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Ecology of tree roots in substrates of The Hague

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ABSTRACT

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The ecology of uniformly and non-uniformly distributed roots in layered and/or heterogeneous substrates, especially sand-peat-clay mixes, have been studied from literature and through a case study. There is a strong interaction between soil layering and/or heterogeneity and local root growth and local branching rate. In principle, the minimum area of root surface that a plant needs is very low. Real situations have much higher root surface areas for several reasons, one being the absence of synchronisation and synlocation of supply and demand of nutrients and water. Physical substrate condition is a balance between structure building factors (like growth of roots and drying) and structure degenerating factors (like softening, decrease of organic matter content, leakage, podsolisation). It may be possible that a substrate that initially has good physical/chemical properties degenerates into poor structureless sand in the course of time. The case study concerned changes in 26-years and 2-years periods. The study considered Cation Exchange Capacity (CEC) and water repellency. Substrates which are very sandy and high in organic matter may be susceptible to water repellency when they dry to low water contents.

Keywords: tree roots, root ecology, tree soil mix, substrate, soil degeneration, nutrition, cation exchange capacity CEC, water repellency, hydrophoby

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Contents

Preface

Planting trees in the infrastructure of highly urbanised towns in The Netherlands is not easy within the framework of various claims that are put on above and below ground space. Already since several decades there has been an increasing interest in the development and use of soil mixtures that would suit both the urban forester –healthy growing trees-, and the urban civil engineer –minor tree root problems with pavements-.

Since about 1970 researchers from some Wageningen research institutes: ICW, Stiboka and De Dorschkamp (that all gradually merged into Alterra during the course of time), started to develop the so called Amsterdam soil mixture, in corporation with the municipal green service of Amsterdam. This mixture was suitable for tree planting purposes, but also as a foundation for pavings of sidewalks, bicycle roads and parking lots, because of its positive load bearing capacities. During the following years these mixtures has been increasingly used by many municipalities while some of them made their own adjustments and modifications to the mixtures. Although trees would thrive well in such mixtures, it occasionally turned out that root development was not according expectation and that the fundamental backgrounds for the variety of rooting patterns that were observed and that were not or only partly studied and understood.

It was our luck to get in contact with Ljuba Arhipova from the Moscow State University who was very interested to perform such a study. And it was more than a coincidence to meet Jos Koolen again -after his retirement as senior scientist from Wageningen University- and to hear of his willingness to coach Ljuba in her research. Jos did many work on soil mechanical aspects of tree soils and already had good contacts with researchers on urban trees of the Moscow State university, among other things within the framework of the corporation between The Netherland Organization for Scientific Research (NWO) and the Russian Foundation for Basic Research (RFBR).

We also highly appreciate the willingness of Evert Ros of New York Boomadvies to assist Ljuba with the excavations and observations in the field. Evert was one of the persons who stood at the cradle of the Amsterdam tree soil. during the time he worked at the Amsterdam municipal green service.

This study was made possible by a financial contribution of the City Management Department of the municipality of The Hague to which we also express our appreciation and in particular to Leendert Koudstaal for his support.

The Landscape Centre of Alterra, i.c. the team Management of Forest, Nature and Urban Green provided the office facilities and part of the technical facilities and support.

It's beyond doubt that with this study a substantial contribution is presented in revealing many questions around tree root ecology in the urban environment and tree root behaviour in artificial soil mixtures in particular.

Joop Spijker (teamleader Management of Forest, Nature and Urban Green)
Jitze Kopinga (sr. researcher arboriculture and urban forestry)

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Many thanks to my supervisor Jos Koolen for skilful research assistance, for his help in carrying out of experiments and delivering technical information during our work. Also many thanks to the landscape Center of Alterra, especially to Joop Spijker and Jitze Kopinga and Evert Ros from New York Boomadvies for opportunity to study this project and for technical assistance.

Summary

Although rooted soil volumes have been studied intensively, many questions still remain. It especially holds true for heterogeneous soil – root systems. Tree soil mixtures are, by definition, heterogeneous. This report concerns a literature study and a case study that both aimed at finding interesting relevant information on the ecology of roots in heterogeneous growing media.

Literature study

- Substrates that have degenerated into sands with little organic matter and poor structure may have poor aeration even at air-filled porosities up to 20 %. In agricultural research, penetrometer resistance is considered to be a poor indicator of mechanical impedance of root growth.
- Several researchers studied local spacing and number of root laterals as affected by local soil compaction and local soil fertility. Unfortunately, observed tendencies are not omnipresent. The most common response to higher nutrient availability is increased root growth rate and root branching rate. It is often associated with reduced growth of parts of the same root system located where nutrients are scarce.
- The complex fertilizer "APION" ("automatic nutrition osmotic pump") has been developed in Russia. It consists of small bags: batches of 3-200 g fertilizer (always 18: 6:18). Rate of nutrients release can be chosen. Maximum operation duration, also for N, is 2 growing seasons. A proper application of APION may promote synchronization and synlocation of nutrients and water supply and nutrients and water demand.
- The uptake rates of a unit of root surface for nutrients and water have maxima. These maximum uptake rates are physiologically based. The maximum uptake rates of a root surface unit can be combined with the necessary uptake rates for plant growth and maintainance, in order to find the minimum total root surface that is needed. This minimum is surprisingly low, implying that, in priciple, the amount of substrate could be very low. Real situations have much higher values. Reasons are: absence of synchronization and synlocation; storage of water and nutrients per unit of substrate volume is limited; speed of transport of water and nutrients through the substrate may be limiting; root growth also depend on the genetic properties of a plant.
- Soils that are very loose have poor root-soil contact, which increases the path lengths that nutrients and water have to travel before they reach root surface.
- A widely accepted plant growth model for a root zone consisting of several layers predicts that water stress in one of the rooted layers is not compensated for by an increase of water uptake from other layers. It means that the instantaneous response of the tree on this water stress is: growth reduction. This reduction is larger when the root content in this layer is, relatively, larger. The tree can only respond by increasing root growth in layers without or with less water stress.
- In moist conditions, the wetted fraction of a root-peat interface is larger than the wetted fraction of a root-clay interface. In dry conditions, the wetted fraction of a root-peat interface is smaller than the wetted fraction of a root-clay interface. In

mixtures with peat and clay, like the The Hague mixture, roots likely prefer to grow where their interface can be most wet. It enhances their water and nutrients uptake the most.
- Bacteria, fungi, and roots all contribute to the formation of soil structure. At similar water content levels under laboratory conditions, the structure-building effect of roots appeared to be by far the largest, simply because root dimensions are by far the largest. In practice, this beneficial effect of roots even more dominates, because roots have the capacity to dry soil to very low water contents efficiently.
- The cation exchange capacity, CEC, of a mixture is an important parameter reflecting the soil's capacity to buffer nutrient and other ions. Basically, the CEC of a mixture can be calculated from the CEC-values of the components of the mixture. Unfortunately, CEC of components like organic matter and clay minerals vary over wide ranges, and cannot be predicted easily without measuring.
- The cone penetration resistance of homogeneous sandfills increases with depth, despite the homogeneity of the sand. The rate of this increase is a measure of the compaction degree of the sandfill.
- Water repellency may affect water regime of soils. High organic matter contents, absence of fine mineral particles, and frequent drying to low water contents may be dangerous.

A case study concerned a paved square with *Tilia* x *europaea*, which was installed on the roof of an underground parking garage in 1981. The substrate is so-called The Hague tree sand. It is composed of sand, peat soil, and clay soil. In April, 2005, a special experimental procedure was initiated in order to be able to collect data on the changes with time of the chemical/physical composition of substrates. Perforated bags from nylon were installed in the root zone of a tree. These bags contained different substrates. Duplicates were stored in a deep-freezer. On February 21 of 2007, the deep-frozen bags were taken out of the deep-freezer and the buried bags were taken out of the root zone of the tree. At the same day, undisturbed core samples and loose soil samples were taken from this root zone. The results of the chemical analyses were compared with Russian and Dutch standards.
- The research site had low values for organic matter, CEC, P, K, Mg. The research site was constructed in 1981. It could be deduced that the decomposition rate of the organic mater was rather normal in the past. It implies that the oxygen contents in the past were above 10 % for a long time.
- The clay soil aggregates and peat soil lumps were severely softened. It is connected with the continuously wet state of the profile and the absence of the structure-promoting influence of roots. It may be speculated that the balance between structure building factors (root action, drying, etc.) and structure degenerating factors (softening etc.) shifted towards degeneration because of the low rooting intensity and/or excessive structure degeneration in the early stage of the tree growth. This low rooting intensity may have been connected with the relatively large ratio between substrate volume and tree canopy size. Excessive structure degeneration may have been connected with a low structure stability of the clay soil and/or peat, and/or wet conditions inducing softening.
- The values of porosities and air contents were unexpectedly high, and seem, at first sight, in conflict with high penetration resistance and low oxygen content measured

at earlier surveys. But high porosities with high air contents can go together with low oxygen contents in case of sandy soils lacking structure. Root growth could ameliorate such bad physical conditions, but root growth is concentrated in the upper layer, and almost absent in the main part of the profile. Also, high porosity can go together with high penetration resistance in case of a constructed homogeneous bed of sandy material. In such homogeneous beds, cone penetration resistance increases with depth.

- Decomposition of organic matter in the bags during their stay in the root zone could not be observed. Probably, the oxygen regime around these bags (recently disturbed sandy soil with softened organic matter) and in these bags prevented this. It is in line with the low root development in the bags. The pH-values and the K- and Mg-saturations of the perforated bags in the root zone of the research site shifted towards the values prevailing in the root zone. The substrate in the bag with the highest organic matter content was strongly water repellent.

1 Introduction

Substrates for city trees are often mixtures of several components. In The Hague, such soil mixtures usually consist of clay soil, sand, peat, and sometimes also compost. Soil mixture components are, by definition, different. Apart from texture, type of solids, structure, these differences relate to quantities like: nutrient supply to the liquid phase of the substrate, the substrate water tension, the oxygen content, the rootability. The values of these quantities are heterogeneously distributed in a soil mixture.

The relative amounts of substrate per tree varies widely. The root zone may be designed such that the substrate is uniformly distributed over the root zone volume, or that the root zone is built up of several layers of different substrates with different properties. The water supply rate to the root zone may be very constant or highly intermittent. Nutrients may be released at a rather constant rate, or at a very fluctuating rate. Time between successive fertilizations may be very different.

Root length per unit of substrate volume varies widely. At small scales, fine roots may be uniformly distributed over the components, or may have the tendency to concentrate against clay aggregates or in peat (and/or compost) lumps. Larger roots of the root system may or may not be uniformly distributed over the growing space. In case of layered root zones, roots may prefer or may avoid certain layers.

The roots take up water and nutrient ions. The water and these ions are stored near the solid phase and in the liquid phase of the substrate, are transported through the liquid phase towards the roots, and are absorbed by the roots. Evidently, these processes are most efficient if the roots are located near the water and nutrients (synlocation) and if the uptake by the roots is in phase with the availability of water and nutrients (synchronization). The involved mechanisms may differ for situations with surplus water and/or nutrients and situations with water stress and/or stress by shortage of nutrients. Losses by leakage of water and nutrients to the subsoil below the root zone are an additional aspect.

For urban trees in relatively narrow, intensively used streets, it is important that the root zone volumes can be minimized at tree growth rates that are intended. Frequency of fertilizing events should be low, and losses should be minimum. Therefore, insight in the above is necessary. This report concentrates on the ecology of tree roots in substrates in The Hague. The report presents some steps forward, but is surely not the final answer.

The first part of the report is devoted to a literature review. Many articles and textbooks on growth, distribution and function of plant roots in growing media exist. A part of these is specifically devoted to heterogeneous growing media. Although this literature only partly concerns roots of trees, general behavior of plant roots can be found in this way. The study is cooperation with the Moscow State Forest

University. Therefore, it was possible to include information from Russia. Root behavior is very complex, and root studies are difficult. There is a big need for information on root behavior that can be generalized. Therefore, some work on modeling root growth and functioning is included (without going into the mathematics).

The second part of the report presents experiments and observations on tree mixes in The Hague. It concerns a wide range of properties and aspects of substrates in The Hague, all located in a research site that has been studied for many years. The site is a well-known square planted with *Tilia europaea* in 1981. The square is paved and has a significant traffic load by pedestrians, parked vans and trucks. The amount of substrate per tree is relatively high. The substrate is rather deep and influenced by groundwater. Values were obtained for: textural composition, degree of compaction, porosity, air content, water repellency. Samples were chemically analysed. Their morphological/structural aspects were assessed at low enlargements. Also the rooting was inspected. Most attention was paid to the root zone substrate that was installed in 1981. The experiments also included substrate bags that were installed in the root zone in 2005. The bags were filled with substrates varying in organic matter content. At the time of installation (2005), duplo's of the bags were stored in a deep-freezer, in order to be able to assess the change of the installed substrates during 2005-2007.

The experimental results are discussed in the Discussion section with ample reference to the literature review part.

2 Root growth and function in relation to soil structure, composition and strength

2.1 Introduction

In the textbook "Root Ecology", edited by H. de Kroon and E.J.W. Visser, A.G. Bengough devoted a chapter to root growth and function in relation to soil structure, composition, and strength (Bengough, 2003). Now, a summary of this chapter follows.

Soil consists of mineral particles and organic matter, interspersed with pores containing solutions and gases. Soil pores can be classified into channels, fissures and packing pores according to their shape in cross-section. Significant size ranges are:

Root diameters: larger than 0.1 mm
Root hair diameters and root cap cells: about 0.01 mm
Pores that are filled with air at field capacity: larger than 0.06 mm
Pores that are filled with air at wilting point: larger than 0.00002 mm
Pores larger than 0.1 mm are named macropores

The roots of any plant will generally experience a wide range of physical conditions and environments, including growth through soil pores of various sizes, aggregates and larger soil structural units under a range of moisture conditions. For simplicity two cases are distinguished: the case where the roots are situated in the bulk of the soil, and the case where the roots are situated in large continuous macropores. In reality, individual roots may enter and leave macropores, and so part of their length may be in the bulk soil, and part in a macropore. It may further be distinguished between root growth and root function (water and nutrients uptake).

2.2 Root growth in bulk soil

2.2.1 Physical limitations to root growth

Water stress depends on the matric and osmotic potentials at the root surface. Water is usually thought of as being available for uptake at matric potentials greater than -1.5 MPa, the wilting point of many mesophytic plants. However, drought stress already slows down root growth at wetter conditions (at potentials greater (wetter) than -1.5 MPa). Root elongation rate decreases more or less linearly with matric potential between field capacity and wilting point.

Poor aeration of the soil often becomes a problem when the air-filled porosity is less than 10% of soil volume, although aeration problems can occur in wet sands with air-filled porosities of up to 20 %. The demand of the root for oxygen may exceed the supply rate by diffusion, creating hypoxia or anoxia in the root. This situation is common in wet compacted, or waterlogged soil where there are insufficient continuous air-filled pores to provide pathways for rapid oxygen transport

Mechanical impedance slows root elongation as the strength of the soil increases, and there are insufficient continuous channels, larger than the root diameter, for unimpeded root elongation. Penetrometer resistance gives an empirical measure of the strength of the soil, but exceeds the penetration resistance experienced by roots by a factor of between two and eight times. There are a number of reasons for this, but one of the main factors is that roots experience a much smaller component of frictional resistance to growth than do penetrometers due to the low-friction properties of root tips: more than 80% of the penetration resistance to a penetrometer can be frictional. But we note that penetrometers are widely used tools in urban greening practice.

Here, we may refer to the textbook of Glinski and Lipiec (1990. The penetration resistance of 3 MPa was regarded as an upper critical mechanical limit (UCML) at which root growths has completely stopped. As a lower critical limit (LCML), the penetration resistance of 1.5 MPa was proposed: it causes a decrease in the root growth rate of 50%. Bennie and Van Antwerpen (Glinski and Lipiec, 1990) proposed compaction classes to evaluate root-impeding characteristics of compacted soil layers. These classes, based on the degree of compaction (ratio of *prevailing bulk density minus minimum density* and *maximum minus minimum density*) are shown in Table 1.

Table 1. Compaction classes after Bennie and Van Antwerpen (Glinski and Lipiec, 1990)

Degree of compaction	Compaction class
<0.5	Low
0.5-0.6	Medium
0.6-0.7	High
>0.7	Very high

As the effect of compaction is decrease of the number of large pores, the fine roots might be expected to penetrate the compact soil easier than the thicker ones. But such a response does not always occur and interpretation of this is difficult. Soil structure may influence root growth and distribution. The response of roots to aggregate size is closely related to the type of roots. Main axes of seminal and nodal roots are longer in coarser aggregate systems, while the length of secondary laterals is lower. The presence of root hairs allows the exploration of a larger soil volume in macrostructured soil, thus increasing nutrient absorption

*Combined limitations***.** In much of the root growth research the root environment has been controlled so that the effect of single physical limitations to root growth (waterstress, poor aeration, mechanical impedance) could be studied in isolation. In practice, a given plant species in a given substrate type may experience wide ranges of moisture conditions and compaction degrees. At different times during a growing season roots may experience very different limiting factors, according to the prevailing water content and soil strength. Recently, several research workers developed the concept of the “window” of not-limiting physical conditions of a soil or substrate. The concept defines a window in a graph with dry bulk density on the horizontal axis and volumetric water content on the vertical axis. The window is an irregular triangle (or polygon). For conditions (bulk density – water content combinations) within the triangle or polygon, root growth is least limited by adverse soil physical conditions (shortage of oxygen and/or excessive penetetration resistance, or by such a low bulk density that soil-root contact limits water and nutrient uptake). For conditions outside the triangle or polygon, root growth is limited by adverse soil physical conditions. The window can be combined with the hydrology of the site, in order to find the number of days on which the soil water content is outside the window and on which the plant will experience growth limitations due to adverse soil physical conditions. It is generally assumed that larger windows are better.

2.2.2 Effects of soil strength on root growth and physiology

Growth of root tips in hard soil. Mechanically impeded roots are shorter and thicker than roots grown in loose soil. Elongation is slowed due to a decrease in both the rate at which new cells are added onto a file (i.e. the cell flux), and a shorter final cell length. The elongation zone is shorter in impeded roots, because the local strain rate (i.e. the extension rate per unit length of root) in this zone is decreased. The turgor pressure in the cells of the elongation zone drives root growth. The turgor is maintained, or even increased, in impeded roots. The slower local strain rate in mechanically impeded roots is partly due to a stiffening of the cell walls in the axial direction, at the rear of the expansion zone, and partly due to the direct externally applied pressure of the soil. Mechanically impeded roots are shorter and thicker than roots grown in loose soil. Mechanical impedance causes root diameter to increase by up to a factor of two - this is mainly due to an increase in cell diameter in the cortex, but extra cell layers are sometimes found. The increase in cell diameter may be associated with the deposition of longitudinally oriented microfibrils in the cell wall that results in the cell walls becoming stiffer axially.

Root branching in hard soil. Root systems growing in hard soils look very stunted compared with those grown in loose soil, although there has been relatively little work to quantify the effects of impedance on root branching. This is no doubt because of the considerable time and effort required to excavate, wash, and measure intact roots grown in compacted soil, and the likelihood of damaging them. It was found that mechanically impeded root growth involves reduction in cell extension while cell numbers are unaffected. The mechanical impedance may affect the spacing of laterals and root branching. Total lateral production remains unchanged, or is decreased by mechanical impedance, even though main axes become more densely branched. The effect of mechanical impedance on root growth depends on soil conditions, plant species, and stage of development of the plant.

2.2.3 Localised compression of soil around roots

Root tips exert pressures of up to 1 MPa as they compress the soil around them. Growing roots compress the surrounding soil, unless they are growing in a continuous channel or fissure wider than the root diameter. The stress exerted by the root on the soil depends on the soil strength, which increases with increasing bulk density and decreasing water content. The stress exerted on the soil decreases with increasing distance from the root apex, and with increasing distance from the root surface. Greatest compression of the soil therefore occurs closest to the root surface. Changes in porosity adjacent to the root surface potentially affect transport of nutrients, air and water to the root surface, and so are of particular interest. The relative increase in density at the root surface, and the distance from the root surface that the soil will be compressed, depends on the root diameter and on how compressible the soil is. The volume of pore space that must be lost from the rhizosphere soil to accommodate the root is equal to the volume of the root.

