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INORGANIC SOIL AMENDMENTS FOR GROWING TREES IN COMPACTED SOILS

by

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AN ABSTRACT OF A DISSERTATION

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Trees transplanted into compacted soils typically fail to thrive due to a failure to re-establish a balanced root/shoot ratio. Incorporating organic matter into a compacted soil can improve soil structure and favor root growth. The benefit of an organic matter amendment typically disappears within a few years and the soil returns to a compacted state. Compacted soils amended with an appropriate amount of an inorganic amendment have not returned to a compacted state in experiments with turfgrasses. It was the objective of this experiment to compare tree root growth in compacted soils amended with organic matter and inorganic amendments.

A field plantation of *Gleditsia triacanthos* var. *inermis* '*Shademaster*' was grown for one season in five different soil mix treatments. These treatments were: organic matter (33%), perlite (33%), vermiculite (33%), topsoil (100%), each by volume and an unamended control. Root length and root branching frequency were measured at

the end of the growing season on samples washed from soil cores. A root branching coefficient was calculated by dividing the number of root branches by the length in each sample. Soil physical and chemical properties were measured for each of the treatments.

There was no significant difference in either root length or the coefficient of branching frequency among trees grown in the different soil treatments due to wide variability in the results.

The lack of significant differences in root growth prevents a conclusion that one or more treatments are superior. A model of a long-term experiment is presented that could better examine root growth among the treatments. It was concluded, based upon soil tests and the literature, that the perlite amendment could be considered for use if soil nutrient levels are adjusted. Discussion addressed drainage problems created by the compacted soil that remains outside the planting hole and one solution of planting in large elevated planting mounds.

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CHAPTER I: INTRODUCTION

Trees in ornamental landscape plantings often fail to thrive because they are planted in compacted soils. Compacted soils develop because of vehicular and pedestrian traffic, paving operations, fill around plant stems, and soil settling (Kozlowski 1985). This is a common problem in tree lawns along streets, and in planting beds adjacent to buildings. Due to mechanical impedance, and or low oxygen/high CO_2 concentrations of compacted soil, root growth is limited. The resulting low root/shoot ratio does not adequately support above ground growth (Berrang et al. 1985). The trees are stressed and are susceptible to drought, pests, and disease infection (Kozlowski 1985).

An ideal soil for tree roots has a low soil bulk density and an adequate porosity with plentiful moisture, air, and nutrients available to the plant. In a forest, nutrients and water can be limiting factors to growth. A compacted urban soil may have sufficient nutrients and moisture, but pore space may not be sufficient to permit surplus water to drain and oxygen to diffuse to the roots. The limiting factors become density and pore space. In an ideal soil, the breakdown of organic matter in the soil provides both nutrients for the plant, and colloids and decomposition products that help bind together soil particles, leaving large pore spaces.

High bulk density soils limit root growth. In soils with a bulk density above 1.7 g cm^{-3}, tree root penetration is highly restricted (Craul 1985). Soils with a high bulk density are common in city tree planting sites (Patterson 1976, Craul 1985, Cool 1976, Ottman 1987). Root extension is important in the first growing season for transplanted trees because most of the root system has been removed. If root growth is severely restricted, the transplanted tree cannot re-establish an adequate root/shoot ratio. For survival and growth to maturity, the roots need to extend to a greater soil volume than that of the typical, prepared planting hole. If the roots are to grow into a soil with a high bulk density, cracks and channels through which roots can extend farther beyond the planting hole need to develop (Hasegawa and Sato 1987, Watson 1987). This is a process that can take many years of freezing and thawing, wetting and drying, and the action of soil organisms. Without soil improvement to enlarge the rooting volume, the transplanted tree may be stressed to the extent that it does not survive, or is more susceptible to insects and disease.

The traditional method to improve soil structure was to amend the backfill of a transplanted tree with organic matter (OM). The purpose was to increase aggregation, moisture holding capacity and penetrability (Buley 1983).

There is general agreement that roots elongate more readily in soil containing OM. However, there is also argument about whether or not the improved porosity and penetrability resulting from using organic matter is a lasting effect (Flemer 1982, Furuta 1982, Foster 1977, Harris 1983, Perry 1982, Ruark et al. 1982, Patterson 1976).

Soil aeration in a natural soil remains adequate because decaying organic matter in the soil is replaced by litter fall and dead roots. Replacement of a portion of the OM does not typically occur in urban tree planting situations because leaf litter is removed. Two alternatives are possible for maintaining aeration. One is to use an inorganic amendment that will maintain aeration without eventual decay and compaction. Expanded clay has succeeded in four year trials (Patterson 1976). Perlite has been used in golf and athletic field turfs (Perlite Institute 1988). The other alternative is to establish a program to maintain aeration of an OM amended soil after organic matter begins to decay. There are mechanical means of drilling or breaking up the soil that have short lived beneficial effects. Another approach is to place an organic mulch on the soil (Watson 1987, Galle and Chadwick 1947, Gartner 1978). An organic mulch over the soil promotes the biological activity of soil micro and macro organisms that build soil structure. If mulch were maintained over a broad area of compacted soil, in a period of several years the potential rooting volume of a tree should enlarge. It was found that tree root extension is greater under an organic mulch than under a lawn cover (Watson 1987, Rice 1984, Litzow and Pellett 1983). However, this latter approach is not often acceptable from a visual standpoint, and it can be expensive in terms of time and materials.

Mulch can contribute to the formation of a porous soil structure. However, if the mineral layer of the soil has a relatively high mechanical impedance, much of the root system may grow in the surface layer of mulch and the top few inches of soil (pesonal observation). The tree can become vulnerable to drought. Deeper rooting, such as to a 30 cm depth allows a tree to draw moisture from a larger soil volume than in a mulch layer.

Due to the placement of a tree in a planting pit of minimum diameter in soil of high bulk density, root extension may be limited. The volume of a small planting hole could be approximately 10 cubic meters (13 cubic yards). If roots cannot penetrate beyond the root ball, the available soil volume could be as small as three cubic meters, the size of a root ball of a typical, transplanted 6.6 cm (3") dbh street tree. Roots must extend to a larger soil volume to support continued above ground growth and provide stability. As an example of the root space the tree will eventually require, a mature tree can transpire in only three days the water available in a loam soil in a root volume of 130 cubic meters (168 cubic yards) (Vrecenak and Herrington 1984).

There are techniques available to provide the large volume of soil when soil compaction limits root growth. Planting in a large volume of replacement soil in a mound, or in a large, below-ground pit of prepared soil, or by planting in a low, raised, shared space planter provides a large rooting volume (Patterson 1987, Watson 1987). Planting in a mound can protect the roots against saturation. Planting in a below-ground pit of prepared soil may require artificial drainage. These methods of creating a large volume of soil also require the preparation of a soil of adequate structure. The goal of this project is to study responses of trees planted in prepared soils of different structures.

There is evidence in the literature that the amendment of a compacted soil with organic matter will improve soil porosity and density, but not for a period of sufficient duration for tree establishment. The establishment period, or period in which the tree returns to a balanced root/shoot ratio and recovers from transplant shock, has been estimated to be up to ten years (Patterson 1987). There is also evidence that soil amended with an inorganic material could maintain adequate porosity for a period long enough for establishment.

Organic matter is typically found in smaller quantities in urban soils as compared to forest soils. Organic matter is an important component of a soil because it contributes to the mineral cycle of plants. Depending upon temperature and moisture, organic matter could slowly accumulate in urban soils from the periodic death of tree roots, mulch or litter if left on the surface, and the distribution of organic matter into the rhizosphere by soil organisms. However, mulch or litter is seldom left on the surface, with the result that OM is usually reduced.

The objective of this project was to determine how five soil mix treatments differed in density, porosity, OM content, and root growth. It was hypothesized in this project that root length in compacted soil amended with inorganic amendments would equal root length in the same soil amended with organic matter. This was tested by examining soil density and porosity, and measuring root growth of trees grown in prepared treatments of previously compacted soil with organic and inorganic amendments.

The organic matter content of the soil also influences root growth. In addition to improvement in soil structure, OM contributes to the fertility of the soil. More finely branched roots should appear in soil with a well decomposed OM (Lyr and Hoffman 1967). Differences in root branching could influence the manner in which tree roots exploit soil resources. It was also hypothesized that root architecture would be different in the different treatments. This was tested by comparing root branching coefficients.

This dissertation is organized in the following sequence:

The second chapter reviews the literature on compacted soils and on root growth. The discussion on soils covers both the characteristics of compacted soils and methods to alleviate compaction. The discussion on root growth focuses on root responses to the chemical and physical problems that are typical of compacted soils. There is also a review of the techniques by which roots can be observed and measured quantitatively.

The third chapter details the experimental model, including both the field experiment and the statistical procedure. In this chapter is the description of the five treatments and the method by which the treatments are prepared.

In Chapter Four, the results of the root measurements are presented, and the characteristics of the treatments at the end of the growing season are displayed and discussed.

In Chapter Five, conclusions drawn from this experiment, an experimental model that could better answer the questions posed, and the practical implications are presented.

CHAPTER II: LITERATURE REVIEW

Introduction

To develop an understanding of how tree roots grow in compacted soils, and how to measure root growth, the literature on root growth, soils, and techniques to observe and quantify root growth, was reviewed and summarized.

Forming generalizations about root growth is difficult because of genotypic differences among species. As the roots of each species encounters different environmental conditions, different root growth responses result. However, some generalizations can be made about root growth in urban soils. Urban soils are first discussed, followed by a discussion of root responses to soils with the characteristics typical of soils in many cities. Finally, the third section discusses techniques to observe and quantify root growth.

Soil factors

Urban soils

Urban soils are almost always an unnatural growing medium for trees. Craul (1985), lists as characteristics: compaction, a tendency to form surface crusts, elevated soil reaction, restricted aeration and drainage, modified soil temperatures, interrupted nutrient cycling, low OM content, reduced soil organism activity, and the presence of foreign materials and contaminants. Urban soils compact when wet and subjected to traffic and large equipment pressures, and tend not to return from that state (Craul 1986, Koslowski 1985). The lack of organic matter in subsoil or mixed soil limits the aggregation of the soil by the activity of micro-organisms. Organic matter (OM) contains the energy for soil organisms that would contribute to the formation of good soil structure. A modified temperature regime in the urban setting limits the freeze/thaw cycles that would contribute to breaking up a forest soil. Soil wetting can be significantly reduced by the occurrence of layers of increased bulk density (Gumbs and Warkentin 1972). Roots elongate only into pores in the soil that are larger than the diameter of the roots (Kozlowski 1985, Ruark, et al. 1982).

A porous soil ensures that the oxygen concentration in the soil is at a level that is needed for root growth (Spomer 1978). The oxygen concentration should be a minimum of 12%. Carbon dioxide levels should remain no more than 5 - 6%. Nursery propagators recommend an air-filled porosity of about 20%, although this depends upon soil texture and the species being grown (Maronek et al. 1985). At lower bulk densities, air-filled porosity ought to be greater; in the 38% range to maintain a 12% oxygen level (Maronek et al. 1985). At a higher bulk density, a lower air-filled porosity will provide the needed oxygen level.

Crusting of the soil surface reduces gaseous diffusion and the infiltration of water. Surface crusts form when raindrops move fine soil particles into the voids between larger particles. Some urban soils are water repellent due to ammonia deposits, or organic matter coatings, or the byproducts of soil organisms (Craul 1985). A plant cover and an organic litter or mulch layer help prevent crusting.

Urban soils often have pH ranges above neutral, while most trees grow best at a pH of 5.5 to 6.5. There may not be observable symptoms in some tree species growing in soil with a higher pH. <u>Acer rubrum</u> and <u>A</u>. <u>saccharum</u> suffer manganese deficiency under high pH (Smiley 1985, Kielbaso and Ottman 1976). Alkaline conditions are usually a disadvantage for plants adapted to acid soils, and in high calcium situations, limit the uptake of nutrient ions by roots. Craul (1985), reported reactions of 6.6 to 9.0 in Syracuse, 7.6 in Philadelphia and 8.0 in Berlin. Conditions that contribute to soil alkalinity are the weathering of cement and masonry building materials, the application of calcium and sodium to de-ice sidewalks and irrigation with calcium containing water. Many urban soils are high in pH, primarily because of the natural alkalinity of subsoil.

Nutrient cycling is limited in urban soils due to the low level of organic matter. Nitrogen, sulfur and phosphorous are part of the chemical composition of humus particles, derived from OM in the soil. Organic matter is in short supply in urban soils since leaf litter and animal wastes are usually removed or are produced in small quantities by small, stressed trees.

Higher soil temperatures are common to cities and suburban areas with a high concentration of hard surfaces. Soil temperature affects root growth, the metabolism of soil organisms, and inorganic chemical processes. Biological processes are increased, up to limiting temperatures. Heterotrophs increase the nitrogen mineralization at higher temperatures, but require an adequate supply of carbonaceous material as a source of energy. Mladendoff (1987), found increased soil N mineralization in forest tree gaps that had higher temperatures. Organic matter decomposed rapidly, resulting in a loss of carbon in the soil. Higher temperatures may delay the hardening off of roots prior to winter, resulting in cold weather injury to the roots (Craul 1985).

Improving compacted soils

Forest soils typically contain a higher percentage of organic matter than do urban soils, replacing the soil OM that is mineralized with leaf and stem detritus, root exudates, and root die-off. As a product of micro-organisms feeding on OM, exuded polysacharides contribute to a binding of soil particles into aggregates that help create a porous structure (Metting 1987). Worms graze on OM, aggregating soil particles. Organic matter helps maintain soil nutrient levels. Organic matter releases N slowly over several years.

In an effort to duplicate the benefit of the organic matter in forest soils, it is a common practice to mix peat or compost into the planting hole backfill of urban trees. Although a widespread practice, several authors suggest that organic soil amendments are not appropriate in responding to aeration problems in urban tree planting (Craul 1985, Harris 1983, Patterson 1976).

Two problems can be created, over time, from amending backfill with OM. First, horizontal and vertical soil interface problems may be created. An interface occurs when the pore size distribution of one soil is significantly different from the pore size of the adjacent soil. This interface can occur between the backfill and the wall of the planting pit. It can also occur between the soil of the root ball that came with the tree, the backfill outside the ball (Patterson 1987), and at large deposits of OM incompletely mixed into the backfill. At the interface, water may not drain from one soil to another, and roots may not extend from a porous soil into a dense soil. The structure of the amended backfill may be different from the surrounding, undisturbed soil. Perched water tables result, flooding the roots and limiting soil oxygen. In addition, roots do not grow through the interface with the high density, undisturbed soil beyond the planting hole, or do so to a limited extent. As a result, the root system remains in the same soil volume as when planted. It becomes important that a balled and burlapped tree should be planted with a backfill that is similar in texture and structure to that of the rooting medium. If a tree is planted bare root, a soil of uniform structure for the entire rooting volume should be specified, as indicated by Whitcomb (1979), Harris (1983), and others. This latter treatment was widely reported and gained favor for planting in a wide range of soils. This simple technique is not indicated if the soil density is high (Craul 1985, Patterson 1976).

Any of the common transplanting techniques can result in the removal of up to 95% of a root system (Watson 1987). Root pruning is a nursery practice that is intended to grow a dense pattern of roots within a small diameter ball of earth so that the tree will have a large root/shoot ratio when transplanted. Many tree species do not regenerate new roots throughout the root system in response to root pruning, but do so only close to the point of the cut (Wilcox 1955, Kuhns et al. 1985). For those species that respond with new roots at the cut point, a large portion of the root system becomes situated near a potential interface with a dense soil.

Nursery grown plants are often propagated and raised in a container in a more porous medium than a field soil. The container mix may not even include soil, but may be formulated of organic matter of different origins and textures (Urbano 1985). If a root ball with such a mix is planted in compacted soil, root growth may be restricted due to mechanical impedance or an interface of widely different pore sizes. A coarse-textured soil could be preapared using amendments that are similar in structure to the soilless mix used in container-grown trees.

The second problem of amending with OM is that, over time, the added OM decays, and without replacement, its contribution to soil aggregation and mineralization ceases. Typically, dropped leaves and stems are not permitted to stay on the soil at the base of urban trees, so litter fall is unavailable to the root zone.

Baker (1986), evaluated organic and inorganic amendments, Patterson (1976) evaluated scintered fly ash and expanded slate, and several authors evaluated pumice, perlite and vermiculite mixes for starting rooted cuttings and container growing in nursery production (Inose 1971, Maronek et al. 1985, Buley 1983, Ward et al. 1985, Cook and Dunsby 1978). Patterson (1976), reported porosity above 41% in trials using 20 - 30% amendments of various inorganic materials. Hensley et al. (1982), used a mix of organic matter, soil and vermiculite for street tree plantings.

Sand is a very difficult amendment to use with compacted soils because a denser, not more porous, soil can result if the proportions are not tailored to the texture of the existing soil. It can be difficult to mix in a sufficient volume for use with trees because of the weight of the amendment, and the depth to which the soil needs to be amended. Patterson (1987), recommends 85% sand when using it as an amendment to compacted soils.

Fly-ash is a product of the electric power-generating industry. It is available in different sized particles that would make it possible to use to amend soils of different textures. Fly-ash is alkaline, and is used as a liming agent (Tisdale et al. 1985), so it would be most appropriate for use in acid soils. Urban soils are almost always alkaline.

Ward et al. (1985), reported that a peat/perlite mix had a higher air-filled porosity than fine sand, 3 mm grit, and coarse bark. They also considered vermiculite, judging its high CEC and moisture retention as advantages, but its structural instability as a disadvantage.

Several authors mentioned polystyrene (Ward et al. 1985, Chong 1987) or polystyrene foam (Baker 1984) granules as an amendment that merits consideration. These plastics are lightweight waste products that create porous soils.

Some problems with toxicity were reported by Ward et al. (1985).

Root growth

The root is the primary water and nutrient absorption organ of the plant. Roots, especially deep, horizontal roots, serve as anchors (Coutts 1983). Good shoot growth depends upon vigorous root growth, and root disturbances impair above ground growth.

The root system has a variable morphology throughout its lifespan and throughout the system at any given moment. At seed germination, dicotyledonous trees develop a tap root, followed by the initiation of four to eleven lateral roots (Perry 1982). The tap root usually withers away, leaving the laterals.

