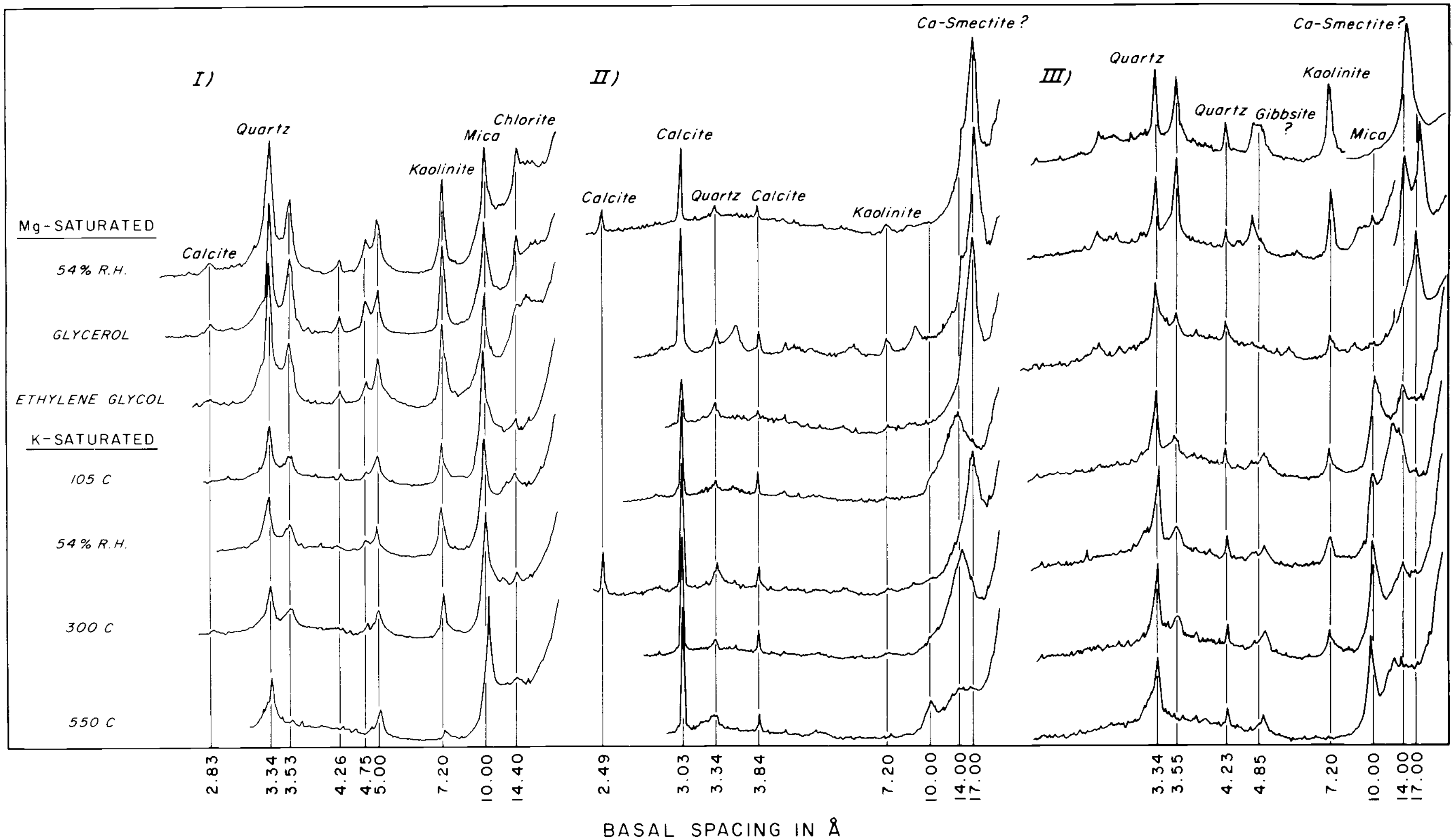

Figure 25. X-ray diffraction patterns of the <2 μm clay obtained from the A horizon (I) and C horizon (II, III) of soil from the study site. The only treatment that I and II received was dispersion in distilled water. Pattern III was obtained after the removal of $CaCO_3$, Fe_2O_3 and organic matter from the soil of the C horizon.

Results and Discussion

The prominent peaks for the A horizon soil belong to chlorite or chloritic integrades, micas, kaolinite, quartz, and calcium carbonate (Figure 25-I). The diffuse nature of the peaks in the low degree 2θ prevents concise identification of clay species in that region. The lack of expansion and collapse with the prescribed treatments refutes the presence of appreciable quantities of smectites. The prominent peaks of the "uncleaned" C horizon belong to calcite (3.84, 3.03, 2.48, and 2.27 Å) and quartz (3.34 Å) (Figure 25-II). The identification of clay species in the low degree 2θ range is difficult due to the diffuse nature of the peaks. More than one species may be present under each peak.

The presence of a 16.59 Å peak (Mg^{2+}, 54% R.H.) which collapses to 10.04 Å (K^+, 550 C), and the absence of second and higher order reflections may indicate the presence of a smectite species with irregular interlayer material (Figure 25-II). The peak at 14.38 Å (K^+, 300 C) may also indicate smectite or a chloritic intergrade since iron rich chlorites collapse at 550 C and this peak disappears at this temperature. However, the second and higher order reflections are absent. The diffuse peak in the range of 7.13 to 7.24 Å might be the second order of this chlorite species, or a not well crystallized kaolinite.

The peak at 16.59 Å with Mg^{2+} as well as K^+ saturation at 54 percent R.H. which does not expand with ethylene glycol but expands to 17.65 Å with glycerol is intriguing. These specimens were probably neither Mg^{2+} nor K^+, but Ca^{2+} saturated! Apparently, the original samples were not sufficiently dispersed in distilled water to allow Mg^{2+} or K^+ to replace Ca^{2+}, or the force of attraction between the Ca^{2+} saturated specimens was so strong that Mg^{2+} or K^+ were not able to substitute Ca^{2+} in the system.

That this species did not expand with ethylene glycol but expanded with glycerol is another source of confusion. Ethylene glycol, with its higher dipole moment than glycerol, should have penetrated the silicate layers more easily than glycerol. Since Harward et al. (1969) obtained expansion with both ethylene glycol and glycerol vapors with Ca-smectites, this behavior may be termed an anomaly.