2.2.4 Water and nutrient uptake

Local compaction of soil in the rhizosphere affects transport of water and nutrients to roots, but the importance of the effect is probably smaller than that of water content and soil texture. Compaction decreases the volume of the pores in the soil of effective diameter greater than about 30 μm. Compaction may decrease the continuity of the large pores, decreasing the saturated hydraulic conductivity, and changing the winding of the flow paths through the water-filled pore space. Changes in bulk density influences diffusion. Both increases and decreases in diffusion rates have been recorded in response to increasing bulk density, depending on soil type, water content, and diffusing ions.

There is an optimum bulk density for water and nutrient uptake. Over-compaction increases mechanical impedance to root growth and decreases the root length available for water and nutrient uptake. Soils that are very loose have poor root-soil contact, increasing the winding of the transport paths to the root surface. The degree of soil-root contact has been measured in repacked soil using thin-section techniques. Apparent soil-root contact was very variable, but increased from 60 to 87% as soil bulk density increased from 1.1 to 1.5 g cm^{-3}. In undisturbed soils the degree of soil-root contact may be much smaller if roots are growing in continuous cracks or biopores.

2.3 Root growth in macropores

2.3.1 Root elongation and distribution in macropores

Channels and fissures, including biopores formed by earthworms and decayed roots, offer pathways for unimpeded root growth. Results from A. R. Dexter and others are reported. Cracks narrower than the root diameter also enable more rapid root elongation than in the bulk soil, by partially decreasing mechanical impedance. Channels and fissures may allow roots to bypass zones of compacted soil, and so access a larger volume of soil containing water and nutrients. Roots encounter channels and fissures partly at random, although it is possible, that gradients in soil properties, such as soil strength or aeration, may bias the direction of growth towards them. Once a root enters a channel or fissure, it will grow along it until an opportunity arises for the tip to re-enter the bulk soil. The distance that the root will follow the channel will depend on penetration resistance of the surrounding soil, the width of the air gap, and the angle of the channel to the preferred direction of growth. The root is more likely to stay in the fissure if the walls are hard, causing the root to buckle instead of penetrate. The chance of a root penetrating the wall is smaller for wide vertical fissures than for narrow horizontal ones. Thick roots have a greater chance of crossing air gaps and penetrating macropore walls, due to their greater buckling stress than thinner roots.

Here, we may add remarks from Glinscki and Lipiec (1990). Compacted soil often has cracks and biopores (wormholes and channels left by previous roots) which may be penetrated by roots. Cracks are natural or artificial. Natural cracks are usually formed by desiccation (water extraction) of swelling/shrinking soils during dry periods or by plant growth (extraction by root water uptake). The usual desiccation crack pattern resulting from land evaporation consists of somewhat irregular polygons. This crack pattern can be modified by the water extraction by roots. When a soil contains cracks between macroscopic structural units (e.g., clods), it is common to find a preferential growth of roots on the clod surfaces rather than within the clods. When the tip of an elongating root grows out of a soil clod and crosses a crack, it can either penetrate the next clod or it can buckle and be deflected along the surface of the clod. The latter is likely for soil aggregates, because of their high bulk densities.

2.3.2 Effect of root clumping on water and nutrient uptake

Regularly spaced roots should, theoretically, extract water and nutrients most efficiently from a soil in which these resources are distributed uniformly. In reality, roots tend to be distributed more randomly and/or clumped in continuous macropores. Results from J. B. Passioura are reported. He performed calculations of the likely effect that root clumping within different arrangements of macropores would have on water uptake. Roots that were confined to macropores were assumed to act as a single root, or plane of roots, of extent equal to the length or area of the macropores. The time taken for the root to extract 63 % of the initial water content was estimated for a dry soil in which the hydraulic conductivity was limiting uptake. If roots were solely confined to biopores, the time was between 10 and 100 days, compared with less than 3 days for evenly distributed roots in the same soil. Different shapes of soil structural unit (slabs, prisms, cubes) resulted in faster extraction of water than the biopores, although still up to an order of magnitude slower than for evenly distributed roots.

2.4 Closure

Bengough (2003) concluded that hard soils with degraded structures present a major limitation to root growth and function. Soil strength and structure greatly influence root distribution and hence exert strong control on nutrient and water uptake by roots. The relations between soil structure and root growth and function are still poorly understood, due to the experimental difficulties in adequately studying root systems in situ.

3 Root foraging responses to spatial heterogeneity in availability of soil-based resources

Foraging by a plant involves the use of its morphological plasticity, in response to heterogeneous conditions, to selectively place resource-acquiring structures, such as roots or leaves, in more favourable patches of habitat. Foraging by plant roots may be defined as the processes whereby the root system searches or ramifies within the soil or substrate, which enhance its acquisition of essential resources. Growth that does not involve changes in form is not a manifestation of foraging.

In the textbook "Root Ecology", edited by H. de Kroon and E.J.W. Visser, the authors M. J. Hutchings and E. A. John (2003) devote a section to root foraging responses to spatial heterogeneity in availability of soil-based resources (Hutchings and John, 2003) They note that the most common morphological responses to higher nutrient availability include increased root growth rate and root branching rate. Such responses occur at a local level rather than throughout the root system, thus enabling the plant to invest resources at scales equivalent to that of nutrient patches, or individual roots.

Hutchings and John (2003) report that M. C. Drew and co-workers grew seminal roots of barley (Hordeum vulgare) downwards through a sequence of three vertically stacked layers of sand, in which the concentration of selected nutrients could be independently controlled. When the sand in only one of the compartments contained a high nitrate, ammonium or phosphate concentration, the section of the seminal root within that compartment produced significantly more primary and secondary laterals, with significantly higher extension rates, than equivalent parts of seminal roots in other compartments and in control treatments. These effects were independent of level of nitrate, ammonium or phosphate in the other compartments. In contrast, there was no effect of potassium on the growth of lateral roots. The rate of extension of the seminal root was not affected by the concentration of single nutrient ions. One important outcome of these experiments was that exposure of only a few percent of the seminal root to nutrient-rich sand resulted, after a short lag, in whole-plant relative growth rates similar to those achieved by plants with their entire seminal root in nutrient-rich sand. This was presumably because localized proliferation of laterals in the heterogeneous treatments allowed nutrient acquisition to match that achieved in homogeneously nutrient-rich conditions.

Many other studies of root behavior of a range of species under heterogeneous conditions corroborate the above results. However, a review of D. Robinson showed that such responses are not omnipresent. The scale of the root foraging response was found to depend on the nutrient that was in patchy supply, the nutrient status of the plant, and the stage of growth.

Hutchings and John (2003) note that localised proliferation of parts of root systems in the nutrient-rich patches of heterogeneous habitats is often associated with reduced growth of parts of the same root system located where nutrients are scarce. The authors report an example from M. Gersani and T. Sachs, who divided the root systems of pea plants equally between two containers of nutrient solution. If the solutions in the containers differed in concentration, root development was greater in the more nutrient-rich container. A greater difference in concentration caused a greater proportion of the roots to develop in the nutrient-rich container, but, overall, the same total number of root primordial was produced in all situations.

4 Local nutrition of plants

4.1 Introduction

In Russia, Trapeznikov et al. (1999) wrote a textbook on many aspects of plant nutrition by fertilizers that are locally applied to the soil. The book presents generalized results of long-term researches of the authors, and from literature, on plant functioning at spreading and at local application of the basic mineral fertilizers. It deals with the influence of these ways of application on distribution and transformation of nutrion elements in soil and on the biological activity in soil. It is shown that the interaction of a part of the plant root system with a centralized high concentration of ions leads to synchronous activation of the main physiological functions, to optimization of the production process, and to its stabilization under adverse growth conditions. Possible mechanisms of action of the centralized high concentration of ions on the physiological condition of plants as a complete, comprehensive, system are discussed. Local plant nutrition is considered as an important factor that contributes to saving resources, to ecological safety and to perfection of the cultivation technology of agricultural crops.

The analysis of the results and the data from literature show that non-uniform distribution of fertilizers in soil leads to significant amplification of the natural heterogeneity of soil, not only with respect to the contents of accessible forms of nutrition elements, but also with respect to a number of other properties.

The fertilizer accommodation zone, which occupies an insignificant part of the root environment, is characterized by an extremely high osmotic potential, so that physical, chemical and biological processes of transformation of nutrition elements and soil organic matter proceed more intensively. The direction and intensity of processes that proceed in the zone are determined in many respects by the amount of applied fertilizer, by soil properties, and also by the functional activity of the plant root system. In the case of local fertilizer applying it is the soil heterogeneity that causes morphological and physiological differentiation in the plant root system, which renders an essential influence on the main plant functions and on production processes.

The question about the possible role of the level of spatial heterogeneity of the soil medium in functioning of root systems and consequently of the whole plant, has a general biological character. In most cases, traditional agricultural technologies aim at the creation of a homogeneous arable layer. Nature has solved the given question differently. Virgin soils, of forests and in grassy ecosystems, are strongly differentiated with respect to the distribution of organic matter and the main bulk of functionally active roots. Hence, the technology of local application of mineral fertilizers in agrocenosises is biological more perfect than a rather uniform distribution of these fertilizers in soil.

In the case of local fertilizer application in soil, a center with increased content of accessible forms of mineral nutritious elements is formed, with which only separate plant roots, named “strongly saline”, interact. In the local application case, the three basic macro-elements (nitrogen, phosphorus and potassium) having various migration abilities, various transformation degrees and various use by the plants and microflora, form a wide spectrum of statuses of roots. One of the roots in Figure 1 functions in conditions of increased contents of all elements, the other only in conditions of increased nitrate nitrogen and ammonia nitrogen. The salt status of one and the same root can essentially vary along its axis. Not only the intensity of influence changes with time, but also its character because of a sharp change of the relative concentrations of phosphorus and potassium in the centre. Therefore, parts of the plant roots or parts of a single root functions a long period of time in conditions of increased concentration of only these two elements. It shows that the variation of salt statuses of plant roots in the case of local fertilizer application is an important factor in using nutritious resources, moisture and light by plants during production processes.

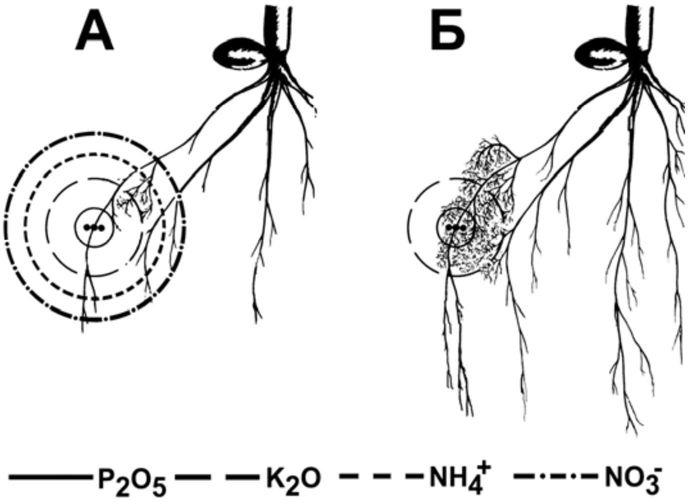

Figure 1 Variety of salt statuses of plant roots at local application of NPK. A - initial, Б - final stage of ontogenesis (Trapeznikov et al., 1999)

4.2 Influence of concentration

Cultivation of wheat plants on Knop solutions (i.e. nutrient solution for hydroponics with main nutrient elements: Ca, K, N, P, Mg, Fe) of various concentrations in isolated compartments of a vessel containing the root system has shown that, if the nutrient medium concentration in the “strongly saline” parts of the vessel is increased by a factor 5-7 or more, axial root growth is inhibited and branching of roots is strengthened (Figure 2). The influence of high concentrations (one vessel with Knop ratio 7 and one with 10) on the wheat root system reduced not only root growth, but also growth of the above ground parts of the plant.

At moisture deficiency the granules of complex fertilizers remain in an undestroyed state for a long time. Cases occurred where recovered granules had strings on them of fine wheat roots. This fact indicates that the meristem of roots of higher branching order has a high degree of adaptation to osmotic influence. It may be possible that roots can absorb a part of the nutrition elements phosphorus and potassium directly from granules, bypassing soil. It is also probable that heterogeneity of the spatial distribution of ions creates conditions at which the process of plant root nutrition is less dependent on the level of moisture provision.

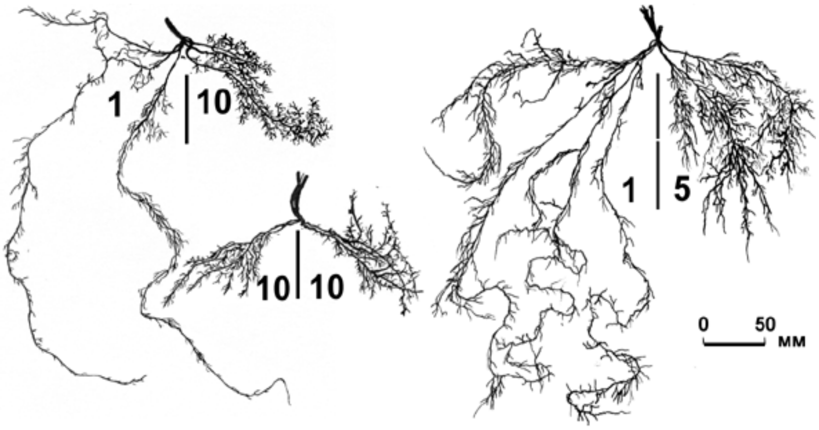

Figure 2 Development of wheat root system at cultivation on nutritious Knop mixtures of various concentrations: 1, 5 and 10 – concentration ratio's of nutritious solutions (Trapeznikov et al., 1999)

4.3 Influence of local application of fertilizers on branching of root systems

Heterogeneous distribution of nutrition elements in soil has a stronger influence than only simple amplification of branching of individual roots. In conditions of sectionally isolated nutrition in a two-sections vessel containing the root system of a potato plant (Figure 3), limiting the application of NPK to one section led to intensive growth of "strongly saline" roots in that section, but formation of stolons and tubers has been observed in the "weakly saline" section. Such differentiation in the formation of organs for storage and for nutrient take up is interesting and deserves deep study.

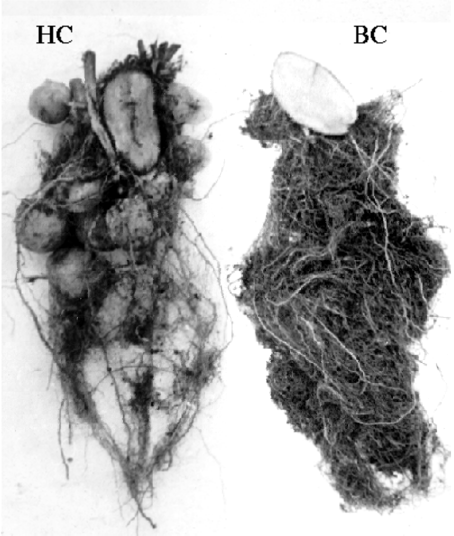

Figure 3 Root system of a potato plant in a vessel at local nutrition: BC - a compartment of the vessel with fertilizer, HC - a compartment of the vessel without fertilizer (Trapeznikov et al., 1999)

The action of mineral nutrients ranges from strong inhibition of plant growth and destruction of the plant to efficient growth optimization, depending on the dose of fertilizer, on its placement with respect to seeds, on adaptive properties of the plant, and on other factors. It is shown that the positive effect of localization is most significant at conditions of moisture deficiency, which gives rise to functional root specialization because of different salt statuses. In one part of the root system, "strongly saline" roots interact with an extreme zone of high ions content. The other part of the roots –consisting of "weakly saline" roots- provides the plant with moisture (Figure 4).

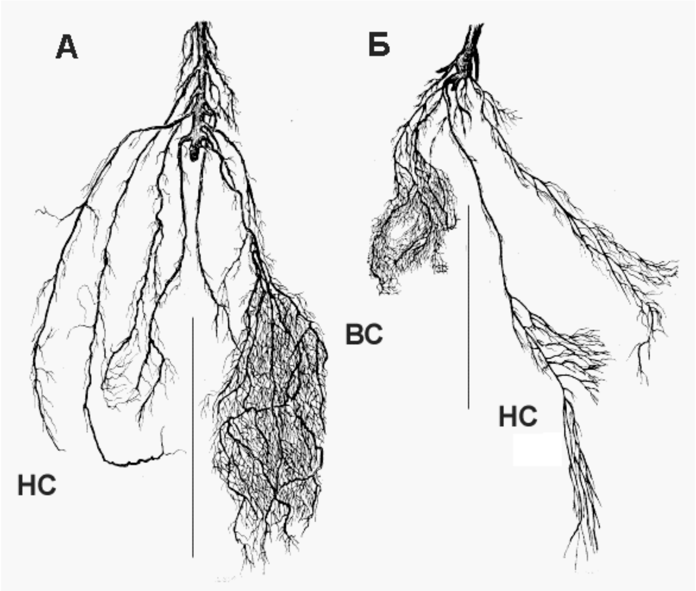

Figure 4 Branching of root system at local nutrition of maize (A) and wheat (Б): BC - the root locks prefer the centers of fertilizer, HC - roots outside of the center (Trapeznikov et al., 1999)

4.4 Closure

From an agricultural point of view, it is possible to attribute a number of positive results to the technology of local application of fertilizers.

It is demonstrated that, in the case of a local fertilizer application, the ratio of the different mineral forms of nitrogen in soil changes for the benefit of ammonium, which is one of the reasons of a smaller accumulation of nitrates in plants.

The given technology is more economic. By local application of fertilizers savings of up to 50% fertilizer may be achieved in comparison with spreading over the soil surface.

Efficiency of plant production increases. Local accommodation of fertilizer creates a centre of high concentration of nutrient elements that positively effects the physiological process in plants occupying a small volume of soil: plant ears with a large number of seeds are formed; growth of roots and absorption of nutrition elements are amplified; the efficiency of use, and also the accumulation in plant storage parts, of assimilates raise; as well as the water holding capacity and nitrate-restoring ability of plant fabric.

The presented technology of fertilizers application confirms the sense of an urban greening practice that confines tree fertilisation to tree root zone projections. Local fertilizer application, creating a centralized high concentration of nutrients, increases the effective uptake by roots and allows root distribution regulation, i.e., the formation of a compact root system.

Considering our The Hague-Moscow-Wageningen project, the interpretation of the technology given above may be as follows. As roots seek for water and nutrient resources, roots may be heterogeneously distributed on a micro scale because of the micro-heterogeneity of tree soil mixtures: fine roots may tend to concentrate against clay-soil aggregates because of lack of resources, especially water, near other soil parts.

5 “APION”

A Russian Doctor of Chemistry, Professor Igor Grigoriants, produced in Russia the preparation “APION” on the basis of the principle of local plant nutrition. It features an essence of optimal cultivation technology: nutrition of plants, which is continuous during the whole vegetative period, supplying the plant root system with a complete nutrient complex in the required quantity at the required ratio of the individual nutrient elements.

“APION”, “automatic nutrition osmotic pump”, consists of small bags: batches of fertilizers enclosed in a half-permeable membrane. When placed in soil, “APION” is entered by soil water and releases fertilizer to the soil during the whole vegetative period. The nutrients output of “APION” is absorbed by the root system. In the case of “APION” application, nutrients are distributed in soil at regular intervals, with a speed equal to the speed of uptake.

The mechanism of the “APION” action is based on known laws for spontaneously proceeding processes (laws from Fick, Van’t Hof, Henry, etc.).

The scheme of the elementary osmotic pump is presented in Figure 5. When the pump is immersed in a wet environment (water, wet soil, humidified air), water moves through the half-permeable membrane, enters the inside of the pump, and starts to dissolve fertilizers, forming a solution. Pressure inside the pump increases and, by this, solution will be pressed out through the apertures, into the soil. The osmotic pump will only stop working when the solution that is formed in it has the same concentration as the concentration of the salts outside.

