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THE EFFECTS OF RESTRICTED VOLUMES OF SOIL ON THE GROWTH AND DEVELOPMENT OF STREET TREES

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Abstract. Street trees are increasingly found in pot-like confinements. The resulting deficits in the supply of moisture and nutrients (especially nitrogen) can be seen in the poor development and inferior aesthetic quality of these trees. The dimensions of a planting hole that are necessary to meet the tree's demands can be estimated based on the water balance and the nitrogen supply. In this paper, some examples are presented of dimensions calculated in this manner, with an emphasis on the supply of nutrients. Preliminary results are also given of research in The Netherlands concerning the effects of restricted rootable soil on the growth of trees.

Résumé. Les arbres de rues se retrouvent de plus en plus confinés comme dans des pots. Les déficits résultants dans les réserves en humidité et en éléments minéraux (surtout en azote) peuvent être observés dans le piètre développement et les qualités esthétiques inférieures de ces arbres. Les dimensions du tronc de plantation qui sont nécessaires pour rencontrer les exigences des arbres peuvent être estimées en se basant sur le bilan en eau et sur les réserves en azote. Dans cet article, certains exemples sont présentés de dimensions calculées de cette manière avec une emphase sur les réserves en éléments minéraux. Des résultats de recherche au Pays-Bas sont aussi donnés concernant les effets d'un sol à enracinement restreint sur la croissance des arbres.

In many urban situations, the amount of soil available for root growth of a street tree leaves much to be desired. Generally, lateral spread of the root system is restricted by high soil density, which makes penetration by the tree roots nearly impossible. Downward root development is generally limited by few possibilities for oxygen diffusion (also a result of the high soil density, i.e. low pore volume) or the height of the ground water level (the latter applies to areas of low elevation such as most of the western part of The Netherlands).

In some cases tree roots are able to grow out of the planting hole to better surroundings such as the front gardens of houses along the street, but the activities of utility services such as public works, which also claim use of the underground space, are a constant threat for such escapes. Besides, in these situations, tree roots often raise pavements, which generally is not appreciated by pedestrians, etc.

Because it is rather uncertain whether tree roots can eventually develop outside the planting hole and to what extent they than run the risk of being damaged, it is increasingly assumed that street trees will be forced to stand in a pot-like confinement for their entire lifetime. In these circumstances, the dimensions of the planting hole and the quality of the growth substrate determine the tree's ultimate size and also greatly influence the utility and aesthetic value of the mature tree.

From this standpoint two inevitable questions arise: what are the minimal dimensions of rootable soil necessary to sufficiently meet the tree's growth requirements?, and, what will happen when a tree has only limited possibilities to root in the surrounding soil?

Calculation of the Optimal Amount of Rootable Soil

Three approaches can be used to estimate a tree's ability to thrive under given circumstances: a) calculation based on field investigations where in a given situation the rooted soil volume is assessed as accurately as possible and related to differences in tree growth; b) calculation based on the water requirements of a tree in relation to the water supplying capacity of the growing site; and c) calculation based on the nutrient requirements of the tree in relation to the presence and availability of nutrients in the soil.

Some Results of Field Investigations. Compared with the amount of research data available on the influence of growth space on trees in the forest, data concerning solitary trees in The Netherlands are quite scarce. From surveys of roadside plantings of Dutch elm *(Ulmus x hollandica)*, Schoenfeld (21) observed that mature trees grow excellently, under normal climatic conditions, when the amount of root soil is at least 45 m^3 or more. Growth was always bad when rooting space was less than 10 m^3, regardless of differences in average wind velocity. In surveys of roadside plantings of poplar *(Populus x euramericana 'Heidemij')* Schoenfeld & Van de Burg (22) found that trees about 20 years old grow optimally with a rootable soil volume of at least 50 to 60 m^3. On the basis of field investigations, Helliwell (9) gives as a rule of thumb that in the average climate of southeast England, a tree generally roots in a soil volume about equal to one-tenth of the volume of its live canopy. However, he also calculated that depending on the soil moisture deficit during the growing season and soil fertility, the volume of rootable soil for a tree with a canopy volume of 1000 m^3 can range from 25 m^3 to 300 m^3.