This "Ca-smectite," when hydrated, has a water layer 16.59-10.09 = 6.50 Å thick. A fully hydrated smectite holds two molecular layers of water or 2.76+2.76 = 5.52 Å, which is about 1 Å less than what was observed. However, if the existence of three layers of water were possible, following Barshad's reasoning (1949), one might have 1.78 + 2.76 + 1.78 = 6.32 Å which is very close to 6.50 Å. Assuming that at 105 C only one molecular layer of water is left in the structure, and at 54 percent R.H., two layers, then:

$$16.59 - 13.58 = 3.01 \text{ Å}$$

which is very close to the thickness of one molecular layer of water. Therefore, the anomaly should be sought in the first layer (or layers) of water which is either 6.50 - 3.01 = 3.49 Å, or 2 x 1.78 = 3.56 Å.

The sample from which interfering materials had been removed, lost its calcite peaks but gained a few peaks as expected. The peak at 14.01 Å (K^+, dry air) which reduces to 13.92 Å after heating to 300 C might indicate a chlorite species (Figure 25-III). However, when the sample is glycerol solvated and the pattern amplitude intensified about five times the same peak gives a d spacing of 14.24 Å. Since this species gives higher order reflections, and collapses at 550 C, it might be an iron rich chlorite. Whether the peak in the range of 7.10 to 7.14 Å is kaolinite or second order chlorite is speculative. The prevailing climatic conditions which include high pH, low precipitation, and cold weather when water is available do not favor kaolinite formation. It is probable that this species was brought to the site by precipitation. Kumai (1961) reported that kaolin minerals accounted for 51 percent of the nuclei of snow crystals in the northern U.S. The presence of a smectite species was confirmed with a very intense peak at 14.60 Å (Mg^{2+}, 54 percent R.H.), expanding to 16.35 Å following the ethylene glycol treatment, to 17.51 Å following the glycerol treatment, and collapsing to 9.99 Å (K^+, 550 C) following the heat treatment. Mica (9.99 Å) and quartz (4.23, 3.34 Å) are the other two identified minerals.

The intensification of peaks by the removal of carbonates is in line with Pettry and Rich's observations (1971). The effects of HCl treatment and Fe removal on bringing out the chlorite line had been observed by Harward et al. (1962) as well. However, these "cleaning" treatments did not help to show the nature of the 16.59 Å peak observed in the "uncleaned" sample (Mg^{2+}, 54 percent R.H.).

Considering that $CaCO_3$ makes up about 65 percent of the weight of the soil under investigation and that studies of Taylor and Howison (1956), Eades and Grim (1960), Eades et al. (1962), and Pettry and Rich (1971) provide circumstantial evidence for the existence of Ca-silicate clays, it is proposed that this species may be a new clay species not identified as of now. The data presented by Eades et al. (1962) support the possible formation of a Ca-clay species with a basal spacing of about 15 Å when a micaceous soil is treated with $Ca(OH)_2$. Taking the thickness of a $Ca(OH)_2$ layer as a 4.88 Å and that of mica as 10.0 Å, this spacing becomes possible indeed.

Two possibilities should be closely examined:

1. The "Ca-smectite" might be a mica + $Ca(OH)_2$ interlayer which can accpet only one molecular layer of water and loses its constituent water when heated to 550 C turning to Ca-mica.
2. The Fe-chlorite might be a mica + $Ca(OH)_2$ interlayer which does not expand upon hydration and collapses when heated to 550 C, behaving like kaolinite in this respect.

Another point which deserves mentioning is the formation of a diffuse peak in the vivinity of 4.83 Å which corresponds to the <u>d</u> spacing of gibbsite. Barnhisel and Rich (1963) contend that if hydroxy-Al montmorillonite is treated with acid (pH <4.3) gibbsite may be formed. Shen and Rich (1962) suggested that in the synthesized hydroxy-Al montmorillonite, the hydroxyl-Al interlayer does not always prevent expansion with glycol or water. They noted that in natural specimens the expansion with glycol may be inhibited by the presence of such interlayers. Whether the hydroxy-Al interlayer was responsible for the observed phenomena remains to be proven. It is probable that hydroxy-Al had been present in the sample and was removed by Na-DCB treatment as reported by Dudas and Harward (1971).

Conclusions

Although the study shed some light on the nature of clay species in the dark brown soil and in the highly calcareous light gray soil, it did not resolve the discrepancy between the calculated surface area and the CEC of this soil. Had the smectites been the sole clay species present, one could have reasoned that Gardner's suggestion of ten molecular layers of water at -15 bar potential is rather exaggerated, and that three to four layers would have been more appropriate. On the other hand, assuming Gardner's proposal to be correct, what has been identified as mica may be biotite which, by its very high charge density, contributes greatly to the CEC, while because of its large particle size relative to smectites does not contribute in the same proportion to the specific surface area of the clay.

It should be realized that the mineral surface in clay is so enormous that no amount of asphalt ordinarily used can be expected to coat it completely (Endersby, 1942). It is therefore concluded that abundance of a "smectite" in the light gray soil facilitates faster deterioration of the asphalt-soil membrane, particularly after cracking due to subfreezing temperatures and infiltration of water through the cracks and into the soil, while the relative lack of expanding clays in the dark brown soil increases the useful life of the membrane.

Whether the chemical breakdown of the membrane took place due to the reaction of acids in the asphalt with Mg^{2+} in the soil (Winterkorn, 1968) to produce hygroscopic and swelling Mg-soap is questionable. The Mg^{2+} contents of the A and C horizon are 2.7 and 1.2 meq/100g, respectively; therefore, the potential breakdown of the membrane on the dark brown soil should have been higher due to this mechanism.

SUMMARY AND CONCLUSIONS

Evaluation of five years of growth data for *Robinia pseudacacia* L., *Cupressus arizonica* G., and *Fraxinus rotundifolia* Mill., planted on plots treated with a special formulation of asphalt, provided information which can be used to evaluate a single application of asphalt as an alternative to the irrigation methods now in use. A regression equation was developed correlating runoff coefficient to the age of the asphalt-soil membrane and the amount of rainfall. This equation may be used to predict the amount of runoff from asphalt treated areas, thus enabling one to examine the merits, and calculate the economic feasibility, of water harvesting systems using asphalt as the soil sealant. Regression equations were developed correlating the growth in height, crown cover, and stem cross section of the trees planted on the asphalt treated and control plots to the precipitation which fell in certain periods of the growing season. The growth equations may be used in concert with the runoff equation to predict the spacing between adjacent terraces needed to achieve optimum growth of trees. These subjects along with other topics pertinent to the study are discussed below.