A root system is comprised of fine roots and woody roots. The fine roots absorb most of the water and nutrients, while the woody roots function as an anchor and as a storage organ. The growing tips are the most actively respiring section of the root. The growing tip, or meristem, is covered by a root cap of living cells. Several millimeters behind the tip, a phloem transport system starts developing, and the root becomes differentiated into an outer cortex and an inner stele. As the root ages, secondary thickening takes place, with a layer of suberized cells called the periderm developing. This layer greatly impedes water absorption into the stele. At the surface of the root in this region, an epidermal layer with unicellular root hairs develops. As the root extends into the soil, the thickening becomes more pronounced, and the cortex is sloughed off. Cortex sloughing can occur within a week of its formation, or can occur months later (Lyr and Hoffmann, 1967, Atkinson, 1985). Dittmer (1949), found that sloughing of the root cortex in *Gleditsia* did not occur until the root was many months old. Head (1966), found white *Ribes nigrum* roots one year old, indicating a substantially longer period before sloughing. A species with fine roots that remain white for a greater length of time may be more able to compete for moisture than the species with roots that suberize soon after developing.

The growing tips of the roots, especially in the root hair zone, are where most of the absorption takes place (Molz 1971). The root meristem, and cell elongation zones also require the greatest amount of oxygen, nitrogen and carbohydrate (Fowler 1975). Older roots become suberized and less absorptive. Since the older roots usually absorb poorly, the roots must continue to grow in order to absorb a large amount of moisture. The ability of older roots to absorb water depends upon the species. While a number of researchers question the efficiency of the rapid suberization of new roots, some evidence suggests that there may be an adaptive strategy. In studies by Wilson and Atkinson (1979), it was found that cherry roots have better absorption of Ca in older roots than in the white, young roots, while for Rb the reverse was true.

The outside of the stele will gradually become woody, protecting the inner vascular system. The cortex that is sloughed off is consumed by soil organisms, such as, nematodes, enchyrtraeid worms, collembola and mites (Head 1973). They begin feeding when the cortex first becomes brown.

Lateral roots form in the pericycle, just inside the endodermis that lies inside the cortex. Laterals arise about 4-10 cm behind the growing tip, and can branch again several times. Multiple branching of roots serves to occupy and extract water and minerals from the soil between main laterals. Kolesnikov (1966), found 5-7 orders of laterals in *Malus*. Laterals tend not to grow as energetically as the extending root tip. Repeated branching, and the production of fine roots, occurs in soils rich with organic matter probably to utilize nitrogen produced by high rates of mineralization. The relative biomass of roots will still likely be higher in poorer soils (Nadelhoffer et al. 1985). More frequent branching can occur in some species associated with infection by mycorrhizae (Head 1966).

Root initiation and termination

In temperate regions, tree roots begin growth in the spring following a period of rest in the winter. The exact time is species and climatically dependent. It is generally agreed that root growth begins prior to shoot growth. However, _Larix_ is one exception in which shoot elongation precedes root growth (Lyr and Hoffmann 1967). Auxins are transported from non-dormant buds to the root, which starts growing. Roots may be able to grow earlier than the shoots because of a lower temperature optimum (Lyr and Hoffmann 1967). Richardson (1958), found that _Acer saccharinum_ roots resume growth at 5°C while buds start expanding at 10°C.

Tree roots grow at varying rates throughout the growing season. The period of greatest root growth in deciduous trees occurs in early summer. The rate varies, even during the period of maximum growth, in part due to environmental conditions. Additional peaks of growth occur in late summer and into the fall. These depend upon environmental conditions and on the species. _Quercus_, with an early cessation of shoot growth, showed strong mid-summer root growth (Lyr and Hoffmann 1967). Primary root growth slows down in late summer and fall, but does continue.

Root growth terminates when the ground freezes. There appears to be no internally regulated dormancy in roots as there is with aboveground parts (Lyr and Hoffmann 1967). This was demonstrated when _Robinia_ roots did not stop growing when heated all winter (Lyr and Hoffmann 1967).

Rooting following transplanting

Unless previously root-pruned, a tree at transplanting time may be losing nearly all of its root system (Watson 1987). This loss affects the capacity of the tree to absorb water and nutrients, and to anchor the above ground parts in the wind. Assimilates produced the previous season and stored in the cortex of fine and woody roots are also lost. The roots become a sink for nitrogen and carbohydrates until an excess develops and these materials are passed onto the shoot. The degree to which loss of roots affects shoot and root growth of a tree transplanted in the spring is not fully understood. Watson et al. (1986), found the shoot growth of eight species of trees to be different depending upon the month in which the trees were transplanted.

Shoot growth can be affected by transplanting because cytokinin, partially responsible for initiating shoot growth, is synthesized in root tips, many of which are removed by transplanting (Bentz et al. 1985, Watson and Himelick 1982).

Trees are capable of preferential growth, and growth to restore a normal root-shoot ratio occurs following transplanting (Kozlowski and Davies 1975b, Stone and Schubert 1959, Struve and Rhodes 1988). Determinant root growth, characteristic of particular species, appeared in the first season following planting in research done in the

Eberswalde root laboratory (Lyr and Hoffmann 1967). Unless the root system is plastic, such as Acer rubrum, rather than determinant, roots will start growing in a predetermined pattern based on adaptation to a particular soil depth.

Mycorrhizal infections:

The growth of symbiotic fungi on roots is a common occurrence in trees. Mycorrhizae benefit the tree by enhancing the uptake of moisture and nutrients. As shown by Brownlee et al. (1983), the tree can become dependent for its water regime upon an infection of the roots.

The many species of mycorrhizae are classified, in part, upon whether the fungus can penetrate the cells of the root (endomycorrhizal), or infect the root by infiltrating the spaces between the cells of the root cortex (ectomycorrhizal). Vesicular arbuscular mycorrhizae (VAM) form storage structures, known as vesicles, and intracellular hyphal systems, arbuscules, that are attached to the root. Combination forms occur, and all forms proliferate in forest trees. According to Marks and Kozlowski (1973), the ectomycorrhizae are the dominate form in most forest trees.

In the ectomycorrhizae, the fungal organism develops a sheath around the surface of unsuberized roots. A net of strands penetrates the inter-cellular spaces of the cortex, and thin hyphae extend into the soil surrounding the root. The hyphae become part of the gradient that translocates water and nutrients from the soil into the root. Hyphae can grow several centimeters in length and can extend the effective exploitation of the roots. Phosphate was found to be absorbed and translocated 12 cm from sites in the soil to Pinus radiata roots in a study by Skinner and Bowen (1974).

Mycorrhizal infection may involve the whole root system, or only parts of the roots may become infected. The extent of infection by mycorrhizae seems to depend on carbon in and around the host root, and upon a compound that roots exude that may stimulate mycelial growth (Hacskaylo 1983). The zone of infection is the unsuberized zone immediately behind the meristem, with the infection zone expanding as the roots grow in length. Mycorrhizal roots tend to be thicker, different in color, and more brittle than uninfected roots (Marks and Kozlowski 1973). Mycorrhizal roots senesce later and live longer than uninfected roots.

Soil fertility plays a role in mycorrhizal infection. An infection can be more extensive on roots growing in poor soils than in rich or fertilized soils (Last et al. 1983). This may be explained by a relationship of fungal auxins to nitrogen levels in the soil (Hacskaylo 1983). Plant growth is enhanced in some VAM endomycorrhizal infected plants due to increased phosphorous uptake (Planchette et al. 1982).

Mycorrhizae proliferate in moist, well-aerated soil, but do inhabit a wide range soils. A few species of mycorrhizae survive in dry soils, and these may give their hosts a competitive edge (Last et al. 1983).

Last et al. (1983), report that there is evidence of a hastening of stem maturation in birch infected with mycorrhizae. This could result in an enhanced internal exchange of gases in trees subjected to anaerobic soil conditions, due to increases in intercellular spaces of the cortex.

Temperature effect on roots

Root growth is affected by soil temperature. Temperature affects metabolic processes, and the conductance of water by cell membranes (Protopapas and Bras 1987). Higher temperatures accelerate root respiration, and the respiration of other soil organisms. Optimal temperatures are lower for roots than for shoots (Lyr and Hoffmann, 1967, Richardson 1958). In studies of _Fagus silvatica_, _Fraxinus excelsior_, _Picea abies, and Abies alba_, Lyr and Hoffmann (1967), found a growth range at temperatures between +2°C to +35°C. Kuhns et al. (1985) found _Juglans nigra_ roots initiated growth at 4°C. Soil temperatures lag behind air temperature fluctuations, on both a daily and a seasonal basis. The effect of this temperature lag is for roots to have a continuous, moderate temperature regime favorable to growth throughout the entire season. However, roots may stop growth and become completely suberized as temperatures rise to the point where soil drying takes place (Khuns et al. 1985). Soil temperatures can rise in soil where there is considerable adjacent pavement. Examples of this situation are along streets, in parking lots and in urban plazas. Raised planters do not have the soil mass to moderate temperatures from fluctuations. Extreme highs and lows in soil temperature typically occur. As discussed above, the cessation of root metabolic activity may be directly caused by high temperatures and indirectly caused by soil drying. The result of cold temperatures can be the die back of roots from winter freezing (Cervelli 1986, Roberts 1977).

Nutrient effect on roots

A tree will respond to increases in nitrogen with increased growth if there are not limiting supplies of water or other nutrients. In soils with low nitrogen, the investment in root biomass is generally greater than in rich soils producing a root/shoot ratio approaching 1:1 compared to a ratio of 1:2 in more fertile soils (Fitter et al. 1985, Lyr and Hoffmann 1967), and 1:2 or 3 of young *Quercus rubra* (Farmer 1975). Meyer (1963), in Lyr and Hoffmann (1976), found *Fagus sylvatica* with twice the root length and dry weight per cm^2 of leaf area, in nitrogen poor, raw humus as in rich decomposed humus. A root system growing in nutrient rich, organic soil layers can be very finely branched. This is believed to be primarily a response to the increased supply of nitrogen in the organic matter (Fitter et al. 1985, Farmer 1975). Drew (1975), found that localized supplies of phosphate, nitrate, ammonium, and potassium resulted in concentrations of roots in the supply areas. Harris (1983), believes that a short, finely branched root system could be a disadvantage to an urban tree because it would be limited in the volume of soil from which it would exploit soil moisture.

Several researchers found root systems with greater biomass in plants fertilized with nitrate fertilizers than with ammoniacal nitrogen (Lyr and Hoffmann 1967, Head 1973). Root growth in the presence of the later form of nitrogen leads to a long, infrequently branched root system that is typical of roots growing in anaerobic soils.

Phosphorous is important for root growth. However, Kozlowski and Davies (1975) report that phosphorous is typically not in short supply for transplanted trees and that trees do not have a high requirement for phosphorous. Soil pH affects the availability of phosphorous for roots. Tisdale et al. (1985), reports that plant roots have 10 times as many ion-binding carriers for the H_2PO_4 form of phosphorous as for HPO_3, and absorption for H_2PO_4 is greatest in low pH soils. The absorption of HPO_3 is greatest in higher soil pH. The degree to which this is a problem is not certain at this time because both forms of phosphorous tend to exchange for the other very readily.

There are different recommendations regarding the necessity of fertilizing newly planted trees. Van De Werken (1981), found no value in fertilizing in the first three years. Generally, P and K fertilizer is not needed. Trees may benefit from N fertilization in subsequent years and to replace N lost to mulch breakdown. Van De Werken (1981), found a response to nitrogen application in three species after ten years when applications were started four years after transplanting. Harris (1983), recommends avoiding fertilizing at planting time to avoid burning new roots that form. In contrast, Harris (1983) found a growth response to surface applied N applications in newly planted magnolias and zelkovas. Gillium (1982), recommends fertilizing nursery stock in the field to improve production. Van De Werken (1970), reported no significant difference as a result of nitrogen fertilization prior to transplanting in the survival of Ginkgo biloba, Quercus paulustris, and Fraxinus Pennsylvanicum.

Root responses to soil reaction

The effect of soil pH on root respiration has received little research study. Some effect on lowering respiration of other soil organisms by lowering pH has been reported by

Bryant et al. (Glinski and Stepniewski 1983). Mycorrhizal activity can be dependent on pH.

Phosphorous and micronutrient uptake can be reduced with higher pH values, even those approaching 7.0 in some soils (Tisdale et al. 1985). Manganese deficiency appears as leaf chlorosis, and correlates to increasing pH (Smiley 1985, Kielbaso and Ottman 1976). Himelick (1978), reported pin oaks with iron chlorosis in soils with a pH of 6.9, and pin oaks without chlorosis in soils with a pH of 6.5. Saturated soils can be alkaline, since basic ions do not leach out of the soil. However, all saturated soils are not alkaline.

The effect of soil gases

Gases in the soil occur in different proportions than in the atmosphere. The atmosphere is typically 21% oxygen, 78% nitrogen and 0.03% carbon dioxide. In the soil, oxygen is in lower supply, while carbon dioxide is in a slightly higher proportion. Nitrogen remains at the same level, except in anoxic soils where de-nitrification can occur by the action of anaerobic micro-organisms such as Pseudomonas, Bacillus and Thiobacillus. Other minerals become less available as anaerobic conditions limit the micro-organisms responsible for mineralization. Carbon dioxide can be distributed evenly between the gaseous and water content of the soil, while oxygen and nitrogen dissolve very poorly in water. The conditions which favor CO_2 increase, such as poor aeration, and a rise in temperature, work in opposition to oxygen production and retention. Glinski and Stepniewski (1983), identify a critical oxygen concentration (COC) in a range of 1.6% to 2.7 % for Elaeagnus angustifolia. The COC is linked to a reduction in the activity of cytochrome oxidase at low oxygen levels. There is evidence that cytochrome oxidase is important in the transfer of anions within plant cells (Glinski and Stepniewski 1983). The rate of respiration also is dependent on the diameter of the root, and the species-related rate of radial O_2 diffusion within the root tissue. Increasing primary root elongation with increasing air-filled porosity is the result of increased exchange of gaseous oxygen, ethylene and carbon dioxide (Voorhees et al. 1975). Species requiring a high gas exchange rate, such as azaleas, need 20% porosity after gravity drainage, while species tolerant of more dense soils can perform adequately in only 5% porosity following drainage (Maronek et al. 1985). There can be localized soil compaction by the growing tip of the root, but apparently gaseous diffusion still takes place at an adequate rate (Voorhees et al. 1975).

At low oxygen levels, root metabolism changes towards fermentation, and the production of increased levels of ethanol (Glinski and Stephniewski 1983). Fermentation is the conversion of glucose to ethanol and CO_2. It is very similar to the normal metabolic function of glycolysis except for the production of ethanol or lactic acid, and the formation of two ATP molecules instead of one. Because ethanol and lactic acid contain so much energy, fermentation is an inefficient process. Ethanol already exists in the plant root, and in slightly elevated levels in the root meristem where metabolism is typically somewhat anoxic. Trees that are tolerant of flooding have both a low production of ethanol compared to intolerant species, and physical mechanisms, such as adventitious roots, for removing excess ethanol. Plants intolerant to flooding show the deleterious effects of increased ethanol content from the Pasteur effect. With the Pasteur effect, there is an increased rate of glycolysis, resulting in a decreasing ATP level in cells. The consequence is increased ethanol production. Ethanol injures by causing damage to cell membranes. This results in the leaking of organic acids, amino acids, sugars and electrolytes from the roots. Crawford (1978), suggests that this process is the reason many species are susceptible to even short-term oxygen stress.

Under conditions of low oxygen supply to the roots, stomata of the aboveground parts tend to close (Kozlowski and Davies 1975). The exact reason is not known, but may be due to increased ethylene production or to a change in the rate at which potassium ions enter into guard cells. The resultant reduction in transpiration may be partly responsible for the decrease in photosynthesis under conditions of low oxygen in the root environment (Sojka and Stolzy 1980). With a reduced uptake of mineral nutrients, water absorption by roots is diminished.

High levels of carbon dioxide have a detrimental effect on root respiration. Harris and Van Bavel (1957), reported inhibition in various crops in concentrations of 5%. Sensitivity varies by species. CO_2 concentrations increase as soil respiration continues without sufficient circulation of soil air to exchange with the atmosphere. The concentration of CO_2 does not usually exceed a few percent of soil air under aerated conditions, but can exceed 20% under anoxic conditions. In paved plazas and in parking lots, soil aeration can become a serious problem. Yelenosky (1963), reported CO_2 levels under asphalt, as well as under compacted surfaces, increasing from 1% in March to 15% in April as root respiration commenced.

Glinski and Stepniewski (1983), found that poor soil aeration diminished the uptake of N, P, and K in most crops, including citrus trees. Ca and Mg uptake is less affected by low soil oxygen.

Root responses to soil moisture

Soil moisture influences root growth, but uptake by a root does not regulate its growth rate. If water uptake by other sections of the root system is adequate, a root can grow through a dry zone (Caldwell 1976, Hunter and Kelley 1946). A plant growing in a dry soil is likely to extend roots to a large soil volume to obtain water and nutrients. Roots growing in a wet soil do not require a large soil volume. However, root systems generally do not grow in zones of excessively high moisture content. In such situations, roots are usually seen near the surface. Those plants that do survive in areas of high moisture content often have internal mechanisms such as aerenchyma, to supply oxygen to the root (Jackson 1986). Kawase and Whitmoyer (1980), found that Salix began to form aerenchyma within 24 hours of being waterlogged, and that large aerenchyma had developed in three days. It was theorized that the high ethylene concentration that developed under anaerobic conditions led to an increase in cellulase activity and the formation of aerenchyma (Jackson 1985).

In dry soils, continued initiation of new roots permits the plant to compete for scarce soil moisture. Roots grow in dry soils by utilizing water absorbed by segments of the root system that are growing in moist soil. However, some species stop investing in new roots when soil moisture potentials become high (Larson and Whitmore 1970). Deeper rooting can be found in dry soils than in very wet, although deep roots usually only serve as important conductors of water when shallow soils are depleted (Gardner 1964).

Roots cease growing in drought conditions before shoot growth stops (Lyr and Hoffmann 1967, Leyton and Rousseau, 1958). Suberization accelerates in dry conditions, reducing the effective absorbing surface area. Regeneration of the growing tips is required before absorption can begin again (Kramer 1950). In extreme dryness, parts of the root system may die. The result is a diminution of nutrient and salt uptake that reduces photosynthetic activity for a long period following a drought.