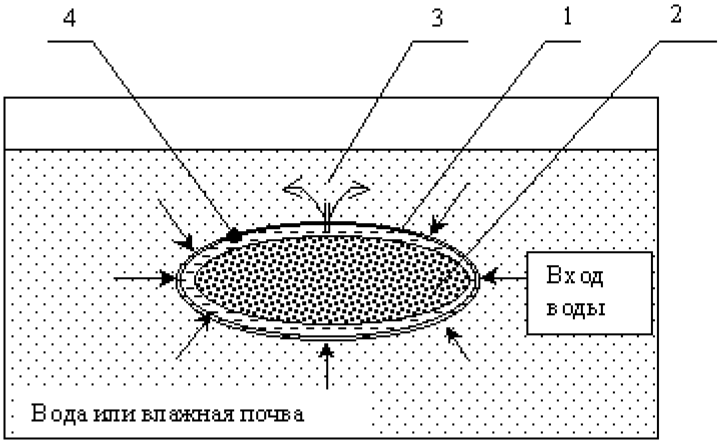

Figure 5 Osmotic pump and scheme of its working. 1 - membrane, 2 - fertilizers, 3 -output of solution, 4- solution of fertilizers

While there is a solid soluble substance (fertilizers) in it, the pump will work with constant speed, i.e., it will isolate equal quantities of solution of substance in each unit of time, providing the soil with fertilizer of constant concentration. If there is another pump in the soil, e.g., a biological pump, the biological pump will also work. In our case this is the plant, which, during the process of release of nutrients solution by "APION", will take up nutrients through its root system. In an ideal situation, the speed of nutrients isolation from "APION" equals the speed of nutrients absorption by the plant. In that case we have a synchronously working system of the biological object (the user) and the technical device ("APION" batches). One doses out into the soil, the other takes up from the soil. "APION" works at a dosing speed which is specific for a certain plant species. Thus, in the soil, concentrations do not increase and superfluous salt do not precipitate.

"APION" has been calculated and made in such a manner that, when the temperature of the surrounding medium decreases, the working speed of "APION" slows down also as plant uptake and the speed of batching decreases. In winter, it practically stops working. In dry soil, "APION" does not work. Moreover, in cases where the plant stops taking up nutrients from the soil solution for any reasons, the salt concentration at "APION" bag positions will increase, bag activity will diminish, and speed of batching will decrease. Thus, "APION" works according to a set mode of nutrients batching, which depends on external conditions (temperature, humidity, concentration of salts in the soil).

The methods that were developed for calculation allow to design and make osmotic "APION" pumps with a batching duration varying from a few tens of hours to several years, and with a batching rate from a part of a milligram per hour up to tens of grams per hour.

To account for the demand of different plant species, a range of 10 "APION" types has been developed, with weights from 3 up to 200 gram and operating times from 2 months up to 2.5 years. Thus, the requirements of different kinds of plants on nutrients quantity and on cultivation season, or requirements with respect to plant development rate, are fully considered.

In Moscow and Moscow Region, more than 10 000 trees and more than 9 000 bushes were planted with "APION" in the year 2006 (Figure 6).

In the Hermitage Garden in Moscow in November, 2003, "APION" was installed under 25 trees of young and old ages (3 – 6 batches per tree).Observations were made in July, 2004. As a whole, specific differences between experimental and control plants were noted. All plants looked well and were poorly injured by pests. But the growth of young shoots was more for the trees with "APION" than for the control plants. In 2006, most of the trees and shrubs in the Hermitage Garden were fertilized with "APION".

Figure 6 Planting trees and shrubs with "APION"

Figure 7 shows Tilia trees which were planted in the winter of 1999. In May, 2004, "APION" was installed under the crown perimeters. At inspection on July, 7, 2004, it was noted that: for the "APION" tree group, blossoming as a whole occurred at 64 % of the trees, and plentifully blossoming at 36 %; and that for the control tree group these amounts were 48 and 22 %, respectively. Both groups were weakly injured by pests; the group of trees with "APION" was less damaged by 12.5 %. Inspection on October 10, 2004, showed that colour of foliage was dark green; trees had a good condition. Average height growth in 2004 was 12 % for the treated group (26 trees) and 2 % for the control (25 trees). The photo (Figure 7) was made in June, 2005. The monitoring was conducted by the research organisation "PRIMA-M".

Important aspects of "APION" are: types with long operation duration are available; the fertilizer is mineral (not organic); it can be installed in relatively large batches at only a few locations.

The most mobile macro-nutrient in soil (in the soil solution) is nitrogen: therefore, in traditional technology, it leaches fastest of all. It quickly flows into the bottom layers of the soil profile and becomes inaccessible for the plant root system. There is an accumulation of nitrates in soil. A main feature of the "APION" operation is; allocation, in its basic operation life, of a saturated solution which basically contains nutrients in the ratio that is present in the "APION" bag from which it is released. During the operation life of "APION" nitrogen releases a little faster than P and K, phosphorus releases faster than K, from N, P, K, potassium releases most slowly, but as a whole the rates differ little. Speed of nutrient releasing also depends on the initial structure of the soluble solid fertilizer.

Figure 7 Tilia platyphyllos at Koroleva street, in Moscow

The saturated solution is released from the bag and distributed in the soil in directions that depend on the position of the “sinks”, whereby, due to differences in mobility, the bulk contents of the individual nutrients more or less separate in layers. It is the main difference with the almost uniform distribution of nutrient ions in the cases where nutrient solutions are applied or nutrient grains are broadcasted. So, the “APION” operation creates soil zones (layers) with different contents of nutrients. Through differentiation of the root system ("specialization" on the absorption of a specific ion) and chemotropism of the root system the plant has the "opportunity" to choose that specific "feed", which is necessary for this plant at a specific moment.

In the work of Trapeznikov et al. (1999) on “Local nutrition of plants” the relative differentiation of a root system is described. In cases of local nutrition of plants (spreading in furrows, pits or placing doses of “APION”) the nutrients (the basic macroelements nitrogen, phosphorus and potassium) are distributed in the soil non-uniformly. The nitrogen runs downwards faster, the potassium further follows, the phosphorus goes more slowly. It leads to a root system that is differentiated (is divided) into "strongly saline" and "weakly saline" parts, each part uptaking the nutrient element which the plant needs in the prevailing period in the required amount. This phenomenon is absent in spreading methods of fertilizers application (spraying water solutions or broadcasting dry fertilizers) at which nutrient elements in soil are distributed uniformly.

Table 2 Nomenclature of "APION" (not complete)

Conditions of cultivation and specification of plants	**Type of APION**
Cultivation of transplants, one and two years age bearing and decorative cultures, ornamental shrubs and perennial plants in nurseries, for winter gardens and greenhouses, for containers. In case of artificial soil mixes add dolomite (3-5 kg / m^2).	APION-30K. 7-10 months operation duration Weight – 30g
Cultivation of transplants, two and three years age of bearing and decorative cultures, ornamental shrubs and perennial plants in nurseries, for winter gardens and greenhouses, for containers. In case of artificial soil mixes add dolomite (3-5 kg / m^2).	APION-50K. 10-15 months operation duration Weight – 50g.
For bearing and ornamental shrubs and trees, for winter gardens and greenhouses, for containers. In landscape design - at planting and the maintenance of large ornamental plants It is recommended for reanimation of old trees	APION-100K. 1 – 1.5 years operation duration Weight – 100g.
Medium-sized young ornamental plants in open ground and containers for gardening: juniper, spiraea, weigela, philadelphus, roses, cornus, thuja, hydrangea, phloxes, partenocissus, etc.	APION-50KΛ. 10-15 months operation duration Weight – 60g.
For use at planting and the maintenance of large bushes and decorative trees of deciduous and coniferous breeds in landscape design. Norm of applying: from 1 up to 6 pieces depending on the sizes of a plant. It is also recommended for the maintenance of large fruit trees.	APION-150KΛ. 1.5-2 years operation duration Weight – 150g.

All types of "APION" have a NPK ratio of 18: 6:18, but this may be modified according to the order of the customer. For long release types of "APION" (1.5 -2 years) especially nitrogen stays active during two growing seasons, but in the second growing year the amount of released nitrogen is less then in the first year after installation. Table 2 gives further information.

Speed of dosing of the different types of "APION" ranges from 0.6-1.5 to 40 mg/hour. There are 12 types of "APION". Weight of bags with "APION" ranges from 3 up to 200g.

The types of "APION" (APION-30 - APION-150KΛ) contain:
N: P_2O_5: K_2O = 18: 6:18
Microelements: 0.2 % in total
Potassium humate: usually 0.2 %, for landscape types up to 0.5-0.7 %.

Closing remarks. For the moment, we do not have enough research results on the application of the given technology under woody plants. However, according to the first experiences with woody plants, these plants react by showing a positive growth tendency and larger annual shoot lengths. The use of the given technology is worthy, and demands conducting monitoring and further studying for plantings of woody plants.

"APION" is a produce of the Company "Scientific and Technical Centre OSMOS" at the Moscow State Industrial University.

Information sources
http://apion.al.ru
http://www.b-online.ru/articles/a_22165.shtml

6 Quantitative root ecology and soil fertility theory

6.1 Introduction

De Willigen and Van Noordwijk (1987) reviewed a vast amount of literature on root ecology and fertilization in order to find behaviour and relationships that may be generalized. They made significant steps toward complete modelling of water and nutrient uptake by roots, transport of water and nutrients through the soil root zone towards the roots, regime of the nutrient pools in the soil root zone. Their models start from the assumption that a plant fully controls its uptake rate (for both nutrients and water) according to its needs in situations of adequate supply.

In their models uptake rates are largely independent of nutrients concentration in the soil or substrate. Daily nutrient requirements of plants are assumed to be constant throughout a main part of the growing season. The total daily uptake requirement of the plant for nutrients and water are divided by the total root length to obtain the required uptake rates per unit root length.

If the roots are uniformly distributed, all units of root length deplete equal amounts of soil.

It is assumed that soil resources are used up at the required rate, until depletion of the root environment has resulted in a limiting concentration at the root surface. At this limiting concentration the physiological abilities of the root allow a just sufficiently high uptake rate. The limiting concentration is determined by plant physiological parameters and by the required uptake rate per unit root (e.g., the limiting concentration halves when the root density is doubled). The limiting nutrient concentration at the root surface which enables the plant to absorb nutrients at the required rate is virtually zero (except for P at low root densities and/or soils of high buffer capacity). Thus when transport of nutrients to the root limits uptake, the root may be described as a zero-sink. The limiting water potential at the root surface at which the plant root can just take up water at the required rate is determined by the most negative plant (xylem) potential that is acceptable, the hydraulic conductivity of the root system, and the required uptake rate (if the osmotic pressure of the solution outside the root surface is negligible).

In the models a constant daily uptake rate per unit root is continued until the required uptake rate can no longer be maintained. When a limiting water content or concentration is reached, a certain amount of available water and nutrients still remains in the soil. For linearly absorbed nutrients this amount is proportional to the amount of nutrients in the soil liquid at the time that the limiting concentration is reached (if amount of soil nutrients only changed by uptake by the roots).

If external supply allows, all roots of a root system are assumed to take up water and nutrients at the same rate per unit root surface, irrespective of age, distance to the root tip and root diameter (i.e. apart from “live” and “dead” roots no distinctions are necessary (main exceptions are probably Ca and Mg uptake, which may in fact be confined to the youngest roots and for which a constant rate of root growth is essential).

Turnover of roots during the growing season is negligible, i.e. roots may function for several months.

Physiologically based maximum uptake rates for nutrients and water determine the minimum root surface area necessary in situations of high external supply; this minimum is determined by the possible water uptake per unit root rather than by the possible nutrient uptake per unit root, as we shall see in the next section.

6.2 Estimate of physiologically required root volume

The “physiologically required minimum root surface area” per plant can be defined as the minimum of the required surface areas for each of the essential nutrients and that for water. For water and each nutrient this root surface area can be estimated from uptake rates per plant required for maximum production at a given plant density, divided by the maximum uptake rates per unit root area. Here the authors concentrate on tomato production under glasshouse conditions in the Netherlands.

For the linear growth phase of a closed canopy, in which tissue is formed at a constant daily rate, the equation for the uptake of a nutrient is:

$$A_{r,n} = \frac{Y_D \times m}{N_p \times A_i \times F_{\max}}$$

where:

$A_{r,n}$ = physiologically required minimum root surface area per plant for nutrient uptake [m^2]
Y_D = dry matter production per day [kg/ha day]
m = element content of plant dry matter [g/kg]
N_p = plant density [number/ha]
A_i = atomic (or molecular) weight of the nutrient studied [g/mol]
F_{max} = maximum uptake rate per unit root surface area for the nutrient considered [mol/m^2 day]

Table 3 shows estimates of $A_{r,n}$ and the corresponding root volume $V_{r,n}$ for given values of Y_D , m , N_p , A_i , *and* F_{max} .

Table 3 Estimates of physiologically required root surface area $A_{r,n}$ and root volume $V_{r,n}$ (assuming all roots to have a root diameter of 0.020 cm) for tomato. Assumed growth rate is 9 g/day. Plant density $N_p = 2.2\ /m^2$. Values for m and F_{max} are given in the table

Nutrient	N	P	K	Ca
m (g/kg)	25	5	50	11
Required uptake per plant (mg/day)	225	45	450	100
Required uptake per plant (mol/day)	16×10^{-3}	1.5×10^{-3}	11×10^{-3}	2.4×10^{-3}
F_{max} (mol/m²day)	6.0×10^{-3}	0.5×10^{-3}	3.5×10^{-3}	0.6×10^{-3}
$A_{r,n}$ (m²)	2.7	2.9	3.2	4.0
$V_{r,n}$ (dm³)	0.14	0.15	0.16	0.22

The minimum root surface area for water uptake can be calculated from: the transpiration rate; plant density; root conductance; osmotic potential of the solution; root water potential. For:

- transpiration rate = 4.4 mm per 6 hours,
- plant density = $2.2/m^2$,
- root conductance = $5*10^{-6}$ $cm^3/(cm^2$ s Mpa) ,
- osmotic potential of the solution = 0.03 Mpa ,
- an acceptable root water potential = -0.5 Mpa,

the minimum root surface area required for water uptake is 4.6 m^2/plant, corresponding to 0.23 dm^3 root tissue per plant.

These estimates show that for normal plant spacing and growth rates, a minimum root surface area of several m^2 per plant may be expected for glasshouse tomatoes and that Ca uptake and water uptake may be the first root functions which become limiting when the size of the root system is reduced.

N.B. In the above minimum calculation, the minimum amount of root tissue per m^2 canopy = the minimum amount of root tissue per plant x number of plants per m^2 = 0.23 x 2.2 = 0.5 dm^3 root tissue per m^2 canopy. We may make a rough comparison with glasshouse tomatoes in rock wool slabs with a trickling point near each plant and free drainage from the slab, and a rough comparison with a street-tree in a defined, limited, root zone volume. According to De Willigen and Van Noordwijk (1987, pg 65) this tomato growing system may in practice have 10 litre of rock wool per plant, which translates into a root zone volume of 22 dm^3 per m^2 canopy. Root zone volumes of street trees are very much larger: several hundreds of dm^3 per m^2 canopy. These two values are much higher than the derived minimum amount of root tissue (0.5 dm^3 root tissue per m^2 canopy). The reason for this is that it is very difficult to supply water and nutrients to the roots in exactly the same amounts as the roots need, at each location in the root zone and at each point of time (exact synlocation and synchronisation is desired, but never reached). Plants tend to make more roots than the minimum amount needed at exact synlocation and synchronisation. This is also related to the genetic properties of the plant. But, from a technical point of view, it is possible to control the amount of root volume by setting a maximum to the pore space available for root growth (this principle was followed in the controlled rooting experiments of De Willigen and Van Noordwijk (1987)).

6.3 Minimal rooted volume and nutrient use efficiency in modern glasshouses

When De Willigen and Van Noordwijk (1987) prepared their thesis, a common growing system for tomatoes in commercial glasshouses was as follows. Usually 4 plants were grown on one piece of rock wool (length x width x height = 180 x 30 x 7 cm^3) with one trickling point near each plant. The rock wool slab was sheathed in polythene foil with drainage slits in one or more places. Nutrient solution was supplied several times a day, excess nutrient solution was lost through the slits to the glasshouse soil. The 10 litre of rock wool per plant holds about 5 litre of nutrient solution, i.e., about twice the average daily demand of transpiration. The composition of the nutrient solution was based on crop-specific recipes. Total salt content of the nutrient solution used was frequently (daily) adjusted on the basis of the pH and the electrical conductivity (EC) of a sample of nutrient solution. Nutrient ratios were adjusted on the basis of complete analysis of samples of solution collected from the rock wool slab twice a month and monthly for trace elements.

The optimal concentration of all nutrients in the nutrient solution for maximum yields (and/or quality) has been established for many plants species in experiments in which many concentration levels, maintained throughout the growing season, were tested. Table 4 presents such information for tomatoes.

Table 4 Estimated daily uptake concentration, C_u *, of nutrients by a tomato crop compared to the recommended composition of the nutrient solution in the rock wool slab. Three system concentrations* C_s *are shown for each nutrient: lowest,* C_s *(l) ; desired,* C_s *(d) ; highest,* C_s *(h)*

Daily uptake mg/(plant day)		Uptake conc. C_u mg/l	System Concentration C_s mg/l		
			C_s (l)	C_s (d)	C_s (h)
N	225	90	84	130	210
P	45	18	15	31	47
S	50	20	32	64	160
K	450	180	160	200	270
Ca	100	40	160	200	280
Mg	30	12	24	48	72

Concentrations higher than C_s (*h*) lead to too high EC values. Concentrations lower than C_s (*l*), lead to shortage of nutrients. In order to remain in the allowed range of C_s , the volume of nutrient solution in the system V_s should be much larger than the daily transpiration from the system W_a . The ratio V_s/W_a is called; buffer capacity. Example: if, for the above growing system, the buffer capacity V_s/W_a is larger than 2, daily fluctuations in nutrient concentration appears to be comparatively small; it means that about 5 litre of moisture or about 10 litre of rock wool per plant are required.

6.4 Non-glasshouse conditions

In culture of plants in soils or substrates, in non-glasshouse conditions, nutrients are added once or at most in a few split applications of fertilizer. Buffering capacity of the soil (as influenced by organic matter and clay content, rooting depth, biological and chemical factors) is necessary to obtain reasonable nutrient use efficiencies under such poor synchronization of supply and demand and to protect nutrients from leaching during periods of excess rainfall. A direct consequence of this buffering is a reduced mobility of the nutrient in the root zone and hence transport distances to the root surface become important. Higher root densities may reduce transport distances as well as uptake requirement per unit root length. Here, the geometry of the system is of considerable importance as it determines the transport distances involved in nutrient and water uptake.

7 Uptake efficiency and root position effectivity

Van Noordwijk et al. (1993) note that, in root ecological studies, three levels of complexity may be distinguished:

1. Studies of single roots interacting with their environment,
2. Studies of root systems in a homogeneous environment,
3. Studies of root systems in a heterogeneous root environment.

For example, penetration of dense layers of soil has often been studied at the single root level. When studied from a whole plant perspective (level 2), negative effects of soil compaction can often be compensated for by improved supply of water and nutrients. When studied in a heterogeneous environment (level 3), penetration of dense soil layers may depend on conditions around other roots or other parts of the same root.

The potential uptake rate of a root system of homogeneously distributed roots in a homogeneous environment can be calculated by a calculation method of De Willigen and Van Noordwijk (1991). This method needs input values of:

- average concentration in soil solution, C_m
- minimum concentration at root surface, required for physiological uptake process, C_{lim}
- depth of soil layer, H
- effective diffusion coefficient for solutes, dependent on soil water content, D_a
- root length per unit volume of soil (root length density), L_{rv}
- root diameter, D_r
- flux of water, V, dimensionless (nutrient transport by mass flow, which is often negligible).

This potential uptake rate is the maximum rate at which the root system, the soil, and the soil solution can deliver a nutrient to the plant. The driving force for that, C_m – C_{lim}, is maximal. Often, the plant does not need a potential uptake, but less. Then, at the same C_m, the concentration at the root surface is higher than C_{lim}. Sometimes, C_m is so low that the driving force C_m - C_{lim} is too small to realize an uptake rate that the plant would require for an unlimited growth. In those cases the plant suffers from shortage of nutrients. An important reference point is the situation where the potential uptake rate is equal to the required uptake rate, and the (real) concentration at the root surface is equal to C_{lim}. The concept "uptake efficiency" is defined as the uptake rate of the root system divided by the available nutrient <u>at this reference point</u>.

If the roots are not uniformly distributed and/or soil-root contact is incomplete, the uptake efficiency is lower. The authors were able to quantify this. Therefore, they defined:
L_{rv} = real root length per unit volume of soil (root length density, cm cm^{-3}) at real (uniform or non-uniform) root distribution.
L_{rv}* = imaginary root length per unit volume of soil at imaginary uniform root distribution, which has the same uptake efficiency as the real root length per unit volume of soil at real (uniform or non-uniform) root distribution.