Runoff

The increase in surface runoff during the first few years after planting, which was an important objective of this study, was achieved through the application of a modified formulation of asphalt onto the soil surface. The efficiency of the asphalt-soil membrane in inducing runoff was about 75 percent immediately after application. This was reduced to about 25 percent after 3.5 years. A regression equation was developed correlating runoff coefficient (y in percent) to age of the asphalt-soil membrane (x_1 in months) and the amount of rainfall (x_2 in mm)

$$y = 47.974 - .63288x_1 - .1017x_2 \qquad r^2 = 0.44^{**} \qquad (7)$$

Extrapolation of this regression line indicates that the runoff coefficient of the membrane theoretically approaches zero five years after its formation. This conclusion is valid only for the asphalt formulation used in this experiment sprayed onto the dark-brown A horizon of the soil found at the study site.

Durability of the asphalt membrane was not satisfactory where it had been formed on the light gray C horizon soil found at the experimental area. Where the C horizon was exposed, due to natural phenomena or terrace construction activities, the membrane deteriorated rapidly, losing much of its runoff inducing potential. The expansion of a "Ca-smectite" present in the C horizon, but not described in the literature, may have been responsible for this poor performance. Whether the high $CaCO_3$ content of the C horizon was also responsible for the observed deterioration is yet unknown.

The main cause of the rapid decrease in the runoff coefficient of the membrane was the low winter temperature. The membrane behaved as a blackbody absorbing sunlight during the winter days, thus expanding due to the acquired heat. Contraction due to temperatures as low as -16 C resulted in formation of cracks in the weak spots. Water subsequently entered through the cracks and froze. The increase in volume of water after freezing heaved the membrane, thus breaking it when the force of expansion exceeded the ductility of the membrane.

Growth of plants through the membrane was another reason for the reduction in runoff coefficient. The growth of these plants was improved by the better soil water condition and soil temperature. The punctured membrane could not decrease infiltration substantially, thus the runoff coefficient was reduced accordingly.

Soil Water Potential

The extra water received by the terraces in the asphalt treated plots resulted in higher soil water potentials both in terraces and microwatersheds. An important property of the light gray C horizon, in which the majority of roots live, merits closer examination. This highly calcareous soil contains about 35 percent water by dry weight at -0.33 bars, thus it behaves like a clay soil at high soil water potentials. When the potential is reduced to -15 bars it releases most of the water and only nine percent is left in the soil, thus it behaves like a sandy soil at low soil water potentials. Apparently, the clay size $CaCO_3$ particles provide the large volume of pore space filled with water at high potentials. However, the same particles do not behave as layered silicates at low potentials, thus releasing most of the stored water.

This soil characteristic which was of equal benefit to both of the asphalt treated and the control trees enabled them to consume most of the water stored in the soil, helping them to survive the droughty summers common to the area.

Survival

Although the seedlings planted on the asphalt treated plots showed higher rates of survival than the controls, these differences were not statistically significant. Apparently, 47.8 mm of precipitation which fell immediately following the planting season in March 1970 and 23.4 mm of rain which fell in July of the first growing season were adequate to establish the seedlings at the same rate both on the treated and the control plots. However, it should be realized that the probability of occurrence of rainfall during the summer in Tehran is extremely low. The probabilities of having more than 10 mm of rain in June, July, and August in Tehran are 4.8, 0.7, and 4.1 percent, respectively (Hashemi, 1969). These probabilities are reduced to 0.5, 0.0, and 0.5 percent for having more than 20 mm of precipitation for June, July, and August, respectively. Therefore, the occurrence of 23.4 mm of rainfall in July 1970 at the experimental site was a rare event. Had the planting been done in 1971 or 1973, the two dry years of the experimental period, the survival results would have been different. The real value of the asphalt treatment would have been more apparent in terms of the success of the asphalt treated plants and failure of the control plants.

Growth

Growth is the result of many interactive mechanisms. The key to growth in a dry environment is water. The extra water provided for the trees planted on the asphalt treated plots resulted in faster rates of growth in height, crown cover, and stem cross section.

Robinia pseudacacia L. proved to be the superior species in this trial. When the response of this species to the extra runoff water is compared with that of Cupressus arizonica G. and Fraxinus rotundifolia Mill. it becomes apparent that Robinia pseudacacia L. can benefit substantially from the extra water provided by the asphalt treatment. The increase of 69 cm in height growth, 1.45 m^2 in crown cover, and 5.59 cm^2 in stem cross section of the Robinia pseudacacia L. seedlings planted on the asphalt treated plots over the trees planted on the control plots, which occurred during five growing seasons, indicate that this N fixing species utilized the extra water provided by the asphalt treatment effectively. Fraxinus rotundifolia Mill. did not benefit as much from the extra water as did Robinia pseudacacia L. The increase in the growth of height, crown cover, and stem cross section of the treated trees over the controls were 30 cm, 0.42 m^2, and 1.86 cm^2, respectively. Cupressus arizonica G. benefitted the least from the asphalt treatment. The trees planted on the asphalt treated plots showed an increase of 19 cm in height, 0.18 m^2 in crown cover, and 3.04 cm^2 in stem cross section over their controls. Apparently, the deficiency in major nutrients, mainly N, limited the growth of Cupressus arizonica G. and Fraxinus rotundifolia Mill.

A series of regression equations were developed correlating the growth to (i) precipitation during certain periods of the so-called growing season and (ii) the age of the seedlings. The objective was to obtain information about the growth of the tree species used in the experiment, and to obtain predictive equations which can be used in planning afforestation projects with and without employing the procedure for water harvesting mechanism, described in this report.

The best regressions for height growth and crown cover growth were obtained when cumulative yearly growth was regressed on cumulative precipitation during April and May of the previous years and the elapsed time since planting. The only exception being crown growth of Cupressus arizonica G. which was dependent on cumulative precipitation which fell during April and May of each year in which growth took place. Apparently, the growing season for height and crown of the species used lasted only about two months. This is in contrast to the common belief that spring and summer form the growing season. Lack of precipitation in summer months shortens the duration of height and crown growth. This parallels Fritts' findings (1966, 1969) regarding the growing season of bristlecone pine in the White Mountains of California, where the low temperatures limit the growing season to less than two months. The dependence of height growth on the previous year's precipitation is in agreement with the common consensus among plant physiologists (Kozlowski, 1971a, p. 375). However, there is an exception. Brown (1973) is of the opinion that growth of Robinia pseudacacia L. is not predetermined, and therefore depends on the current year's rainfall. The findings presented in this thesis refute this statement.

