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Soil Water Dynamics and Growth of Street and Park Trees

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Abstract. Soil water dynamics were studied in 100 street tree planting pits and in the soil surrounding five park trees. Volumetric soil water content and stem cross-sectional area increment were measured on both park and street trees. Different levels of irrigation were implemented on the 100 street trees. Winter assessments of soil wetness at field capacity showed that the water retention capacity was lower in street planting pits than in the park soil attributable to the rather coarse substrate used in the planting pits. High variability among street tree planting pits in regard to water retention capacity was determined and may be related to poor standardization of the substrates, but may also be affected by varying drainage conditions. The rate of water loss in the street tree planting pits was very high immediately after rainfall or irrigation and decreased exponentially during the first 10 days after water input. This was attributed to rapid drainage. The water loss rate in the park soil was on average slightly higher than in the nonirrigated control street pits but showed a more linear decrease over time. We concluded that the water loss in the park soil during summer was primarily driven by transpiration of trees (above 10 L/day [2.6 gal/day]), which complies with common Danish forest experience. The relationship between water loss and tree growth was reversed in the street tree planting pits. The street trees did consume water for growth, but growth and transpiration of the street trees were not a noticeably driving mechanism in the planting pit hydrology. The large variation in street tree increment is attributed to the variation among street planting pits in their ability to retain water. The faster the water loss rate, the slower the tree growth. Irrigation did not prevent final depletion of the soil water resource in planting pits, but irrigation elevated the water content for limited periods during the growing season and thereby enhanced tree growth. Besides the obvious possibilities for improved water balance by horizontal and vertical expansion of the rooting zone, we also suggest improving the water retention capacity of planting pit soil by adding clay nodules. Options for continuous monitoring of tree vitality and soil water content to optimize maintenance are discussed.

Key Words. Drainage; irrigation; park trees; soil characteristics; soil water; street trees.

Poor vitality of urban street trees is commonly acknowledged (Fintelmann 1877; Pauleit et al. 2002; Trowbridge and Bassuk 2004) and poor water relations are considered to be a major problem (e.g., Hampel 1893; Kühn 1961; Gilbertson and Bradshaw 1985; Befeldt 1989; Clark and Kjelgren 1990; Balder et al. 1997; Tomiczek 2003). Flooding of roots is a problem when drainage from the planting pits of street trees is poor (Harris et al. 1994; Sæbø et al. 2003), but lack of water of street trees tends to be a common problem caused by, for example, small planting pits; interception of precipitation from paving, buildings, or the tree itself; surface runoff; limited root extension both horizontally and vertically; and increased evapotranspiration resulting from elevated urban temperatures (Lemaire and Rossignol 1999; Tomiczek 2003). Furthermore, hydrologic parameters of the soil material influence the soil water balance. Soil porosity is important for drainage (Hillel 1998), and soil texture strongly influences the relationship between water content and the soil water potential and thus the plant availability of soil water. Furthermore, the soil material in street tree planting pits is often subjected to compaction, which increases surface runoff and reduces the gas exchange between the soil and the atmosphere (Lichter and Lindsay 1994; Rolf 1994; Hillel 1998).

The purpose of this study was to achieve a better understanding of the soil water balance in a typical planting pit design frequently used in Copenhagen, Denmark. Furthermore, it was intended to investigate effects of soil water dynamics on the growth of the street trees. Nearby park trees were included in the investigation to improve comprehension of the basic differences between street and park sites. Phenology and growth responses of the investigated trees were reported by Bühler et al. (2006), and the soil water dynamics and soil water–tree growth relationship is reported in the present work.

MATERIALS AND METHODS

Test Plants and Test Sites

The study was carried out in 2004 and included 100 street tree planting pits with *Tilia cordata* trees along Frederikssundsvej in Copenhagen and five root zones of *Tilia* park trees at “Vestvolden.” The distance between the street tree and park tree site is 1 km (0.6 mi). The trees were established 7 to 8 years before the investigation. The street planting pits are on average 6.4 m^2 (69.1 ft^2) large (1.5 × 4 m [5 × 13.2 ft]) and are surrounded by elevated curbs. The park trees grow on an unsealed, nutrient-rich soil, which had been improved by a 25 cm (10 in) layer of good topsoil. The park trees were spaced 10 m (33 ft) apart, and the soil was covered with herbaceous ground vegetation that was mowed twice during summer.