Other research in Europe on the rooting pattern of trees has generally been focused on the (maximal) lateral spread or depth of the root system (e.g. 8, 17, 23) although some research (2) also studied the pattern of water extraction from the soil.

Estimates Based on the Water Comsumption. In his research on the water consumption of containerized trees, Bakker (1) established that, on a yearly basis, the evaporation of a solitary tree averages about 1.5 times more than the evaporation of the same tree in a forest. On the basis of these findings and those of past surveys in the field (21) combined with data on average rainfall during the growing season and the reference evaporation for vegetation, Bakker introduced the rule of thumb that a tree standing in a soil with a so-called hanging-water profile (= a soil without influence of ground water) requires approximately about 3/4 m^3 of rootable soil of "reasonable" quality (medium coarse sand with a organic matter content of 3 to 7%) per m^2 of crown projection. In more recent publications (20), the addition was made that 1/2 m^3 per m^2 crown projection suffices when the soil is of "good" quality (medium coarse sand with an organic matter content of 7 to 8%).

Estimates made by researchers abroad are similar: 0.6 m^3 per m^2 crown projection (24, 25) or somewhat lower: 0.3 m^3 per m^2 of crown projection (18).

The estimates presented here are of course no more than rules of thumb. Even when enough is known about annual precipitation and the water supplying capacity of the existing soil, more information is needed before the methods can be accurately applied to practical situations. More should be known about:

- Infiltration of rain water (precipitation minus runoff, interception and direct evaporation from the soil) under given climatic influences.
- Water consumption per unit of leaf area. This may vary substantially among the different tree species. Braun (4), for example, found that the evaporated water per m^2 leaf surface for Norway maple *(Acer platanoides)* was 56 liters in contrast to 159 liters for willow *(Salix alba 'Liempde')* in the same time period and under conditions of optimal water supply.
- Water consumption per unit of leaf area, in relation to the leaf distribution in the canopy. Evidence suggests that leaves evaporate less when their exposure to direct sunlight is lower (18). It is also likely that the LAI (Leaf Area Index) changes with the age of trees (27).

Estimates Based on Nitrogen Demand. Rootable soil volume can also be calculated based on the available nitrogen supply to the leaves. This method is somewhat more "direct" than calculations based on the water balance of a tree, because it depends less on unpredictable factors and it indicates directly how many leaves of a certain quality can be produced in a growing season, regardless of the leaf distribution in the canopy.

Nitrogen is especially important in the nutrient supply of trees. It is not part of the mineral particles of the soil, therefore its availability is determined by the amount of organic matter present in the soil and the rate at which it is mineralized.

Deficits in the supply of nitrogen can be expected when the content of organic matter, namely the N-total figure, is low or when the organic matter is of inferior quality (expressed by the C:N ratio), or when the amount of soil in which the mineralized nitrogen comes available is too small.

Deficits in the nitrogen supply cause slow growth (e.g. the length of the annually formed shoots) and a reduction in aesthetic value (yellowish, small leaves and a decreased leaf distribution in the canopy).

Recently, Van den Burg (7) presented a somewhat modified version of a calculation example for the nitrogen demands of urban trees (10) based on the nitrogen demand of poplar. Given a poplar stand in the terminal fase, with 100 trees per hectare (planting distance: 10 X 10 m and an average crown diameter of 8.6 m), the leaf mass will be about 4000 kg of dry matter per ha, or 40 kg of dry matter per tree. A N-content in the leaves of 25 g/kg in August could be considered as a "reasonable" supply of N. This amounts to 1000 g N per tree. When the intake of N from the air and the internal translocation of N in the tree itself is neglected, it follows that 1000 g N is taken from the soil by the tree. If it is (reasonably) assumed that 1 m^3 of soil, with a content of 5% "good" organic matter (with a N-content of 3%) and an annual N-mineralization of 2% of the total bulk, provides about 23 grams of available N and that 75% of it is taken up by the tree, then the necessary rootable soil volume is 43 m^3. If the rooting depth is 3/4 m, then the root projection is about equal to the crown projection.