The best fit regression equations for stem cross section growth for all of the three species used in the experiment were obtained when cumulative yearly growth was regressed on cumulative precipitation which fell during April through October of the previous years. This is in contradiction with the consensus among plant physiologists regarding the stem growth of mature trees. It should be realized, however, that stem growth of seedlings is not commonly studied, and the published results usually deal with pole size trees. Therefore the conclusion arrived at here may not be valid refuting the established principles.

The increase in growth due to the extra water provided by the asphalt treatment is presented in Figure 26-I. The increase in the growth of the asphalt treated trees may not look very impressive after the five year experimental period. However, it should be realized that this study was done for the first time and no previous experience was available.

The most limiting factor, assuming everything else to remain constant, was the area of the microwatersheds. To predict the sizes of the asphalt treated trees relative to those of their control two hypothetical situations were examined by using the data presented in Table 30 and the regression equations presented in Tables 36, 38, and 41. Figure 26-II summarizes the results of calculations made assuming that the area of the microwatersheds were twice as large as those reported in this thesis, i.e., the horizontal projection of the

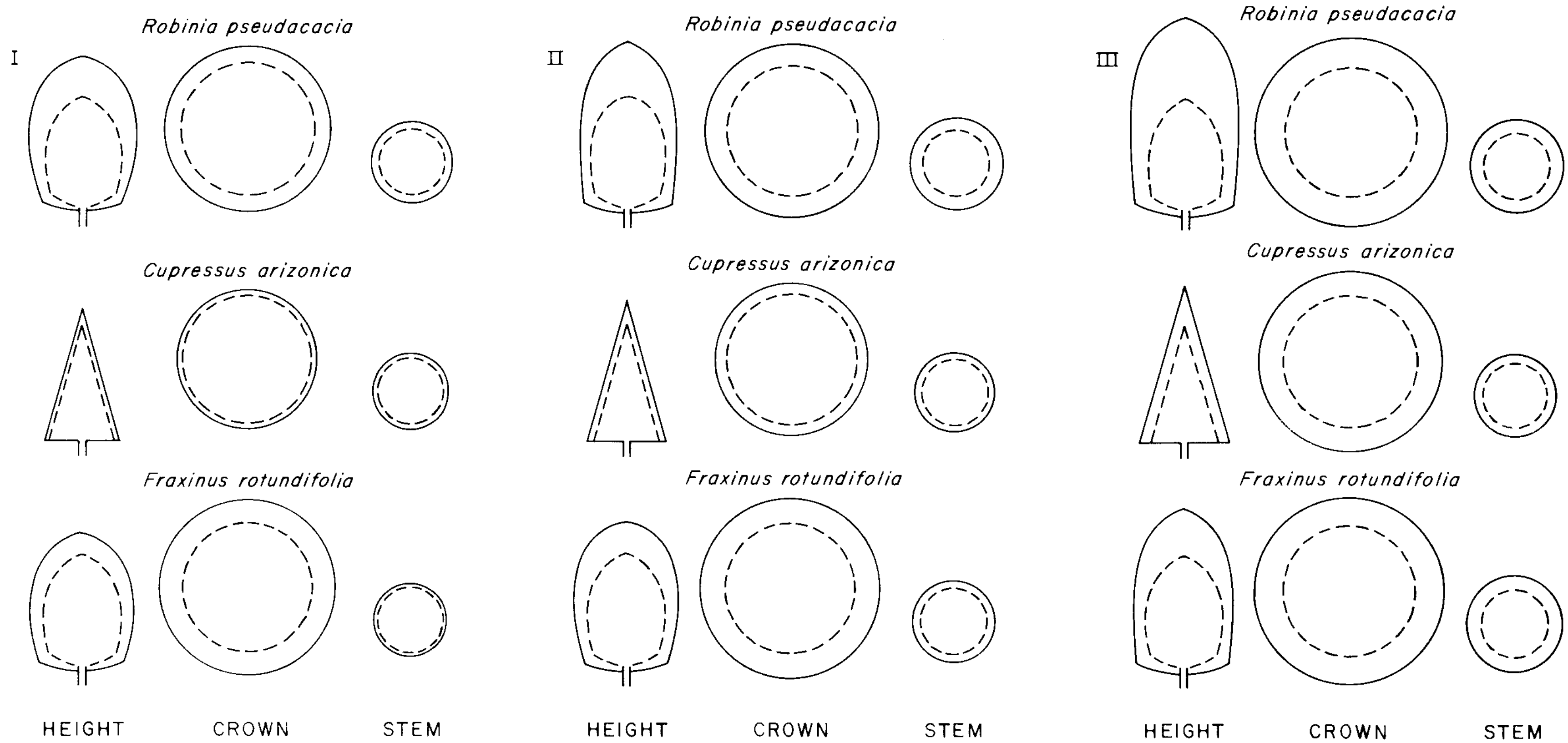

Figure 26. Schematic presentations of the height and horizontal projections of crown cover and stem cross section of the five year old tree species used in the experiment. Solid lines indicate plants on the asphalt treated plots, broken lines indicate plants on the control plots. I. Trees planted on terraces with a microwatershed to spreading basin ratio of 1.5. Based on experimental data. II. Same as I, for a microwatershed to spreading basin ratio of three. Based on extrapolation of experimental data. III. Same as I, for a microwatershed to spreading basin ratio of six. Based on extrapolation of experimental data.

microwatershed length were six m. This would have occurred if the vertical interval were 2.4 m long instead of 1.5 m. Figure 26-III presents the results of calculations made assuming that the area of the microwatersheds were four times as large as those reported in this thesis, i.e., the horizontal projection of the microwatershed length were 12 m. This would have occurred if the vertical interval were 4.2 m long instead of 1.5 m. The same results would have been achieved if the runoff coefficient of the asphalt-soil membrane were twice or four times higher than it was in this experiment.

In arriving at these conclusions it has been assumed that the increase in the area of microwatersheds does not affect growth of the control trees and that a linear extrapolation describes results. The first assumption is valid for all practical purposes considering that trees were not crowding each other. An increase in the spacings would not affect their micro-environment significantly.