The soils on both locations are anthrosols (Table 1). At establishment of the street trees, the original soil was removed to an approximate depth of 60 cm (24 in) and the pits were filled with a sand/compost-mixed substrate. The material at the bottom of the profile was heavy clay, but the quality of the underlying material may vary from pit to pit as a result of prior construction work. The soil surface was covered with a layer of bark mulch, and during winter, the planting pits were protected from deicing salt by plastic screens.

Assessment of Water Dynamics

The volumetric soil water content was determined by time domain reflectometry (TDR) (Topp and Davis 1985; Nissen and Møldrup 1994). Three measurement points were established in every street tree planting pit and next to five of the park trees. Each measurement point consisted of two stainless steel rods spaced 50 mm (2 in) apart. The rods were installed vertically in the soil beneath the bark mulch layer. Two of the measurement points were installed at 55 cm (22 in) distance from the stem and measured volumetric water content to a depth of 25 cm (10 in) and 50 cm (20 in), respectively. The third measurement point was installed at a distance of 110 cm (44 in) from the tree and measured soil wetness to a depth of 25 cm (10 in). It was attempted to install measurements points measuring to a depth of 80 cm (32 in) as well, but this was impeded by the compacted clay subsoil below 60 cm (24 in).

The 25 and 50 cm (10 and 20 in) rods provided data on the water content in the 0 to 25 cm (0 to 10 in) and 0 to 50 cm (0 to 20 in) soil profiles, respectively. Based on those two measurements, it was possible to calculate the water content in the 25 to 50 cm (10 to 20 in) profile. All measurement points were established on the west-facing side of the trees. The measurements were conducted with a Tektronix 1502C metallic TDR cable tester (Tektronix Inc., Richardson, TX, U.S.) connected to a Husky FS3 handheld computer (WPI Husky Computers Ltd., Coventry, England) with the AUTOTDR-program (Thomsen 1994). TDR assessments were generally scheduled 1 day before and 1 day after each irrigation. Supplemental assessments were carried out during spring and autumn and during periods of high precipitation, when irrigations were cancelled.

Table 1. Soil profile on the two investigated sites.

Site	Hor.	Depth	Texture	Structure	Color	Roots	Comments
Park soil	Ah_1	12 cm (4.8 in)	Sandy loam	Granular	Very dark brown	Weed trees	Nutrient-rich, probably on filled topsoil after landscaping
	Ah_2	27 cm (10.8 in)	Sandy loam	Light granular	Dark brown	Trees	
	B_1	39 cm (15.6 in)	Silt loam	Compacted	Light gray	None	Compacted from landscaping traffic
	B_g	65 cm (26 in)	Silt loam	Cracked with root channels	Gray + very extensive red mottling	Trees	“Undisturbed” subsoil
Street planting pit	O_1	7 cm (2.8 in)	Bark mulch	Very coarse	Brown	None	
	O_2	9 cm (3.6 in)	Bark mulch, structure lost	Under decomposition	Light brown	Tree fine root	
	Ah	64 cm (25.6 in)	Artificial topsoil substrate	Light compacted at 9 to 29 cm (3.6 to 11.6 in), below slightly hard, no granulation	Gray	Many tree roots; few roots grow under curbs	High sand content, little humus, little silt, no clay; concrete fundament of curbs to 50 cm (20 in)
	B_1	>64 cm (>25.6 in)	Loamy clay	Puddled	Yellow–light brown	Very few tree roots	Not accessible for roots

Table 2. Irrigation in the different treatments.

Date	Day of year	Treatment 1 L/tree	Treatment 2 L/tree	Treatment 3 L/tree	Treatment 4 L/tree	Sum
26/27 May	147/148	100	50	50	100	6000
		100	50	50	100	6000
10 June	162	100	50	—	—	3000
15 July	197	80	40	—	—	2400
26 July	208	80	40	40	80	4800
2 August	215	100	50	—	—	3000
11 August	224	100	50	50	100	6000
26 August	239	80	40	—	—	2400
Whole period (liter)		640	320	140	280	27600
Whole period (UK gal)		141	70	62	31	
Equivalent precipitation (mm)		100	50	22	44	
Equivalent precipitation (in)		3.9	1.95	0.87	1.73	

Irrigation Treatments

The street tree planting pits were treated with varying irrigation regimes (Table 2). The irrigations deviate from the originally planned treatment schedule because of extraordinary high precipitation during part of the summer period (Figure 1). The control sample (denoted treatment 5) and the park trees (denoted treatment 6) received no irrigation. The water was applied manually to the soil surface with a water hose with a sprayer and water meter.