The previous example applies to poplar, about which much is currently known from forestry research. Data on the leaf mass of solitary trees in an urban environment were hardly available until the last decade when more information was provided by research in Chechoslovakia on maple *(Acer pseudoplatanus)* and linden *(Tilia cordata)* (26, 27). Using these data, combined with those on the N-demand of trees at "just sufficient" and "sufficient" supply levels (6, 7) and assuming a leaf weight of 1 g dry matter per 100 cm^2 of leaf surface and the same mineralization of N as are given above, it is fairly simple to calculate how much rootable soil a tree needs. An example for maple is illustrated in Figure 1.

With calculation examples such as these it is interesting to determine how much the dimensions calculated from the model agree with practical situations. Just such an opportunity arose when the early eighties, in the framework of the activities of OBIS (10) when an experiment was set up by the ICW (Institute for Land and Water Management Research), Stiboka (Soil Survey Institute) and De Dorschkamp. In this experiment which used plane *(Platanus x acerifolia)* as the test tree, the effects of different sizes of planting holes on both water consumption (ICW) and the uptake of nutrients (De Dorschkamp) (5) were studied. The sizes of the planting holes were 1 m^3, 4 m^3 and 7 m^3 and the planthole fill consisted of a mixture of sand and sewage sludge. It appeared that the N-supply of the trees in all three sizes of planting holes had already decreased substantially within five years. The level for visible N-deficiency in the leaves (ca. 15 g/kg) was reached after 6 growing seasons in both the 1 m^3 and 4 m^3 holes, irrespective of the quality of the growing substrate. By that time, the N-supply of the planting hole of 7 m^3 was just a slightly higher (7) (Figure 2).

From those initial results, the following preliminary conclusions can be derived. (Van den Burg, De Dorschkamp, pers. com.): a) The

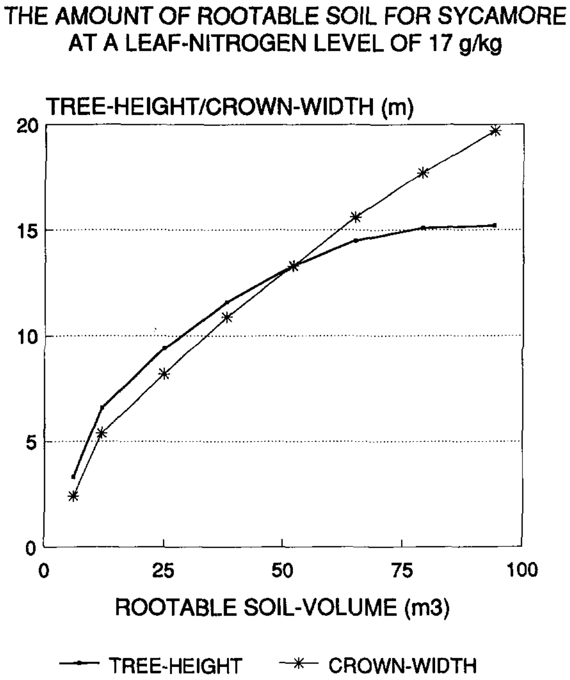


Figure 1. The necessary volume of rootable soil in relation to tree height and crown width for solitary maples *(Acer pseudoplatanus)* at a Nitrogen supply-level of 17 g/kg of the leaves. The soil contained 5% organic matter, the annual mineralization rate was 2% of the total quantity of organic matter, and the N-uptake rate was 75%. Source: Van den Burg (7) and Vrestiak (27).

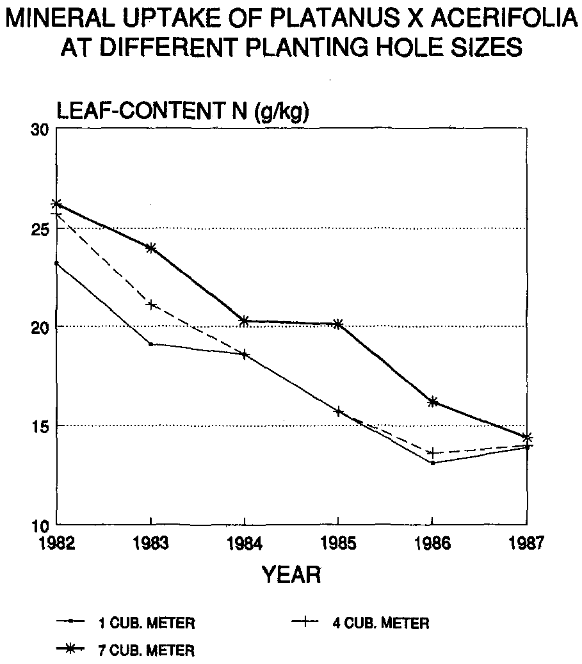
decrease in the availability of nitrogen depends on both time and rootable soil volume. b) The decrease in the availability of phosphorus depends on both time, as far as direct availability is concerned (the so called P-AL figure), and the rootable soil volume. c) The decrease in the availability of potassium is independent of the soil volume. However, how much of the decrease in this situation can be attributed to a planting hole effect or to rapidly declining availability (as a rule, the K-content of sewage sludge is poor) is unclear.