Tree Species Selection

All of the tree species tried in this study performed well and are suitable for future planting using the asphalt treatment. *Robinia pseudacacia* L. is superior in terms of height growth and crown growth which enables it to cover the land surface rapidly and effectively. The establishment of a suitable ground cover would undoubtedly reduce the soil erosion which is of paramount concern in Iran. *Fraxinus rotundifolia* Mill., a drought tolerant species, is not as fast growing as *Robinia pseudacacia* L., but still recommendable. The detrimental consequences of monocultures prevent *Robinia pseudacacia* L. to be the sole deciduous species recommended for afforestation, therefore, *Fraxinus rotundifolia* Mill. is another good choice. *Cupressus arizonica* G., the only evergreen species tried in the experiment, although not very effective in using the extra water provided for it by the asphalt treatment is aesthetically a favored species. The deciduous trees have leaves five to seven months a year, in the Tehran area, but healthy evergreens are always covered with leaves and therefore are functional as far as environmental purification is concerned.

Certain individual trees which appeared to be of different genetic varieties grew substantially larger than others of their kind. The final height of the tallest *Robinia pseudacacia* L., *Cupressus arizonica* G., and *Fraxinus rotundifolia* Mill. which grew on the asphalt treated S exposure were 465, 312, and 392 cm, respectively, while the average final heights were 331, 194, and 247 cm for *Robinia pseudacacia* L., *Cupressus arizonica* G., and *Fraxinus rotundifolia* Mill, respectively, on the asphalt treated S exposure. These individual varieties which may be readily identified will be recommended for the future afforestation projects.

Contamination Potential of Asphalt

Under the present system of application there is no potential for pollution of the environment with asphalt products. Asphalt is not a contaminant because it is insoluble in water. Some of the solvents used in diluting asphalts may be hazardous to plants or animals if direct contact is made. However, these solvents are usually aromatics which evaporate fast and do not remain in asphalt for more than a few days. An important factor which facilitates rapid evaporation of aromatics is the time of application of asphalt onto the soil surface. Asphalt is usually applied in the summer when the heavy tankers which carry asphalt can climb dirt roads with sharp slopes. The vehicles cannot be operated when these roads are wet and slippery. During the dry season little contamination occurs due to the lack of precipitation when the asphalt membrane is curing and losing its aromatics.

Assuming that it rains during the curing period, or that some of the potentially hazardous oil components remain in the membrane, the terrace system prevents the spread of contaminated water. The 10.5 mm of rain which fell in less than 20 minutes on July 19, 1974, caused extensive damage in the Jajrood Watershed which borders the experimental site on the east. The flood stage of some of the streams in that watershed was surpassed by at least two m. There was absolutely no surface runoff from the terraced experimental site.

The possibility of contamination of underground water by asphalt is very remote. The amount of precipitation, even when concentrated on the terraces by the asphalt treated microwatershed, is not enough to wet the soil more than three m. This is the upper limit assuming that the annual precipitation of about 250 mm falls in a period of no more than 30 days.

Savings in Irrigation Water

The water used for irrigation of the greenbelt already planted around Tehran is about 5000 m^3/ha/year. This is enough to supply 50 persons per year in the capital. Only 2.5 million of the 3.6 million people of Tehran had direct access to the water system in 1972. Tehran is a growing city and its water need is on the rise. Therefore, the limited supply of water becomes more valuable as the city expands. The need for curtailing large scale forest irrigation is becoming more urgent.

Construction of at least one reservoir which can supply the capital was seriously under consideration and as of this writing may be under construction. However, the plight of centers of population in arid climates is ever present.

In a rigorous analyses of 60 years of precipitation data for Tehran, Hashemi (1969) concluded that the probability of having more than 200 mm of annual precipitation is 61.8 percent. The probability for the annual precipitation to exceed 300 mm is 22.1 percent. The probability of receiving less than 200 mm of precipitation per year is 38.2 percent. The monthly precipitation values for Tehran for 1918 through 1967 are given in Appendix Table 1. Assuming that the watersheds which supply Tehran follow the same trend in receiving precipitation as does Tehran, the probability of having less than average precipitation is very alarming indeed.

The alternate method for establishing the greenbelt, namely irrigation is both costly, and, in certain situations, wasteful. It is estimated that the capital outlay for installing the irrigation system in the experimental site was about $1500/ha in 1970. A drip irrigation system installed in another afforestation project, while resulting in substantial savings in water, cost about $4000/ha in 1974. It is fortunate that Iran can afford these expensive irrigation projects. However, they may not be very useful in the event of prolonged droughts.

The method presented in this thesis cannot function if the soil water reserve is not replenished following severe droughts. However, the chance that the trees planted with this technique survive the drought is much higher than that of irrigated trees which do not receive water regularly. Non-irrigated trees usually have deep root systems which absorb water and nutrients from deeper levels than the relatively shallow rooted irrigated trees. When the surface soil which is occupied by the roots of irrigated trees dries up due to lack of irrigation, the probability of mortality is very high. Non-irrigated trees in the same environment utilize the water held at deeper levels, thus the survival rate in them is much higher than that of the non-watered irrigated trees.

No definite figure can be given for the cost of asphalt spraying. The cost mostly depends on the transportation fees, size of the area to be sprayed, current wages, and the season in which the work is done. A 50 ha piece of land 35 km from the Tehran Oil Refinery was sprayed with asphalt in 1971 during August through October at the average cost of about $250/ha. Since the asphalt was provided and sprayed through the courtesy of the Petroleum Mulches Project, itemization of the cost is impractical. The figure of $250/ha was arrived at by reconstructing the cost of the materials and services used and the depreciation of the machinery, therefore it is subject to wide variations.

Additional Experiments in Progress

Observations made during 1970 and early 1971 indicated the need for additional research in several areas of importance for the success of similar water harvesting projects. These experiments are discussed below.

Asphalt Improvement

The maximum benefit from a water harvesting project using asphalt as the soil sealant is realized if the asphalt-soil membrane is durable. Modifications in physico-chemical properties of the asphalt can be made to improve its runoff inducing characteristics as well as its durability. The Research Institute of Forests and Rangelands has worked closely with the Petroleum Mulches Project of the Ministry of Agriculture and Natural Resources and the Mulch Laboratory of the National Iranian Oil Company Research Center.