Tree Growth

Based on weekly measurements of stem circumference on all street and park trees, stem cross-sectional area (CSA) increment was assessed and growth curves were modeled for each individual tree (Bühler et al. 2006). Based on these growth curves, the absolute CSA increment of each tree in five periods characterized by decreasing soil water content was calculated.

Precipitation data for the Copenhagen area was obtained from the Danish Meteorological Institute.

Data Analysis and Statistics

The 100 street trees and their planting pits were allocated to four blocks and five irrigation treatments (including a nonirrigated control) amounting to 20 repeats per treatment. Irrigation treatments were distributed randomly in each of the four blocks.

Data were analyzed using SAS version 8.2 (SAS Institute Inc., Cary, NC). The box and whisker plots in Figure 2 present the median, the two central quartiles (the box), the 10% and 90% percentiles (the whiskers), and the outliers (dots). The spatial differences analyzed in Figures 3 and 4 were statistically tested with t-tests (SAS Proc t-test) carried out for every single combination of treatment and assessment day to ensure independence between observations. The slope of the trend lines in Figure 4 was tested with analysis of covariance with an interaction term (model 1). Treatment effects in Table 3 and Figure 4 were tested by analysis of variance (model 2):

$$Y_{jk} = A + T_j + \beta_j T_j D_{jk} + \beta_j T_j D_{jk} + \varepsilon_{jk} \qquad (1)$$

where

Y_{jk} is the dependent variable in observation k in treatment j
A is a constant
T is treatment
D_{jk} is day of the year
β is slope of covariates

$$Y_{ijk} = A + B_i + T_j + \varepsilon_{ijk} \qquad (2)$$

where

Y_{ijk} is the dependent variable in observation k in block i and in treatment j

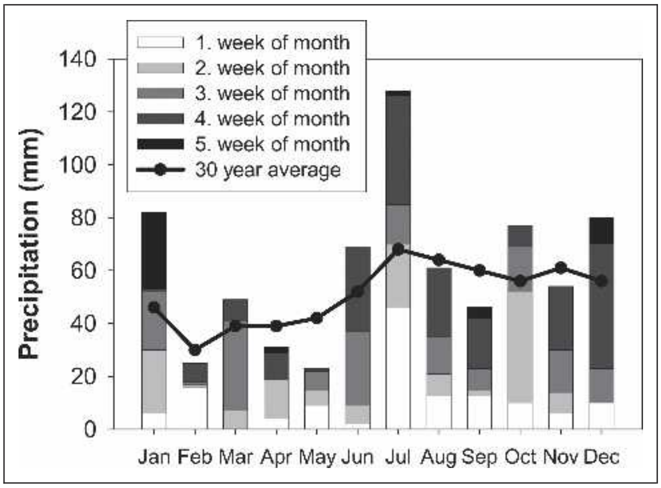

Figure 1. Precipitation during 2004 distributed to weeks (stacked bars) within months. The 30-year average precipitation is provided for reference. Source: Danish Meteorologist Institute, Copenhagen.

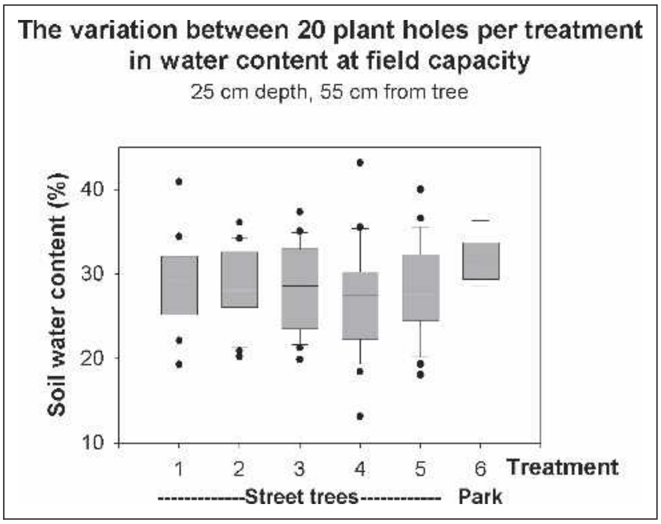

Figure 2. Box and whisker plots of the volumetric water content assessed at 55 cm (22 in) distance from the trees and to a soil depth of 25 cm (10 in) in 8 December 2004 when the soil was saturated to field capacity. The analysis reveals the immense variation in water retention capacity between planting pits of the street trees.