If we have a value of root length per unit soil volume, L_{rv} , we would be able to calculate the uptake efficiency if the roots were uniformly distributed, by the above-mentioned calculation method of De Willigen and Van Noordwijk (1991). But it is also possible to estimate the uptake efficiency for the condition of the non-uniform root distribution. Therefore, L_{rv} in the mentioned uptake efficiency calculation method is simply replaced by L_{rv}* , which can be calculated from L_{rv} and the Root Position Effectivity Ratio, R_{per}, defined, as:

$$R_{per} = L_{rv}^* / L_{rv},$$

R_{per} can be calculated from the frequency distribution of distances from points in the soil to the nearest neighbour root (nearest distances between source and root). In the case of a uniform distribution of nutrient ions, these points should be randomly distributed over the soil. Oherwise, the points should be distributed over the soil in proportion to the local concentrations of the nutrient ions. Values of R_{per}:

- in the case of homogeneously distributed resources and homogeneously distributed roots: $R_{per} = 1$;
- in the case of homogeneously distributed resources and non-uniform root distribution: $0 < R_{per} < 1$;
- in the case of clustered resources and synlocation of root and resources: $R_{per} > 1$.

In other words, at the same uptake efficiency:

- the more the roots are non-uniformly distributed and/or the smaller soil-root contact, the higher the root length density must be,
- root length density is lower in the case of synlocation with root clustering,
- root length density is higher if root clustering is present, but synlocation is absent.

Thus, the ability of a plant to forage precisely for nutrients also depends on the existence of a match between the root length development of its root system and the scale of environmental heterogeneity, and on the plant's ability to perceive and respond to the heterogeneity. In addition, the precision with which roots can be located in nutrient-rich patches depends on the positions of those patches with respect to the place at which the plant starts growing. Thus, a plant with its root system growing in a nutrient-rich patch may produce all of its roots within the patch. It will have high precision, and this will be beneficial to its growth. Non-regular root distribution in structured soils usually means that nutrients, water and/ or oxygen are also non-homogeneously distributed. A measure of spatial correlation between roots and resources (synlocation) is needed to quantify these effects. It would tell the degree of synlocation of roots and resources. Ideally, in a heterogeneous environment, root distribution over soil patches of different quality should be in proportion to the benefits that may be obtained from each patch ($R_{per} > 1$). Root patterns differ from regularity for two types of reasons: an inherent pattern because branch roots originate from main axes and are originally close to them, and an imposed pattern, because soil characteristics such as structure and distribution of resources restrict or stimulate root development locally.

Van Noordwijk et al. (1993) offer a computer method for measuring the frequency distribution of distances from points in the soil to the nearest neighbour root (nearest distance between source and root). It is based on the creation of pixels images of a cross-section of a root and neighbouring soil, followed by a special computer-image-analysis procedure. Figure 8 illustrates the method. It presents created pixels images of cross-sections through a root and neighbouring soil at different degrees of root-soil contact. The root is designated by number 0. Numbers 1, 2, 3 … 8 represent distance steps between the root and a resource location. At full contact between the root and the soil we obtain a symmetric figure (Fig. 8a). In this case, the 8-steps contour is relatively far away from the root. Figures 8 b, c and d represent cases with incomplete contact between the root and the soil: no contact is assumed at the pixels marked with the symbol x. In the cases b, c, and d the percentages of root-soil contact are 75, 50, and 25, respectively. The steps-contours now appear to be asymmetric, meaning a non-uniform availability of a resource to the root. It can be seen that the 8-steps contour is closer to the root as the degree of soil-root contact decreases. Or, in other words, if root-soil contact is incomplete, the mean real travel distance between points near the root and the root is longer than in the case of complete contact, the difference being larger with a lower degree of roil-root contact. The computer method allows the calculation of R_{per} from thin soil sections.

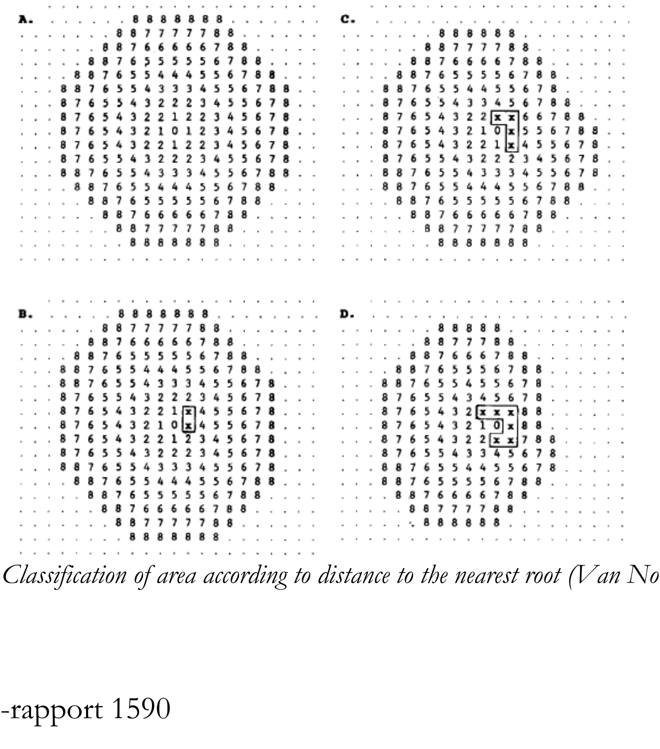

Figure 8 Classification of area according to distance to the nearest root (Van Noordwijk et al, 1993). See text

Table 5 gives some results of R_{per} measurements on a root pattern observed from thin soil sections obtained in a Lovinkhoeve soil ecology project. $R_{per}(100)$ and $R_{per}(25)$ were calculated assuming complete or 25% root-soil contact, respectively, for all roots, and assuming random orientation of the root-soil contact zones. The R_{per} values that were found (assuming complete root-soil contact) were in the range 0.8-0.9, close to that expected for random patterns for realistic values of N (number of root sections per unit surface area). For clustered patterns R_{per} values were in the range 0.7-0.85, depending on N and average number of roots per group (intensity of the clustering). Table 5 includes results for 25% root-soil contact as well. The Table shows that for higher numbers of root intersections per unit surface area, N, and complete root-soil contact R_{per} is less and effectivity of uptake is less; for smaller N, values of R_{per} are higher and effectivity of uptake is higher. The effect of partial root-soil contact on R_{per} was smaller than expected. Further checks of the method are needed.

Table 5 Root densities and root position effectivity ratio (R_{per}) for horizontally oriented thin-section samples from three depths at two fields (12B and 16A) of the Lovinkhoeve soil ecology experiment, under winter wheat (Van Noordwijk et al., 1993)

Depth, m	N/cm^2		R_{per} (100)		R_{per} (25)	
	12B	16A	12B	16A	12B	16A
0.15	4.90	4.25	0.79	0.80	0.73	0.75
0.25	2.85	1.86	0.82	0.82	0.78	0.77
0.40	0.81	0.28	0.88	0.89	0.85	0.87

8 Water stress in relation to soil layering and a non-uniform root distribution

If the evapotranspiration of a tree is not limited by too wet or too dry soil conditions, it is called potential evapotranspiration T_p. If it is limited by too wet or too dry soil conditions, the actual evapotranspiration, T_a, is lower than T_p. It is widely accepted that for homogeneous soil conditions and a uniform root distribution, the relation between T_a and T_p can be presented by a reduction factor *a*, according to:

$$T_a = a * T_p, \qquad 0 \leq a \leq 1$$

Usually, this reduction factor α is given graphically, an example being Figure 9.

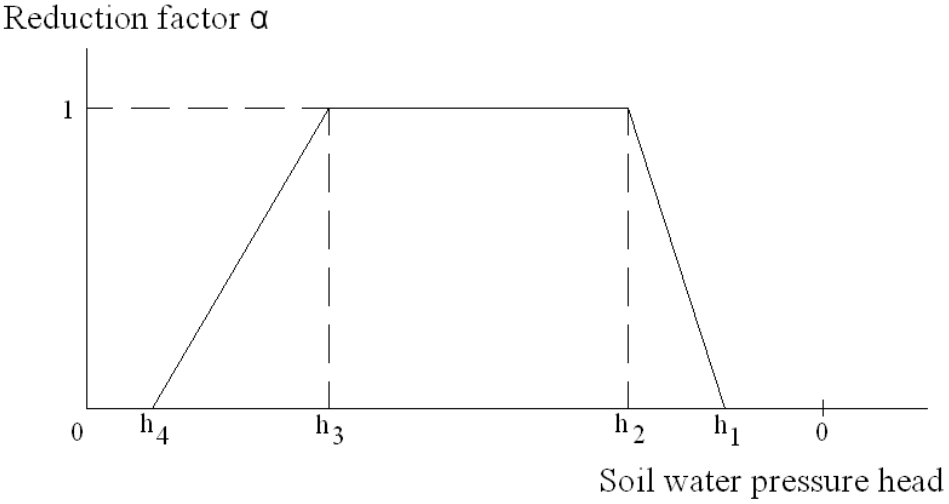

Figure 9 Reduction factor a for the evapotranspiration of a tree with a uniform root distribution in a homogeneous soil volume (see text).
h_1 = limiting pressure head above which no water extraction is possible,
h_2 = h below which optimal uptake starts,
h_3 = h below which water uptake reduction starts,
h_4 = wilting point, no water uptake at lower pressure heads

Often, the soil conditions and the root distribution are not uniform. For a layered root zone with *n* layers and root lengths $l_{r,i}$ in layer *i*, it is widely assumed that the potential water uptake from layer *i* equals (Kroes and Van Dam, 2003):

$$S_{p,i} = \frac{\text{root length in layer } i}{\text{total root length}} \times T_p$$

The sum of all $S_{p,i,}$ equals $T_{p.}$
For non optimal conditions in layer *i*, the potential uptake from layer *i*, $S_{p,i,}$ is reduced by a reduction factor a_i.

$S_{a,i} = a_i * S_{p,i,}$

The factor a_i is defined analogous to *a*. See Figure 10.

where $S_{,a,i,}$ is the actual water uptake from layer *i*.

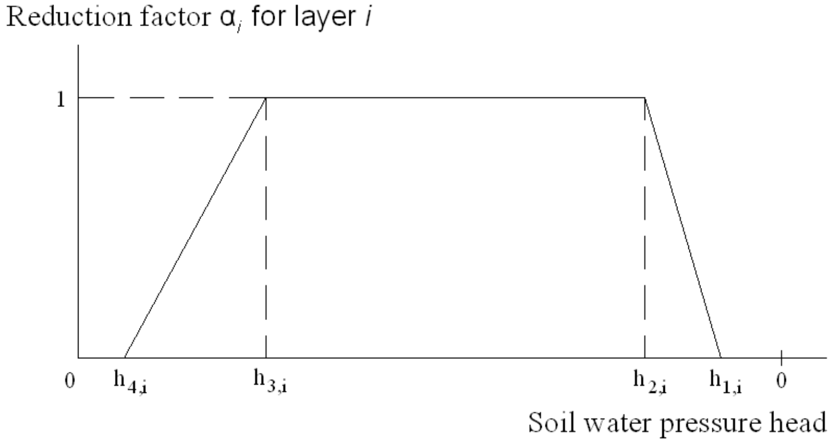

Figure 10 Reduction factor a_i *for the water uptake from layer i in a layered root zone..*
$h_{1,i}$ *= limiting pressure head in layer i above which no water uptake from layer i occurs,*
$h_{2,i}$ *=* h_i *below which optimal water uptake from layer i starts,*
$h_{3,i}$ *=* h_i *below which water uptake reduction in layer i starts,*
$h_{4,i}$ *= wilting point of layer i*

If, in one or more layers, the soil and root conditions deviate from "normal" (e. g., fine roots growing near one side of a macro-pore or a fissure and/or a non-uniform distribution of the roots within the layer), the above concepts may still be used. Then, for each layer, the layers root length may be replaced by an effective layer root length using the root position effectivity ratio (as defined in (Van Noordwijk et al., 1991), see chapter 7) of each layer.

The above model, which is widely accepted in plant growth modeling, predicts that water stress in a rooted layer is not compensated for by an increase of water uptake from other layers. It means that the instantaneous response of the tree on this water stress is: growth reduction. This reduction is larger when the root content in this layer is, relatively, larger. The tree can only respond by increasing root growth in layers without or with less water stress. The model also demonstrates the importance of avoiding changes of local water regimes within the substrate (changes in time from place to place): it would be very disadvantageous if the tree develops many roots in a layer which later will suffer from drought.

9 Water uptake from heterogeneous substrates under water stress

Herkelrath et al. (1977) studied the water uptake of a plant that rooted in soil layers with different water regimes. In particular, they studied ecological aspects of roots in a soil layer under water stress between two well-watered layers.

The water to be taken up flows in the direction of decreasing water potential through the soil to the root surface, and across the root membrane into the xylem. The flow system in a homogeneous soil layer is approximated by a network of cylindrical roots withdrawing water from concentric soil cylinders, each with an outer radius equal to one-half of the average distance between roots. Flow to individual roots is assumed to be purely radial. The water content in the soil cylinder is nearly constant except in a thin shell next to the root. To a good approximation, the water content at the circumference of the soil cylinder can be set equal to the average water content of the soil cylinder. The major resistance to water uptake is in the root and not in the soil. Within the root, the longitudinal resistance to water flow (xylem resistance) is small compared to the root membrane resistance. Therefore, the resistance of a unit of root length to water uptake is independent of depth. It is assumed that, within the xylem of the entire plant root system, the water potential does not vary from place to place.

The authors hypothesized that the decrease in extraction rate occurring when water stress starts is due to a decreasing area of contact between the root and the soil water. As water is withdrawn by the roots, the air-water interface retreats in smaller fillets, leaving areas of the root surface unwetted and hence unavailable for water uptake. The authors assumed that the effective conductivity of a root segment is proportional to the wetted fraction of the surface area of that segment. The authors further assumed that this wetted fraction, f, is equal to:

$f = \theta/\theta_s$

with:
θ = volumetric water content of the soil layer,
θ_s = volumetric water content of the soil layer at saturation.
The authors verified their theories by experiments. For the soil layer, θ depends on the pF value of the soil layer. This dependency is given by the soil-specific pF-curve. Also θ_s depends on the pF curve. Thus, f of the layer is fully determined by the pF value and the pF curve of the layer. If f is mall, the root experiences the soil as a dry soil.

Let us now consider substrates that are mixtures of sand, peat and clay soil. Figure 11 presents pF curves of a number of soil types (Bolt et al., 1972). Assume that the substrate was for a long time, and is, in a condition imposing water stress to the tree, e.g., pF=4, and that the clay-soil and peat components are the soils with numbers 7 and 6, respectively. Number 7 is a marine clay soil. Number 6 is a young peatmoor peat. The values of θ at pF=4 and θ_s can be read from the curves at pF=4 and pF="0", respectively. It can be seen from the pF-curves that, for this state of dryness, the f-value of the peat is much smaller than the f-value of the clay soil. It means that, at rather dry conditions, the roots experience the peat as more dry than the clay soil, although the pF-value is uniform throughout the substrate. According to root ecological principles, a logical consequence is that the fine roots would have developed most intensively in and near the clay-soil aggregates. On the other hand, in case the roots would have developed in a moist soil water regime, without any waterstress, it might be speculated that the fine roots preferred to grow in and near peat parts, because peat generally has a higher CEC than clay soil. If after this optimal period a sudden drought sets in, the root concentration at the peat may appear to be suboptimal, causing non-synlocation of water and roots. It seems that, for heterogeneous mixtures, a stable non-fluctuating water regime is important.

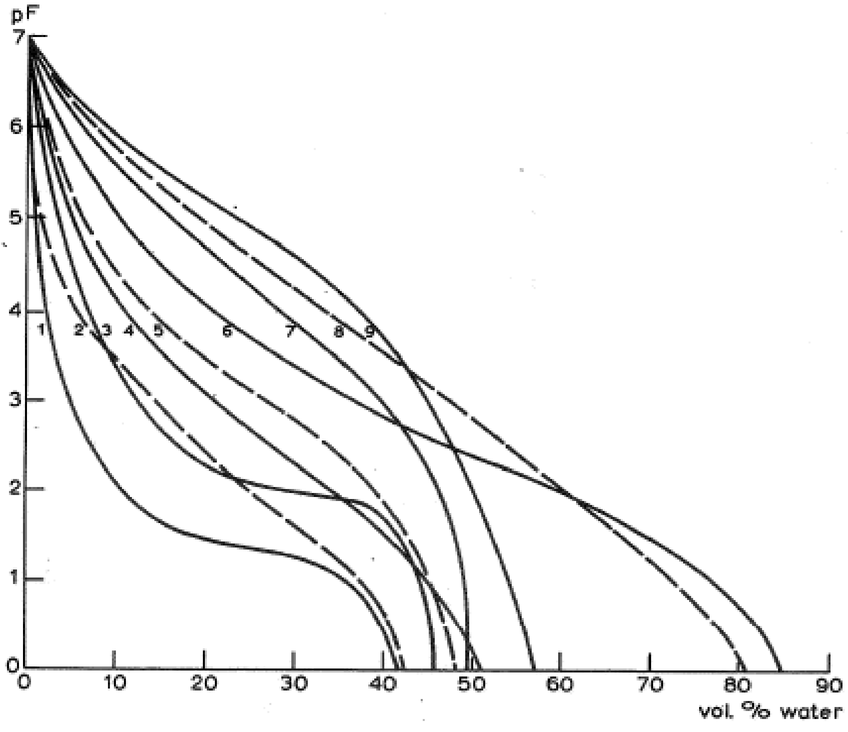

Figure 11 pF-curves of several dutch soil types. 1. dune sand; 2. loamy sand; 3. calcareous fine sandy loam; 4. calcareous loam; 5. silt derived from loess; 6. young oligotrophous peat soil; 7. marine clay; 8. eutrophous peat soil; 9. river basin clay (Bolt et al., 1972)

10 Aggregation of soil particles by soil biota

Dorioz et al. (1993) did experiments in order to find the role of roots, fungi and bacteria in clay particle organization. It is known that these organisms support the aggregation of clay particles. But it is difficult to separate the specific role of each organism and to reveal the basic phenomena involved in the initiation and stabilization of aggregates. Most research on this subject addressed the stabilization of pre-existing aggregates rather than the first stages of aggregation in initially structureless clays.

The authors tested monocultures of various species of bacteria, fungi and young roots (up to 7 days) with root hair of grass, in three different substrates. The substrates were pastes of montmorillonite, kaolinite, and an alpine clay-soil fraction. Water potential during the tests was controlled. Water potential regime was constant or followed a predetermined variation. To avoid contamination and interaction, appropriate measures were taken. The development of clay particle organization in each treatment was studied through Cryo-Scanning-Electron-Microscopy, in order to preserve the wet-state organizations.

With fungi, 3 main effects were observed in moist conditions: orientation of clay particles around the cells; secretion of polysaccharides that induced local binding of clay particles; and a general packing effect by hyphae. With bacteria, polysaccharide-mediated aggregation was predominant. With grass roots, modifications of the microstructure were more complex than with fungi and occurred at a larger scale.

The authors distinguish 4 basic effects of soil biota on initiating and stabilizing microaggregates:

1) mechanical effects due to penetration of roots or hyphae or due to water adsorption by the organisms,
2) a polysaccharide effect due to the secretion of polysaccharides by bacteria, fungi and roots,
3) extended effects due to the initiation and development of cracks and fissures from locations that were modified by soil biota,
4) packing effects due to entangling by mycelia and by roots and root hairs.

Bacteria were responsible for micrometer-scale microenvironments, fungi for 5 – 20 micrometer ones. Roots and root hairs induced organisation of the solid matrix on the scale of a macroenvironment (20 – 200 micrometer). Filamentous organisms exerted a large-scale packing effect (50 – 1000 micrometer).

We may complement the above findings of Dorioz et al. (1993) with more general information on the dynamics of soil structure (Di Gleria et al., 1962). A prevailing soil structure is a balance of the effects of factors that favour aggregate formation and factors that favour soil physical degradation. A main degradation factor is: softening (slaking, weakening) by wet conditions. Softening is especially operative in soils with high dust content (silt and silt-like fraction sizes). Also very sensitive is much decomposed peat (black peat) the structure of which has been upgraded by freezing/thawing/drying actions (such peats are called "tuinturf" in The Netherlands, and "Humintorf" in Germany). We may also note that especially plant roots have positive effects, because of their ability to withdraw large fractions of soil water, and to dry the soil to very low water contents.

11 Cation-exchange capacity (CEC)

Cation-exchange capacity (CEC) is defined as the degree to which a soil can adsorb and exchange cations.