Seven different formulations of asphalt were sprayed onto the dark-brown soil of the study site in replicated runoff plots. One of these formulations was mixed with a herbicide. Bayer et al. (1962) had earlier studied the influence of petroleum mulch on performance of several herbicides. Statistical analyses of the runoff data along with cost and pollution potential will determine the most suitable asphalt formulation for water harvesting.

Microwatershed to Spreader Area Ratios

By decreasing the width of terraces while keeping the vertical intervals between them constant, higher ratios of microwatershed to spreader area can be obtained. This reasoning was employed in designing a new terrace (Figure 19). This was achieved by locally changing the angle of the bulldozer blade for a cost of only about $100. The width of cut on a 30 percent slope is about 120 cm and the width of berm formed by the spoil is about 30 cm. Using the same vertical interval of 1.5 m as before, the ratio of microwatershed area to the spreading basins area increases from the original of 1.5 to 2.3, an increase of 60 percent, resulting in more runoff water per unit terrace. Vertical intervals of 1.5, 2, and 3 m, using the 150 cm wide terrace is under investigation. The soil of the study site has enough capacity to store the runoff and prevent overflow from terraces.

This method of construction exposes much less of the light gray C horizon, therefore, the durability of the asphalt-soil membrane is enhanced. Furthermore, by planting only one tree seedling in a terrace instead of two, as was done in the study reported in this thesis, more water per tree will be available, thus higher rates of survival and growth are assured. As an added advantage, the cost of construction of this narrow terrace is about 60 percent cheaper than that of a two m wide terrace.

Asphalt Sprayed Trenches

This technique is a modification of the "underground moisture barrier" developed by Erickson et al. (1968). Trenches one m wide and one m deep were dug on contours at vertical intervals of 1.5 and 3 m. Sides and bottoms of these trenches were sprayed with MC_2 asphalt at the rate of one liter/m^2. These trenches were filled with the dark-brown soil of the A horizon after one week of curing. The light gray soil of the C horizon which had been extracted from the trenches made the berm of the terraces formed by the filled trenches. Asphalt was sprayed onto the soil surface between the trenches. Thus theoretically there was a continuous asphalt-soil membrane alternating over and under the soil surface (Figure 27).

Seedlings of apricots, peaches, apples, grapevines, Russian olives, and some shade trees which had been used in the experiment already reported in this thesis, were planted in trenches in March 1972 with the spacings of three m. Eighty percent of peach trees set fruit in 1974. Although no ill effects have been observed in the people who consumed the fruits, this method can be recommended only after extensive analyses of the fruits for asphalt derivatives, such as 3-4,benzpyrene, have proven the fruits safe for human consumption.

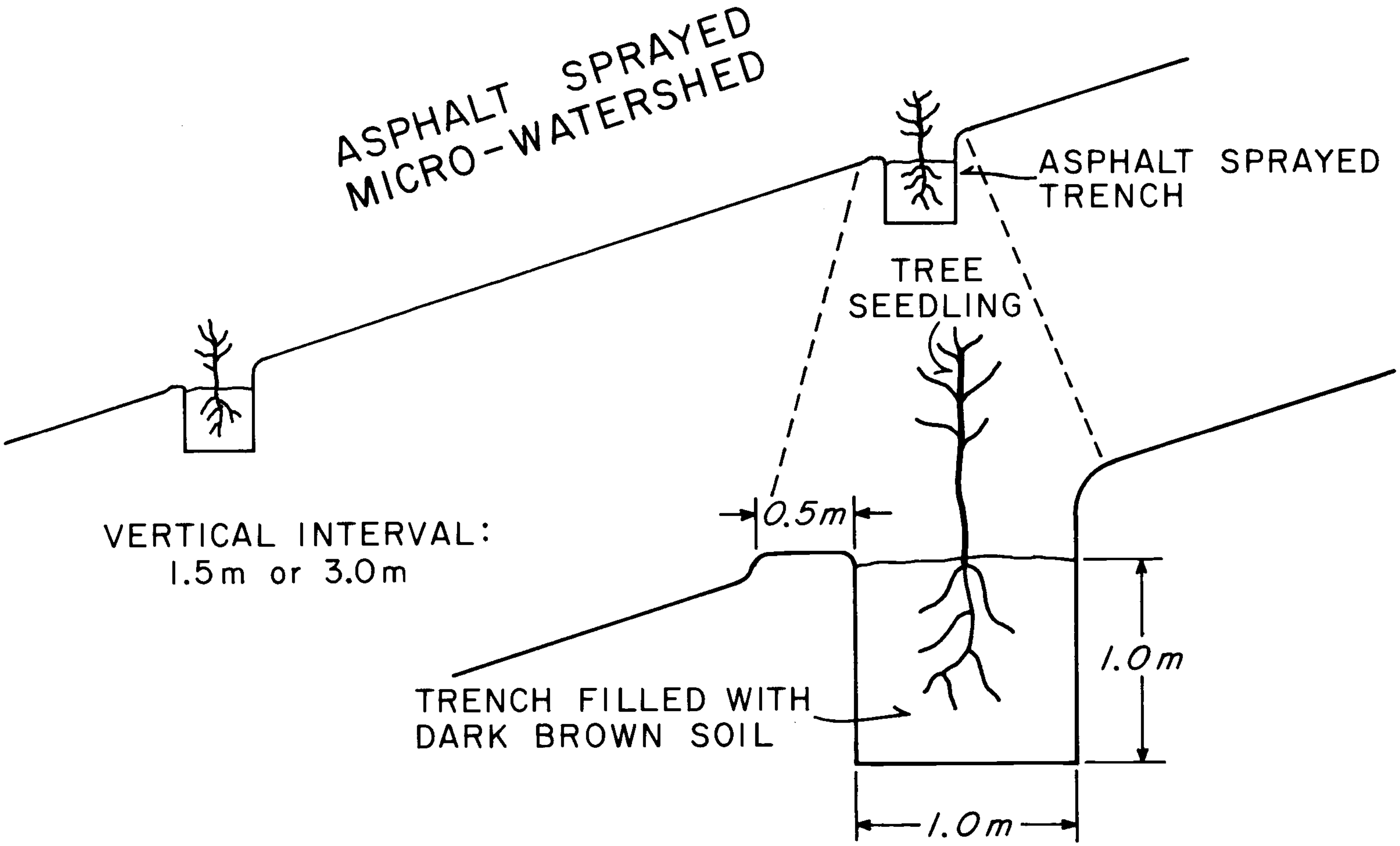

Figure 27. Schematic diagram of the asphalt treated micro-watersheds and trenches used in establishing a fruit orchard.