A is a constant
B is block
T is treatment

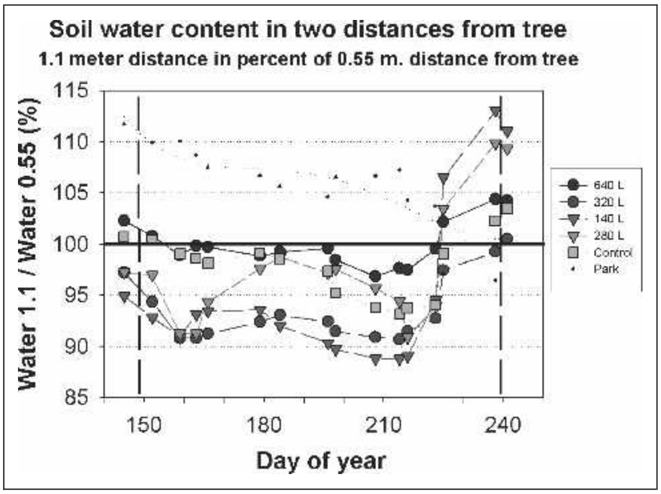

Figure 3. Horizontal variation in soil water content in street and park trees. Data are running averages (of the current assessment and the ones before and after) for improved clarity of lines. The vertical dashed lines show the time of the first and the last irrigation.

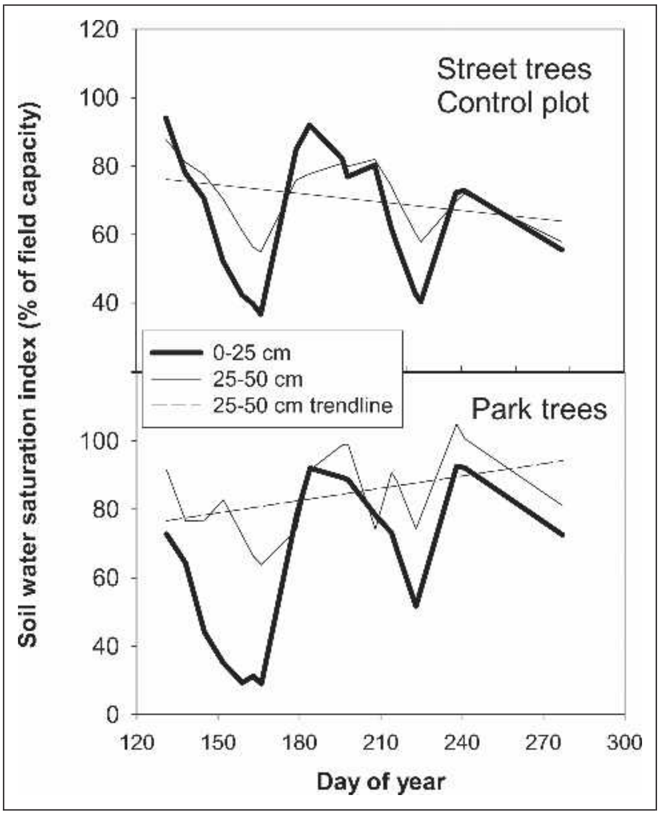

Figure 4. The development of the soil water saturation index at two different soil depths in the control plot of the street tree pits and beneath the park trees. The curves are based on averages of tree pits. A first polynomial trend line for the 25 to 50 cm (10 to 20 in) horizon is added in both plots. Analysis of covariance revealed for both horizons significant negative trend lines for street tree pits and significant positive trend lines for the park soil.