Any element with a positive charge is called a cation and in this case, it refers to the basic cations, calcium (Ca+2), magnesium (Mg+2), potassium (K+1) and sodium (Na+1) and the acidic cations, hydrogen (H+1) and aluminum (Al+3). The amount of these positively charged cations a soil can hold is described as the CEC and is expressed in milliequivalents per 100 grams (meq/100g) of soil. The larger this number, the more cations the soil can hold. A clay soil will have a larger CEC than a sandy soil.

Colloidal particles of clay and organic matter have negative charges on their surfaces. Mineral cations are adsorbed to the negative surface charges or the inorganic and organic soil particles. Once adsorbed, these minerals are not easily lost when the soil is leached by water and they also provide a nutrient reserve available to plant roots.

These minerals can then be replaced or exchanged by other cations (i.e., cation exchange). In general, the more clay and organic matter in the soil have the higher the CEC. Clay content is important because these small particles have a high ratio of surface area to volume. Different types of clays also vary in CEC.

The adsorbtion capacity depends on mineralogical structure of fine-dispersed fractions of soil: the adsorbtion capacity is higher if the soil mineral part contains more minerals of montmorillonite groups and hydromicas. The CEC is much less if fine-dispersed parts of minerals contain much more kaolin and amorphous hydrates of iron and aluminium (Table 6). Hence, the soil containing mainly montmorillonite or vermiculite will have adsorbtion capacity much higher then soil, which contains kaolin or illite, if other conditions being equal (Table 6).

Table 6 CEC of clay minerals at pH=7 (Soldatov et al, 1978)

Minerals	CEC, meq/100g soil
Kaolin	3-15
Montmorillonite	60-150
Illite	10-40
Peach	10-40
Vermiculite	100-150

The soil organic colloids have higher adsorbtion capacity than mineral colloids. For example, the adsorbtion capacity of humus acids from podsolic soils is approximately 350 meq/100g soil (at pH=7.0), and the adsorption capacity of humic acids from chernozem and chestnut under the same conditions is 400-500 meq/100g soil. The adsorbtion capacity of montmorillonite clay matter does not exceed 80-120 meq/100g soil. However, organic matter of most soil types contributes to adsorbtion capacity for approximately 5 %, because of their predominately consist of mineral colloids. It explains the high adsorbtion capacities of peat soils and chernozem soils, which are rich in humus substances, and the low adsorption capacities of podsolic soils, enriched with clay substances.

Hence, different fertilities of different types of soil, with similar texture and ratio of organic and mineral parts, are caused by presence of different groups of mineral colloids in them.

Organic matter an amorphous material rather than the crystalline structure of clay. The source of the net negative charges is unsatisfied carboxylic groups (-COOH) that have a dissociated hydrogen ion (becoming –COO-). There are many more of these negative charges per unit of surface area of organic matter as compared to clay, giving organic matter a much greater cation-exchange capacity. This fact provides an additional reason for the extreme importance of organic matter to the character of the soil properties (Craul,1993).

The organic matter has the greatest adsorbtion capacity. For example, humus absorbs up to 180, and humus acids up to 286 meq 100 g^{-1} of soil.

The amount of absorbed cations depends on size and the contents of particles with different sizes and especially colloids, i.e. from soil texture. The dependence of capacity of cation adsorption from soil texture is shown in Table 7.

Table 7 Dependence of capacity of cation adsorption from soil texture (Zelikov,1999)

Particle size, mm	0.25 – 0.005	0.005 – 0.0001	0.0001 – 0.00025	< 0.00025
Amount of cations, meq/100g soil	0.3	15.0	37.5	63.9

Thus, the amount of cations and anions in soil depends basically on texture, mineralogical soil structure and organic matter content. The more soil contains small particles, the more ions it keeps in the adsorbed condition. For different soils the capacity of adsorption is different (Tables 8 and 9).

In general, the CEC of most soils increases with an increase in soil pH.
Two factors determine the relative proportions of the different cations adsorbed by clays. First, cations are not held equally tight by the soil colloids. When the cations are present in equivalent amounts, the order of strength of adsorption is $Al^{3+} > Ca^{2+} > Mg^{2+} > K^{+} = NH_4+ > Na^{+}$.

Table 8 Examples of CEC values for different soil textures (www.wsu.edu)

Soil texture	CEC (meq/100g soil)
Sands (light-colored)	3-5
Sands (dark-colored)	10-20
Loams	10-15
Silt loams	15-25
Clay and clay loams	20-50
Organic soils	50-100

Table 9 CEC values for different soils (Zelikov,1999)

Type of soil	CEC (meq/100g soil)
Sandy soil	1-5
Loamy sand soil	7-8
Loamy soil	7-8 - 15-18
Clay soil	15-30
Loamy podzol soil	12-18
Sod-podzol soil	16-25
Chernozem	30-50

Second, the relative concentrations of the cations in the soil solution influence the degree of adsorption. Very acid soils will have high concentrations of H+ and Al^{3+}. In neutral to moderately alkaline soils, Ca^{2+} and Mg^{2+} dominate. Poorly drained arid soils may adsorb Na in very high quantities.

11.1 Base saturation.

The proportion of CEC occupied by the basic cations (Ca, Mg, K, and Na) is termed percentage base saturation (BS%). This property is inversely related to soil acidity. As the BS% increases, the pH increases. The availability of nutrient cations such as Ca, Mg, and K to plants increases with increasing BS%.

Base saturation is usually close to 100% in arid-region soils. Base saturation below 100% indicates that a part of the CEC is occupied by hydrogen and/or aluminum ions. Base saturation above 100% indicates that soluble salts or lime may be present, or that there is a procedural problem with the analysis.

11.2 CEC and availability of nutrients.

Exchangeable cations may become available to plants. Plant roots also possess cation exchange capacity. Hydrogen ions from the root hairs and microorganisms may replace nutrient cations from the exchange complex on soil colloids. The nutrient cations are then released into the soil solution where they can be taken up by the absorptive surfaces of roots and soil organisms.

11.3 In our case study it was observed that roots in bags with substrates (especially with substrate with 12 % organic matter) were present near organic matter aggregates. It may allow the conclusion that it occurred because of the high adsorbtion capacity of organic matter and thus, high CEC. It may appear to the plant as local nutrition.

12 Cone resistance of sand fills

The cone resistance of a homogeneous sand fill is zero at the soil surface, increases linearly with depth at shallow depths, and is nearly constant (nearly independent of depth) at greater depths (CROW, 2004). The boundary between both depths is called "transition depth". The cone resistance in the shallow depth region is indicated as "inclination of the cone resistance" (cone resistance at a particular depth divided by this particular depth, MPa/m). The transition depth is deeper for larger cones and higher sand compaction degrees. The inclination of the cone resistance increases with increasing compaction degree of the homogeneous sand fill. The cone resistance increase at shallow depths may be explained as follows. A moving cone in sand moves sand grains relative to other grains. These relative movements are accompanied by grain-grain frictional forces. At shallow depths, these frictional forces are proportional to the weight of the overburden soil, thus proportional to cone depth. Below the transition depth, the grain movements are limited to a slip zone that is entirely located within the sand fill, not experiencing any influence of its overburden.

The penetration resistance of clays is dominated by cohesive forces rather than by frictional forces. There is no clear relationship between soil cohesion and weight of overburden. So, the concept of "inclination of cone resistance" does not apply to clays.

Kareva (2005, pg 72) reports earlier work from "New York Boomadvies" indicating that the inclination of the cone resistance of the sand fill above the underground parking of "Het Plein" equals about 8 MPa/m. This was measured with a 10 mm^2 cone. According to a transformation table for cone sizes, Fig. 2.39b and Fig. 2.11 of (CROW,2004) it means that the compaction degree of the "Het Plein" sand fill is 91-96% of the standard Proctor density. For tree sands, this range may be considered as rather high.

13 Water repellency

Hydrophobic soil is wetted with difficulty, as it repels water. In this case the amount of soil water accessible to plants is decreased and, as a consequence, lack of soil water reduces availability of nutrients to plants, suppressing growth further and reducing productivity of plants. Besides, water which cannot penetrate into the soil surface runs off and increases soil erosion.

Causes of water repellency. It has been recognized for many years that the water repellency of a soil is a function of the type of organic matter contained in it. Organic matter induces water repellency in soils by several means:

- irreversible drying processes in organic matter can induce water repellency, mainly in the surface layers of peat soils, which rewet with difficulty after drying;
- organic substances that leached from plant litter can induce water repellency in sandy and coarse-grained soils;
- hydrophobic microbial by-products that coat mineral particles may induce wetting resistance; mineral particles need not be individually coated with hydrophobic materials;
- intermixing of mineral soil particles with particulate organic matter, like remnants of roots, leaves and stems, may also induce severe water repellency.

Organic coating does not necessarily cover the soil particle(s) completely nor is it always very thick. A thin and/or partial covering of the soil particle can render it water-repellent.

It was supposed earlier, that the reason of water repellency is the presence of fungal hyphae covering separate particles of soil. By means of a scanning microscope it was possible to identify some of such species (*Helminthosporium, Alternaria, Curvularia*). However, particles with fungi have been found both in hydrophobic and in hydrophilic soils. Therefore it is considered that the development of fungi can only promote the formation of water repellency, but is not the direct reason of its formation.

The coating is believed to originate from living or decomposing plants and/or micro-organisms, but its exact chemical nature is not completely understood (Figures 12 and 13).

Some debate has arisen over the question whether the repellent coating belongs to the humic or fulvic acid fraction of the organic matter. Humic acids have been regarded by numerous researchers as the origin of hydrophobicity.

Most forms of organic matter in a soil possess both hydrophilic and hydrophobic groups. The hydrophilic groups interact with water molecules when the soil is wet, but tend to interact with each other in dry soil. Furthermore, freeze-drying converts a very severely water repellent soil into a readily wettable soil, while subsequent rewetting and oven-drying regenerates the original water repellency. These changes have also been ascribed to changes in the molecular conformation of the organic compounds. When the soil is oven-dried, the loss of the water may make the polar groups interact with each other, and the organic matter then has largely only non-polar groups (e.g., methyl and methylene) on its surface. Ma'shum et al. (1988) found that hydrophobic materials contain extensive poly-methylene chains, including both long-chain fatty acids and esters. It was shown by Valat et al. (1991) that the humic polymers found in most decomposed peats contain polar as well as non-polar sites, the former groups being hydrophilic and the latter hydrophobic. They claimed that, in the drying process, polar groups associate with Fe- and Al-oxides and –hydroxides, causing the system to become hydrophobic when dry.

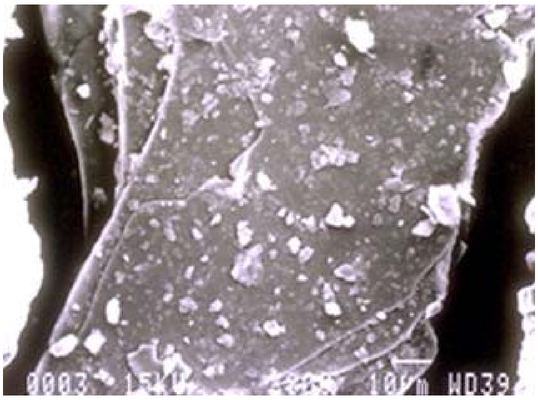

Figure 12 Electronic micropicture of a sandy particle taken from a site with water-permeable (hydrophilic) sand. http://hcs.osu.edu/sk/notes

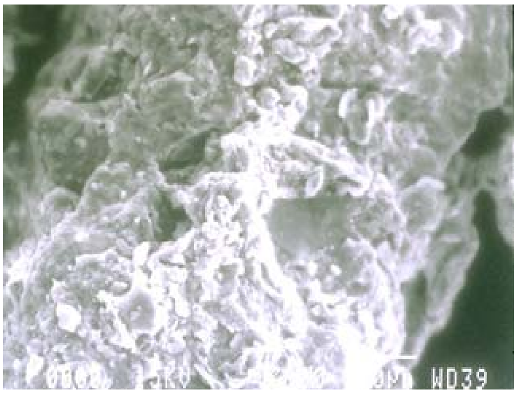

Figure 13 Electronic micropicture of a sandy particle taken from a site with hydrophobic sand (the nature of coating is not established). http://hcs.osu.edu/sk/notes

Moisture content. Water repellency of a soil depends on its moisture content. The fundamental principles underlying the process of wetting show that a reduction in the surface tension of a solid substance to be wetted reduces its wettability. Conversely, a reduction in the surface tension of the applied liquid increases wettablity. The liquid-solid contact angle is dependent on the surface tension of the liquid. In general, when the surface tension of the liquid decreases, the liquid-solid contact angle will also decrease.

An air-dry soil repels water the most. Wet soil might not be water repellent. The severity of water repellency is not the same for all dry soils and can be determined using either of two tests: a test based on the measurement of water drop penetration time, and a test based on the alcohol percentage of a drop that shows a defined penetration rate. The Water Drop Penetration Time (WDPT) test consists of the following. Three drops of distilled water from a standard medicine dropper are placed on the smoothed surface of a soil sample, and the time that elapses before the drops are absorbed is determined (Figure 14). This test may be applied to dry as well as to field-moist samples. Five water repellency classes may be distinguished (Table 10). The second method is the alcohol percentage test. Water containing increasing concentrations of ethanol is applied in drop form to the surface of soil samples until a concentration is reached where immediate infiltration occurs. At this concentration, the aqueous ethanol drop has a sufficiently low surface tension to overcome the surface water repellency restriction to infiltration. If a high concentration of ethanol is required for incipient infiltration, this is indicative of hydrophobic soils.

Table 10 Classification of the persistence of soil water repellency

Class	WDPT	Nomenclature
0	< 5	wettable; non-water repellent
1	5 – 60	slightly water repellent
2	60 – 600	strongly water repellent
3	600 – 3600	severely water repellent
4	> 3600	extremely water repellent

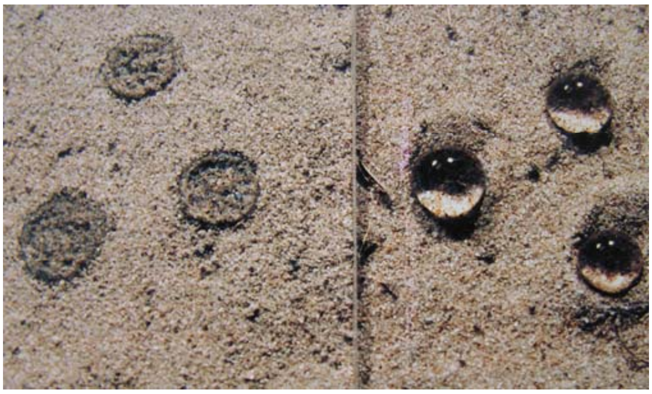

Figure 14 Test of water drop penetration time (WDPT)

Rates of infiltration into water repellent soils can be considerably lower than into wettable soils. Moreover, wetting patterns in water repellent soils can be quite irregular and incomplete (Figure 15). Soil water repellency in superficial layers appears to be most expressed. The most severe water repellency usually occurs in the top 1-2 inches of the profile. However, occasionally, hydrophobic soil is found at a 6-inch soil depth.

Figure 15 Non-uniform distribution of painted (marked) water in the top layers of a soil structure in hydrophobic dune sand (Dekker, 1998)

Soil hydrophobicity is influenced by season and by soil moisture content. In most cases, soil hydrophobicity decreases (but does not disappear) during the winter months and is most severe during the summer. This seasonal variation may be due to temperature and/or soil moisture conditions. Long, hot dry periods are most conducive to the formation of hydrophobic soil. Likewise, extremely wet weather can lessen or even eliminate hydrophobicity for several weeks. There appears to be critical moisture content for each hydrophobic soil. When soil moisture content is above this critical point, the water-repellency effect is temporarily eliminated. When soil moisture falls below this critical point, the soil returns to a hydrophobic condition. It is unclear what governs this critical moisture point, but it varies among soils and is largely influenced by soil texture.

Soil texture. Capriel et al. (1995) investigated the hydrophobicity of the organic matter in soils with widely differing textures and organic-C contents. They found that the organic matter of sandy soils contains relatively more alkyl-C and less carbohydrates and proteins compared with the organic matter of clayey soils. In other words, the organic matter of sandy soils is more hydrophobic.

Coarse-textured, sandy, soils are most likely to become water-repellent, because sand has a relatively small surface area per unit of volume, making it much more susceptible than clays. Soils with high contents of organic matter are also susceptible to hydrophobicity. In many cases, adding small amounts of clay or other materials with a large surface area can reduce or even eliminate water repellency of a predominately sandy medium. However, this practice may create other problems such as reduced water infiltration, layering, increased likelihood of compaction, etc. The ability of clays to disperse and thus to spread over the hydrophobic surfaces of the sand grains was found to be important. An important property of clays with respect to their ability to increase wettability is dispersability.

The efficiency of clay in decreasing the severity of water repellency of sands is dependent on the ease with which they can be dispersed, and this is related to both their sodicity and particle shape, which is primarily determined by mineralogy. Thus, because of their microstructure, kaolinite and illite are more effective in decreasing hydrophobicity than montmorillonite.

In the experiments of Ma'shum et al. (1988) various raw clays were applied to test their ability to render hydrophobic sands wettable. Factors of concern in the mixing of dry clays with sands included the aggregate size of the crushed clays and the possible role of the organic matter present in clays. Four crushed clays were sieved to give particle size fractions of < 0.053 mm and 0.053-0.090 mm. While the finer fractions were generally more efficient than the coarse fractions, the differences were not large, but it became clear that the clays based on kaolinite and illite were more efficient than the clay based on smectite.

One controlling factor of the dispersibility of clays is the nature of the exchangeable cations. A second factor is the shape and packing of individual clay particles, which is usually related to clay mineralogy. Particles of kaolinite are usually blocky and rigid with a width to thickness ratio of about 2, illite particles are platy and rigid with width to thickness ratios around 10, while montmorillonite units are thin flexible sheets with width to thickness ratios more than 100. Thus, particles of kaolinite and illite cannot be packed together as well as sheets of montmorillonite, and micro-aggregates of kaolinite and illite are more readily dispersible than those of montmorillonite, especially with Na on the exchange complex. The influence of exchangeable cations on dispersibility clearly influences the efficiency of clay fractions to reduce water repellency.

Considering our The Hague-Moscow-Wageningen project, water repellency of sand and organic matter of substrate may occur in summer time and may be a reason why fine roots develop near clayey non-hydrophobic aggregates in their search for water.

14 A research site with trees and The Hague substrate

A green square, each side of which being an alley of two rows of *Tilia* x *europaea,* was installed on the roof of an underground parking garage in 1981. The surface of the site is paved with 10 cm thick bricks on a 10 cm thick sand layer. The root zone is a 1.6 m thick substrate volume that is covered by the sand layer and overlays the roof of the underground garage. This roof has, at its circumference, a raised edge causing a perched water table.

The substrate is so-called The Hague tree sand. It is composed of sand, peat soil, and clay soil. At the time of installation, the substrate had an organic matter content of 4-5 %, a median of the sand fraction of 0.200-0.300 mm, and a clay particles content of almost 10 %.

The site was evaluated in 2002/2003. It was found that the perched groundwater layer had a thickness of half a meter in winter and of a decimetre in early summer (Figure 16). The substrate was more or less leached. Locally, organic matter content had decreased to 3 %. A survey in 2005 revealed that: the soil at the 40 cm depth was intensively rooted with fine roots; the soil in the 50-140 cm layer contained fine roots; the soil deeper than 140 cm did not contain roots; air content decreased with increasing depth; cone resistance increased with increasing depth; reduction phenomena started at a depth of 1 m.