EPILOGUE

Arid regions which cover large expanses of land in the developing, as well as in technologically advanced, countries pose important problems for responsible authorities. Are there ways to lighten the burden of the inhabitants of the dry lands, or should the situation be considered hopeless? It is fortunate that simple techniques which have been tried for millenia in some parts of the world are applicable, sometimes with modifications, to other areas. Thus given the will and resources, some advances may be made in alleviating the water shortage problems.

Water harvesting is one of these methods. If used properly, along with sound agronomic practices, it provides a practical and economical way to benefit from the limited precipitation which falls on the arid lands. The use of asphalt in water harvesting for the purpose of growing trees is an example of what could be accomplished if proven engineering and biological principles are combined.

The discussed method which has been proven to be effective for Tehran is equally effective, or even more so, in warmer areas, since subfreezing weather is the most damaging element to the integrity of the asphalt-soil membrane. The only limitation, as far as the author can foresee, is the availability of resources for implementation of the developed technique.

Water harvesting for afforestation is only a small step in using the present technology where some immediate benefit can be gained.

The potential for other usage, namely domestic consumption, agriculture, and animal husbandry is virtually unlimited.

The findings presented in this thesis, along with the improvements which have been made in the past six years, make the asphalt spraying technique a logical alternative to irrigation for establishing greenbelts where the resources are available.

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APPENDIX

Appendix Table 1. Monthly precipitation values for Tehran for 1918-1967 in mm (after Hashemi, 1969).

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Total
1918	3.3	66.6	72.9	24.1	5.6	5.3	--	--	--	9.4	7.6	10.8	205.5
1919	80.0	30.2	3.3	31.0	11.9	--	--	--	2.0	--	--	38.9	197.3
1920	42.0	72.6	39.4	53.6	17.5	1.5	4.3	5.3	18.3	19.6	46.5	42.4	363.0
1921	15.5	48.5	94.0	99.6	47.0	--	--	2.5	--	7.6	45.7	10.4	370.8
1922	3.3	116.3	46.5	11.4	22.9	--	--	--	--	--	--	359.7	560.1
1923	221.0	87.4	69.8	43.4	5.8	7.1	--	5.6	10.9	19.3	7.1	36.8	445.6
1924	120.4	67.3	59.2	40.9	12.2	4.6	--	10.9	--	16.3	16.0	34.0	381.0
1925	1.1	12.2	10.7	19.3	4.3	--	--	--	9.6	34.0	31.8	6.9	129.9
1926	94.5	79.8	18.0	32.1	--	20.1	--	--	--	--	9.4	24.4	298.3
1927	--	41.4	18.0	22.9	3.6	2.0	1.7	--	--	0.2	12.5	50.3	152.0
1928	16.5	56.4	29.7	35.8	6.1	0.8	0.2	3.0	--	--	23.1	27.2	200.8
1929	52.8	37.6	19.0	0.8	12.2	2.5	--	--	--	0.2	10.9	16.5	152.5
1930	32.3	25.4	16.8	21.3	32.3	0.5	--	--	0.2	5.3	16.8	37.8	188.7
1931	30.2	86.9	25.9	19.8	39.6	3.3	--	2.8	--	--	31.0	245.1	484.6
1932	29.5	8.4	29.0	33.3	7.1	15.8	11.7	0.5	1.1	3.8	10.5	17.8	171.5
1933	34.0	21.8	32.8	32.5	--	--	--	--	--	--	15.2	66.5	202.8
1934	37.6	82.5	29.5	66.5	43.9	5.8	0.5	--	--	--	39.9	34.8	340.8
1935	37.8	38.9	43.7	16.3	40.4	18.0	--	--	3.3	--	65.0	30.2	293.6
1936	12.7	24.4	21.6	16.5	20.6	--	--	15.2	--	--	4.6	24.9	140.5
1937	38.0	32.5	1.8	4.3	38.9	1.6	--	--	--	16.8	7.6	7.6	149.1
1938	43.2	27.4	63.2	11.9	3.8	--	--	4.6	--	5.8	14.5	95.2	269.6
1939	46.2	34.3	69.1	24.4	--	--	--	--	--	9.9	39.6	10.7	234.2
1940	71.6	55.4	12.2	19.0	8.1	--	--	--	--	1.1	21.1	34.3	222.8
1941	9.9	21.3	41.7	64.3	2.8	--	--	--	--	5.3	11.2	66.3	222.8
1942	17.0	28.9	34.0	8.2	--	2.0	--	--	--	24.0	68.5	6.0	188.6
1943	25.4	33.5	104.1	18.8	37.1	--	0.8	--	--	0.8	5.1	19.6	245.2
1944	28.4	11.2	5.8	11.4	15.0	--	--	--	--	--	9.4	10.2	91.4

continued --

Appendix Table 1. Continued.