The soil water losses from tree planting pits and from the park soil during five selected periods characterized by decreasing soil water content were analyzed in models 3 and 4, and the relation of tree growth with soil water loss during these five periods was analyzed in model 5. The variables of the models are described in detail in the following.

$$W_{ijk} = A + \beta_l L_{ijk} + \beta_2 RL_{ijk} + \beta_3 RL_{ijk} S_{ijk} + \beta_{4ij} P_i T_j D_{ij} + \beta_{5ij} P_i T_j I_{ijk} \quad (3)$$

$$W_{ijk} = A + \beta_l L_{ijk} + B_j T_j I_{ijk} \quad (4)$$

$$I_{ijk} = A + \beta_l L_{ijk} + \beta_j T_j W_{ijk} \quad (5)$$

where

W_{ijk} = average water loss (L/day) of tree number *k* in period *i* in treatment *j* expressed in positive values. Data are from 1.1 m (3.6 ft) distance from the tree and 0 to 25 cm (0 to 10 in) soil depth.
A = constant
P_i = period *i*, $i = 1$ to 5
T_j = treatment *j*, $j = 1$ to 6

Table 3. Significance level for treatment differences.[z]

				↓		↓					↓		↓	↓		↓		↓			
Day		131	138	145	152	159	163	166	179	184	196	206	208	214	216	223	225	238	241	277	343
1 to 5	Water content	NS	NS	NS	NS	NS	***	***	NS	NS	NS	***	***	NS	***	**	***	NS	+	NS	NS
	Saturation index	NS	NS	NS	NS	NS	***	***	NS	NS	NS	***	***	NS	***	***	***	+	**	*	
5 to 6	Water content	NS	NS	*	NS	NS	NS	NS	**	**	***	***	**	***	***	***		**	***	***	*
	Saturation index	*	NS	***	**	*	NS	NS	NS	NS	*	**	NS	**	***	**		+	**	***	

[z]An analysis of variance was carried out within every assessment day. The upper two rows are comparisons of the five street tree planting pit samples, and the lower two rows is a comparison of the street control pits and the park soil. The arrows at the top designate the time of irrigations.

NS = not significant.

L_i = length of period (days) used as a covariate

$RL_i = 1/L_i$

S_{ik} = soil water saturation level at the beginning of the periods (%)

D = dummy variable; 1 = irrigation on the day immediate before TDR assessment at the beginning of a period, 0 = no irrigation before the first TDR assessment

I_{ijk} = average daily stem basal area increment (mm^2/day) of tree k during period i in treatment j

β = estimates of slopes for the various effects

RESULTS

Precipitation

Precipitation in Copenhagen in 2004 was 703 mm (28 in), which was 90 mm (3.6 in) higher than the 30-year average. Precipitation during the growth period from April to September amounts to 320 mm (12.8 in), which is 55 mm (2.2 in) above average. The distribution of rainfall over time differed distinctly from average. Figure 1 reveals a very dry period from mid-April to mid-June, an exceptionally wet period from mid-June to the end of July, and a somewhat drier period during September. Assuming that all precipitation infiltrated into the planting pit, each pit would have received 2048 L (532.5 gal) of water alone through precipitation during the growth period. This transformation, however, is only indicative, because the interception by buildings, trucks, tree crowns, and bark mulch is considered to be considerable but unknown.

Variation in Water Retention Capacity Among Street Planting Pits

The last TDR assessment was carried out on 8 December. At this time, water content of the soil was assumed to be close to field capacity, because above-average precipitation had replenished soil wetness and strongly reduced evapotranspirational losses at this time of the year. Thus, this assessment provides an expression of the maximum water retention capacity of each planting pit. TDR measurements from 8 December show a large variability among street planting pits, ranging from 12% to 42% water content at field capacity (Figure 2). This analysis shows that the soil hydrology varies noticeably between planting pits. A water content value that is close to field capacity in one planting pit may be approaching the wilting point in another pit. It is remarkable that the soil of the park trees was characterized by a generally higher water retention capacity and a much lower variability than the soil of the street trees. Figure 2 also shows that the planting pit sample of treatment 4 (280 L [72.8 gal]) was characterized by a negative sampling bias, which was not significant.

The *water saturation index* is the water content on a given point of time in relation to water content at assumed field capacity (at 8 December). It should be noted that the saturation index is related to field capacity and not to full water saturation of the soil. This index provides more adequate analysis of the soil water dynamics, and the saturation index may better reflect the amount of plant-available water in the soil.