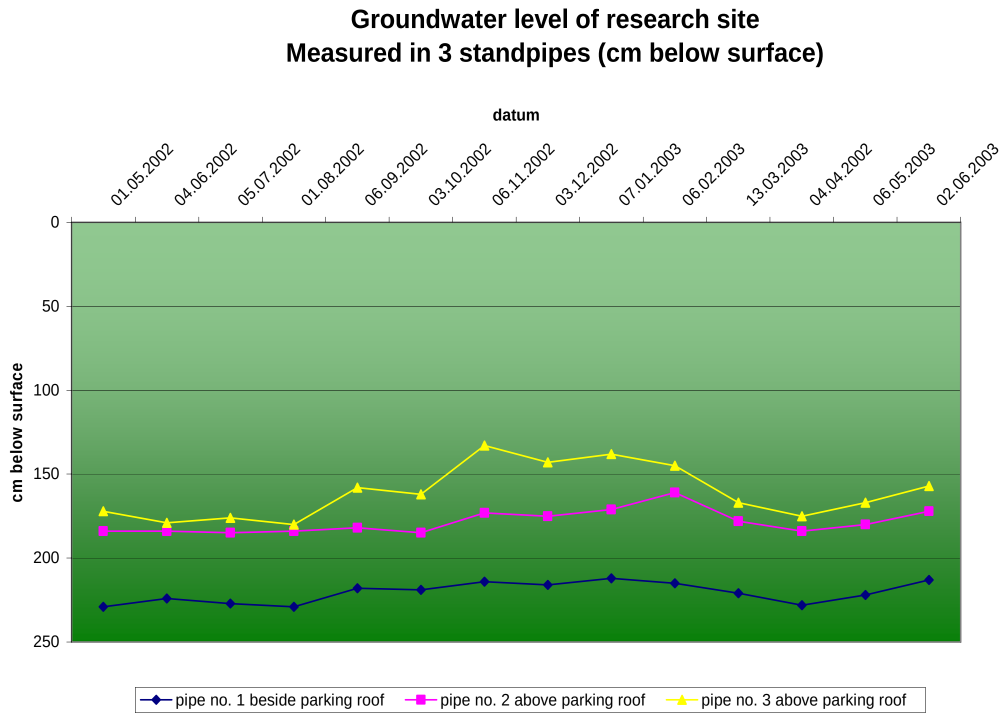

Figure 16 Course of groundwater level at 3 locations during May, 2002, - May, 2003. The bottom of the substrate is 180 cm below surface. (By courtesy of New York Boomadvies)

In April, 2005, a special experimental procedure was initiated in order to be able to collect data on the changes with time of the chemical/physical composition of substrates (Kareva, 2005). This procedure was followed in the root space of a tree with code no. 43 of the site. Four perforated 2-liter bags from nylon were installed in the root zone of this tree (Figure 17). These bags contained different substrates: a commercial substrate with organic matter content = 12 %; a substrate that was made in the laboratory by mixing a specific sand type and specific compost (organic matter content of the mix ≈ 7.5 %); the original substrate. The commercial substrates, the sand, and the compost were supplied through the City The Hague. Duplicates were stored in a deep-freezer. Physical/chemical properties of deep-frozen soil material do not significantly change with time. It was intended to take out the 4 buried bags and 4 deep-frozen bags after 2 years, to analyse them, and to compare the analysis results in order to establish to what extent physical/chemical properties had changed.

Figure 17 Installation of bags with substrates in a tree root zone (Kareva, 2005)

On February 21 of 2007, the 4 deep-frozen bags were taken out of the deep-freezer and the 4 buried bags were taken out of the root zone of tree no. 43. At the same day, undisturbed core samples and loose soil samples were taken from this root zone at 3 depths. The following sections of this report deal with this sampling, the samples analysis, the analysis results, and the discussion of the results.

15 Materials and methods

On February 21 of 2007, the soil profile of the root zone of tree no 43 of a research site in The Hague (see Section 14) was visually inspected and sampled. The samples included undisturbed and disturbed soil samples, and a sample from a tree soil improver (Dendromix) that was installed some years ago. The samples were analysed in the laboratory. The analyses included: physical analysis; chemical analysis; texture determination; water repellency test; rooting; structure assessment.

Figure 18 Layering of soil profile of root zone of tree no. 43 and groundwater table

The soil profile showed a clear layering. The layers could be distinguished precisely. Layering and wet and anaerobic circumstances in the bottom part of the hole can be seen in Figure 18. The origin of the horizontally oriented layers lies in the way of making the sand filled at the time of installation. Also a groundwater table can be seen in the figure. The top layers of the soil profile were more strongly compacted than the bottom layers. It was revealed, that tree roots in the digging zone were located non-uniformly in a lengthways direction in the soil profile. All mass of the roots in this digging zone were developed within a 2-years period. They were confined to an upper soil layer, to a depth up to 1 m. The bulk mass of the roots (basic fine and average roots) was concentrated in the top layer of soil (up to 40 cm depth) under the pavement foundation. Between 40-100 cm the amount of roots varied from place to place, there were some locations without roots, and some locations with a few roots. Between 100-140 cm very few roots were present. There were no roots at depths deeper than 140 cm because of great influence of ground water on the bottom layer. The soil in the bottom layer was very wet, saturated with water, and had a blue colour, Anaerobic conditions had developed there.

Figure 19 Taking undisturbed core samples at 3 depths on February 21, 2007. Six metal cylinders can be seen in the wall of the pitch

The samples included (Table 11):

Perforated bags were in the root zone at a depth of 55 cm for two years. The bags were made from woven nylon grid (fiber thickness 0.6 mm; spacing of fibers 1.4 mm)
Bag with 5% soil mix
Bag with 12% soil mix
Bag with 7.5% soil mix
Bag with soil mix that came out of the tree pit (root zone mix) in April 2005

Duple bags were stored in the deep-freezer at the time that the perforated bags were installed in the root zone
Bag with the 5% mix
Bag with the 12% mix
Bag with the 7.5% mix
Bag with root zone mix

Undisturbed core samples in 250 cm^3 metal cylinders (Figure 19)
3 cylinders from the 40 cm depth (nrs 1, 2, 3)
3 cylinders from the 80 cm depth (nrs 7, 8, 9)
3 cylinders from the 120 cm depth (nrs 4, 5, 6)

Loose soil samples
from the 40 cm depth
from the 80 cm depth
from the 120 cm depth

Dendromix sample
Chemical analysis was also applied to a sample taken from a soil improver, called "Dendromix" that was installed in the root zone some time ago. Figure 20 shows the Dendromix column after removing the overlaying soil. At the time of sampling, the Dendromix had a brown colour and no roots in it.

Figure 20 Column of improver Dendromix after removing the overlaying soil

Compound mix (duple's of 500g each)

Each of the 2 compound mixes (500g) consists of the following components:

- loose soil from 40 cm depth -100g
- loose soil from 80 cm depth – 100g
- loose soil from 120 depth – 100g
- root zone soil out of deep freezer – 100g
- root zone soil out of perforated bag – 100g

Table 11 Codes of samples

B - 5	Bag with 5% soil mix from root zone
B - 7.5	Bag with 7.5% soil mix from root zone
B - 12	Bag with 12% soil mix from root zone
B - t	Bag with soil mix from the tree pit (root zone mix)
Bf – 5	Bag with the 5% soil mix from deep-freezer
Bf - 7.5	Bag with the 7.5% soil mix from deep-freezer
Bf - 12	Bag with the 12% soil mix from deep-freezer
Bf - t	Bag with soil mix from the tree pit (root zone mix) from deep-freezer
C40 - 1	Cylinder with root zone mix from the 40 cm depth nr 1
C40 – 2	Cylinder with root zone mix from the 40 cm depth nr 2
C40 – 3	Cylinder with root zone mix from the 40 cm depth nr 3
C80 – 7	Cylinder with root zone mix from the 80 cm depth nr 7
C80 – 8	Cylinder with root zone mix from the 80 cm depth nr 8
C80 – 9	Cylinder with root zone mix from the 80 cm depth nr 9
C120 – 4	Cylinder with root zone mix from the 120 cm depth nr 4
C120 – 5	Cylinder with root zone mix from the 120 cm depth nr 5
C120 – 6	Cylinder with root zone mix from the 120 cm depth nr 6
Ls – 40	Loose root zone mix from the 40 cm depth
Ls – 80	Loose root zone mix from the 80 cm depth
Ls - 120	Loose root zone mix from the 120 cm depth
Dm	Dendromix sample from the Dendromix in the root zone
Plm - 1	Loose compound mix
Plm - 2	Loose compound mix

The analyses and observations included:

Physical analysis of the undisturbed core samples

This analysis provides for the 40, 80, and 120 cm depths:
prevailing water content,
prevailing bulk density,
porosity,
prevailing air content.

Chemical analysis

The chemical analysis included the determination of:
pH-KCl, N-total, P-total, K-HCl, Mg-NaCl, Organic matter content, Cation Exchange Capacity CEC,
of:
3 samples of loose soil from the 40, 80, and 120 cm depths,
4 samples from the perforated bags from out of the root zone,
4 samples out of the deep freezer,

1 Dendromix sample.
2 compound mixes.

Water repellency
Water drop penetration time WDPT was measured according to Section 13:
on loose soil from the sampling depths of 40, 80, and 120 cm,
on soil from the bags taken out of the root zone,
at a nearly air-dry condition.

Rooting and structure assessment
Amount of roots was measured for:
the perforated bags from the root zone.
Composition of the mixtures and the quality of the components were visually assessed for:
the cylinder samples,
the perforated bags from the root zone,
the bags from the deep freezer,
rooting of the perforated bag with root zone soil.

16 Results of bags with substrates

The results of the bags with substrates are presented in the following sections: Rooting of the original substrate near the root zone bags; Visual inspection of the deep-freezer bags and the root zone bags; Rooting of root zone bags. The chemical analysis and water repellency test results are given as appendices.

16.1 Rooting of the original substrate near the root zone bags

At digging out the root zone bags, not any root was revealed in the soil near to the bags with 5 % and 7.5 % of organic matter. Near to the bags with soil mix of 12 % organic matter and with the root zone mix interlacing fine roots were found, which had penetrated to the inside of the bags. Most roots were found near the bag with the root zone mix (Figure 21).

Figure 21 Digging out bags with substrates installed in root zone of no.43 tree

16.2 Visual inspection of the of the deep-freezer bags and the root zone bags

The contents of the recovered root zone bags and the bags that were stored in the deep-freezer and thawed were visually inspected. The results of this inspection are given in Table 12. The structures of the substrates do not greatly differ between samples from deep freezer and from root zone. The main differences between the substrates are colour differences and the presence of different organic matter contents. The organic matter of the substrates from the root zone is more decomposed than the organic matter the deep freezer substrates, but fibres of organic matter are still visible. Figures 22-25 illustrate the substrates in the perforated bags from the root zone. Structure of substrate is not greatly different between samples from deep freezer and from Het Plein. The organic matter of substrate from Het Plein is more decomposed, but there are fibres of organic matter still visible.

16.3 Rooting of root zone bags

The rooting of the perforated surfaces and the contents of the root zone bags were inspected, and the roots were separated from the bag surfaces and bag contents using a pair of tweezers.

Not any root could be revealed from the contents and the surface of the bag with substrate with 5 % organic matter. The substrate was loose, with fine organic-matter aggregates smaller than 1 cm.

The contents of the bag with substrate with 7.5 % organic matter contained separate individual young, lignified roots of white colour; with diameters of 1-2 mm. Fine roots were not present. Roots had concentrated at aggregates of organic matter. The substrate inside the bag was loose, homogeneous, with organic-matter aggregates smaller than 1 cm.

At the surface of the bag with substrate with 12 % organic matter, roots with diameters up to 3-4 mm were found. Approximately 55 % of the internal surface of the bag was covered with fine roots. Inside the bag, at regular intervals, numerous interlacing of fine and average roots occurred. The roots had diameters up to 4 mm. The major part consisted of fine branching roots. The fine roots were concentrated at aggregates of organic matter. All roots were well advanced; the large roots were lignified and had a brown colour. The substrate inside the bag was loose and finely lumpy.

Table 12. Comparison of characteristics of the substrates in the root zone bags and the deep freezer bags (OM = organic matter).

	Bag with 5 % OM	Bag with 7,5 % OM	Bag with 12 % OM	Bag with Het Plein mix
Root zone	Substrate is loose, homogeneous, there are aggregates of OM with d <1-1.5 cm, fine fibres of OM are visible	Substrate is loose, homogeneous, OM is not completely decomposed, fine single fibres of OM are visible, there are aggregates of OM with d < 1 cm	Substrate is loose, homogeneous, OM is not decomposed, fine fibres of OM are visible, but they are no much, there are aggregates of OM with d <2 cm	Substrate is loose, practically homogeneous, there are aggregates of OM with d < 1 cm and aggregates of clay with d =1.5 cm
Deep freezer	Substrate is loose, homogeneous, OM is not decomposed, there are aggregates of OM and clay with d= 1-1.5 cm. Sticks, numerous fibres of OM are visible	Substrate is loose, homogeneous, OM is not decomposed, sticks, numerous fibres of OM are visible, , there are aggregates of OM with d < 1 cm	Substrate is loose, homogeneous, OM is not decomposed , the presence of fibres of OM is numerous, there are aggregates of OM with d <1.5-2 cm	Substrate is loose, practically homogeneous, there are numerous aggregates of the same soil with d < 1-1.5 cm, there are single aggregates of OM with d < 1.5 cm

For the bag with the root zone mix it was found that the great bulk of all present roots (diameters 1-1.5 mm) were concentrated at the bag surface. Inside the bag individual lignified medium-sized roots were found, with brown colour and 1-1.5 mm diameters. Fine roots were not present. The substrate in the bag was homogeneous and loose.

After separation, the roots were washed and weighed. The weight of roots is given in Table 13. The results of weighing clearly show that the bag with substrate with 12 % organic matter contained most roots. We may assume that this bag was a local nutrition for tree roots.
Figures 26-30 illustrate all roots that were collected from the bags (plate diameter = 14 cm).

Table 13. Weight of fresh roots separated from bags with substrates.

	Bag with 5 % organic matter	Bag with 7,5 % organic matter	Bag with 12 % organic matter	Bag with root zone mix
Weight of bag with roots and substrate, g	1290,5	1528,98	1775,50	1799,86
Weight of washed roots, g	0	1,19	9,77	2,71

Figure 22 Bag from research site with substrate with 5% organic matter

Figure 23 Bag from research site with substrate with 7.5% organic matter

Figure 24 Bag from research site with substrate with 12% organic matter. Interlacing of roots is visible

Figure 25 Bag with root zone mix. Single roots are visible

Figure 26 Roots from bag with root zone mix

Figure 27 Roots from bag with 7.5% organic matter

Figure 28 Roots from bag with 12% organic matter

Figure 29 Roots near organic matter (from bag with 12 organic matter)

Figure 30 Fine roots near organic matter (from bag with 12 organic matter)

Chemical analysis and Water repellency test results are given as appendices.

17 Results of undisturbed core samples

The results of the undisturbed core samples include: physical properties; visual inspection at enlargement; chemical analysis. The physical property measurements and the visual inspections are treated in this section. The chemical analysis results are given in an appendix.

Physical properties. Undisturbed soil cores were taken with metal sampling cylinders (Section 15). After sampling, each cylinder with core sample was placed on a metal plate. The samples, together with the cylinders and plates, were weighed, and placed in an oven for drying at temperature 105 ºC for 3 days. During the drying period, the samples were repeatedly weighed in order to find the drying state where residual water content was negligible. On the basis of the received data of weight of soil in wet and dry conditions, data of water content, bulk density, porosity and air content were calculated. The formulas for the calculations are listed below.

Water content:

A – weight of wet soil + cylinder + plate, g
B – weight of dry soil + cylinder + plate, g
C – weight of cylinder + plate, g

Weight of water = A – B, %
Weight of dry soil = B – C, %

$$Gravimetric\ water\ content = \frac{Weight\ of\ water}{Weight\ of\ dry\ soil} \times 100 = \frac{(A-B)}{(B-C)} \times 100,\ \%$$

$$Volumetric\ water\ content = \frac{Gravimetric\ water\ content}{Dry\ bulk\ density},\ \%$$

Bulk density:

$$Dry\ bulk\ density = \frac{Weight\ of\ dry\ soil}{Volume\ of\ cylinder} = \frac{(B-C)}{V},\ g/cm^3$$

V – volume of cylinder, cm^3
Measured V = 248.23 cm^3
Nominal V = 250 cm^3

Density of solids:

Organic matter (OM) fraction of soil mix from 40 cm depth = 0.018 (see appendix)
from 80 cm depth = 0.019 (see appendix)
from 120 cm depth = 0.016 (see appendix)
Lutum fraction = 0.08 (estimated from the The Hague regulations for substrates)
Sand fraction = 1-0.08 – 0.028 = 0.892
d = bulk density of solids. For Dutch soil components, the following values are often used:

$d_{om} = 1.4$ g/cm^3
$d_{lutum} = 2.88$ g/cm^3
$d_{sand} = 2.66$ g/cm^3

(Organic matter fraction + lutum fraction + sand fraction) should be 1

$$d_{mix} = \frac{1}{\frac{Organic\ matter\ fraction}{d_{om}} + \frac{lutum\ fraction}{d_{lutum}} + \frac{sand\ fraction}{d_{sand}}}, g/cm^3$$

$$d_{mix,40} = \frac{1}{\frac{0.018}{1.4} + \frac{0.08}{2.88} + \frac{0.892}{2.66}} = 2.66 \quad g/cm^3$$

$$d_{mix,80} = \frac{1}{\frac{0.019}{1.4} + \frac{0.08}{2.88} + \frac{0.892}{2.66}} = 2.66 \quad g/cm^3$$

$$d_{mix,120} = \frac{1}{\frac{0.016}{1.4} + \frac{0.08}{2.88} + \frac{0.892}{2.66}} = 2.67 \quad g/cm^3$$

Porosity:

$$Porosity = \left(1 - \frac{Dry\ bulk\ density}{d_{mix}}\right) \times 100,\ \%$$

Air content:

$$Air\ content = Porosity - Volumetric\ water\ content,\ \%$$

Results of the calculations are presented in Tables 14 and 15. Table 14 presents results of calculations of physical properties of soil samples from the root zone on the basis of measured volume of sample cylinders (V=248.24 cm^3); Table 15 presents results of calculations of physical properties of these soil samples on the basis of nominal volume of sample cylinders (V=250 cm^3). The results are mean values of 3 samples per sampling depth. Extreme values for bulk density within each group of 3 samples were 1.53-1.58, 1.45-1.53, and 1.33-1.38 g/cm^3 for the 40 cm, 80 cm and 120 cm depths, respectively (based on V = 248.24 cm^3).

Interpretation of these results may use the following information. For the development of root systems of woody plants best conditions are created if porosity of the soil equals 55-65 %; at porosity = 35-40 % roots get into the soil hardly. Non-capillary porosity provides penetration of air into the soil: aeration. For the horizons most mastered by roots non-capillary porosity is more than 10 %; at its decrease to 3 % the bottom horizons become inaccessible for roots. For normal development of plants it is important that soil has a high capillary porosity and that its aeration porosity is not less than 20 % of the soil volume.

According to the calculation results (Tables 14 and 15) it may be concluded that porosity increases with depth. Values of porosity in layers of soil profile at depths of 40 and 80 cm are less than normal, which is connected to compaction of top layers of soil as a result of traffic on the paved surface. At the depth of 120 cm porosity is a little higher and, accordingly, compaction of soil is less. So porosity for top layers is less than optimal for plants.

Table 14. Calculated mean values of physical properties of soil samples from the root zone (according to measured cylinder volume V=248.24 cm³).

Depth	Gravimetric water content,%	Dry bulk density, g/cm3	Volumetric water content,%	Porosity, %	Air content, %
40	17.61	1.56	27.40	41.51	14.11
80	21.36	1.48	31.66	44.22	12.56
120	21.86	1.35	29.53	49.40	19.87

Table 15. Calculated mean values of physical properties of soil samples from the root zone (according to nominal cylinder volume V=250 cm³).

Depth	Gravimetric water content,%	Dry bulk density, g/cm3	Volumetric water content,%	Porosity, %	Air content, %
40	17.61	1.55	27.21	41.92	14.71
80	21.36	1.47	31.44	44.62	13.18
120	21.86	1.34	29.32	49.75	20.43

For maintaining the best conditions of the gas composition of soil air (aeration) for the growth of plants and development of microorganisms, it is necessary that porosity of aeration of the top horizons of the soil profile should be within the limits of 15-20 % of the soil volume.

Air content (porosity of aeration) in the root zone also increases with depth (Tables 14 and 15). The values of air content are less than optimal for plants but it is normal for this period of year (winter period (February)).

For plants, the value of bulk density of the top horizons of soil is optimum if it is within the limits of 0.95-1.15 g/cm^3. If bulk density of soil equals 1.6-1.7 g/cm^3, roots of woody plants practically do not penetrate into the soil (if density of soil solids equals 2.66 - 2.70 g/cm^3).

According to a Russian classification for humus horizons (Table 16) the soil at the research site is highly compacted.

Table 16. Russian classification of soil bulk density of top horizons (Zelikov,1999).

Bulk density, g/cm^3	Nomenclature
0.9-0.95	Loose
0.95-1.15	Normal
1.15-1.25	Compacted
>1.25	Highly compacted

Visual inspection. The dried-out soil from the cylinders was examined under a microscope. It was observed that soil structure was disturbed during the time, sand particles were distributed and almost uniformly mixed with organic matter, but part of the organic matter and clay aggregates can still be recognized. In general, the soil structure is weakened and amorphic.