An excess of water in the soil can severely limit the extent of rooting due to the reduced root metabolism of low oxygen/high carbon dioxide levels and low soil temperatures. Saturation is in itself not detrimental, if adequate aeration and temperatures could be maintained. This has been demonstrated by artificial water cultures (Lyr and Hoffmann 1967). Slow moving water in the soil can produce the low oxygen and high carbon dioxide levels that shift the redox potential, and can lead to the production of damaging hydrogen sulfide gas by anaerobic micro-organisms in the soil.

Water in the soil limits gas exchange in three ways. First, water filled soil pores slow the exchange of soil gas with atmospheric gasses, preventing the discharge of respired carbon dioxide, and the intake of atmospheric oxygen (Kozlowski 1985, Jackson 1986). Second, the diffusion of oxygen from air-filled pores in the soil across a film of water is about ten thousand times slower than through air. The thickness of the film of water surrounding the root influences how much oxygen gets to the root, and how quickly. Third, high concentrations of water vapor in the soil reduces the proportion of soil pores that hold oxygen.

Roots in wet areas tend to be long and infrequently branched, while those in drier soils have more frequently branched, fine roots.

Root density

The density of roots in a given volume of soil is important in the ability of a tree to compete with other plants for soil resources. A more dense root system can exploit more of the moisture and nutrient of the soil volume (Atkinson et al. 1976). Lyr and Hoffmann (1967), have found different densities in growing fine roots of different species. *Larix leptolepsis*, *Betula pendula*, and *Pseudostuga menziesii* showed an intensive penetration of the soil, *Quercus rubra* var. *maximum*, a weak system, and an intermediate density for *Populus euramerica* and *Robinia pseudoacacia*.

Mycorrhizae can compensate for a weak root density and thereby effectively occupy nearly the entire soil volume. This usually occurs in the upper soil layers where mycorrhizae occur more frequently.

The effect of mechanical impedance on root growth

Increased soil strength affects tree roots by creating resistance to root elongation, and by slowing gaseous exchange of oxygen and carbon dioxide (Cruse et al. 1980, Martin 1968, Wiersum 1957, Warnaars and Eavis 1972, Simmons and Pope 1988). Root growth was found to be inhibited in several studies when bulk density ranged from 1.4 g cm^{-3} to 1.8 g cm^{-3} (Kozlowski 1985). Zisa et al. (1980), found pine seedling roots restricted at bulk densities of 1.4 g cm^{-3} and 1.6 g cm^{-3}. In a study by Richards and Cockroft (1974), when compaction reduced soil air space to 15% root growth was inhibited, and root growth was negligible when air space was reduced to 2%. The conclusion that 20% air space was required for gas exchange was reached by Bakker and Hidding (1970). Roots that proceed to penetrate high density soils require higher rates of respiration and root growth is reduced (Glinski and Stepniewski 1985). Glinski and Stepniewski (1985), report that although they found a five-fold CO_2 increase from roots respiring under compaction, total CO_2 production from roots, and root dry weight, declines as a result of high bulk density. Higher respiration requires more oxygen, which may not be available in the compacted soil.

Root observation and quantification

One of the difficulties in studying roots is that they grow unseen. The growth responses of roots have been observed in studies that date back to the Greeks over two thousand years ago, although most of the publications date from the last three centuries (Lyr and Hoffmann 1967). Until this century, observation of roots required digging up the plant, usually destroying or interrupting the development of a section of root, if not the whole plant. As an alternative, some other factor that affects the root system could be observed, and an inference about the root system made (Upchurch 1984).

In more recent years, root observation and quantification has been attempted either with a visual system in which roots growing in soil are viewed undisturbed, through a glass wall, or by counting root segments washed out of known volumes of soil removed from the ground near a plant under study.

A widespread practice of digging trenches, and lining the walls with glass to observe roots growing against it has been used by many researchers. Atkinson at East Malling, and Lyr and Hoffmann at Eberswalde used pits in which the observer could go below ground level. At Eberswalde, trees were grown in compacted sandy soil, to provide uniform conditions (Lyr and Hoffmann 1967). The glass in the pits at East Malling used an etched grid to quantify root extension (Atkinson et al. 1976). Richards et al. (1979), used a photo-electric cell to count intersections of roots with lines.

Bohm et al. (1977), gave the name "mini-rhizotrons" to a suggestion by Bates in 1937 to place clear tubes in the soil to make root observations. Bohm et al. (1977), found that use of the mini-rhizotron technique with a hand-held mirror for root counting was a time saving technique compared to four others. Upchurch and Ritchie (1983), developed the technique of using a miniaturized color video camera inside the tubes to make observations that could be studied later. Upchurch (1984), addressed the problem of comparing the work of various researchers by developing a standardized procedure for the use of mini-rhizotrons, and the analysis of data. The basic purpose of the mini-rhizotron method is to make some assumption about the number of root intersections observed against the buried tube, and the root length density in the surrounding soil (Upchurch 1984, Upchurch et al. 1988). Upchurch (1984), compared root intersections observed with the video camera and the length of roots found in soil removed from cores and gridded trenches in the soil surrounding buried tubes in a field of cotton. He found that a minimum of eight tubes per treatment had the best correlation to core measurement techniques.

Soil coring to remove a known volume of soil, followed by washing the roots from the soil and measuring them, is a frequently employed procedure (Bohm et al. 1977, Smucker et al. 1982, Tennant, 1975). Barnett et al. (1983), found cores to be a successful method of studying root density following transplanting. Tennant (1975), found Neuman's intercept method of counting root interceptions with the lines on a grid to have a high correlation with hand measurements.

Conclusions

1. Urban tree planting sites are not like natural sites. One of the most important differences is severe soil compaction. Typically, as a result of compaction, soil porosity is low and soil density is high. Organic matter is also typically present in smaller percentages.

2. Improvement of soil structure can provide a tree a more favorable rooting environment in which it can attain a balanced root/shoot ratio.

3. The improvement in porosity and density can be achieved by amending the soil with inorganic or organic amendments. The latter is expected to lose its effect in about three years as per Patterson (1987). Some inorganic amendments that have been reported to successfully improve the effects of compaction are calcined clay, sintered fly-ash, perlite and sand.

4. In isolation from other environmental improvements, relieving compaction will not completely reproduce the benefits of the forest environment. Leaf litter responsible for much of the nutrient cycle will not be replaced under typical urban tree management. Programs to mulch will be needed to provide some of the benefit of a litter layer, and the slow accumulation of organic matter in the soil by root mortality may be the major source of material for mineralization.

grading was accomplished without filling in order that the planting sites be of relatively consistent density. A soil test showed the soil to be 49.8% sand, 24.7% silt and 25.4% clay. The soil was a sandy loam that compacts very tightly. In some spots, a hand-held penetrometer would not penetrate the soil surface at all. Organic matter was negligible. The soil pH was 7.3.

The experiment was placed on one 20 m by 60 m (66' by 197') area. A grid of four rows by seven tree locations in each row was laid out on the site with fifteen foot spacing (Figure 1). Three tree locations in the grid were left unplanted. Tree planting pits, 2.4 m (8') in diameter were dug with a backhoe. The treatments were randomly assigned to the planting pits using a table of random numbers.

Treatments:

Soil from each planting hole was individually processed in a large Royer soil mixer with its assigned amendment (Figure 2). Physical and chemical tests were made on the five treatments which are described below and in Table 1.

Horticultural vermiculite was mixed with soil removed from the planting holes in proportions of 1/3 amendment and 2/3 soil by volume. This material is a heat expanded form of mica. It has a high cation exchange and a high water retention capacity. A coarse grade of horticultural vermiculite was used, supplied in bags.

```
                    Row numbers

                    4          3          2          1

                    o          o          o          o
Tree              c   c      c   c      c   c      c   c
numbers   1     o   *   o  o   *   o  o   *   o  o   *   o
                  c   c      c   c      c   c      c   c
                    o          o          o          o

                    o          o          o          o
                  c   c      c   c      c   c      c   c
          2     o   *   o  o   *   o  o   *   o  o   *   o
                  c   c      c   c      c   c      c   c
                    o          o          o          o

                    o          o          o          o
                  c   c      c   c      c   c      c   c
          3     o   *   o  o   *   o  o   *   o  o   *   o
                  c   c      c   c      c   c      c   c
                    o          o          o          o

                    o          o          o          o
                  c   c      c   c      c   c      c   c
          4     o   *   o  o   *   o  o   *   o  o   *   o
                  c   c      c   c      c   c      c   c
                    o          o          o          o

                    o          o          o
                  c   c      c   c      c   c
          5     o   *   o  o   *   o  o   *   o
                  c   c      c   c      c   c
                    o          o          o

                    o          o          o
                  c   c      c   c      c   c
          6     o   *   o  o   *   o  o   *   o
                  c   c      c   c      c   c
                    o          o          o

                    o          o          o
                  c   c      c   c      c   c
          7     o   *   o  o   *   o  o   *   o
                  c   c      c   c      c   c
                    o          o          o
```

Legend: * = tree location; 0 = minirhizotron tube; and
c = location of core sample.

Diagrams not to scale. The trees are planted on a row spacing of twelve feet, and a tree spacing of fifteen feet.

Figure 2. Soil in the hopper of the soil mixer moving up the belt toward shredding blades and discharge shoot.

Grade #4 perlite was mixed with soil removed from the planting hole. The treatment was mixed in proportions of 1/3 amendment and 2/3 soil. Perlite is a stable, expanded volcanic material. It was obtained in bags.

The organic matter treatment was composed of partially decomposed leaf mold, mixed with soil in a manner similar to the other treatments. The leaf mold was stockpiled for at least two years, and was obtained from the MSU Grounds Department.

The loam top soil was a shredded mix of organic matter and sandy loam made by the MSU Grounds Department. OM was 2.2%, and the mineral component of the soil was 70% sand, 16.4% silt and 13.4% clay. This treatment was used as a 100% replacement, and was not mixed with soil removed from the planting holes.

A control of existing soil was used unamended, but was processed through the soil mixer.

Table 1. Summary of soil chemical and physical characteristics.*

Treatment	% organic matter	bulk density	CEC	pH	N ppm	P ppm
test site soil	--	1.92	17	7.3	--	1
unamended control	--	1.58	17	7.3	466	1
33% organic matter amended	6.5	1.07	20	7.8	3150	7
33% perlite amended	1.0	1.26	15	8.0	748	0.5
33% vermiculite amended	1.1	1.40	15	8.0	1424	0.5
100% topsoil replacement	2.2	1.38	11	7.7	1882	22

* Bulk density is in grams per cubic centimeter and was tested on samples drawn in November 1988. CEC is in milliequivalents per 100 grams of oven dry soil. %OM is by wet digestion. N is total nitrogen, and is by sulfur digestion in March 1989. CEC, pH, P, and %OM were tested on samples drawn in May 1988. P was tested by the Bray P procedure.

The unamended treatments of existing soil and of topsoil were also processed through the mixer to remove a potential source of variation between the treatments. A front-end loader was used to place the ingredients into the hopper of the mixer. This method was useful for loading the soil from the pits, and for loading the topsoil. The 33% OM treatment was pre-mixed on the ground. Front-end loader bucket loads of soil and OM were placed in a pile and then lifted and dropped, spread and pushed together using the loader. The rough mix was then placed into the mixer for further mixing and shredding. The inorganic amendments were added by shoveling the amendment into processed, existing soil as it came from the mixer. The force of the soil coming from the discharge shoot mixed the soil and amendments (Figure 3). This procedure was employed because the wind blew the vermiculite and perlite out of the mixes as the processed soil dropped almost two meters to the ground from the discharge port of the mixer.

The trees:

The trees chosen for the study were honeylocusts: *Gleditsia triacanthos inermis* var. '*Shademaster*'. The genus is named after the German botanist, J.D. Gliditsch, and its valid Latinized name, *Gleditsia*, is from Linnaeus, 1753, having priority over Gleditschia of Scopoli, 1777 (Allen and Allen 1981). *Gleditsia* is a genus native to North America, Asia, Africa, and South America. *G. triacanthos* is native to temperate North America, and ranges from Pennsylvania to Illinois, and from Texas to South Carolina. *G. triacanthos* is a mesic, intolerant species (Potts and Herrington 1982). Honeylocusts are fast rooting, and are one of the most tolerant to poor soil aeration. The species is a frequently planted urban tree, and was chosen for this

Figure 3. Side view of soil mixer. Shredded soil is shown being discharged from mixer into hole. Organic matter treatment is shown in the planting hole beyond the mixer.

research project, in part, for this reason. Honeylocusts were heavily promoted as a disease and pest-free replacement for American elms (Wyman 1965). These characteristics are important to municipal arborists (Gerhold and Steiner 1976). Several pests, such as aphids and webworms, have since emerged as serious problems (Dirr 1983). Richards and Stevens (1979), reported the drought effects of premature senescence, tissue damage, and early mortality in urban plantings. Honeylocusts have a high water requirement, due in part to an inability to close leaf stomata during moisture stress (Halverson and Potts 1981). Regardless of these problems, it is still widely chosen and used, due to its light shade, low cost and tolerance to urban conditions.

The honeylocust trees used in this experiment were all park grade, 4.5 cm (1 3/4 inches) dbh., and were transplanted from a single area of Cottage Gardens Nursery. The root balls averaged 71 cm (28 inches) across and 60 cm (24 inches) deep, and were wrapped in burlap and wire containers. The soil in which the trees were grown in the nursery was a well drained sandy clay loam. The trees were dug the second week of May, and were delivered to the project site the following week (Figure 4).

Figure 4. Balled and burlaped honeylocust trees at Cottage Gardens Nursery being loaded for delivery to the experiment site.

Planting technique:

The planting holes were formed in a dish-shape to improve the soil in a shape that reflects natural root distribution (Keever et al. 1985). The holes were 2.4 m (8 feet) in diameter and 20 cm (8 inches) deep (Figure 5). A central platform of undisturbed soil raised the bottom of the root ball 15 cm (6 inches) to keep the roots in a volume of soil above a zone where excess water tends to collect (Watson 1987). The shallow planting hole required that a mound of soil above the normal soil level be created to accommodate the root ball. The mound required soil in addition to the amount removed from the hole. The extra soil needed for the amended treatments was provided from three extra holes dug on the site, and from the holes into which the topsoil treatment was placed.

The holes took about a half day to dig using an articulated backhoe/front-end loader. Soil mixing took nearly three days due to the frequent jamming or breakdown of the soil mixer. The trees were picked up from the nursery once the planting holes were prepared.

Holes were dug in the mound of amended soil in each planting pit, and the root ball of the tree rolled into it. Rope ties and burlap were cut away from the top of the rootball. Soil was returned to the hole in layers, tamped and soaked with water. Soil was added in two more layers and irrigated. Holes were later dug for the observation

Figure 5. Planting hole being excavated in compacted soil. Photo shows dish-shaped hole.

tubes, the tubes placed and the narrow holes backfilled with tamping and irrigation. When finished, the backfilled holes were given a mound shape, with a watering saucer in the top and 4 cm (1.6 inches) layer of mulch applied (Figure 6).

Measurements:

One-hundred 5 cm (2 inches) square by 30 cm (12 inches) long cores were taken in late October 1988. The cores were driven to the same depth and at the same angle as the implanted minirhizotrons in order that future comparisons could be made (Figure 7). The soil cores were stored in plastic bags in a cold room. Roots were then washed from the soil in a hydropneumatic elutriation system as described by Smucker et al. (1982). The roots were sealed in plastic bags in a water and 15 - 20% methanol solution and stored at 2-3°C. Each sample of roots was placed in a white pan with water, gently separated and the root tips counted. Each piece of root without an obvious branch was assumed to have one tip. This assumption was based upon observations of roots dug from other sections of the planting pits. Fifteen root samples were hand measured for a weight/length comparison. Each sample was then placed in a paper bag, oven dried and weighed.

Temperature and moisture measurements were taken throughout the summer and fall in anticipation of correlations between temperature, moisture, mound shape and

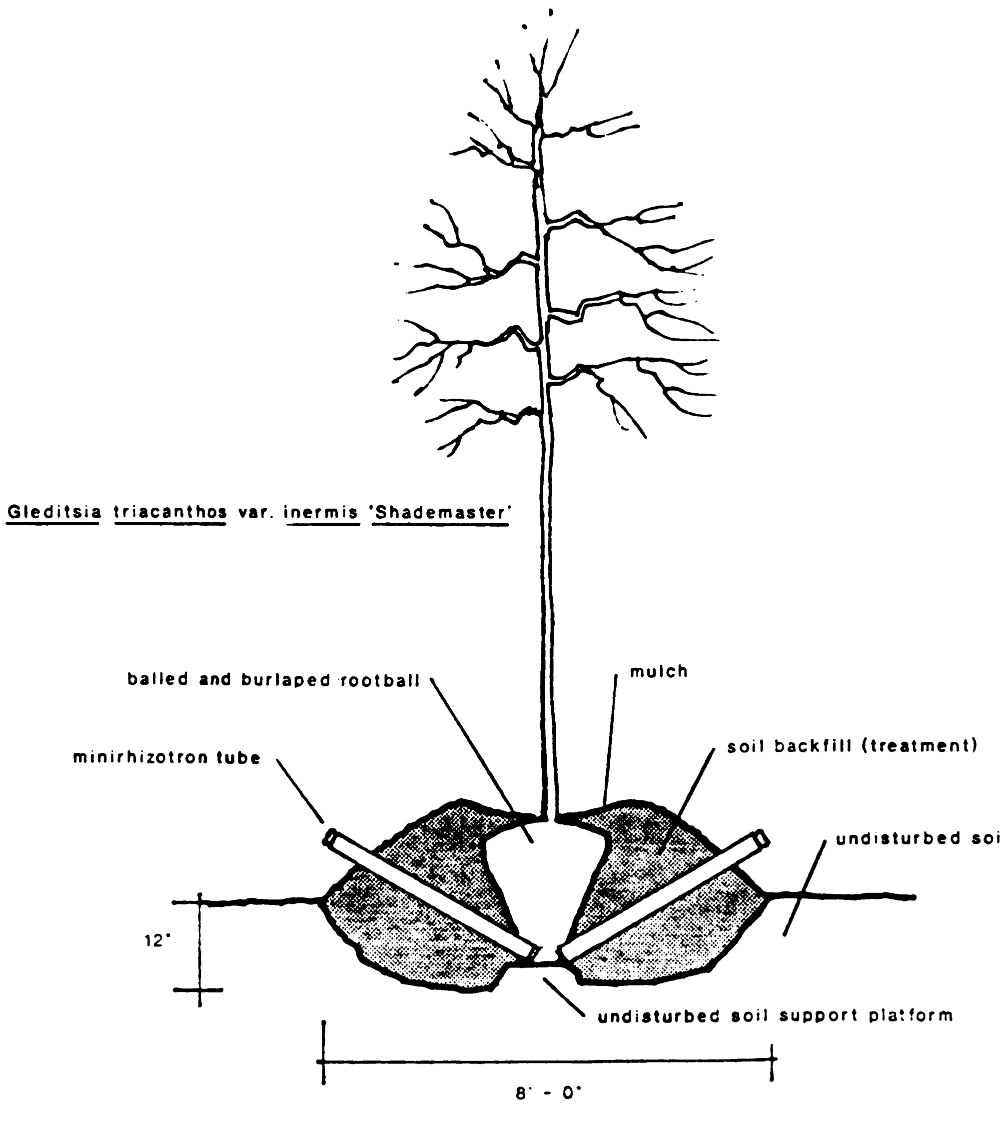

Figure 6. Section view of tree planting, showing hole shape, dimensions, rootball position, and minirhizotron placement.