The experimental results presented here and the data from Figure 1, lead to the conclusion that a large and flourishing tree with a reasonable leaf mass development can reach the limits of a "fairly large" planting hole (e.g. 10 m³) in 10 to 20 years.

Elms along the canals in Amsterdam

The need for sufficient rootable space for the growth, development, and also the aesthetic value, of street trees can best be illustrated by situations along the canals in the centers of some of our old cities, such as Gouda (13) and Amsterdam. Amsterdam is probably the best example because an especially large number of Dutch elms *(Ulmus x hollandica)* have been and continue to be planted there. These trees are expected to grow to full size and maintain their aesthetic value for a long time. However, the width of the planting strip, the planting distance and the limits of rooting depth (which is determined by the water level in the canals), all indicate that the trees do not have an optimal quantity of rootable soil. It is therefore characteristic that trees planted somewhat "higher", namely close to the entrances of the bridges, are as a rule larger and also have a better developed crown than the lower standing trees (see Plate 1).

In the framework of the research into the application of colour-infrared pictures for the assessment of the vitality of street trees (11) conducted in 1986 along two canals, 43 mature trees were sampled for their average shoot length and leaf surface and the content of the elements N, P, K, Ca, Mg and Cl in the leaves. Judged by the appearance of the trees they were classified into three different vitality-groups: "good", "moderate" and "poor". Very distinct differences



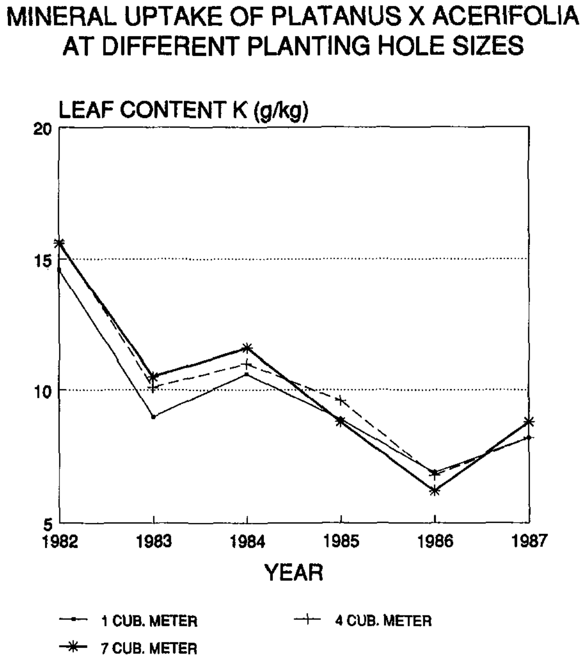


Figure 2. The development in time of the N-supply (above) and K-supply (below) of plane trees *(Platanus x acerifolia)* in planting holes of different sizes, filled with a mixture of sand and sewage sludge.
Source: Van den Burg (6) and Van den Burg, pers. com.

in shoot elongation and in the supply of N and K appeared between these classes (Table 1).

In the "poor" group N and K were at levels low enough for the deficiency to be visibly evident (6, 7). In addition to a significant correlation between N-uptake and shoot elongation (Figure 3), there also appeared to be a slight but significant correlation between K-uptake and shoot growth. The latter could be regarded as either an effect of restricted root growth (which would be unlikely) or a low level of K in the soil (which was not examined further).