There are no specific differences between soils from cylinders from different depths. Figures 31-33 illustrate soil structure in field-moist conditions at low enlargement. It is possible to distinguish separate aggregates.

Figure 31-a Cylinder with root zone mix from the 40 cm depth

Figure 31-b Cylinder with root zone mix from the 40 cm depth (clay and organic matter aggregates)

Figure 31-c Cylinder with root zone mix from the 40 cm depth

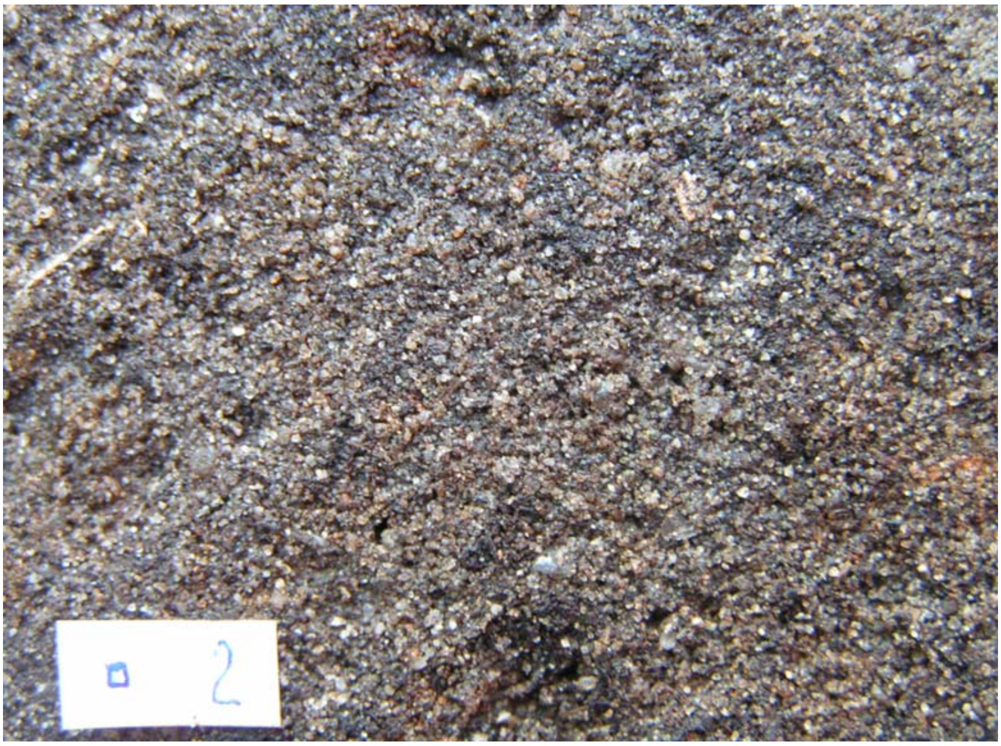

Figure 31-d Cylinder with root zone mix from the 40 cm depth (organic matter with sand)

Figure 31-e Cylinder with root zone mix from the 40 cm depth

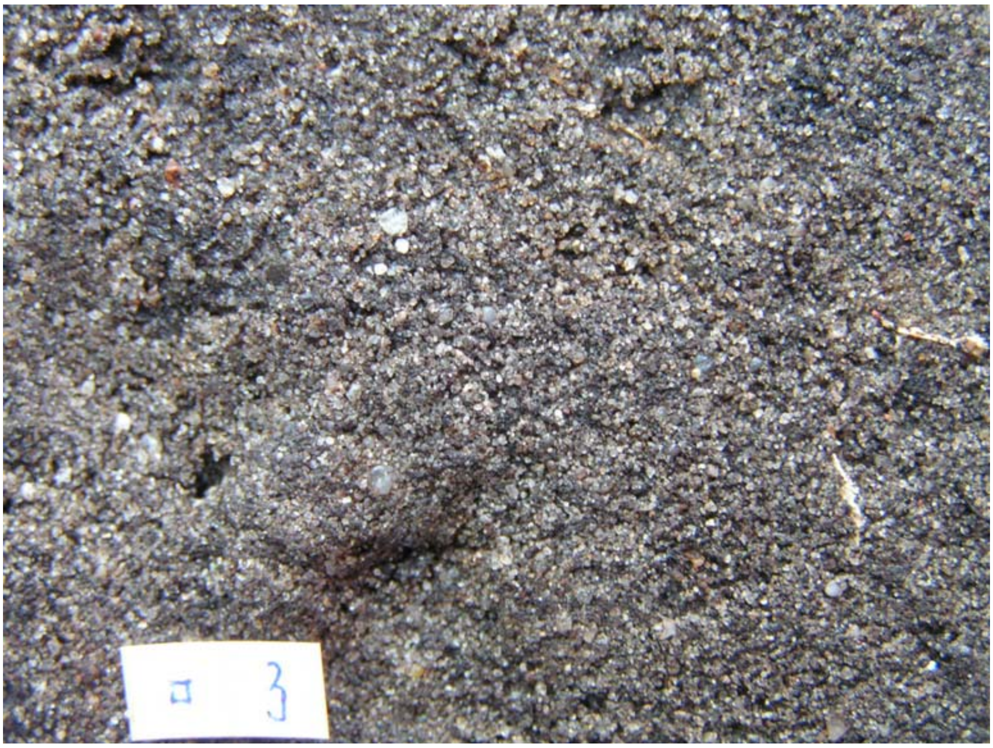

Figure 31-f Cylinder with root zone mix from the 40 cm depth (organic matter aggregate)

Figure 32-a Cylinder with root zone mix from the 80 cm depth

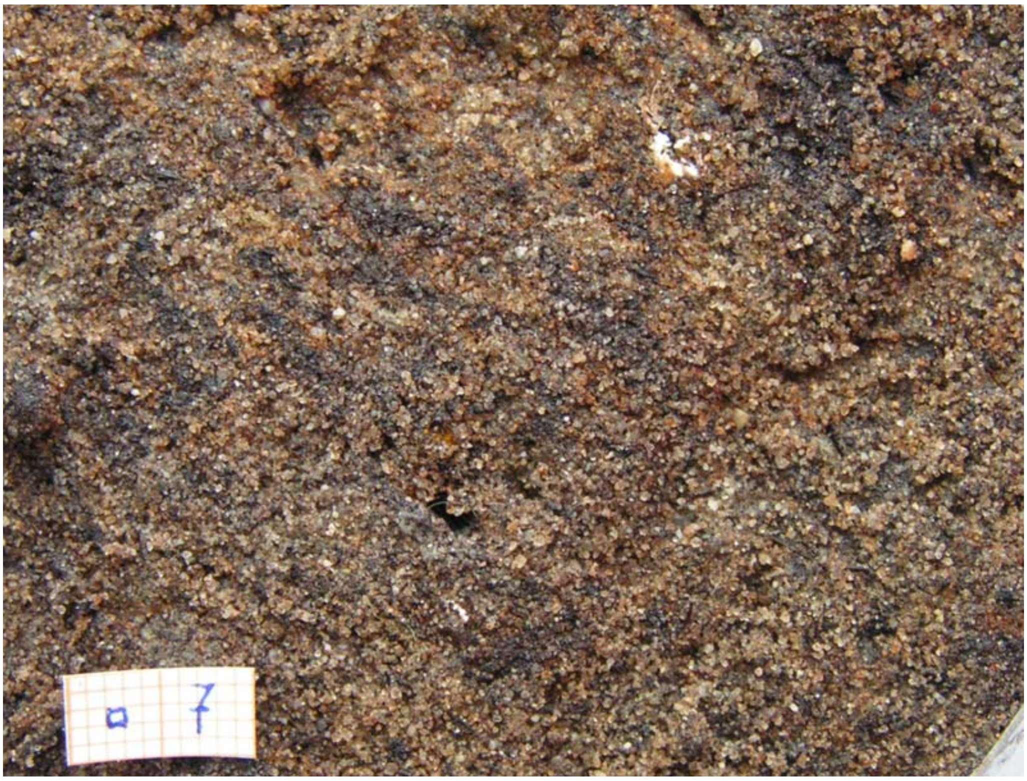

Figure 32-b Cylinder with root zone mix from the 80 cm depth

Figure 32-c Cylinder with root zone mix from the 80 cm depth (organic matter with sand)

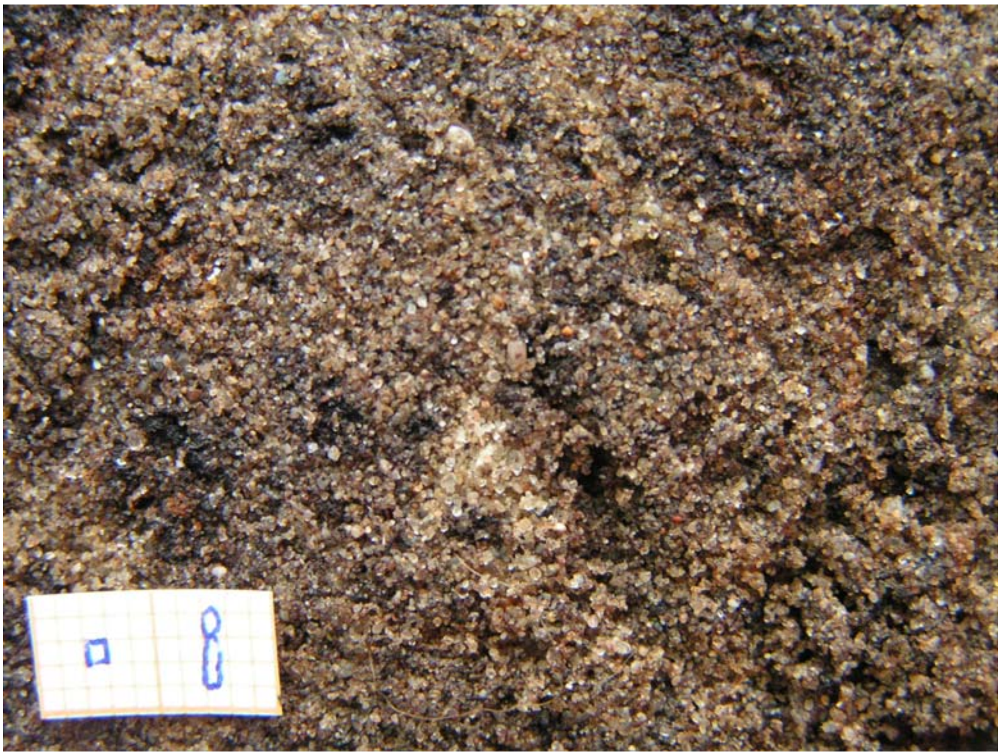

Figure 32-d Cylinder with root zone mix from the 80 cm depth

Figure 32-e Cylinder with root zone mix from the 80 cm depth

Figure 32-f Cylinder with root zone mix from the 80 cm depth

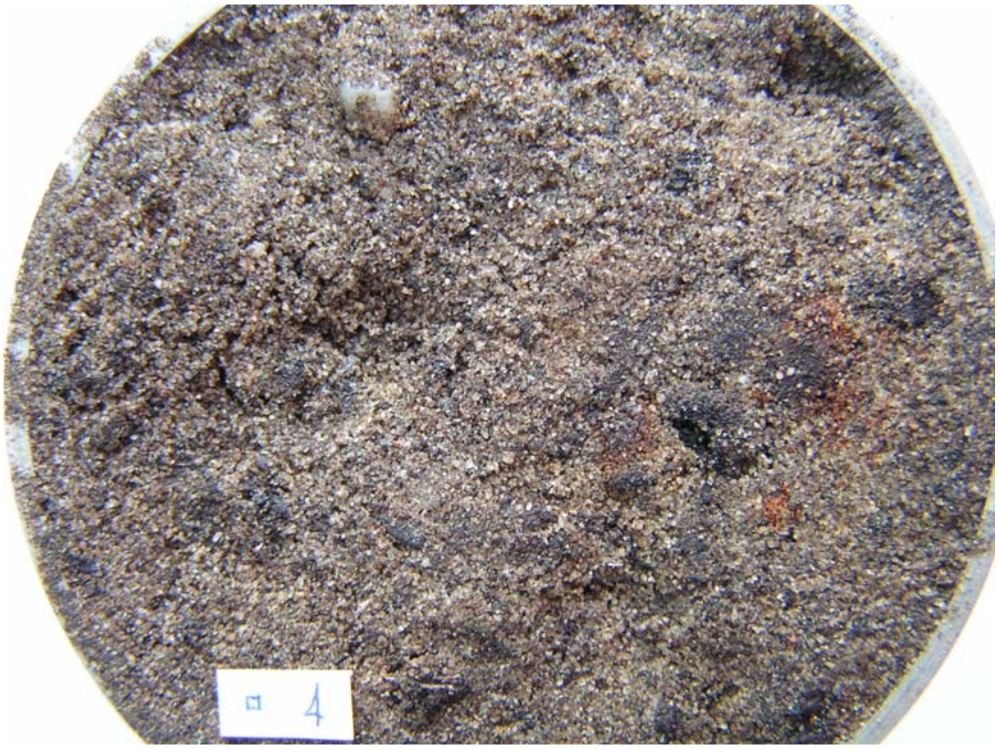

Figure 33-a Cylinder with root zone mix from the 120 cm depth

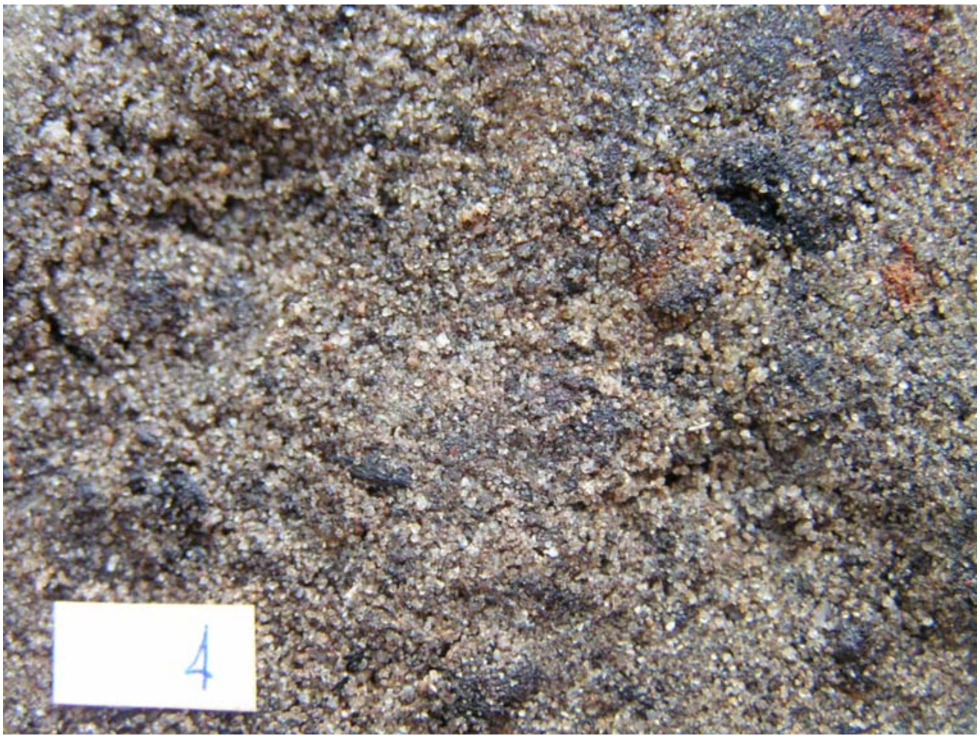

Figure 33-b Cylinder with root zone mix from the 120 cm depth (organic matter aggregates)

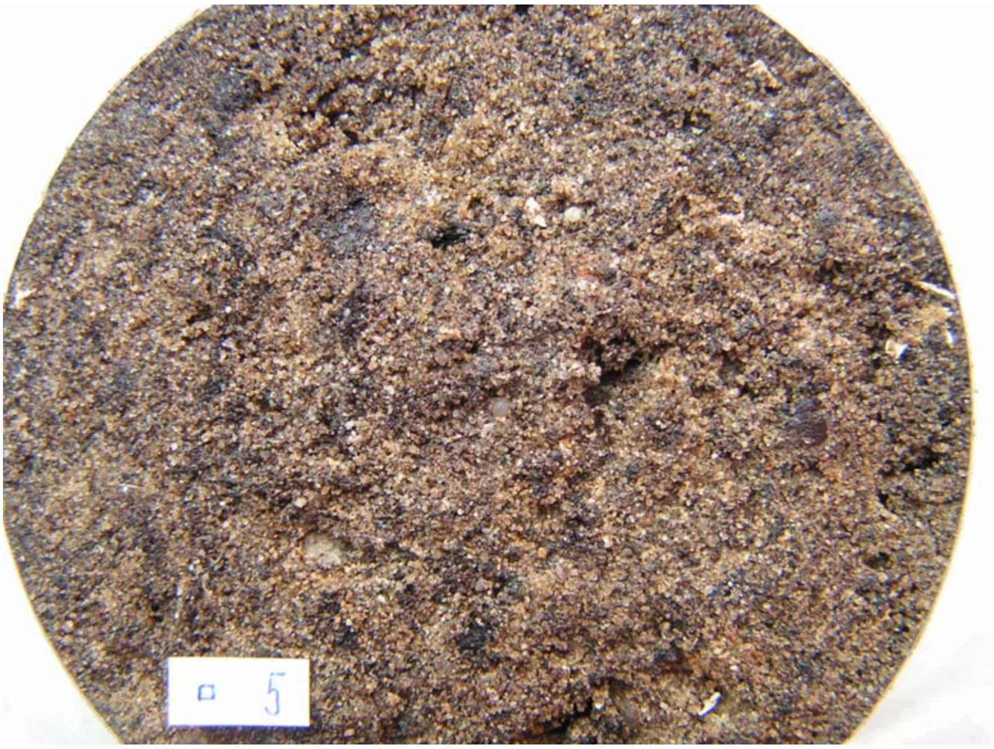

Figure 33-c Cylinder with root zone mix from the 120 cm depth

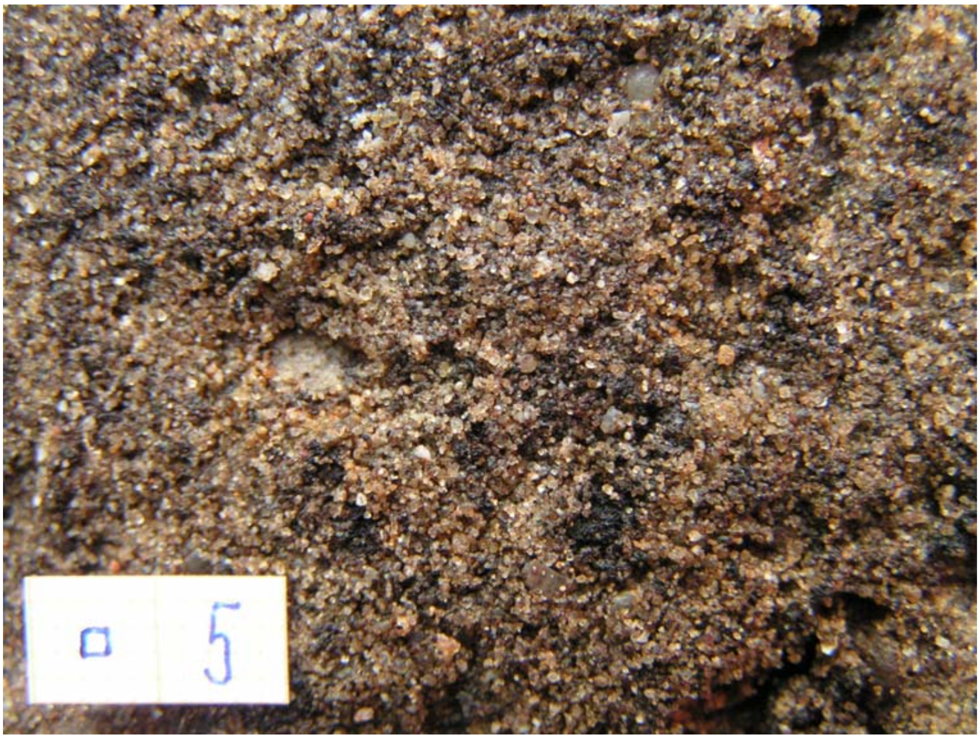

Figure 33-d Cylinder with root zone mix from the 120 cm depth (organic matter with sand)

Figure 33-e Cylinder with root zone mix from the 120 cm depth

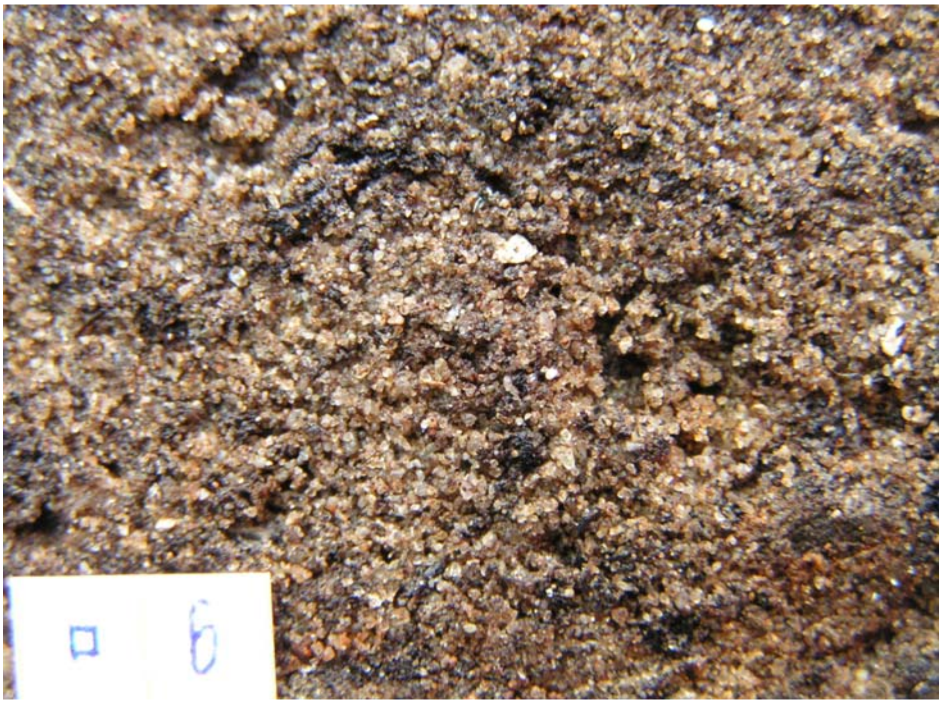

Figure 33-f Cylinder with root zone mix from the 120 cm depth (organic matter with sand)

Figure 33-g Cylinder with root zone mix from the 120 cm depth (clay aggregate)

Chemical analysis and *Water repellency test* results are given in appendices A and B, respectively.