Figure 7. View of core sampling of roots growing in the different soil treatments. Photograph was taken in late October 1988.

root response. Temperature measurements were made with a 24 inch soil probe. Moisture measurements were made with a tensiometer for the latter part of the growing season, and with a moisture meter for the early part of the season. An attempt to calibrate the two systems found the moisture meter to have wide variability. The planting technique and video image recording were successfully tested in the summer of 1987 in a pilot study. As a result of the 1987 pilot project, refinements were incorporated into the 1988 project.

Minirhizotron tubes:

Minirhizotron tubes, two inch diameter clear butyrate plastic tubes, each three feet long were buried in the backfill shortly after planting time. Four tubes were installed in each planting hole. The lower end of the tubes were closed off with tightly fitted rubber stoppers. The upper ends were sealed with a loose fitting stopper to keep out the rain. The tubes were set in the backfill at a 30 degree angle away from the trees. The bottom of the tubes were placed against the bottom of the root ball. These tubes were installed for the purpose of making periodic video records of the tree roots over the growing season. Equipment breakdowns made it impossible to record sufficient image sets to complete a first year analysis. The tubes remained in the ground for future study.

In the first week of November, 1988, core samples of the treatments were taken for the purpose of determining bulk density, volumetric moisture and air-filled porosity. Four core samples were taken at each tree. This provided a replication of twenty samples per treatment. The core cylinders were metal, 7.2 cm diameter by 7.2 cm deep. The cores were saturated and then sequentially placed on a 40 cm tension table, 1/3 bar, 1 bar pressure plates and oven dried for 72 hours at 105°C. The cores were weighed following each stage. Bulk density, air-filled porosity and gravimetric moisture content were computed. Volumetric moisture was calculated from the gravimetric moisture and bulk density of each treatment. Separate soil samples, taken in mid December 1988, were air dried, and passed through a 2 mm sieve. Larger material was excluded. There were five replicates of each treatment. An approximation of the moisture content at high moisture potential was made by placing these samples on a fifteen bar pressure plate, and subsequently weighing the samples both prior to and following oven drying.

A test for total soil nitrogen was performed on soil material provided by the mid-December sampling. Five 0.75 subsamples of each treatment were tested using sulfur digestion and photometric analysis in a Technicon Autoanalyzer II.

Operationalization of variables:

Hypothesis #1:

The first hypothesis was based upon the assumption that the soil treatments improve porosity about equally, and that the generation of roots in these porous soils during the first growing season will be equal, with an error due to chance of 5%. The null hypothesis and alternative hypotheses can be stated as follows:

Null hypothesis number 1. There is no difference among treatments in the length of root growth in the first season.

Alternate hypothesis number 1. The length of root growth in the first season in the organic matter or topsoil treatments will be significantly different compared to the inorganic amended compacted soil or the control.

The measure of root generation used was the season total of root length. Length was the dependent variable. Length was measured in millimeters. Length for each sample was based upon calculations of typical weight per unit length measurements of root samples. Treatment and replications were the independent variables. Wide variation was expected in root response within the different sectors of the planting pit. Therefore, each soil core is considered a replication.

Hypothesis #2

The second hypothesis was based upon evidence in the literature that roots branch more frequently in fertile, organic matter-rich soils (Drew et al. 1973, Russell 1977). This could result in a greater number of root tips per unit length of root in soils containing organic matter if the tree responds with differential rooting. A test for branching frequency is a rooting coefficient. The coefficient, R, is equal to the length of roots divided by the number of root tips of each core sample (Bohm 1979).

$$R = \frac{\text{length of roots in a sample (mm)}}{\text{number of root tips in a sample}}$$

The null and alternative hypotheses are expressed:

Null hypothesis number 2. There is no difference in root coefficients among treatments.

Alternate hypothesis number 2. The root coefficient is significantly different among treatments.

An analysis of variance was used to identify differences in root coefficients between treatments. The dependent variable is the rooting coefficient. The independent variables are treatment and replication.

CHAPTER IV: RESULTS

Root length, root branching coefficient and shoot growth were measured and analyzed. Soil bulk density, air-filled porosity, volumetric moisture, water potential, temperature, pH, CEC, total nitrogen and phosphorus were also measured.

Root length:

There was no statistical difference in root length among treatments that could not be due to chance occurrence at the .05 level. The means of root lengths were 1291.5 mm for the unamended control, 2226.3 mm for the organic matter (33%) treatment, 1634.2 mm for the perlite (33%) treatment, 1038.4 mm for the vermiculite (33%) treatment and 1547.6 mm for the topsoil (100%) treatment (Table 2). By comparing the means it can be shown that during the first season the roots attained the greatest length in the organic matter treatment. The mean of root length in organic matter is more than double the mean of root growth in the vermiculite treatment. Root length was greatest in the organic matter treatment, followed by the perlite, topsoil, vermiculite, and control treatments respectively.

The reason for the greater root length in the organic matter treatment may be due to greater soil nitrogen and phosphorus. Root growth can respond to soil fertility, as was discussed in the literature review on page 25. It could be expected that the greatest root growth would be in the organic matter treatment, which was shown to be highest in total nitrogen in Table 1. This may have indeed occurred, but due to high variability the statistical significance was masked. Analysis of variance is summarized in Appendix Table 6. There is a discussion in Chapter Five on the sources of this variation and measures to limit variation in future experiments.

Table 2. Treatment means, highs, lows, and standard error for length of roots in millimeters per core. 1988.

Treatment	Low	Mean	High	Standard error
Unamended control	174	1291.5	3571	202.0
Organic matter	204	2226.3	8592	529.0
Perlite	95	1634.2	6035	337.0
Vermiculite	338	1038.5	2721	141.0
Topsoil	247	1547.6	4635	281.0

Variation in the data is displayed in the Appendix Tables A1 - A4. Among all of the samples in all treatments, root length ranged from 95 mm to 8592 mm. In the unamended soil, root lengths of individual core samples ranged from 174 mm to 3571 mm. In the organic matter treatment, root length ranged from 204 mm to 8592 mm. Root length in the perlite treatment ranged from 95 mm to 6035 mm while the range in the vermiculite treatment was from 338 mm to 2721 mm. In the topsoil treatment, root length ranged from 247 mm to 4635 mm.

Root branching coefficients:

There was no statistical difference in root branching coefficients among treatments. The means of coefficients were 9.98 for the unamended control, 26.4 for the organic matter treatment, 26.2 for the perlite treatment, 13.4 for vermiculite treatment and 12.4 for the topsoil treatment (Table 3). The means show that there were more branches per unit length in roots grown in the unamended control. The least frequent branching occurred in the organic matter (33%) and perlite (33%) treatments. Coefficients in the vermiculite (33%) and topsoil (100%) treatments were approximately twice that of the OM and perlite treatments. Due to wide variation, there was no significant difference among treatments. The variation may have masked real treatment differences. There is a discussion in Chapter

Five on reasons for the wide variation and measures that could be taken to limit variation in future experiments.

Therefore, there is no evidence in this data from which to conclude that there is a statistical difference among treatments in the frequency of branching as one component of root architecture. Analysis of variance was also performed on coefficients. This is summarized in the Appendix Table 7.

Table 3. Treatment means, highs, lows, and standard error for coefficient of branching frequency per core. 1988.

Treatment	Low	Mean	High	Standard error
Unamended control	4.2	9.98	25	1.4
organic matter	1.6	26.4	237	11.5
perlite	3.0	26.2	168	9.8
vermiculite	3.0	13.4	49	1.9
topsoil	4.1	12.4	41	2.9

Coefficients of branching ranged from 1.6 to 237. In the unamended soil, the range was 4.2 to 25. In the organic matter treatment, the coefficient ranged from 1.6 to 237. In the perlite and vermiculite treatments, the coefficient ranges were 3.0 to 168, and 3.0 to 49 respectively. In the topsoil treatment, the coefficients ranged from 4.1 to 41.

Variation is high for both the root length data and the coefficients. This can be seen in the data tables in the appendix, and in the summary tables of means. Standard error is also included in Tables 2 and 3. High variation is a frequent problem when collecting data on roots because tree roots do not normally extend from the trunk in an even distribution. This is due both to phenology and to environmental conditions encountered by the growing roots.

There appeared to be a possible correlation of deviation with means in both sets of data. This was examined using T-tests and by log transformation of the data (Little and Hills 1978, Steel and Torrie 1980). T tests were performed on data between pairs of treatments. There was significance in only one pair at the .05 level. Out of ten pairs, this could be assumed to happen by chance occurrence. Neither the ANOVA performed on the untransformed nor on the transformed data were significant.

Root morphology

Although there was no significant difference found among treatments in the frequency of branching, roots excavated at various periods in the growing season exhibited different morphologies. A few woody roots of about 4 mm were obtained in the core samples. These were light brown in color and were ridged with dark brown strands that formed an open, tightly adhered net on the root. The woody roots were stiff, and an occasional root branched from it at right angles. Fine roots were found exiting the root ball into the backfill by the end of June, about three weeks after planting. Typically, these were firm, white roots about two millimeters in diameter. From the end of June into mid-July, the unsuberized white root tips were six to ten centimeters long. At the end of July only approximately three centimeters of unsuberized root appeared at the apices of most roots. In the first week of September, very few root tips remained white. These were about one centimeter long. The suberized sections of the roots were a very dark brown to black color.

In late October, most of the suberized root surfaces had a dense covering of very stiff hairs. Fine roots in the corings sampled in late October measured from one to three millimeters in diameter. Only one white root-tip was found in late October.

Two distinct root architectures were found. These were a single branch architecture (two orders of branching) and an architecture of multiple orders of branching (greater than two orders). With rare exception, roots with two orders had root branches that did not exceed five centimeters. Roots with single side-branches one to three centimeters long were found as far as one meter outside the treatment mix of one planting hole. Roots with up to four orders of laterals typically had first order branches approximately fifteen centimeters long. Second to fourth order root branches rarely exceeded five centimeters in length.

An example of root architecture can be seen in Figure 8. The root sample in the drawing displays two distinct branching patterns within a distance of 15 centimeters. Laterals nearest the root tip have no further branches. The roots farther from the extending tip have several orders of branches.

A visual inspection of the roots suggested that there was an extensive mycorrhizal infection. However, this proved to be a dense proliferation of root hairs and an irregular root surface (Figure 9). Two root samples were tested with blue stain and examined under a dissecting microscope. The hairs did not stain as expected for mycorrhizal hyphae, and microscopic examination showed the hairs to be unicellular with broadened bases. Sutton (1980), also reported suberized root hairs in honeylocusts. See Appendix, Figures A1 - A6.

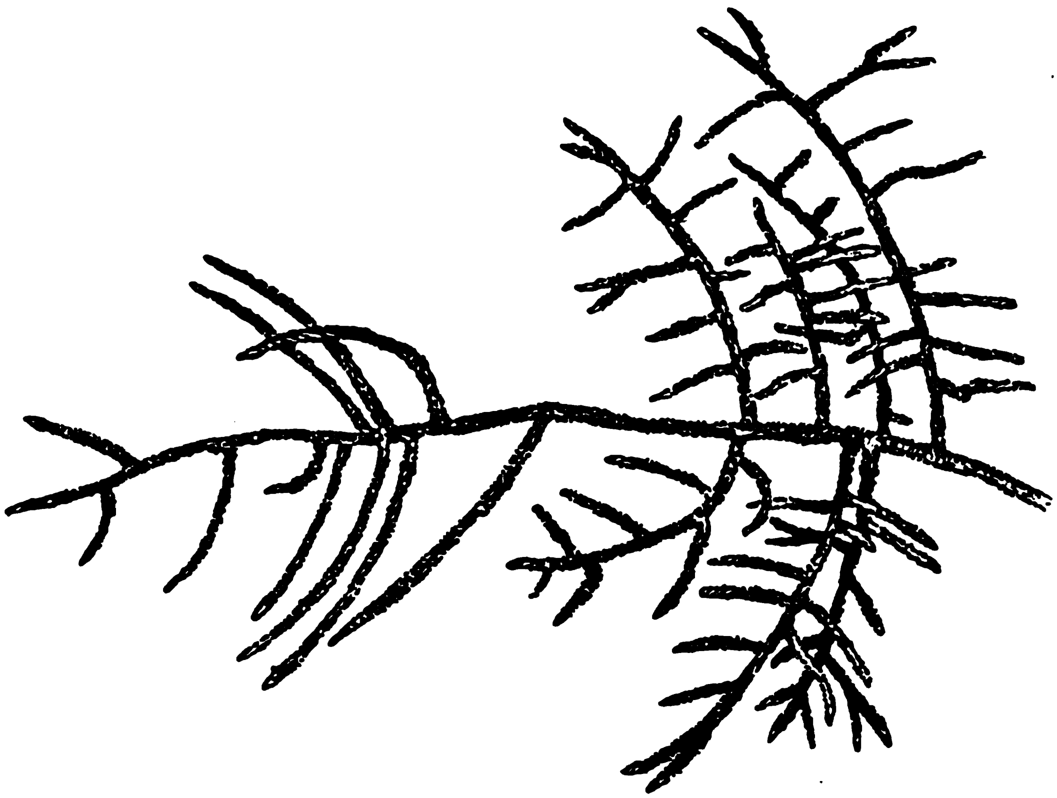

Figure 8. Sketch of root specimen taken in late October 1988. The drawing shows one root with both multiple orders of branching followed by single, unbranched side roots. Drawing is life-size.

Figure 9. Photograph of root excavated in April 1989. Close-up shows dense covering of root hairs.

Above ground tree growth:

The trees were delivered to the study site in mid-May with leaf buds beginning to open on all but two of the trees. It was feared that these two had not survived, but they began bud expansion and opened about a week later. This did not appear to affect season shoot or root growth, as both shoot and root growth in these two trees were similar to other trees. Full flush continued for three weeks, and shoot growth continued into early July.

The trees averaged about 4.5 cm (1 3/4 inches) dbh, and five to six meters tall. The crowns on the trees were approximately two meters in height. Crown diameter ranged from about one to one and one half meters. In fifteen trees the leader was substantially above the bulk of the crown.

In the first few weeks following planting, the trees exhibited physiological drought. This was due to transplant root loss, unseasonably high temperatures and clear skies. The root system was unable to meet transpiration demand.

Air temperatures reached above 39°C during the summer, often on cloudless, windy days. Wilting for short durations was observed, but recovery was always complete by the next morning. This was also observed on honeylocusts adjacent to the experimental site.

A measurement of shoot growth was made to determine if there were inherent differences in the reserves of the trees that could account for anticipated differences in root growth. Shoot-growth of the trees was measured in mid July, after the first season of shoot flush had finished.

In Appendix Table A 8, the means of shoot growth for trees in the various treatments are presented. Appendix Table A 9 presents the ANOVA performed on the data to test for differences. No significant differences were found in first year (1988) shoot growth of the trees that could not be attributed to chance occurrence.

Leaf senescence began in late September, and by the end of the first week of October approximately 80% of the leaves had senesced. Leaf drop was complete by the fourth week of October.

Soil:

Moisture

Soil moisture was measured throughout the growing season. A moisture meter was used at the beginning of the season to monitor soil moisture. A tensiometer was employed later in the season. An attempt was made to calibrate the moisture meter with the tensiometer. However, an accurate calibration was not possible due to a wide range of readings on the moisture meter. Early and mid-season soil moisture cannot be reliably reported.

The 1988 season was exceptionally dry. Approximately one centimeter of precipitation fell from the time the trees were planted until July 16th, as recorded at the Crop and

Soil Sciences Research Farm at MSU. Supplemental watering by hand provided an equivalent of about 0.4 cm (0.16 inch) per week per entire planting pit. Because water was delivered to the center of the planting pit, it is reasonable to assume that the center of the planting pit received an amount greater than 0.4 cm and that the periphery of the pit received somewhat less. This was roughly estimated to be 2.5 cm (1 inch) for the following ten weeks. Evaporation averaged 2.5 cm (1 inch) per week in June, about 2.3 cm (.9 inch) per week in July, 0.8 cm (0.32 inches) per week in August and about 0.5 cm (.2 inch) per week in September (Table 4). Evaporation was recorded at the Horticulture Farms at MSU.

During the periods when supplemental water was provided, soil water potential averaged 20 centibars, and ranged from 12 to 50 centibars. The autumn was very wet, and supplemental water was discontinued on September 18th. In late August and through September, soil water potential remained in a range from 4 centibars, essentially saturated, at the bottom of the root zone to 20 centibars near the surface.

Table 4. Evaporation, precipitation, and irrigation addition in cm and inches, as weekly averages for the growing season, 1988. Readings were taken daily at the Michigan State University Horticulture Farms. Irrigation addition was calculated from amounts provided by hand watering.