The possible effect of restricted root growth based on the uptake of K is remarkable. From data of diagnostic research into the causes of poor growth of street trees it appeared that K-deficiency may be more problematic than was previously believed. It most often occurs in poorer calcareous sandy soils and in acidic (peaty) sandy soils, especially when the latter are wet (12, 13, 14, 16).

Another opportunity to study the effects of restricted root growth on the uptake of nutrients presented itself in an ongoing experiment that was set up to research root penetration into nonwoven textiles of artificial fiber at the nursery of De Dorschkamp (15). In this experiment, poplars *(Populus x euramericana 'Dorskamp')* were planted in 60 liter containers whose bottoms had been removed and which were placed on textiles of various thicknesses before being filled with soil from the nursery (a sandy soil containing slight to moderate amounts of humus). When distinct differences appeared in both the extent of root penetration and the above ground development of the test trees, 48 of the trees still left in the trial in 1989 were sampled for average shoot elongation and leaf surface and the leaf content of N, P, K, Ca and Mg, in addition to the usual recordings of root penetration.

Plate 1. Dutch elms along the canals in Amsterdam City.

It also became apparent in the experiment that among the five elements the uptake of both N and K rose significantly in relation to the number of roots which had escaped from the container and to the improved development of the above ground part of the trees (Figure 4). Otherwise, the supply of all five elements was sufficient.

Nothing is yet known about the conditions under which the size of a planting hole and thereby restricted root volume, has an influence on the uptake of K. For the time being, the quality of the growing substrate seems to be more important for the availability of K than the size of rootable space.

Conclusions

In practice, the influence of restricted root growth on the uptake of K may be of little importance, because K-deficiency can be corrected with one simple and long lasting application of a K-fertilizer. However, this applies to situations where low K-contents occurs naturally in the soil such as in lutum-poor, acidic or calcareous soils. In cases where K-deficiency is caused by water

Table 1. Average shoot length, leaf surface (cm2 per leaf) and stem circumference (cm) on breast height (1.3 m), and element content of the leaves (in g per kg dry weight) per tree in three vitality-classes of Dutch elm *(Ulmus x hollandica)* along the Bloemgracht and the Egelantiersgracht in Amsterdam. Sampling data: 12 September 1986.
(The average values are presented ± the standard deviation)

Class	*"good"*	*"moderate"*	*"poor"*
No. of trees	7	19	17
Shoot length (cm)	23.0 ± 8.1	16.7 ± 5.6	9.0 ± 1.7
Leaf area (cm^2/leaf)	37.9 ± 5.4	38.1 ± 11.6	29.5 ± 3.2
Stem circumference (cm)	176 ± 25	137 ± 20	123 ± 18
N (g/kg)	19.9 ± 3.5	16.7 ± 3.2	13.1 ± 1.8
P (g/kg)	01.7 ± 0.2	01.6 ± 0.2	01.5 ± 0.2
K (g/kg)	12.0 ± 3.0	08.3 ± 3.2	06.6 ± 2.1
Mg (g/kg)	02.6 ± 0.3	03.1 ± 0.7	03.1 ± 0.6
Ca (g/kg)	24.4 ± 2.1	26.7 ± 2.7	23.9 ± 3.0
Cl (g/kg)	10.4 ± 1.2	10.2 ± 1.4	10.0 ± 1.3

stagnation or other problems with the soil oxygen diffusion, measures must be taken first to improve these factors structurally, such as the installation of a draining or soil ventilation system.

The nitrogen supply of trees can also be corrected by fertilizers, but these have to be applied at least once a year. When young trees in evident pot-like confinements are concerned, one could wonder whether this is indeed the right approach. Namely, as a result of nitrogen fertilization, the root/shoot relation is shifted more to aboveground parts of the tree, which can theoretically lead to increased sensitivity to drought, increased instability and a higher risk of wind damage. Therefore, in these situations, enlarging the rootable soil volume is a preferable solution.

For older trees, especially when they are in locations with sufficient moisture from groundwater, some positive effects can be expected from regular N-fertilization, without the occurrence of any substantial problems. What N-fertilizer one chooses for this purpose is of less importance. This includes slow-acting fertilizers, because their effects continue only slightly longer than one year and they are also more expensive (Van den Burg, De Dorschkamp, pers. com.). When using organic fertilizers for the correction of N-deficiency, it is important to realize that oxygen is used for their conversion in the soil. This could give rise to problems in situations where air diffusion in the soil is already less than desirable.