18 Results of loose soil samples

Loose soil that was collected from 3 depths of the root zone (Section 15) was visually inspected, tested for water repellency, and subjected to chemical analysis. The appendices present the results of the water repellency test and the chemical analysis. *Visual inspection.* The results of the visual inspection follow below.

The soil from a depth of 40 cm was lumpy and relatively homogeneous. The aggregates were up to 3 cm in diameter. Organic-matter aggregates of size 1-1.5 cm were found. The organic matter was not completely decomposed: at breaking of aggregates it was possible to find fibres. Roots were not present.

The soil from a depth of 80 cm was lumpy and relatively homogeneous. Aggregates from organic matter or clay, with sizes of about 1 cm were found, with intact structure. The aggregates were rather dense, and could be crushed (broken). Roots were not present.

The soil from a depth of 120 cm was lumpy and relatively homogeneous. Aggregates with not decomposed organic matter, and with diameters up to 4 cm, were found. Clay aggregates with diameters up to 2 cm were also found. The aggregates were dense and could be crushed (broken). Roots were not present.
Figures 34-36 illustrate the soil conditions.

Figure 34-a Soil from depth 40 cm

Figure 34-b Soil from depth 40 cm (organic matter aggregates)

Figure 35-a Soil from depth 80 cm

Figure 35-b Soil from depth 80 cm (clay aggregates)

Figure 35-c Soil from depth 80 cm (organic matter aggregates)

Figure 36-a Soil from depth 120 cm

Figure 36-b Soil from depth 120 cm (clay aggregates)

Figure 36-c Soil from depth 120 cm (organic matter aggregates)

Chemical analysis and *Water repellency test* results are given as appendices A and B, respectively.

19 Discussion

The following sections concentrate on current state, changes with time in the past (history), and possible developments in the future (prediction), respectively.

19.1 Current state

The discussion of the ecological aspects of the prevailing state of the research site is organized according to; morphology of the roots, water phenomena and soil structure; soil physical/mechanical aspects; chemical aspects.

19.1.1 Morphology of roots, water phenomena, and soil structure

Roots

At the profile scale, it appeared that the major part of the roots are in the upper part of the substrate volume. If the soil water content and nutrients concentration are not higher in this upper part, synlocation is absent. It is most likely that water content and nutrients concentration of the installed tree mix bed are homogeneously distributed or increases a little with depth, because of nutrients uptake by the roots and leaching. Absence of synlocation makes the tree more sensitive to situations where amount of water and/or nutrients have reached low values.

At the scale of the installed perforated bags, it was expected that most bags were rooted very intensively at the time of recovery, as most bags contained relatively rich mixtures. But the rooting of the bags was surprisingly low.

At the agregate scale, fine roots in the bags concentrated in and around organic-matter (peat) clumps rather than at clay soil aggregates. Probably, the water content levels have not been so low that they were in the range where roots experience organic matter as more dry than clay soil (see Section 9).

Water phenomena

The perched water table and the reduction phenomena were very striking features of the water regime. They are likely connected with the water balance of the substrate bed and the shallow rooting. Infiltration of rainfall into the substrate bed is normal; the substrate lays on an impermeable roof with elevated edges; evapotranspiration of the trees canopy may be low relative to the large storage capacity of the substrate bed; water discharge possibilities may be very low. So, a perched groundwater table is not unlikely. The limited amount of water that the trees need is mainly taken from the upper layers, where the major part of the roots is located. So, the drying potential of the root system mainly benefits the upper part of the profile.

No dry spots due to water repellency were observed (Section 13). This is likely connected with the time of observation (winter period) and the fact that, according to the water balance, wet conditions usually prevail.

Soil structure
At the profile scale, distinct layering was observed. It is connected with the way of construction of the substrate bed. At the time of installation, layers of some decimeters thickness were filled and compacted. The mixture of a layer may have been nonuniform and/or sorted before and during the handling at installation, or rainfall between subsequent layer installations may have sorted particles.

At the aggregate scale, the visual inspection of the undisturbed soil cores at low enlargements learned that the clay soil aggregates and peat soil lumps were severely softened. In comparison with the amount of clay soil added and the amount of organic matter that is still present, distances between detected aggregates and lumps were very large. It means that many of the aggregates and lumps have been degenerated and fallen apart into amorphous and dust-like material, filling the pores between the sand grains. It is connected with the continously wet state of the profile and the absence of the structure-promoting influence of roots.

19.1.2 Soil physical/mechanical aspects

Section 17 presents the results of a core sampling at various depths, in order to find values of porosity and air content. The elaboration of the data followed a relatively detailed and accurate procedure. It accounted for the influence of organic matter content on the bulk density – porosity relationship, and it accounted for the influence of any cutting edge distortion on effective volume of sampling cylinders. The porosities that were found did not vary much between locations, implying that the sand bed has a rather homogeneous degree of compaction. The values of porosities and air contents were unexpectedly high, and seem, at first sight, in conflict with penetration resistance and oxygen content measured at earlier surveys.

But, according to Section 2, high porosities with high air contents can go together with low oxygen contents, in case of sandy soils lacking structure. Root growth could ameliorate such bad physical conditions (Section 10), but root growth is concentrated in the upper layer, and almost absent in the main part of the profile.

Also, according to Section 12, high porosity can go together with high penetration resistance in case of a constructed homogeneous bed of sandy material. That Section explains that, in such homogeneous beds, cone penetration resistance increases with depth, and its rate of increase is a measure of compaction degree. According to the information in Section 12, the research site has an intermediate degree of compaction, although the penetration resistance below shallow depths exceeds 3 Mpa, which is often seen as a limiting penetration resistance value above which plant roots cannot elongate anymore. In agricultural research it is currently believed that cone penetration resistance is a poor measure of the impedance that roots really encounter (see also Section 2). According to Section 12, the boundary depth above which the penetration resistance increases with depth, is larger for larger cones. So, from a soil mechanics point of view, it is unlikely that thick roots would develop at greater depths.

19.1.3 Chemical aspects

Table 17 presents data of the results of the chemical analysis and their interpretation according to standards from Moscow and The Netherlands. These norms are given in Table 18. Analyzing the changes with time of the parameter values we may conclude the following.

Organic matter. The decrease of organic matter content at the research site since 1981 seems normal.

Decomposition in the bags from the root zone cannot be observed. Probably, the oxygen regime around these bags (recently disturbed sandy soil with softened organic matter) and in these bags prevented this. It is in line with the low root development in the bags. The bag with root zone mix may have had slightly better oxygen regime because of its low organic matter content (better diffusion possibilities), which may explain its rooting.

The organic matter content remained virtually unchanged. It means that either no decomposition occurred, or enrichment from above occurred.

CEC values seem to be lower for the bags from the root zone. Because the organic matter contents of the bags remained unchanged, it can only be explained by loss of clay minerals to the sublayers. CEC of the root zone mix is lower than optimal and slightly increased with depth, probably because of leaching of ions from upper layers.

pH. From the loose soil samples we learn that the pH of the root zone is about 7.7 . The bags from the deep-freezer have the lowest pH values. The root zone bags have intermediate values. It means that the pH of the root zone bags shifted a little toward the pH value that prevails in the root zone.

P-total of the root zone mix is low. Also this value is low for all bags.

K-saturation and Mg-saturation. The K-saturation of the adsorption complex is defined as the fraction of the CEC that is occupied by K-ions. Numerically, it is the amount of meq K-ions per 100 g soil, divided by CEC (which also applies to 100 g soil). In the same way, Mg-saturation is defined.

The molecular weight of K_2O = 2*39 + 16 = 94
So, 94 mg K_2O = 2 meq,
or, 1 mg K_2O = 2/94 meq.

The molecular weight of MgO = 24.5 + 16 = 40.5
So, 40.5 mg MgO = 2 meq,
or, 1 mg MgO = 2/40.5 meq.

In Table 19, K-saturation and Mg-saturation are given in the last two columns, respectively.

Table 17. Results of chemical analysis, compared to the requirements.

Code	pH-KCl	Norm	Conclusion	P-total	Norm	Conclusion	CEC	Norm	Conclusion
				% ds			meq/100 g		
B - 5	7.1	4.5-6.5	high	0,0018	> 0.0218	low	13,4	> 15	low
B - 7.5	7.2		high	0,0051		low	14,1		low
B - 12	5.8		normal	0,0015		low	14,8		low
B - t	7.5		high	0,0023		low	6,7		low
Bf - 5	5.8		normal	0,0020		low	14,6		low
Bf - 7.5	7.3		high	0,0056		low	14,9		normal
Bf - 12	4.5		normal	0,0020		low	16,9		normal
Bf - t	7.3		high	0,0023		low	7		low
Ls - 40	7.6		high	0,0023		low	7,1		low
Ls - 80	7.7		high	0,0025		low	6,7		low
Ls - 120	7.7		high	0,0022		low	8,6		low
Dm	8.3		high	0,17		good	28,3		normal
Plm 1	7.7		high	0,0045		low	7,3		low
Plm 2	7.8		high	0,0028		low	6,6		low

Code	K-HCl	Norm	Conclusion	MgO	Norm	Conclusion	Org. mat.	Norm	Conclusion
	mg/100 g			mg/kg			%		
B - 5	3	10-20	low	39	> 60	low	4.1	3 - 5	normal
B - 7.5	8		low	30		low	4.5		normal
B - 12	2		low	57		low	10.0		normal
B - t	2		low	13		low	2.1		low
Bf - 5	26		high	154		good	3.6		normal
Bf - 7.5	126		high	160		good	4.3		normal
Bf - 12	8		low	211		rather high	9.5		normal
Bf - t	1		low	19		low	2.2		low
Ls - 40	1		low	9		low	1.8		low
Ls - 80	2		low	10		low	1.9		low
Ls - 120	3		low	10		low	1.6		low
Dm	92		high	563		rather high	15.1		normal
Plm 1	3		low	97		good	2.0		low
Plm 2	1		low	11		low	2.0		low

Table 18. Normative characteristics for plant soil mixes.

Characteristics	Dutch norms	Moscow norms	Oosterbeek lab. (BLGG) norms
pH - KCl	4.5 - 6.5 - normal	5.5 - 6.0	5.0 - 7.0
	> 6.5 - high		
	< 4.5 - low		
pH - H_2O		6.1 - 7.1	
(NO_3 + NH_4), mg/kg		50 - 200	
P_2O_5, mg/100 g	20 - 40	100 - 200	
P-AL, mg/100 g	< 10 - low		20 - 50
	10 - 20 - moderate		
	> 20 - good		
P-total, %	< 0.0153 - low		
	0.0153-0.0218 moderate		
	> 0.0218 - good		
K_2O , mg/kg		100 - 200	
MgO, mg/kg	for sandy soils		80 - 120
	< 30 - low		
	30 - 60 - moderate		
	> 60 - good		
Org. matter, % dry matter	< 3 - low	4 - 15	3 - 5
	> 3 - sufficient		
CEC, meq/100 g		> 15	

General comment on dutch norms for tree soil mixes. These norms are usually applied to the conditions at the time of planting (time of installation of the substrate).

Table 19. Saturation of soil with elements K and Mg.

Code	$\frac{\text{meq K}}{\text{100 g}}$	$\frac{\text{meq Mg}}{\text{100 g}}$	CEC meq/100 g	$\frac{\text{meq K}}{\text{CEC}}$	$\frac{\text{meq Mg}}{\text{CEC}}$
B-5	0.064	0.193	13.4	0.0048	0.0144
B-7.5	0.170	0.148	14.1	0.0121	0.0105
B-12	0.043	0.282	14.8	0.0029	0.0191
B-t	0.043	0.064	6.7	0.0064	0.0096
Bf-5	0.553	0.761	14.6	0.0379	0.0521
Bf-7.5	2.681	0.790	14.9	0.1799	0.0530
Bf-12	0.170	1.042	16.9	0.0101	0.0617
Bf-t	0.021	0.094	7.0	0.0030	0.0134
Ls-40	0.021	0.045	7.1	0.0030	0.0063
Ls-80	0.043	0.049	6.7	0.0064	0.0073
Ls-120	0.064	0.049	8.6	0.0074	0.0057
Dm	1.957	2.780	28.3	0.0692	0.0982
Plm1	0.064	0.479	7.3	0.0088	0.0656
Plm2	0.021	0.054	6.0	0.0032	0.0082

The root zone is much larger than the total volume of the bags, and has relatively stable saturation values. It may be concluded that the saturation values of the bags in the root zone shifted towards the root zone values, by exchange of cations.

19.2 Changes with time in the past

The nominal value of the organic matter content of the substrate at the research site at the time of installation (1981) was 4.5 %. According to the chemical analysis (appendix), organic matter content was 2 % in February, 2007. Kopinga (1991) stated that, in a tree soil mix with an initial amount of 4.5 % organic matter, 2 % of the organic matter mineralizes yearly. Applying this rule to the research site it means that the expected organic matter content in February, 2007, is 4.5*(1-0.02*26) = 2.16 %. The measured value is 2 % (see appendix). Also, this rule predicts the measured values from the earlier surveys well. So, it may be concluded that the decomposition rate of the organic matter was rather normal in the past. It implies that the oxygen contents in the past were above 10 % for a long time. Obviously, the peat lumps and clay soil aggregates resisted softening and falling apart for a long time. It may also imply that, initially, penetration resistance had values below 3 Mpa throughout the bed of substrate. It may be speculated that the balance (Section 10) between structure building factors (root action, drying, etc.) and structure degenerating factors (softening etc.) shifted towards degeneration because of the low rooting intensity and/or excessive structure degeneration in the early stage of the tree growth. This low rooting intensity may have been connected with the relatively large ratio between substrate volume and tree canopy size. Excessive structure degeneration may have been connected with a low structure stability of the clay soil and/or peat, and/or wet conditions inducing softening.

The elaboration of the chemical analysis showed that the pH-values and the K- and Mg-saturations of the perforated bags in the root zone of the research site shifted towards the values prevailing in the root zone. One significance of these values is that they indicate rates of change. The observed quantitative changes (shifts) are specific for the duration that the bags were in the root zone of the research site, bag dimensions, composition of the adsorption complex of the root zone, and water regime of the root zone.

19.3 Possible developments in the future

Organic matter decomposition releases nitrogen, phosphorus and further elements. Anions like NO_3^- and $H_2PO_4^-$ are adsorbed at the anion-adsorption complex. Uniformly distributed fertilizers form a further stock of nutrients. Ions like K^+, Mg^{++}, Ca^{++}, Na^+, NH_4^+ are adsorbed at the cation-adsorption complex. A measure of the size of this complex is CEC (meq per 100 g dry substrate).

Apart from aspects of pH, electric conductivity, organic matter, anion-adsorption complex, uniformly distributed fertilizers, composition of adsorbed ions, water supply and tree stability, we may distinguish the following root-space types:

1) A relatively small, homogeneous, substrate volume with high CEC and uniformly distributed roots with a high root length density.
2) A larger homogeneous substrate volume with lower CEC but the same summed CEC (CEC summed over the total dry weight), with the same amounts of roots.
3) At the same amount of roots and the same summed CEC, layered or heterogeneous substrate volumes.
4) Application of local fertilization in case of nutritions shortage in the original substrate volume.

Type 1 will have the highest efficiency: the amount of nutrients that is left at the moment that shortage starts, is minimal. Type 2 has a lower efficiency: shortage starts at higher nutrients levels. Type 3 may have better or worse efficiency than type 2. In case of synlocation, it is better. Otherwise, it may be worse. Note that, for this type, synlocation may be absent for several reasons. Rich patches may have a too high degree of compaction for the roots to penetrate in, or suffer from lack of oxygen. Peat lumps may be in a pF-range where roots experience peat as relatively dry, and prefer to concentrate at clay aggregates rather than at the peat lumps. In cases with shortage of nutrients, which are locally fertilized (type 4), optimal growth will never be reached anymore. Synlocation of local fertilization diminishes the growth reduction, but never to zero-reduction. New root growth may improve synlocation, but this takes time.

The above paragraph concentrated on CEC. Similar reasoning may be followed for organic matter, anion-adsorption complex, and uniformly distributed fertilizers. The above paragraph applies to each nutrient element individually.

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Appendix A. Results of chemical analysis of substrate samples

	pH-KCl	N-total	P-total	K-HCl	MgO	Organic matter	CEC
Sample		% dm	% dm	mg/100 g dm	mg/kg dm	% dm	meq/100 g dm
B - 5	7.1	0.026	0.0018	3	39	4.1	13.4
B - 7.5	7.2	0.022	0.0051	8	30	4.5	14.1
B - 12	5.8	0.014	0.0015	2	57	10.0	14.8
B - t	7.5	0.0076	0.0023	2	13	2.1	6.7
Bf - 5	5.8	0.0090	0.0020	26	154	3.6	14.6
Bf - 7.5	7.3	0.023	0.0056	126	160	4.3	14.9
Bf - 12	4.5	0.015	0.0020	8	211	9.5	16.9
Bf - t	7.3	0.0074	0.0023	1	19	2.2	7
Ls - 40	7.6	0.0065	0.0023	1	9	1.8	7.1
Ls - 80	7.7	0.0060	0.0025	2	10	1.9	6.7
Ls - 120	7.7	0.0055	0.0022	3	10	1.6	8.6
Dm	8.3	0.090	0.17	92	563	15.1	28.3
Plm 1	7.7	0.0071	0.0045	3	97	2.0	7.3
Plm 2	7.8	0.0055	0.0028	1	11	2.0	6.6

Appendix B. Results of test on water drop penetration time

Seven samples were tested on WDPT: samples of soil substrates from 4 perforated bags and loose soil samples from 3 depths (40, 80, 120 cm), all out of the root zone . All samples were dried to the air-dry state. The results of the WDPT test are shown below.

Code of samples	Time, sec	Class of water repellency	Nomenclature
B-5	27	1	slightly water repellent
B-7.5	38	1	
B-12	97	2	strongly water repellent
B-t	1	0	wettable; non-water repellent
Ls-40	1	0	
Ls-80	1	0	
Ls-120	1	0	

Results of WDPT test.

The results show that there is no problem with water repellency of the original root zone mix. But the substrates in the perforated bags were slightly (B-5 and B-7.5) and strongly (B-12) water repellent. The reason of it may be a differing amount of organic matter that can be water repellent.