Week	Evaporation		Precipitation		Additional Irrigation	
	cm	inches	cm	inches	cm	inches
5/22-28	5.3	2.1	0	0	1.3	0.5
5/29-6/4	6.1	2.4	0	0	1.3	0.5
6/5-11	6.4	2.5	0	0	2.5	1.0
6/12-18	6.1	2.4	0	0	2.5	1.0
6/19-25	8.4	3.3	0	0	2.5	1.0
6/26-7/2	5.1	2.0	0	0	2.5	1.0
7/3-9	7.1	2.8	0	0	2.5	1.0
7/10-16	6.9	2.7	4.1	1.6	2.5	1.0
7/17-23	3.6	1.4	0.5	0.2	2.5	1.0
7/24-30	5.3	2.1	1.5	0.6	2.5	1.0
7/31-8/6	6.6	2.6	1.5	0.6	2.5	1.0
8/7-13	5.3	2.1	0.5	0.2	2.5	1.0
8/14-20	5.1	2.0	5.1	2.0	0	0
8/21-27	3.0	1.2	1.5	0.6	0	0
8/28-9/3	3.3	1.3	0.8	0.3	0	0
9/4-10	2.8	1.1	0.5	0.2	0	0
9/11-17	2.5	1.0	0.8	0.3	0	0
9/18-24	4.1	1.6	7.4	2.9	0	0
9/25-10/1	2.3	0.9	2.0	0.8	0	0

Temperatures

Soil temperatures were recorded twice weekly during the growing season at two depths, 10 cm and 50 cm, and in two to three replications within each treatment. There was no significant difference in soil temperatures among the different treatments. Temperatures recorded at equal depths were within 1°C among treatments and are reported as an average for both depths. These are shown along with air temperatures recorded at the MSU Tree Research Center, one mile distant, in Fig. 10. Soil temperatures at the surface approached air temperature, which reached a recorded maximum of 35°C. Lyr and Hoffmann (1967) report that root growth ceases above 35°C. Soil temperatures at 50 cm reached a maximum of 24°C. By the end of October, temperatures at 50 cm were down to 10°C. While the temperature at 50 cm remained relatively constant, air temperatures fluctuated above and below 0°C. Roots at 50 cm probably remained metabolically active through October (Kuhns et al. 1985).

Bulk density and porosity:

Bulk density and air-filled porosity were measured on soil samples taken in early November 1988 from the different treatments, and from the undisturbed test site soil surrounding the planting holes. These properties are summarized in Tables 1, 5, 6 and 7, and Figures 11 and 12. The raw data on bulk density is displayed in Table A 5 of the Appendix. A summary of soil porosity, bulk density and moisture holding capacity is displayed in Table 5, and significant differences among treatments for these properties is labled.

The test site soil had the highest bulk density, 1.92 g cm^{-3} (Table 5), and processing this soil through the soil mixer resulted in a significant decrease in bulk density to 1.58 g cm^{-3}, measured six months after mixing.

The organic matter (33%) treatment had the lowest bulk density, 1.09 g cm^{-3}. The bulk density of this treatment was significantly different from all the other treatments. This material was light and crumbly in the hand, and could be compressed by squeezing. The perlite (33%), vermiculite (33%) and topsoil (100%) treatments had bulk densities of 1.26 g cm^{-3}, 1.41 g cm^{-3}, and 1.39 g cm^{-3} respectively. The vermiculite and topsoil treatments were the only treatments not significantly different. The perlite treatment was very friable, but could not be easily compacted by squeezing. The topsoil was friable, and could be slightly compacted. The vermiculite treatment showed signs of breaking down in the mix, and formed a smaller, sticky mass upon squeezing.

Porosity was significantly different between the amended soils and the test site soil, although not significantly different between the test site soil and the unamended soil processed through the mixer. The soil amended with organic matter had 49.8% porosity and was significantly different than all treatments except the topsoil (Table 5). Porosities of the other amended soils were 45% for the topsoil, 43.2% for the vermiculite and 42.4% for the perlite amended soil. The unamended, mixed soil had a porosity of 38.5%.

Volumetric moisture was measured. The treatments with significantly more water available for plant use, measured at 1/3 bar were the organic matter mixture with 22.7% and the perlite mix with 20.7%. Water was significantly more available in all the treatments than in the test site soil except for the topsoil treatment. Processing the test site soil significantly increased moisture holding capacity to 19.9%. The vermiculite and the unamended, processed soil were not significantly different, with 19.5% and 19.9% respectively.

Table 5. Soil physical properties at the end of the first growing season. November 1988. Means and standard error of five treatments and test site soil for porosity, moisture holding capacity and bulk density.

	Porosity	Moisture Holding Capacity at 1/3 Atmosphere	Bulk Density
	%	%	g cm^3
Test site soil	31.2 d	16.9 e	1.92 a
unamended soil mixed	38.5 cd	19.9 cd	1.58 b
33% organic matter	49.8 a	22.7 a	1.09 e
33% perlite	42.4 bcd	20.7 bcd	1.26 d
33% vermiculite	43.2 bcd	19.5 bed	1.41 c
100% topsoil	45 abc	18.1 e	1.39 c

Means followed by different letters within columns are significantly different at P .05 (Fishers LSD).

Table 6. Air filled pores at different levels of tension in existing and treated soils. 1988

Treatment	Sample size	40 cm mean	Std. error	1/3 bar mean	Std. error	1 bar mean	Std. error	oven dry mean	Std. error
		%		%		%		%	
test site soil	4	6.1	.50	12.3	.69	12.2	.77	29.2	.71
unamended soil mixed	20	9.4	.78	17.0	.97	12.7	.94	36.8	.92
33% organic matter amendment	19	20.0	1.43	29.3	1.17	30.3	1.15	51.5	1.39
33% perlite amendment	17	11.9	.82	19.8	1.08	19.0	1.50	40.1	1.19
33% vermiculite amendment	20	12.2	1.15	22.0	1.23	22.6	1.25	41.4	1.44
100% topsoil replacement	20	12.8	1.12	25.4	.72	25.5	.66	43.5	.79

Table 7. Volumetric moisture content at different levels of tension of existing and treated soils, in percent. 1988

Treatment	Sample size	Saturated mean	Std. error	40 cm mean	Std. error	1/3 bar mean	Std. error	1 bar mean	Std. error
		%		%		%		%	
test site soil	4	56.0	.71	44.4	.32	32.4	.41	32.4	.15
unamended soil mixed	20	58.0	.92	43.5	.56	31.4	.41	30.2	.39
33% organic matter amendment	19	55.0	1.39	34.3	1.09	24.4	.54	23.3	.51
33% perlite amendment	17	51.0	1.19	36.5	.83	26.1	.57	26.8	1.41
33% vermiculite amendment	20	58.0	1.44	41.3	1.11	27.3	.51	26.5	.60
100% topsoil replacement	20	60.0	.79	42.4	1.12	24.8	.45	24.8	.43

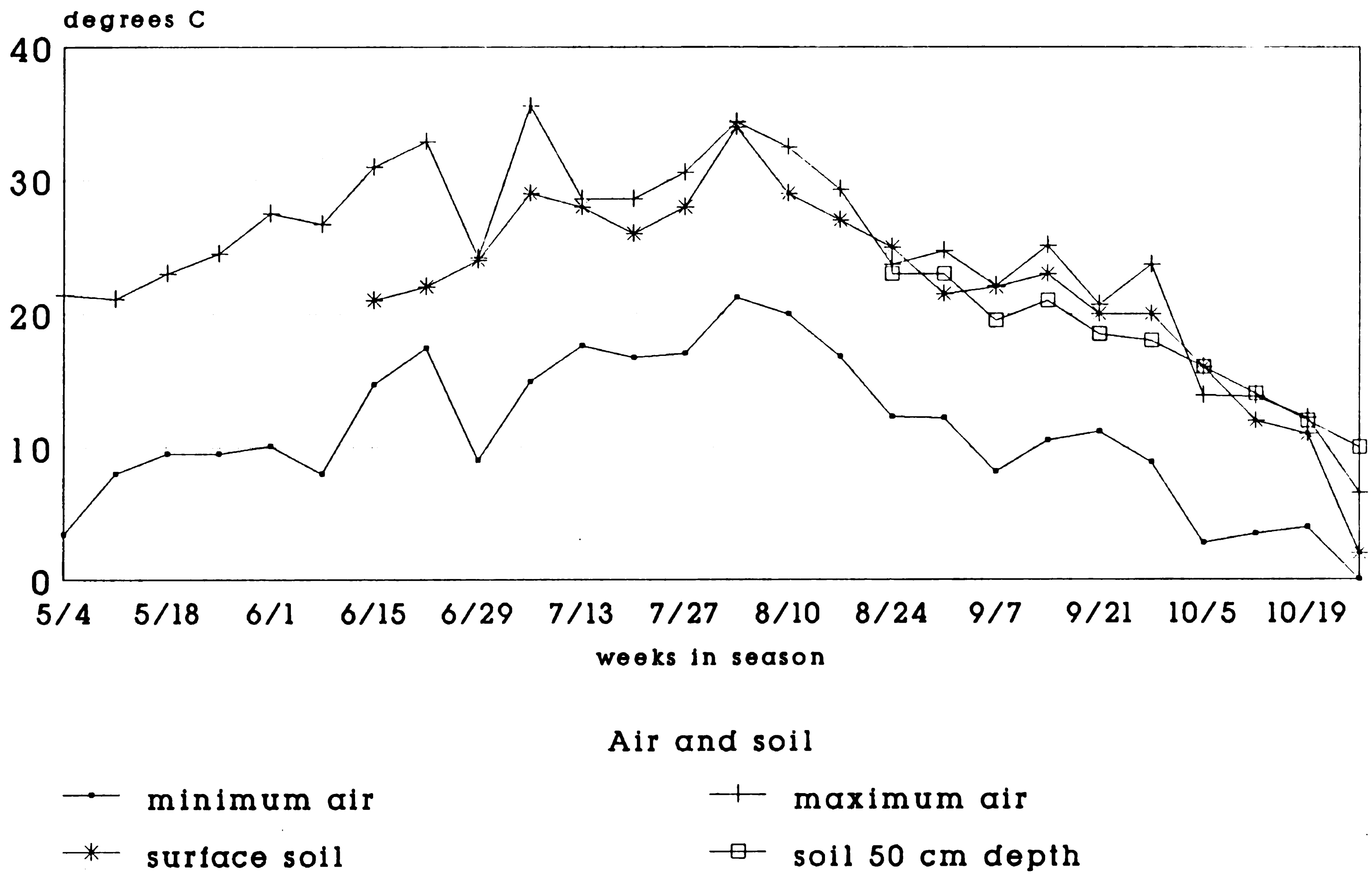

Figure 10. 1988 air and soil temperatures. Weekly averages in degrees C.

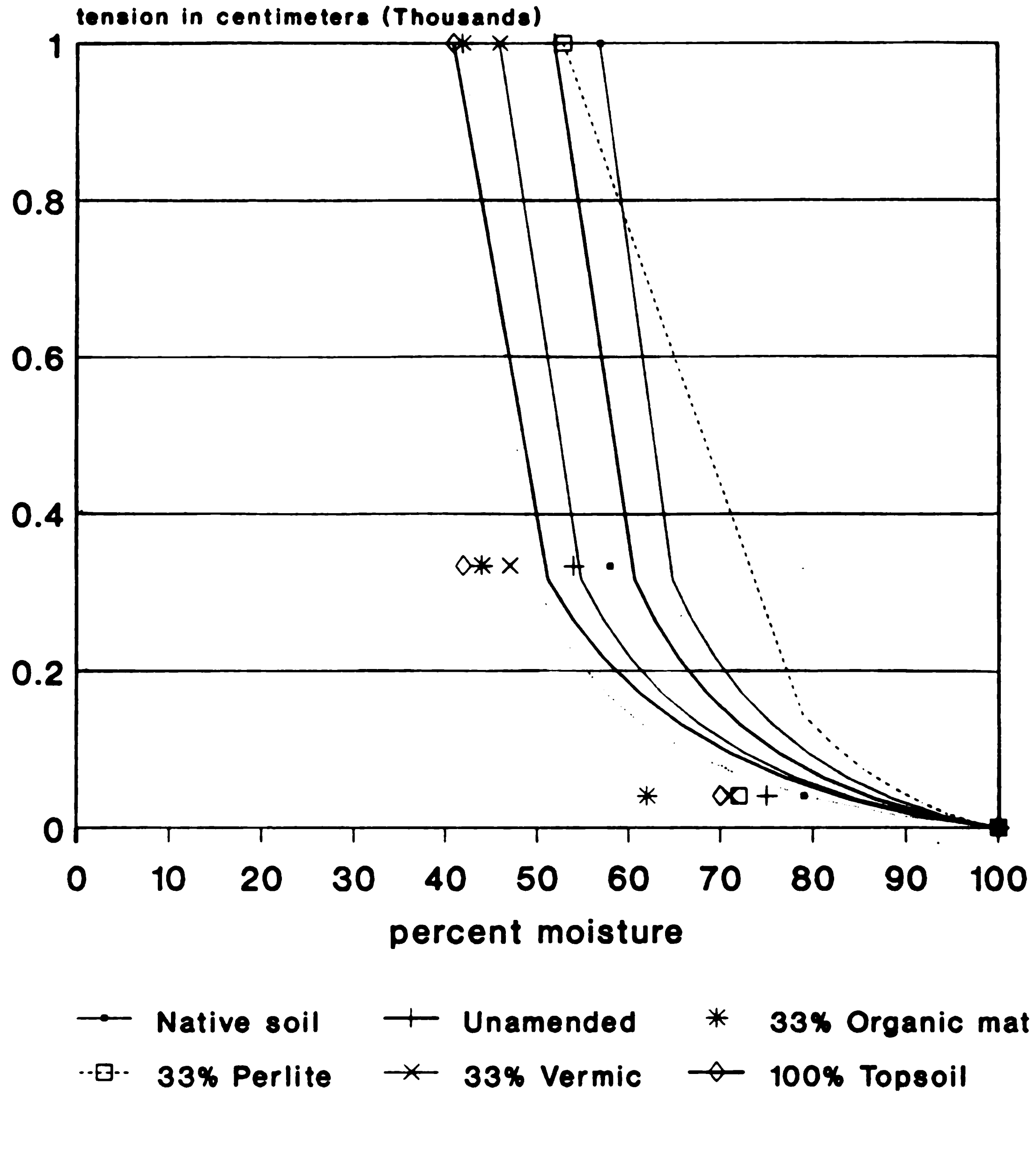

Figure 11. Accumulated percentage of volumetric moisture in soil treatments at various tensions. Lines are best fit curves. 333 cm tension point is missing for perlite treatment.

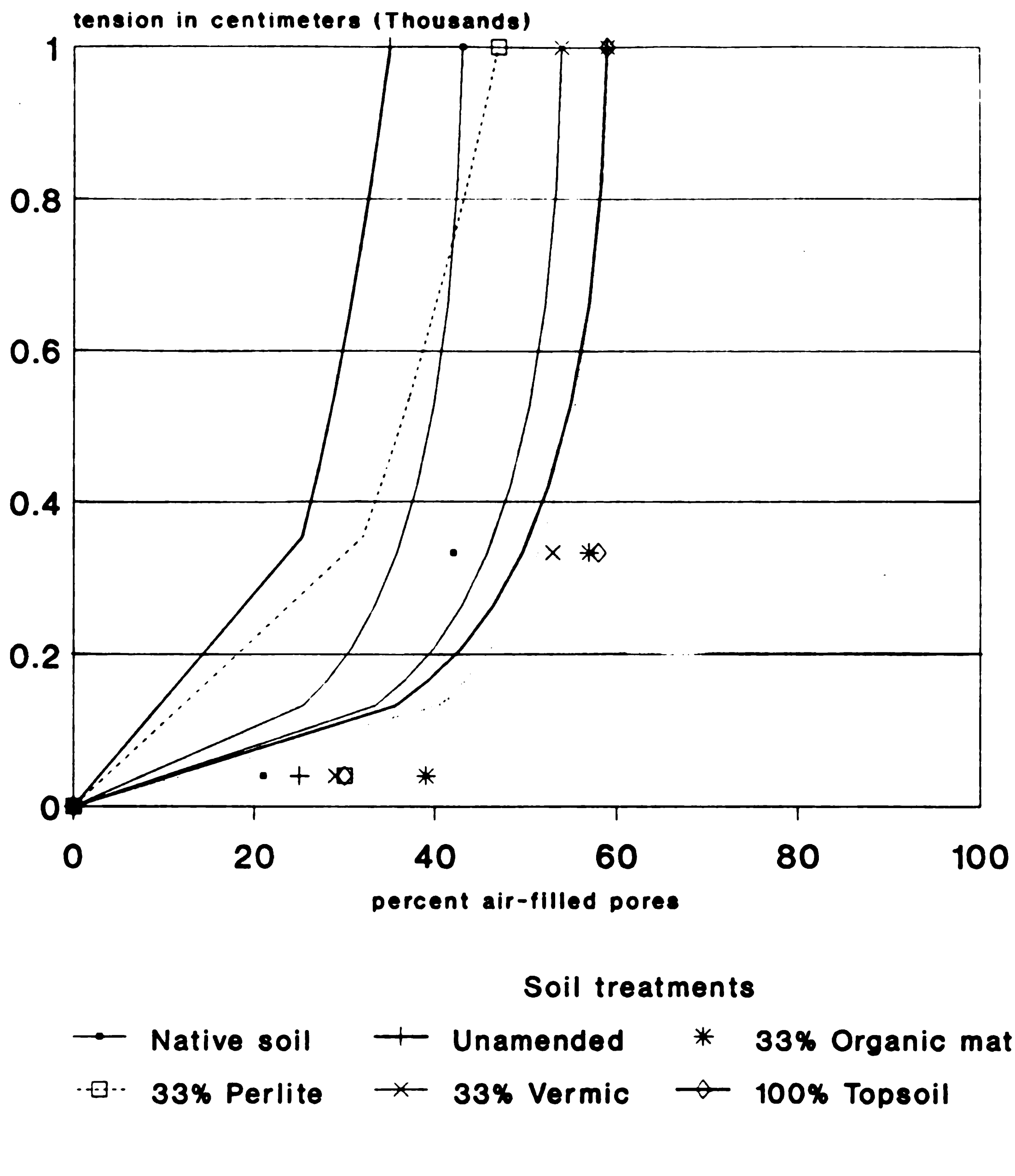

Figure 12. Accumulated air-filled porosity. Lines are best-fit curves. 333 cm tension points are deleted from the unamended and perlite treatments.