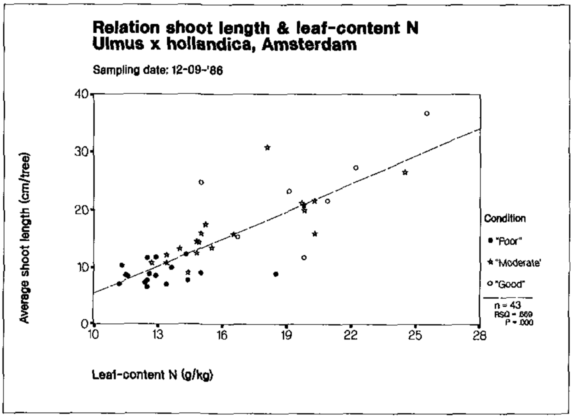


Figure 3. The relation between shoot length and N-content of the leaves of Dutch elm *(Ulmus x hollandica)* along the Bloemgracht and the Egelantiersgracht at levels for N-supply varying from insufficient to optimal. Sampling data: 12 September 1986.

Injecting and implanting trees with N-fertilizers is relatively unknown, especially in The Netherlands where this method has no practical application thus far. Before choosing this approach one should consider the effects of wounding the tree, which are inherent in these methods and which could eventually be in time disadvantageous to the tree. Using the figures in the examples presented above, a calculation can also be made to determine how much material must be injected or implanted to sufficiently increase the N-supply, namely the N-content of the leaves, by some

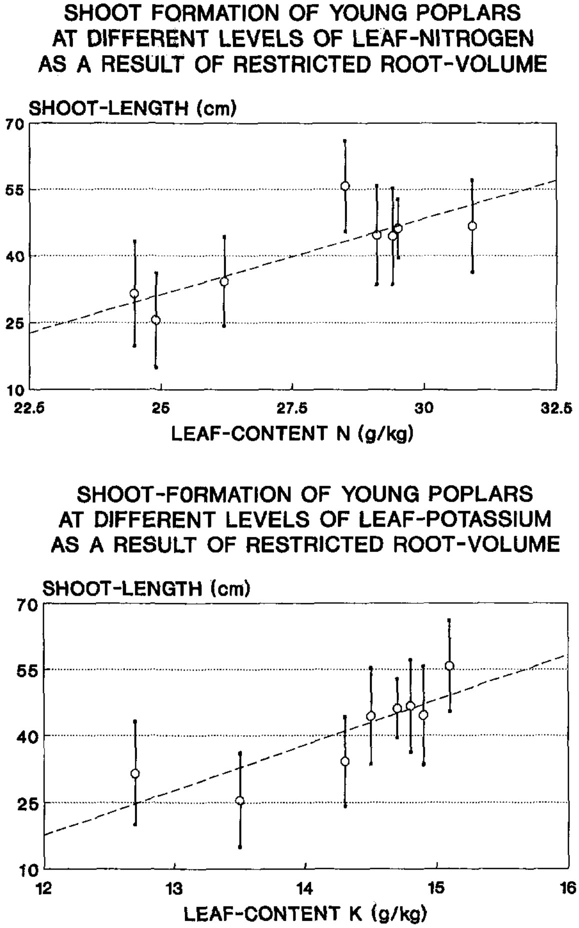


Figure 4. The relation between shoot length and N-supply (above) and K-supply (below) of young poplar trees *(Populus x euramericana 'Dorskamp')* in a container-trial with varying levels of root restriction. Sampling period: early September 1989. (The points represent the means of the 6 observation values; the vertical lines represent the standard deviation. Correlation factors (R-Pearson) for N (total population): 0.49 at p = 0.000 and for K (total population): 0.69 at p = 0.000.

grams per kg dry matter. This would probably indicate that the method can be disregarded for practical use.

An additional benefit of the "structural" solution for correcting the nitrogen-supply, namely enlarging the volume of rootable soil (possibly in combination with soil amelioration), is that the water supply to the soil is more guaranteed, which can be of major importance for soils with so-called hanging water profiles.

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