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Total
1945	95.1	6.8	44.1	14.4	10.1	1.7	--	--	--	2.6	109.1	17.6	301.5
1946	93.5	32.3	36.0	38.9	10.1	--	--	2.6	2.6	1.1	0.5	42.6	260.1
1947	48.5	22.4	27.2	4.9	12.9	0.1	--	--	--	0.3	6.1	8.8	131.2
1948	8.5	3.6	38.5	74.6	9.8	5.4	--	--	--	--	12.6	87.6	240.6
1949	37.8	18.3	41.2	12.6	14.6	--	--	--	--	--	--	47.0	171.5
1950	41.7	4.4	31.1	25.9	6.4	--	--	--	--	--	3.2	14.3	127.0
1951	55.5	67.0	11.3	8.3	13.5	4.1	--	--	17.0	10.8	61.5	15.9	264.9
1952	16.5	28.4	32.4	45.1	51.3	10.7	--	--	0.9	--	35.1	35.3	255.7
1953	17.3	8.1	11.5	64.3	10.9	--	0.5	0.5	1.0	15.2	59.8	42.0	231.1
1954	27.4	58.0	31.6	51.3	2.9	3.0	6.6	22.4	--	--	40.1	23.2	266.5
1955	54.6	9.5	53.0	5.9	14.7	--	--	--	--	4.2	--	11.4	153.3
1956	9.9	72.4	60.6	30.0	--	--	3.2	--	--	--	--	13.7	189.8
1957	51.1	24.7	65.2	49.2	16.8	11.1	1.2	--	--	41.8	94.8	15.4	371.3
1958	26.5	4.0	42.8	13.0	1.3	3.8	--	--	--	5.4	3.3	67.8	167.9
1959	48.0	20.7	12.8	20.5	27.2	1.2	--	--	--	4.2	38.3	15.3	188.2
1960	7.7	1.7	28.0	60.0	--	0.2	--	--	--	--	44.1	4.3	146.0
1961	40.2	32.2	16.0	21.0	9.0	0.1	0.6	1.2	--	--	0.7	19.0	140.0
1962	14.1	108.2	4.5	130.9	4.8	3.9	--	--	2.4	15.6	5.4	14.7	304.5
1963	11.0	12.1	9.4	25.1	37.6	0.7	--	12.2	1.0	3.4	19.2	62.7	194.4
1964	2.3	33.3	9.6	17.0	--	0.3	--	--	--	--	11.1	25.0	98.6
1965	117.3	8.2	29.8	15.7	6.6	0.2	--	0.6	10.0	15.2	15.9	8.1	227.6
1966	14.2	33.3	40.4	10.7	15.6	1.5	0.9	--	0.6	21.8	--	21.2	160.2
1967	8.8	20.9	6.6	22.4	12.9	--	--	--	--	7.5	18.9	7.0	105.0

Appendix Table 2. Climatological data for Tehran (after Dewan and Famouri, 1964).

Station: Tehran (Mehrabad)
Period of record: 1943-1960

Location, latitude: 35° 41' N
longitude: 51° 19' E
Elevation: 1,198 m

Month	Mean precipitation	Temperature				
		Mean max.	Mean min.	Abs. max.	Abs. min.	Mean monthly
	mm	°C	°C	°C	°C	°C
January	37.3	14.0	- 7.1	18.4	-16.1	3.5
February	23.2	17.4	- 7.1	23.0	-13.4	5.2
March	36.3	21.9	- 2.9	26.1	- 8.0	10.2
April	30.9	27.8	2.0	32.0	- 4.1	15.4
May	13.9	33.8	7.4	36.2	2.0	21.2
June	2.0	38.1	12.8	40.1	5.7	26.1
July	0.7	40.0	17.3	42.5	14.7	29.5
August	1.4	39.1	16.4	42.2	11.1	28.4
September	1.2	36.1	13.0	38.0	8.3	24.6
October	5.3	30.8	5.8	34.4	1.7	18.3
November	28.8	22.8	- 0.6	25.0	- 7.5	10.6
December	27.0	16.2	- 5.6	19.4	-15.0	4.9
	208.0					

Appendix Table 3. Description of a representative profile of the soil found at the study site

Tentative classification: Mollic Calciorthid

Horizon	Depth	Description
A	0-30	Dark-brown (10 YR 3.5/3 moist) clay-silty clay, granular structure, plastic and slightly sticky when wet. Gravel, 20 percent; organic matter, 1.9 percent; $CaCO_3$, 1.75 percent; all by dry weight. Numerous roots. pH = 8.0
C	30-	Light-gray (5 Y 7/2.5 moist) loam, massive, very hard when dry, friable when moist, plastic and sticky when wet. Gravel, 31 percent; organic matter, 0.27 percent; $CaCO_3$, 65 percent; all by dry weight. Many roots. pH = 8.5

Appendix Table 4. Particle size distribution of the soil of the experimental site.

Horizon	A	C
Depth (cm)	0-30	30-
Color (moist)	10 YR 3.5/3	5 Y 7/2.5
	dark-brown	light-gray
percent larger than 2 mm (stones)	20.00	31.00
particle size distribution of material smaller than 2 mm		
very coarse sand (2-1)	4.68	3.67
coarse sand (1-0.5)	2.77	5.37
medium sand (0.5-0.25)	1.84	5.41
fine sand (0.25-0.1)	2.95	9.18
very fine sand (0.1-0.05)	4.94	7.74
total sand (2-0.05)	17.18	31.37
coarse silt (0.05-0.02)	13.38	8.56
fine silt (0.02-0.002)	26.28	33.24
total silt (0.05-0.002)	39.66	41.80
total clay (<0.002)	43.16	26.83
Textural class	clay-silty clay	loam

Appendix Table 5. Chemical analyses of the soil of the experimental site.

Parameter	Horizon A	Horizon C
pH (water)	8.0	8.5
P, ppm	22	5
K, "	444	32
Ca, meq/100g	34	38
Mg, "	2.7	1.2
Na, "	0.13	0.10
B, ppm	0.52	0.34
C.E.C., meq/100g	25.3	9.4
CaCO3, %	1.75	64 64
Organic matter, %	1.9	0.27
Total N, %	0.09	0.03
Zn, ppm	0.58	0.29
Fe "	110	1.3
Cu "	4.5	8.9
Mn "	7.3	1.7
SO_4-S	9.5	17.1

Appendix Table 6. Number of tree seedlings which made up the means used in the statistical analyses.

		Treatment	
Species	Exposure	Asphalt	Control
Robinia pseudacacia L.	S	30	30
	SE	30	28
	NE	30	30
	N	30	30
Cupressus arizonica G.	S	30	30
	SE	30	30
	NE	23	12
	N	30	30
Fraxinus rotundifolia Mill.	S	30	30
	SE	30	28
	NE	30	24
	N	30	30

Appendix Table 7. Monthly precipitation recorded at Qootchak Station from March 1970 to June 1975.

Month	1970	1971	1972	1973	1974	1975
	-mm-					
January	not available	1.8	21.6	25.0	27.8	24.6
February	"	20.0	19.6	76.4	40.6	112.8
March	47.8	29.8	92.0	28.7	20.0	31.2
April	30.0	58.2	23.5	32.4	85.8	44.0
May	17.6	6.8	82.2	3.8	7.4	108.6
June	--	--	13.0	--	11.5	7.4
July	23.4	2.4	--	--	42.4	
August	--	--	13.0	--	6.4	
September	0.4	--	--	--	6.6	
October	1.2	5.8	17.4	--	--	
November	42.8	51.4	87.8	31.7	32.0	
December	44.8	17.0	56.8	7.7	101.6	
Total	208.0	193.2	426.9	205.7	382.1	