Spatial Variation in Soil Water Content

Analysis of the horizontal variation is based on assessments at 0.55 cm (0.22 in) and at 1.1 m (3.6 ft) distance from the tree. The water saturation index at 1.1 m (3.6 ft) distance was related to the index at 0.55 m (1.8 ft) distance (Figure 3). This analysis shows that the water content decreased with distance in the street trees, whereas the opposite is found in the park trees. The horizontal differences were significant in t-tests in all treatments except treatment 4.

The vertical distribution of soil water is illustrated in Figure 4. This figure shows that the water content was generally higher in the deeper 25 to 50 cm (10 to 20 in) horizon than in the surface soil. It was only during a period of strong precipitation (days 173 to 195) that the surface soil had a higher or equally high water content. T-tests revealed that the differences between soil horizons were significant for street trees in the two dry periods (until day 170 and between day

208 and day 235). In the second dry period, the differences between soil horizons in the park soil were not significant.

The seasonal fluctuations in soil water are smaller in the 25 to 50 cm (10 to 20 in) soil horizon than in the surface horizon (Figure 4). The standard deviations from the four samples, which are plotted in Figure 4, were 10% and 12% for the 25 to 50 cm (10 to 20 in) horizon and 19% and 23% for the surface horizon for street planting pits and park soil, respectively.

Effect of Irrigation Treatments and Site on Soil Water

Irrigation effects were analyzed both in terms of the volumetric water content and in terms of the soil water saturation index. Significant responses to the irrigation treatments were found after all treatments except for the first irrigation on day 147 (26 May) (Table 3).

Figure 5 shows the treatment effects related to the control plot. For simplicity, the figure is based on water assessments from seven of 18 campaigns. Four campaigns within the treatment period with the highest (days 208 and 241) and the lowest (days 166 and 223) soil water saturation levels were selected for illustration of the treatment effects. All treatments in Figure 5 resulted in improvement of the soil water status. The irrigation treatments of 640, 320, 280, and 140 L water (166.4, 83.2, 72.8, and 36.4 gal) caused the soil water level to be on average 26%, 18%, 7%, and 4%, respectively, above the control during the treatment period. The park soil—after a very dry period during May/June—continuously and significantly improved its water status in comparison to the street tree pits (Table 3). This is confirmed in Figure 4, showing that the soil water saturation index at a depth of 25 to 50 cm (10 to 20 in) has a significantly increasing trend line in the park soil and a significantly decreasing trend line in the street tree planting pits.

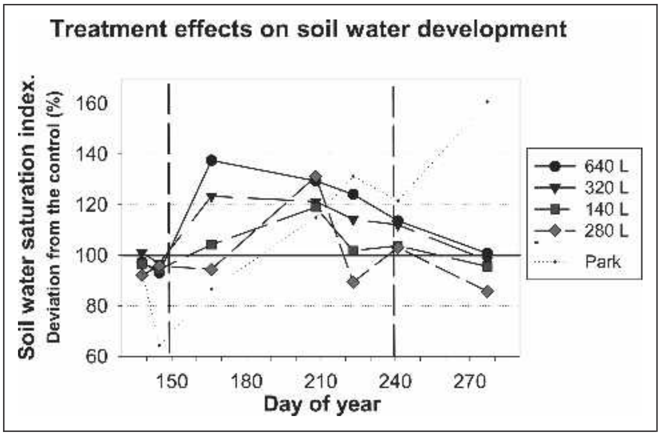

Figure 5. The deviation of the treatments from the street tree control is calculated on the basis of the saturation index. The park soil assessments are also shown as a further reference. The vertical dashed lines show the beginning and end of the irrigation treatment.

Time Domain Reflectometry Responses Immediately After Irrigation

At five different times during the project, the soil water content was measured 1 day before and 1 day after the irrigation (on irrigation day 239, the soil water assessment was carried out 2 days after the irrigation). The absolute water content (in liters) was calculated from TDR data in the upper 25 cm (10 in) soil layer before and after the irrigation. Consequently, an increase in soil water was estimated from the TDR assessments. In theory, this increase should reflect the amount of irrigated water.