At 15 bars of tension, the organic matter mix had the highest remaining gravimetric moisture, 12.2%. The water retained in the other treatments dropped to 6.5% for the processed, unamended soil, 5.9% for the perlite mix and 6.3% and 6.1% for the vermiculite and topsoil treatments respectively.

Soil chemistry

Soil pH, cation exchange capacity, total nitrogen, and phosphorous were measured for the treatments. These are summarized in Table 1. The pH, phosphorus and cation exchange capacity were tested by the Michigan State University Soil Testing Lab. Nitrogen was tested in the Forest Ecology lab in the Department of Forestry using a concentrated sulfuric acid digestion method and analyzed by a Technicon Autoanalyzer II.

The soils were alkaline, ranging from 7.3 in the unamended soil to 7.7 for the topsoil, 7.8 for the organic matter amended soil and 8.0 for the perlite and vermiculite amended soils. Phosphorous and micronutrients could be made unavailable at these pH levels (Tisdale et al. 1985, Smiley 1985).

Cation exchange capacity (CEC) ranged from 11 to 20 meq/100g (Table 1). The organic matter (33%) treatment was highest at 20 meq/100g, the unamended soil had a CEC of 17 meq/100g, the perlite (33%) and vermiculite (33%) amendments each had 15 meq/100g. The topsoil (100%) treatment had the lowest CEC at 11 meq/100g.

Total nitrogen ranged from a low of 466 ppm in the unamended soil to a high of 3150 ppm in the organic matter amended soil. The perlite amended soil was the next lowest with 748 ppm. The vermiculite amended soil had 1424 ppm, and the topsoil replacement had 1882 ppm.

There were three pounds of available phosphorous in the unamended soil the year prior to planting the trees. Phosphorous was tested using extraction by Bray Solution (Table 1). No fertilizer was applied to the site. Phosphorous levels of only one pound per acre were found in both the perlite and vermiculite amended soils, while the topsoil had fifty-six pounds per acre and the organic matter amended treatment had eleven pounds per acre.

Summary

1. There was no significant difference found in either root length or in root branching coefficients. There was high variability in the root data.

2. Soil bulk density tests found the vermiculite (33%), topsoil (100%), perlite (33%) and organic matter (33%) treatments to be within a range that is favorable to root growth for some species. See page 35. The test site

soil, and the unamended, processed treatment tested at or above the density that has been found to be restrictive.

3. Moisture was most available to plants in the organic matter and perlite treatments. The lowest amount of available water was in the test site soil and unamended control treatments.

4. Soil water, provided by hand irrigation, maintained an adequate level of soil moisture. The trees were not drought stressed. However, evaporation demand was approximately equal to the water supplied.

5. Air-filled porosity was highest in the organic matter (33%) treatment. Porosity was somewhat lower in the inorganic amended soils, but porosity was within recommendations provided in the literature. See page 29. Porosity in the test site soil, and in the unamended soil tested below recommendations.

6. The roots were found to have a nearly complete covering of suberized root hairs, and to have different root architectures throughout the system.

CHAPTER V: CONCLUSIONS AND DISCUSSION

This chapter is divided into three sections. The first section presents conclusions based upon the research project. The second section presents an experimental model of the project designed to address the problems encountered in the experiment conducted in 1988. The final section discusses implications for the practical application of the results of this research in conjunction with the research presented in the literature.

Conclusions

The project was designed to answer the question of whether root length in a compacted soil amended with an inorganic amendment would equal root length in the same soil amended with organic matter. By examining root length means in the different treatments, a distinct difference is demonstrated. Root length is greatest in the organic matter (33%) treatment, while in the perlite (33%) and topsoil (100%) treatments root lengths are a distant second and third respectively (Table 2).

However, there were no statistical differences among the treatments due to high variability. An example of the high variability can be seen in Appendix Table A-1. Root lengths in the OM treatment (second set of columns) ranges from 204 mm to 8592 mm, a forty two-fold difference.

Bohm (1979), indicates that high variability is common to root research. Persson (1979), found standard errors (SE) larger than means in root ingrowth from root-free cores. For Pinus sylvestris, the mean, in g m^{-2} was 22 (45 SE). Standard error was 45, larger than the mean. In the same study, large standard errors were found in Calluna vulgaris: mean 11 (7 SE), and in Vaccinium vitus-idaea: mean 16 (14 SE). Wagar (1985), found mulberry and Zelkova root/stem ratios with means of 0.9 (1.75 SE) and 0.2 (0.4 SE) respectively, both standard errors greater than means.

To be able to defend the conclusion that root growth is different among treatments, treatment effects must be sufficiently powerful to create a statistical difference in root growth. In first-year root growth of honeylocusts in amended, compacted soil, this is not the case, and therefore, sufficient evidence cannot be found to disprove the null hypothesis that root growth is equal among treatments.

The question arises concerning the adequacy of a first-year study compared to a multi-year study. A transplanted tree will die if a balanced root/shoot ratio cannot be re-established. Due to the loss of up to 95% of the root system (Watson 1984), a great amount of the loss must be made up the first year. This first-year study examines an important period in the growth of tree roots in compacted soil. A multi-year experiment is also necessary to both measure root growth and to monitor soil characteristics of the amended soil. It is valuable to measure root growth over time, allowing the root system to fully occupy the soil according to the genotypic responses to the particular soil environment. Variation should be reduced if roots more fully occupy the soil. The behavior of the amended soil, over time, is also a concern because evidence in the literature suggests that some soil amendments will deteriorate over time. Patterson (1976), found that sewage sludge, an organic amendment, did not maintain a favorable bulk density and porosity after a four-year period. At the end of the study, the sewage sludge amendment had little or no effect on soil porosity and bulk density. A multi-year study is detailed later in this chapter.

The second question for which the experiment was designed was to determine if root architecture would be different in a compacted soil amended with an inorganic amendment from root architecture in the same soil amended with organic matter. If the means of root branching coefficients are examined, distinct differences among the treatments can be observed. The root coefficient in the organic matter (33%) treatment was 26.4, and that in the control was 9.9 (Table 3). The root branching coefficient in the perlite (33%) treatment was nearly identical to that in the OM at 26.2. The root branching coefficient in the topsoil (100%) treatment was 12.4, while that in the vermiculite (33%) treatment was 13.4. If the means were considered without analysis of variance, it could be seen that the most frequently branched roots were those grown in the unamended control. The least frequently branched roots were those grown in the organic matter and perlite treatments. This was not the expectation, as the bulk of the literature, reviewed on pages 24 and 32, suggest that frequent branching is the result of higher fertility. However, Fitter (1977) suggested that a dense root system may be a searching mechanism invoked when the soil environment is dry or of low nutrient level. Neither conclusion can be drawn because there is not statistical evidence that there was a root response to fertility differences.

Variation was high, and may have masked treatment effects. Again, variation is typically high in root research, and the strength of the treatment effects may not have been sufficient to display significant differences. On the basis of the analysis of variance, the null hypothesis that the root coefficient will be equal among treatments can not be refuted.

Root branching coefficients are one method for studying root architecture. The adaptive significance of differences in root architecture needs more study, and continued research should produce refined methods. The method followed for this study has several problems that may have led to the high variation. First, the procedure did not adequately distinguish root tips broken off the main root, and branch stubs that might also be counted as a root tip. This duplication probably resulted in a higher count for root tips, and a resulting smaller root branching coefficient. Second, the root branching coefficient was based on length as a function of root weight. Some of the samples contained woody sections of roots 4 mm in diameter. These roots had infrequent lateral branches. Due to the greater weight, the samples yielded into a substantial length without side branches, and thus high root branching coefficients. An improved method of measurement of branching frequency is described later in this chapter in a discussion of a different experimental model.

An integral component of the experiment was soil porosity and density. It can be concluded from the soil tests, in conjunction with evidence presented in the literature, that in the first year the topsoil (100%), and perlite (33%) amendments can be recommended for compacted soils as better than or equal to an unamended compacted soil or a compacted soil amended with organic matter. On the basis of the physical and chemical tests alone, an interpretation might be that the OM treatment was the optimum medium. However, there is sufficient evidence that the porosity will decline and density increase within a period of four years.

The unamended soil treatment, processed through the mixer, resulted in a bulk density of 1.58 g cm^{-3} at the end of six months, which was slightly above the upper end of a desirable density for tree growth for pine (Zisa et al. 1980), and approaches that for other species. Craul (1985), stated that root growth was substantially reduced at 1.7 g cm^{-3}. It can be expected that continued settling over the winter and in the subsequent seasons could result in a bulk density that contributes to a reduction in root growth (Craul 1985, Patterson 1987). Therefore, using no amendment in a compacted soil is not recommended.

Vermiculite (33%), displayed an adequate porosity at 41.4%, and a bulk density of 1.4 g cm^{-3}. Vermiculite deteriorates rapidly, and a similar fate of increased density and decreased porosity following a certain period of time can be expected.

Perlite is the preferred inorganic amendment, since it has a desirable bulk density of 1.26 g cm^{-3}; moisture holding capacity higher than the compacted soil, 29% and 20% at 40 cm and 1/3 bar compared to 23.1% and 16.9%; and porosity of 11.9% and 19.8% compared to 6.1% and 12.3% of the compacted soil at 40 cm and 1/3 bar tension levels. The topsoil(100%) and perlite (33%) treatments both showed acceptable values of porosity and strength. Physically, both are similar, as bulk density of the topsoil, 1.38 g cm^{-3}, is within a favorable range of 1.25 to 1.50 g cm^{-3} (Maronek et al. 1985). At the lower tension ranges, the topsoil treatment contained slightly more air-filled pore space, 12.8% and 25.4% at the 40 cm and 1/3 bar tension levels compared to 11.9% and 19.8% respectively. Moisture retention was equal at 1/3 bar, at 20.7%, while at 40 cm tension topsoil contained 30.7% and the perlite treatment 29%. The topsoil treatment was the more fertile. Topsoil contains more nitrogen and phosphorous than the perlite amendment, 1883 ppm N and 11 ppm P compared to 748 ppm N and 0.5 ppm P. If replacement of the soil is practical, based upon the results of this experiment, topsoil is the recommended treatment. In a situation where amendment is the more practical, perlite should be chosen. Factors that affect the choice are discussed on page 96.

Proposed experimental model

Background

A different experimental model is proposed to answer additional questions and to provide refinement of the 1988 experiment. The model described below is designed with a greater number of replicates to reduce variation, and a multi-year period to address research questions that examine the extent of root growth and the architecture of roots over time.

Proposed field experiment

It is proposed that transplanted trees be grown in five soil treatments for four years. For the purpose of collecting baseline data, the trees will be grown and observed for two years prior to transplanting, and a block of trees remain at the nursery without transplanting. This latter block will be observed for the same period of time as the transplanted trees. Observations will be of both above ground and below ground portions of the trees. The treatments are an unamended compacted soil (100%), perlite (33%), coarse construction sand (50%), organic matter (33%), and topsoil (100%). Each treatment will be replicated five times. Thirty trees will be planted. Four minirhizotron tubes will be placed with each tree. The tubes will be placed in the soil around the trees for the two years prior to transplanting, and new tubes will be placed in the soil around the transplanted trees. Video-taped images will be recorded monthly during the growing seasons. Root lengths will be measured and recorded as a progression of growth through the season, and as a total seasonal growth (live minus dead roots). Root architecture will be studied by recording the distances between root branches. The experiment is designed as a split-split plot randomized block design in which the observations are split by monthly video tapings each year, and split over each of the four successive years. The baseline data collected from the trees prior to transplanting, and from the trees left in the nursery will be used with data collected from the transplanted trees in an analysis of covariance. Soil physical and chemical properties will be measured yearly. Coefficients of correlation will be made between length and branching distance, and bulk density, air-filled porosity, available nitrogen and phosphorous.

Research site

The area east of Baker Woodlot at Michigan State University has a large deposit of subsoil that has remained undisturbed for ten years. The subsoil is a relatively close approximation of a typical urban soil (Craul 1985). The soil is a sandy loam with approximately 50% sand, 25% clay and 25% silt. It has a bulk density of 1.92 g cm^{-3} as measured in four locations in 1988. A 50 m by 50 m area for tree planting will be cleared and graded to a uniform plane that slopes 5%. An adjacent area will be graded for the stockpiling of materials. This area will be located lower on the slope to prevent leaching from stockpiles into the test plots.

The trees in the plot on the research farms will be placed 8 m apart in five rows of five trees. Trees designated to remain at the nursery will also be spaced 8 m apart. The treatments will be randomly assigned to locations in the planting grid, and the trees will also be randomly assigned.

Each amended treatment will be prepared by mixing the amendment with existing soil excavated from the site in a soil mixer. Each tree will be planted in ten cubic meters of prepared treatment. The 1988 study used two cubic meters of soil for each tree. A broad mound with a shallow slope will be formed, into which the trees and minirhizotrons will be placed. The large volume of soil is necessary to reduce the effects of the interface of amended soil with the edge of the planting pit, and to permit yearly soil core sampling without interfering with root growth in the vicinity of the minirhizotrons. An erosion control fabric will be placed on the mound slopes in lieu of mulch. In a four year period, the decomposition of mulch could contribute mineral nutrients to the treatments.

The treatments were selected on the basis of the 1988 experiment and the literature. One treatment will be the unamended compacted soil. A one-third amendment was a standard ratio listed by several authors (Patterson 1976, Buley 1983, Cook and Dunsby 1978). Perlite will be one of the treatments. The porosity and density of the perlite

(33%) treatment used in 1988 were within a desirable range of 40 to 45% porosity and 1.3 to 1.6 g cm^{-3} (Patterson 1976). A second inorganic amendment will be sand. Due to the 50% sand component of the existing soil, a 50% sand amendment will be added to create a treatment that is 75% sand. Patterson (1987), states that a sand amended soil must be 75 to 85% sand to prevent compaction. Composted leaf mold will be the organic matter amendment. Using a composted amendment should avoid the problem of nitrogen depletion of the soil from using fresh organic matter (Tisdale et al. 1985). Topsoil will be the fifth amendment. This treatment is a sand, silt, clay and organic matter mixture processed by the MSU Grounds department. There is evidence from the 1988 study that the inorganic amended treatments were low in nutrients, and organic carbon that supports soil organisms. The organic matter content of the topsoil should supply these elements.

The tree selected for use in this experiment is the honeylocust. Honeylocust gained acceptance as an urban tree, and its adaptation to low oxygen soils may ensure the survival of the trees planted in the unamended control.

The minirhizotron tubes will be placed with the backfill as the trees are planted, one meter from the tree and slanted away at 30°C (Upchurch 1984). The lower end of each tube will be sealed to prevent the entry of moisture, and the top ends will be fitted with rubber stoppers to be removed for video taping. Calibration marks will be inscribed along the tubes to enable the identification of treatments, tube locations and depth of the soil profile. The exposed end of the tube will be painted to exclude light. Core samples will be made once a year to provide a calibration of root lengths observed in the minirhizotrons.

Soil nitrogen, total and nitrate, and phosphorous will be measured yearly. Yearly nitrate measurements can demonstrate the amount of leaching of soluble N.

Soil bulk density, air-filled porosity and volumetric moisture content will be measured yearly using soil cores at the surface, and at a depth of 50 cm.

Two tensiometers will be installed in each plant pit and at the nursery at each of two depths, 10 cm and 50 cm. Soil water potential will be monitored throughout the growing season.

A drip irrigation system will be installed so that a water supply can be monitored and balanced with evapotranspiration demands.

Proposed hypotheses

The first hypothesis was developed based upon the assumption that porosity and density are limiting factors, and that over a four year period, the treatments employing inorganic amendments will maintain adequate porosity and density and the control (unamended compacted soil) and organic matter amended soils will decline to the point of limiting root growth. One set of root images taken at the end of the fourth season should provide the evidence for analysis of this hypothesis. Periodic, interim data will enable determination of trends in root development, and gain a better understanding of rhizosphere dynamics. Root length is expected to be greatest in the organic matter and topsoil treatments in the first few years. By the fourth year, the organic matter is expected to be completely decomposed, and the differences in root length among treatments to have disappeared. The dependent variable is root length. Treatment and replication are the independent variables.

Null hypothesis number one: There is no difference in the length of root growth among the treatments following four years of growth.

Alternate hypothesis number one: The length of root growth in the organic matter or topsoil treatments will be greater following four years of growth.

The second hypothesis examines root architecture, and assumes from evidence presented in the literature that root branching is more frequent in more fertile, organic matter enriched soils. The question remains as to the significance of differences in root architecture. The distance between root branches that appear in video images will be measured and subjected to analysis of variance among treatments. The dependent variable will be length of branch spacing, and independent variables will be treatment and replication.

The null hypothesis number two: There is no difference in the length between root branches among treatments.

The alternate hypothesis number two: Root branching will be spaced more frequently in the organic matter and topsoil treatments.

Testing the first hypothesis is expected to reveal which of the treatments most favors root growth. Testing the second hypothesis is expected to determine whether a difference in branching frequency occurs among the treatments. Determining coefficients of correlations between root length and branching frequency, and soil physical and chemical factors is expected to provide some explanation of why the roots are responding in the observed manner.

Practical Applications

The results of the 1988 experiment, in concert with support from the literature, suggest a direction for further research and applications of inorganic amendments for compacted soils.

The choice of using topsoil or a perlite amendment depends upon factors not directly addressed in this experiment. The use of these two amendments is explored in the discussion that follows. However, a generalized recommendation covering a choice between these two treatments, and practical applications is of limited value due to variations in site conditions.

The two most frequent situations in which urban trees are planted are along streets in the narrow strip between the curb and the sidewalk, and in large areas of pavement. The planting strips are also called tree lawns. Examples of the second situation are urban plazas, parking lots and sidewalks that cover the entire space between the curb and the face of buildings facing the sidewalk. In planting strips, the exposed soil space can be a few feet to fifteen feet in width, but are most often about four to six feet. In the planting strip, amending the soil will probably be the more practical approach since soil is already in situ, and the available root zone area, and the soil volume could be quite large. In the paved plaza or wide sidewalk, construction will have removed or have damaged the structure of a large amount of soil, and replacement may be necessary or recommended.

Adding an amendment involves mixing the soil. This requires bringing machinery to the site. Mixing the soil can be done with a soil mixer or with a rototiller. Soil from the site could be placed into the mixer with the backhoe that does the excavation. A wide shallow hole can be dug, but the mound that results requires more than the soil removed from a level planting site, even with the additional volume created by the amendment. Alternatives include using some form of rototiller to mix the soil and amendment on the planting site, or mixing with a pick up and turn over motion of a front-end loader. Patterson (1976), incorporated amendments in situ with a rototiller.

If soil cannot be mixed at the site, consideration needs to be given to the type of replacement soil. This could be a loam topsoil, or a previously mixed soil of some specification. A judgment should be made based upon the availability of good topsoil, and of the cost to the operation of trucking in part of the soil used in a planting site, and the cost of hauling away the soil found at the site if a complete replacement was used. Naturally occurring topsoil may become unavailable for some municipalities because it is not a quickly renewable resource. Stockpiling topsoil may have some negative effects on soil biological properties which influence nutrient cycling and mycorrhizal infection (Stark and Redente 1987).

Any change in soil physical properties needs to be examined in light of potential soil interfaces. The porous medium in which a tree is grown forms one side of an interface when the rootball is placed in contact with existing compacted soil or the backfill soil. The backfill can form another interface with undisturbed soil outside the planting hole. With a large diameter planting hole, the interface is placed farther from the tree. As the diameter becomes greater, there is a smaller root restriction. The question of how large in diameter the planting hole should be was not directly faced by this experiment. The magnitude of the problem is addressed in the literature, and solutions that place the interface at the maximum practical distance from the plant are suggested. One approach is to plant in large, shared root-space planters containing amended existing soil or replacement soil. A second approach is to prepare wide, shallow planting pits. The latter is the approach used in this experiment. Both approaches try to increase the rooting potential in a broad, shallow volume of soil that reflects the normal rooting pattern of most trees.

The use of Gleditsia triacanthos in this experiment has both advantages and disadvantages. This species is used extensively in urban settings, making the experiment applicable to the needs and interests of urban foresters. It is also readily available, and relatively inexpensive. For this reason it is easier to fund and conduct the experiment. Some early successional trees are also better able to compete for soil nitrogen (Tilman 1986). A question arises as to how much of the success of the rooting of these trees, especially in the higher density soils, is due to the species. If this is the case, another species may display significant differences in root growth under the conditions of the experiment.

This experiment should be followed with one designed to address other trees that are used in urban settings. A few of the other genera that are used in urban sites, such as *Fraxinus* and *Platanus* are also adapted to low oxygen soils. For reasons of visual quality or survival under polluted conditions, several *Quercus*, *Acer*, and *Tilia* species and *Ginkgo* are considered highly desirable.

One purpose of follow-up experiments with other tree species should be to test them with a range of amendments and amendment/existing soil proportions. The above-mentioned trees will certainly grow better in a soil that has had the bulk density reduced from 1.9 g cm^{-3} to 1.3 g cm^{-3} so that improved growth and survival can be assumed. Both the topsoil and the perlite treatment have bulk densities in the 1.26 to 1.38 g cm^{-3} range, but the size of the aggregates in the soil are different. In the 1988 experiment, perlite granules ranged to about 4mm in diameter. Although the topsoil has a variety of component particle sizes, including small stones up to several centimeters across, aggregate size was finer and more uniform than the perlite. Pore sizes will be different, resulting in different relationships of capillary water and air-filled space. There may be a different root growth response among species to the differences in soil structure. Perlite is available in a variety of size grades (Perlite

Institute 1988), and the various grades should be considered for mixtures with soil.

Each of the soil treatments had a higher soil reaction than is generally found in the surface horizons of forest soils, and higher than recommended for ornamental trees. This reflects the subsoil origin of the soil used for 66% of amended treatments and all of the control. If compacted soil in an urban tree planting is to be amended, then the pH of the existing soil, and that of the amended soil needs to be tested and adjusted. Soil in such planting situations will likely increase in alkalinity due to alkaline water sources, and the weathering of masonry building materials. Adjustment of the pH to slightly below neutral will help promote nutrient ion absorption. The existing soil used in this experiment is too low in phosphorous and results in inorganic matter soil mixes that are low in phosphorous. Tisdale et al. (1985), suggest that 7 ppm in solution is adequate for most plant growth. This can be calculated the rate to be approximately 17 lbs/acre P in a 1.5 g cm^{-3} bulk density soil. Approximately 14 to 16 lbs/acre P needs to be added to the soil used in this experiment. Each planting soil needs to be tested for soil nutrients. Phosphorous needs to be incorporated into the backfill when it is mixed since phosphorous does not move readily in the soil.

Correcting the physical problems of high soil density and low porosity are possible with inorganic amendments.

However, a serious problem remains because the mix has few components that will readily break down into usable nutrients and does not provide organic material and energy for micro-organisms that contribute to mineralization and soil aggregation. The perlite amended soil contained less than 1% organic matter, and a low among the amended treatments of 748 ppm total nitrogen. Depending on the proportion of total nitrogen that is available for plant use, 748 ppm may be adequate nitrogen for the first few years of tree growth. Beyond that period, more nitrogen may be needed. Nursery production of ornamentals requires about 50 ppm of available N (Gillium 1982). Carbon is probably not adequate, and root mortality of the planted trees will probably accumulate organic matter very slowly, if at all. Higher temperatures of urban planting sites will cause a rapid breakdown of organic matter.

Further research should investigate carbon supplies for urban tree plantings. Sources could include mixing a small amount of organic matter into the soil with an inorganic amendment, mulching the soil yearly and allowing tree litter to accumulate. Organic matter, either mixed with the soil or applied as a mulch, should have a carbon:nitrogen ratio of no more than 20:1 to prevent nitrogen depletion of the soil (Tisdale et al. 1985). An organic amendment source should be readily available, wettable, and of a particle size that allows it to mix thoroughly in the soil. Peat moss could help reduce typically high soil reactions. However, peat moss is difficult to wet, expensive, and hard to mix with compacted soil (Kelly 1989). Patterson (1976), has used sewage sludge.

Due to the problem of compaction, documented in the literature, the proportion of organic matter should be smaller than the 33% used in this experiment. Trials using several mixtures need to be made. Proportions of the amendments would depend upon the texture of the soil being used as the base, and the size of the organic matter amendment and its degree of breakdown due to processing and length of composting.

Trees planted with spaced pavement blocks or tree grates over the soil have no provision for an organic matter layer. Trees planted in this manner will require a porous soil with good structural stability to prevent compaction from foot traffic and gravity. These trees would benefit from the perlite mix but would always need supplemental feeding. Positive drainage and an adequate water supply are also necessary. The soil in the backfill in this situation should not include any substantial organic matter.

Trees in various types of raised planters can be mulched. Leaf and twig litter could only accumulate in a planter having a large surface area. Permitting litter to accumulate in an urban setting also may require a program that distinguishes leaf litter from trash. Municipalities may have ready supplies of chipped or shredded wood from tree removal programs and leaf compost. Wood products can be useful mulches but unless composted require the addition of nitrogen. Leaf compost, the mulch and amendment used in this experiment breaks down more rapidly. This can be a benefit for the soil and the trees, but requires more frequent replacement, and is not an effective weed barrier (Borland and Weinstein 1989).

The concept of the large, shared root-space planter offers the opportunity to solve several problems that contribute to the stress of urban trees. A shared root-space planter is a planting bed that can accommodate more than one tree, and may also accommodate shrubs and groundcovers. Minimum dimensions are about five meters on a side, allowing at least twenty five square meters of surface area, or about 225 square feet. Various cities already plant trees in large planting beds in which the soil is level with the surrounding pavement, but the concept should include large beds with the sides raised 15 to 45 centimeters, and raised planters with the soil placed in a mound. See Figure 13 for an illustration of a shared root-space planter. This form of planter can limit soil compaction by elevating the surface above foot and vehicular traffic. Soil temperature extremes will be moderated by the large mass of soil. Surface water runoff containing salts can be directed around and not into the planting soil.

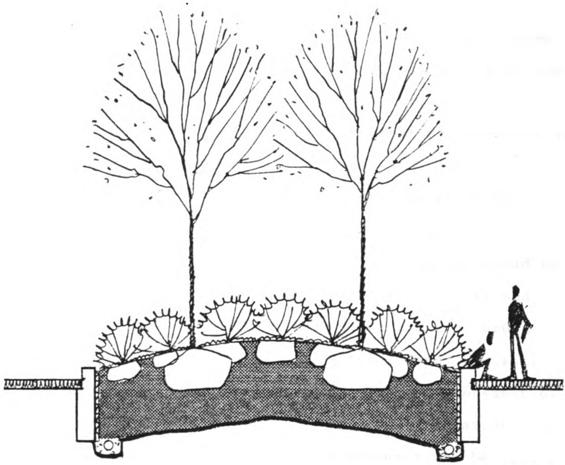

Figure 13. Shared root space planter within pavement showing raised edge, soil mass, and multiple plants. This is a section view, and is not drawn to scale.

Drainage can be more easily controlled than in a pit dug into the compacted ground. Mulch that is applied will not get scattered across the pavement. Leaf litter can be allowed to accumulate. A groundcover or small shrub layer would add additional organic matter from root mortality and leaf drop, and would help shade the soil surface. A groundcover layer would also help stop erosion of mulches or leaf litter on a mounded surface.

Root production is vital to the development of the whole tree, but baseline data on root growth and root turnover is almost non-existent. This information would be helpful in assessing the effects of temperature, air and water pollution and soil structure on the roots of urban trees. Soil temperatures, air and water content and soil structure are influenced by the dimensions and placement of the pits into which urban trees are placed. Variations in the dimensions and forms of planting spaces could be tested to determine the effects on the plant and on the soil biological community.

The trees in this experiment were planted in shallow holes to raise as much of the rootball above a potential saturation zone as possible. The result is a tree growing in a steep-sided mound that looks unusual. Mulch was constantly washing from the sides of the mound leaving the bare soil to erode in a heavy rain. The size and shape of mound used also results in a small soil volume for the tree to extend roots. Each of the mounds contained approximately two cubic meters of soil treatment. Planting the trees on a raised soil platform was probably instrumental in keeping the trees alive and insured the completion of the experiment. Three empty, unused holes dug on the site filled with water following each rain and remained filled for more than a week at a time. It is likely that the trees in the experiment would have died from drowning had they been planted flush with the ground surface as is normal in such situations. The small mounds are not suitable for an extended experiment. The soil volume is much less than a tree expected to grow toward maturity would require to supply water and nutrients, and soil sampling takes a large enough proportion of the soil that the integrity of the root zone will be a problem if sampling were to continue in subsequent years. A much larger mound should be used, although this requires more amendment materials and more time in preparation.

A raised planter is not the answer to trying to grow trees in lawn areas along streets in residential areas. The planter could get in the way of circulation between the street and the sidewalk. When compaction is severe, with a bulk density above 1.7 g cm^{-3}, an inorganic amendment should be incorporated into the top 30 cm of the soil and a low mound created over as large an area as possible. A lawn can be planted over part of the mound, except close to the tree.

If a mound is not possible, and the bulk density is high, no tree should be planted. With a bulk density between 1.7 g cm^{-3} and 1.3 g cm^{-3}, a species tolerant to low oxygen soils should be planted. Gleditsia triacanthos var. inermis 'Shademaster', used in this experiment is an example.

The video imaging of roots from inside minirhizotrons remains a technology that has applications to follow-up research to this experiment. Refinements in both the hardware and the analysis software continue to be made and will allow more consistent and reliable results. The minirhizotron is useful in answering questions about the dynamics of roots over time. Urban environments provide stresses that may manifest changes in roots that could be observed and quantified in time periods within seasons and over multiple seasons.

APPENDIX

Table A 1. Root length, in millimeters, sorted by treatment and listed by core sample. 1988

tree loc	trmt	root length	tree loc	trmt	root length	tree loc	trmt	root length	tree loc	trmt	root length	tree loc	trmt	root length
		mm			mm			mm			mm			mm
r1t3a	cl	174	r1t4b	om	204	r1t1b	pl	95	r3t1c	ts	247	r4t3b	vm	338
r4t7c	cl	399	r1t4c	om	295	r2t6c	pl	334	r2t3c	ts	265	r2t4d	vm	382
r3t3a	cl	477	r2t5d	om	412	r3t4c	pl	365	r2t2d	ts	486	r2t4b	vm	438
r3t3d	cl	538	r4t4d	om	538	r2t6b	pl	477	r3t1d	ts	529	r4t1d	vm	568
r1t3b	cl	655	r4t2c	om	629	r1t2a	pl	503	r2t3d	ts	551	r4t3c	vm	590
r4t6d	cl	690	r1t4a	om	694	r1t2b	pl	508	r2t2c	ts	581	r2t7a	vm	651
r3t3b	cl	803	r4t2a	om	1089	r1t1d	pl	560	r2t2b	ts	642	r3t2d	vm	681
r1t3d	cl	894	r2t1b	om	1133	r2t6a	pl	564	r3t5b	ts	907	r4t3a	vm	772
r4t6c	cl	898	r4t4b	om	1293	r1t2c	pl	751	r3t1a	ts	924	r2t3c	vm	798
r3t7b	cl	916	r2t5c	om	1302	r3t4d	pl	885	r4t5d	ts	933	r4t1a	vm	803
r3t3c	cl	929	r2t5b	om	1315	r3t4a	pl	1271	r2t3b	ts	1107	r4t1b	vm	829
r4t7d	cl	1007	r1t4d	om	1458	r1t1a	pl	1575	r4t5a	ts	1306	r3t2b	vm	851
r1t3c	cl	1076	r4t2b	om	1501	r2t6d	pl	1831	r4t5c	ts	1445	r2t4a	vm	933
r4t7a	cl	1306	r2t1d	om	1896	r1t2d	pl	2105	r2t3a	ts	2087	r4t3d	vm	1198
r4t7b	cl	1953	r2t1a	om	2500	r3t6b	pl	2139	r3t5a	ts	2157	r2t7c	vm	1332
r3t7d	cl	2270	r4t4a	om	2630	r3t6d	pl	2864	r2t2a	ts	2482	r3t2a	vm	1475
r4t6a	cl	2330	r2t5a	om	4500	r1t1c	pl	2877	r3t1b	ts	2773	r2t4c	vm	1519
r4t6b	cl	2400	r2t1c	om	5155	r3t6c	pl	3311	r3t5c	ts	2916	r2t7b	vm	1545
r3t7c	cl	2543	r4t4c	om	7390	r3t4b	pl	3615	r4t5b	ts	3979	r4t1c	vm	2343
r3t7a	cl	3571	r4t2d	om	8592	r3t6a	pl	6053	r3t5d	ts	4635	r2t7d	vm	2721

Treatments: cl = unamended soil; om = soil amended with 1/3 leaf mold; pl = soil amended with 1/3 perlite; vm = soil amended with 1/3 vermiculite; ts = replacement with loam topsoil.

Tree locations are listed by r = row number; t = tree number; and a - d = core sample.

Table A 2. Root branching coefficients, sorted by treatment and listed by cores. 1988

Tree	trmt	coef	Tree	trmt	coef	Tree	trmt	coef	Tree	trmt	coef	Tree	trmt	coef
		mm			mm			mm			mm			mm
r4t7c	cl	4.2	r1t4b	om	1.6	r1t1b	pl	3	r3t1d	ts	4.1	r4t3b	vm	3
r4t3a	cl	4.4	r1t4c	om	3.7	r2t6a	pl	3.5	r3t1c	ts	4.2	r2t4d	vm	3.5
r3t3c	cl	4.5	r1t4a	om	5.5	r2t6c	pl	3.7	r4t5d	ts	4.4	r4t3d	vm	4.3
r4t6d	cl	4.6	r4t2b	om	5.8	r2t6b	pl	4	r2t3c	ts	4.6	r3t2b	vm	4.6
r3t3d	cl	4.8	r4t2a	om	5.8	r3t4c	pl	4.3	r3t5b	ts	5.2	r4t3c	vm	4.9
r1t3d	cl	4.8	r2t1b	om	6.1	r1t1d	pl	4.6	r4t5a	ts	7.8	r3t2a	vm	5.5
r1t3a	cl	5.3	r4t2c	om	6.4	r1t2c	pl	5.4	r2t3b	ts	9.4	r2t4b	vm	5.6
r4t7d	cl	6.6	r4t4d	om	7	r3t4d	pl	6.4	r2t2b	ts	9.6	r4t3a	vm	5.8
r1t3b	cl	6.8	r4t4b	om	8.7	r3t4a	pl	6.4	r3t1a	ts	10.2	r3t2d	vm	6.1
r1t3c	cl	7	r1t4d	om	8.7	r1t1a	pl	7.2	r2t3d	ts	11.2	r3t2c	vm	7
r4t6c	cl	7.2	r4t4a	om	11.1	r1t2b	pl	8.1	r2t3a	ts	11.5	r4t1a	vm	8.2
r3t3b	cl	7.4	r2t5c	om	15.9	r1t2a	pl	11	r2t2c	ts	11.6	r2t4c	vm	10.7
r4t7a	cl	10.4	r4t4c	om	17	r2t6d	pl	13.7	r2t2d	ts	12.2	r2t7a	vm	11.4
r3t7b	cl	10.9	r2t5b	om	17.3	r1t2d	pl	15.7	r3t5a	ts	12.5	r2t7b	vm	11.5
r4t7b	cl	11.2	r2t1d	om	21	r3t4b	pl	20.3	r4t5b	ts	14.5	r4t1b	vm	12.7
r3t7d	cl	16.2	r4t2d	om	25.5	r1t1c	pl	33.5	r3t5c	ts	14.8	r4t1d	vm	20.3
r4t6a	cl	16.8	r2t5a	om	30.8	r3t6c	pl	34.9	r4t5c	ts	18.1	r2t7c	vm	26.6
r3t7c	cl	19.9	r2t5d	om	45	r3t6b	pl	40.4	r3t5d	ts	19.2	r4t1c	vm	31.2
r3t7a	cl	21	r2t1c	om	48.6	r3t6d	pl	130.2	r3t1b	ts	22.9	r2t7d	vm	36.8
r4t6b	cl	25	r2t1d	om	237	r3t6a	pl	168.2	r2t2a	ts	40	r2t4a	vm	49.1

Coefficient = length of roots in core sample/number of root tips.

Treatments: cl = unamended soil; om = soil amended with 1/3 leaf mold; pl = soil amended with 1/3 perlite; vm = soil amended with 1/3 vermiculite; ts = replacement with loam topsoil.

Tree locations are listed by r = row number; t = tree number; and a - d = core sample.

Table A 3. Root length, by core, sorted by treatment and by tree. Length is in millimeters. 1988

tree loc	trmt	root length	tree loc	trmt	root length	tree loc	trmt	root length	tree loc	trmt	root length	tree loc	trmt	root length
		mm			mm			mm			mm			mm
r1t3a	cl	174	r1t4a	om	694	r1t1a	pl	1575	r2t2a	ts	2482	r2t4d	vm	382
r1t3b	cl	655	r1t4b	om	204	r1t1b	pl	95	r2t2b	ts	642	r2t4a	vm	933
r1t3c	cl	1076	r1t4c	om	295	r1t1c	pl	2877	r2t2c	ts	581	r2t4b	vm	438
r1t3d	cl	894	r1t4d	om	1458	r1t1d	pl	560	r2t2d	ts	486	r2t4c	vm	1519
r3t3a	cl	477	r2t1a	om	2500	r1t2a	pl	503	r2t3a	ts	2087	r2t7d	vm	2721
r3t3b	cl	803	r2t1b	om	1133	r1t2b	pl	508	r2t3b	ts	1107	r2t7a	vm	651
r3t3c	cl	929	r2t1c	om	5155	r1t2c	pl	751	r2t3c	ts	265	r2t7b	vm	1545
t3t3d	cl	538	r2t1d	om	1896	r1t2d	pl	2105	r2t3d	ts	551	r2t7c	vm	1332
r3t7a	cl	3571	r2t5a	om	4500	r2t6a	pl	564	r3t1a	ts	924	r3t2c	vm	798
r3t7b	cl	916	r2t5b	om	1315	r2t6b	pl	477	r3t1b	ts	2773	r3t2a	vm	1475
r3t7c	cl	2543	r2t5c	om	1302	r2t6c	pl	334	r3t1c	ts	247	r3t2b	vm	851
r3t7d	cl	2270	r2t5d	om	412	r2t6d	pl	1831	r3t1d	ts	529	r3t2d	vm	681
r4t6a	cl	2330	r4t2a	om	1089	r3t4a	pl	1271	r3t5a	ts	2157	r4t1a	vm	803
r4t6b	cl	2400	r4t2b	om	1501	r3t4b	pl	3615	r3t5b	ts	907	r4t1b	vm	829
r4t6c	cl	898	r4t2c	om	629	r3t4c	pl	365	r3t5c	ts	2916	r4t1c	vm	2343
r4t6d	cl	690	r4t2d	om	8592	r3t4d	pl	885	r3t5d	ts	4635	r4t1d	vm	568
r4t7a	cl	1306	r4t4a	om	2630	r3t6a	pl	6053	r4t5a	ts	1306	r4t3a	vm	772
r4t7b	cl	1953	r4t4b	om	1293	r3t6b	pl	2139	r4t5b	ts	3979	r4t3b	vm	338
r4t7c	cl	399	r4t4c	om	7390	r3t6c	pl	3311	r4t5c	ts	1445	r4t3c	vm	590
r4t7d	cl	1007	r4t4d	om	538	r3t6d	pl	2864	r4t5d	ts	933	r4t3d	vm	1198

Treatments: cl = unamended soil; om = soil amended with 1/3 leaf mold; pl = soil amended with 1/3 perlite; vm = soil amended with 1/3 vermiculite; ts = replacement with loam topsoil.

Tree locations are listed by r = row number; t = tree number; and a - d = core sample.

Table A 4. Root branching coefficients listed by core, and sorted by treatment and by tree. 1988

Tree	trmt	coef	Tree	trmt	coef	Tree	trmt	coef	Tree	trmt	coef	Tree	trmt	coef
r1t3a	cl	5.3	r1t4a	om	5.5	r1t1a	pl	7.2	r2t2a	ts	40	r2t3c	vm	49.1
r1t3b	cl	6.8	r1t4b	om	1.6	r1t1b	pl	3	r2t2b	ts	9.6	r2t4a	vm	5.6
r1t3c	cl	7	r1t4c	om	3.7	r1t1c	pl	33.5	r2t2c	ts	11.6	r2t4b	vm	10.7
r1t3d	cl	4.8	r1t4d	om	8.7	r1t1d	pl	4.6	r2t2d	ts	12.2	r2t4c	vm	3.5
r3t3a	cl	4.4	r2t1a	om	6.1	r1t2a	pl	11	r2t3a	ts	11.5	r2t4d	vm	11.4
r3t3b	cl	7.4	r2t1b	om	48.6	r1t2b	pl	8.1	r2t3b	ts	9.4	r2t7a	vm	11.5
r3t3c	cl	4.5	r2t1c	om	21	r1t2c	pl	5.4	r2t3c	ts	4.6	r2t7b	vm	26.6
t3t3d	cl	4.8	r2t1d	om	237	r1t2d	pl	15.7	r2t3d	ts	11.2	r2t7c	vm	36.8
r3t7a	cl	21	r2t5a	om	30.8	r2t6a	pl	3.5	r3t1a	ts	10.2	r2t7d	vm	5.5
r3t7b	cl	10.9	r2t5b	om	17.3	r2t6b	pl	4	r3t1b	ts	22.9	r3t2a	vm	4.6
r3t7c	cl	19.9	r2t5c	om	15.9	r2t6c	pl	3.7	r3t1c	ts	4.2	r3t2b	vm	7
r3t7d	cl	16.2	r2t5d	om	45	r2t6d	pl	13.7	r3t1d	ts	4.1	r3t2d	vm	6.1
r4t6a	cl	16.8	r4t2a	om	5.8	r3t4a	pl	6.4	r3t5a	ts	12.5	r4t1a	vm	8.2
r4t6b	cl	25	r4t2b	om	5.8	r3t4b	pl	20.3	r3t5b	ts	5.2	r4t1b	vm	12.7
r4t6c	cl	7.2	r4t2c	om	6.4	r3t4c	pl	4.3	r3t5c	ts	14.8	r4t1c	vm	31.2
r4t6d	cl	4.6	r4t2d	om	25.5	r3t4d	pl	6.4	r3t5d	ts	19.2	r4t1d	vm	20.3
r4t7a	cl	10.4	r4t4a	om	11.1	r3t6a	pl	168.2	r4t5a	ts	7.8	r4t3a	vm	5.8
r4t7b	cl	11.2	r4t4b	om	8.7	r3t6b	pl	40.4	r4t5b	ts	14.5	r4t3b	vm	3
r4t7c	cl	4.2	r4t4c	om	17	r3t6c	pl	34.9	r4t5c	ts	18.1	r4t3c	vm	4.9
r4t7d	cl	6.6	r4t4d	om	7	r3t6d	pl	130.2	r4t5d	ts	4.4	r4t3d	vm	4.3

Coefficient = length of roots in core sample/number of root tips.
Treatments: cl = unamended soil; om = soil amended with 1/3 leaf mold; pl = soil amended with 1/3 perlite; vm = soil amended with 1/3 vermiculite; ts = replacement with loam topsoil.
Tree locations are listed by r = row number; t = tree number; and a - d = core sample.

Table A 5. Soil bulk density, sorted by treatments. Bulk density is Pb, in grams per cubic centimeters. 1988

core	trmt	Pb g/cm3	core	trmt	Pb g/cm3	core	trmt	Pb g/cm3	core	trmt	Pb g/cm3	core	trmt	Pb g/cm3	core	trmt	Pb g/cm3
405	ns	1.96	441	cl	1.63	103	om	1.1	435	pl	1.37	443	ts	1.29	430	vm	1.5
408	ns	1.87	420	cl	1.51	124	om	1.2	445	pl	1.27	468	ts	1.27	122	vm	1.38
407	ns	1.84	421	cl	1.36	425	om	1	403	pl	1.69	455	ts	1.39	651	vm	1.44
406	ns	2	429	cl	1.73	466	om	0.89	664	pl	1.17	668	ts	1.36	656	vm	1.69
			417	cl	1.65	456	om	1.28	404	pl	1.36	460	ts	1.08	116	vm	1.26
avg		1.92	424	cl	1.63	660	om	1.04	415	pl	1.09	115	ts	1.43	658	vm	1.48
			449	cl	1.68	454	om	0.78	670	pl	1.52	446	ts	1.52	470	vm	1.41
			422	cl	1.27	655	om	1.01	402	pl	0.85	471	ts	1.46	427	vm	1.61
			440	cl	1.35	457	om	0.93	675	pl	1.32	672	ts	1.4	469	vm	1.27
			467	cl	1.68	101	om	0.96	426	pl	1.42	474	ts	1.2	653	vm	1.48
			410	cl	1.39	461	om	1.02	418	pl	0.97	444	ts	1.35	111	vm	1.28
			439	cl	1.63	654	om	1.25	665	pl	1.22	475	ts	1.5	428	vm	1.51
			434	cl	1.53	666	om	1.18	413	pl	0.99	459	ts	1.48	102	vm	1.37
			438	cl	1.55	401	om	0.89	669	pl	1.11	120	ts	1.45	659	vm	1.11
			432	cl	1.75	412	om	1.1	667	pl	1.29	463	ts	1.46	465	vm	1.61
			419	cl	1.53	125	om	1.08	436	pl	1.5	663	ts	1.45	652	vm	1.2
			437	cl	1.77	462	om	1.17	416	pl	1.23	110	ts	1.36	661	vm	1.36
			450	cl	1.6	105	om	0.81				671	ts	1.34	657	vm	1.53
			433	cl	1.68	458	om	1.84				448	ts	1.36	464	vm	1.08
			411	cl	1.71	414	om	0.77				662	ts	1.38	107	vm	1.35
			avg		1.58	avg		1.07	avg		1.26	avg		1.38	avg		1.40

Note: ns = the soil as it occurred on the site; cl = the unamended soil that was passed through the mixer; om = soil mixed with 33% leaf mold; pl = soil mixed with 33% perlite; vm = soil mixed with 33% vermiculite; and ts = 100% replacement with topsoil.

Table A-6. ANOVA of root length. 1988

SOURCE	DF	SUM OF SQUARES	MEAN SQUARES	F	P>F
blocks	19	40143713	2112827	0.99	.5
treatments	4	15861459	3965365	1.86	.12
error	76	1.624E+08	2136920		
Total	99	2.184E+08			

Table A-7. ANOVA of root branching coefficients. 1988

SOURCE	DF	SUM OF SQUARES	MEAN SQUARES	F	P>F
blocks	19	16080.7	846.35	0.85	.66
treatments	4	5094.28	1273.57	1.28	.27
error	76	75868.4	998.27		
Total	99	97043.3			

Table A-8. Shoot growth means, in centimeters, and standard deviations of Gleditsia triacanthos var. inermis 'Shademaster' grown in five soil treatments. 1988.

Treatment	Means	Standard deviation
Unamended	28.6	8.9
Organic matter	24.1	9.8
Perlite	25.9	6.6
Vermiculite	26.6	9.3
Topsoil	23.8	10.4

Table A-9. ANOVA OF Gleditsia triacanthos var. inermis 'Shademaster' first season shoot growth. 1988.

Source	df	SS	MS	F
Total	24	1733.97		
treatment	4	76.29	19.07	.23
error	20	1657.68	82.88	

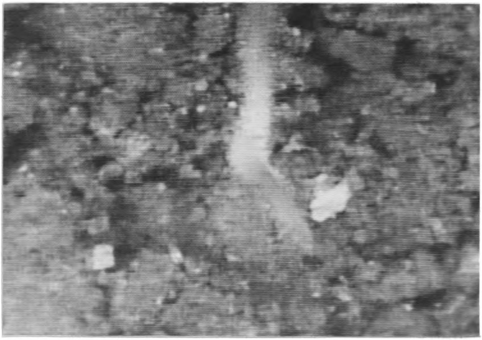

Figure A 1. New white root and root hairs growing in vermiculite amended treatment. Roots are observed via a minirhizotron with a video camera. Photograph represents an image size of 17.4 by 11.6 mm.

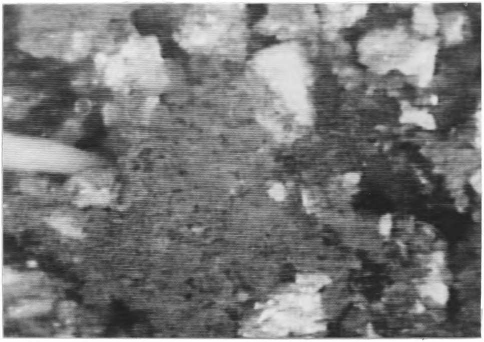

Figure A 2. Root tips shown growing into a macropore in soil amended with perlite. Photograph represents an image size of 17.4 by 11.6.

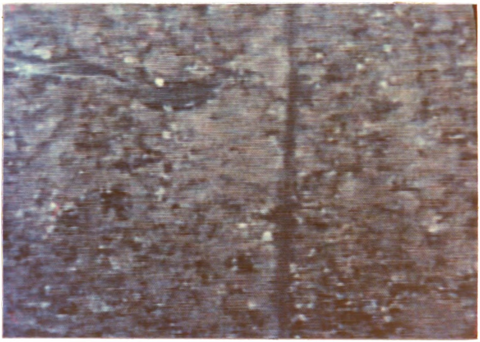

Figure A 3. Roots growing in topsoil treatment. Vertical root is older, with a dark, thickened epidermis. Newer root is growing in from the left by following an existing channel. Photograph represents an image size of 17.4 by 11.6 mm.

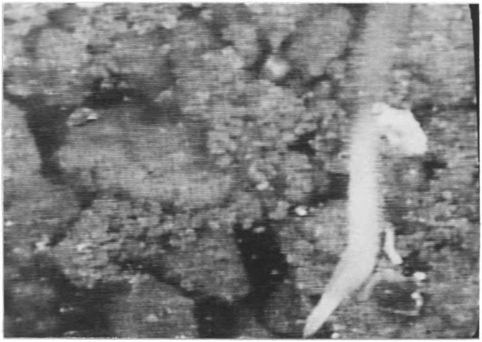

Figure A 4. Root growing in an organic matter amended treatment. Photograph shows new root tip with root hairs on both white root behind tip and on suberized section farther from tip. Photograph represents an image size of 17.4 by 11.6 mm.

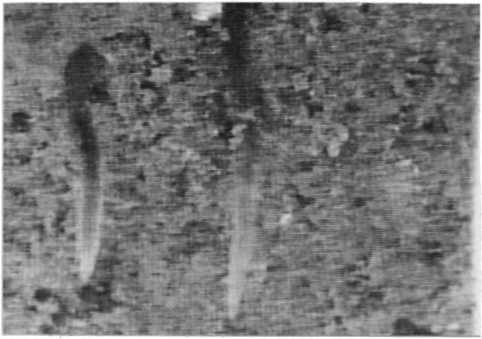

Figure A 5. New roots growing in unamended soil treatment. Shown are growing root tip and suberized section behind tip. These roots are pushing the soil aside and not growing into existing channels, requiring a higher rate of respiration.

Figure A 6. Roots excavated from perlite amended soil in April 1989. Close-up photo shows the rare absence of root hairs. These roots range from 1 mm to 3 mm in diameter.

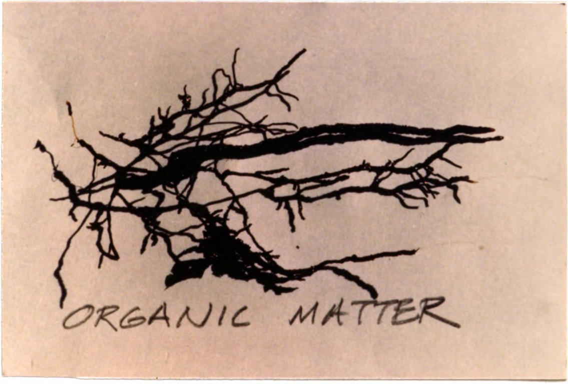

Figure A 7. Photograph of roots grown in the organic matter amended treatment, excavated in September 1988. Roots are toughened and covered with root hairs. Branches exhibit two orders of laterals.

Figure A 8. Photograph of roots grown in the vermiculite amended treatment, excavated in September 1988. Roots show root hairs and only one order of lateral branches.

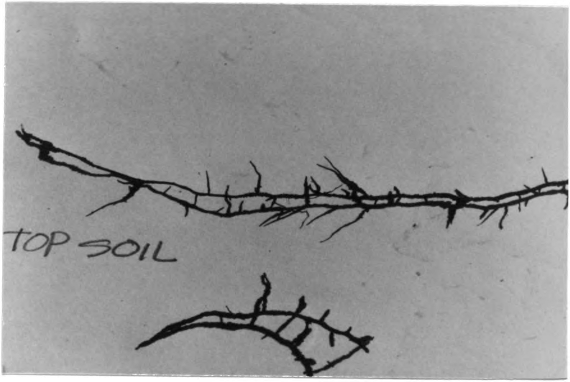

Figure A 9. Photograph of roots growing in the topsoil treatment, excavated in September 1988. Branches show only one order of lateral.

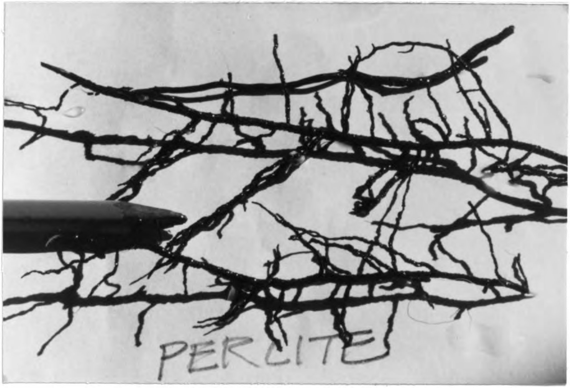

Figure A 10. Photograph of roots grown in the perlite amended treatment, excavated in September 1988. Roots are covered with root hairs and branches show two orders of laterals.

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