Figure 6 shows the TDR-estimated increase in soil water in a planting pit after irrigation as a function of the added amount of water. If the change in estimated soil water precisely reflected the irrigated amount of water, all observations should be on the solid reference line in Figure 6 with a slope of 1.0 (i.e., estimated soil water change is identical to the amount of water that was added). However, the TDR-estimated soil water change after irrigation treatments tends

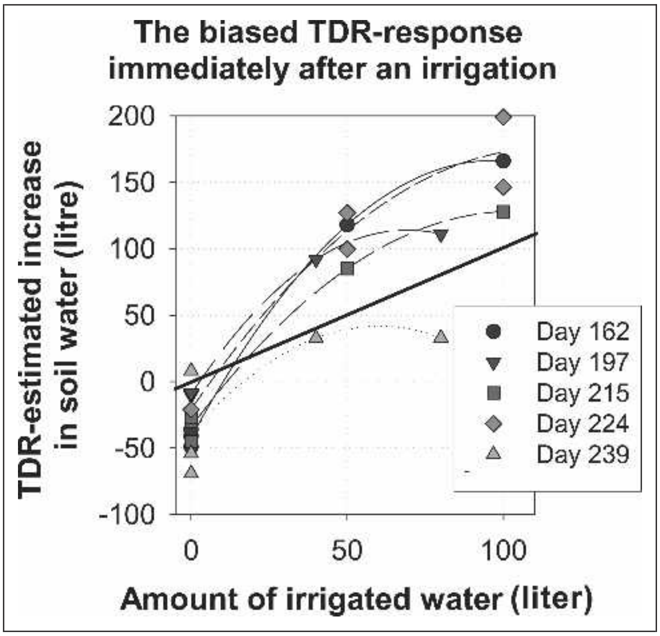

Figure 6. This analysis questions whether the time domain reflectometry (TDR) assessments on the day after irrigation reflect the amount of added water to the street tree planting pit. Five irrigation events are analyzed. The thick, straight reference line is where *Y* = *X*. On days 162, 197, 215, and 224, the irrigation response was measured on the next day. On day 239, the response was measured 2 days after irrigation. The figure shows that overestimation happens when TDR measurements are carried out on the first day after heavy water input.

to be strongly overestimated when TDR assessments were carried out on the first day after the irrigation. In the case of irrigation day 239, when the TDR assessments were postponed to the second day after irrigation, the soil water change is slightly underestimated (Figure 6). However, at this event, the "underestimation" tends to correspond quite well with the estimated water loss in the control plot.

Causality of the Soil Water Loss in Street Tree Pits

Whereas increase in soil water is related to either precipitation or irrigation, it is of interest to analyze the periods of decrease in soil water for at least two reasons: (1) the results in Figure 6 indicate that the TDR-measured soil water value tends to decrease very fast during the first 2 days after irrigation (methodological problem), and (2) we had an *a priori* hypothesis assuming that the water consumption of the trees might contribute to the soil water decline. If so, could differences in soil water decline on soils near either fast- or slow-growing trees be detectable?

During the assessment period, evident reductions in soil water content were found in the following five periods: days 131 to 145, days 152 to 159, days 198 to 214, days 216 to 223, and days 241 to 277. T-tests for differences in absolute water amount between the start-day and the end-day of the respective periods revealed highly significant decreases in soil water except for the park trees during the last of five periods. The first period from day 131 to day 145 was before and the following four periods were after initiation of the irrigation treatments. Highly significant differences between treatments in extent of average daily water loss (see also Figure 8) were found in the four latest periods but not in the day 131 to 145 period when tested with model 2 (excluding treatment 6). The total water loss from all five periods is shown in Figure 7. Practically all the additional water from irrigations tends to get lost during the five periods of soil water decline. Furthermore, it can be calculated from the figure that the average daily water loss rate in nonirrigated street and park trees was 8.5 and 10 L/day (2.21 and 2.6 gal/day), respectively.

The absolute loss of water (L/day and planting pit) in each of the five periods was calculated for each of the 100 planting pits and for the five park soil sites. The variation in daily water loss between planting pits was large. In the period from day 216 to 223, the water loss rate within the 20 control planting pits ranged between 6.3 and 30.3 L/day (1.64 and 7.88 gal/day). The equivalent variation in the park soil was between 25 and 37 L/day (6.5 and 9.62 gal/day). Seven explanatory variables were used for analysis of the rate of soil water loss:

1. The amount of water irrigated just before the studied periods;
2. The soil water saturation level at the beginning of the period;
3. The length of the studied period in days;
4. The average daily basal area increment of the trees in each of the five periods;
5. As a result of the methodological error mentioned in the previous section, a dummy variable (0, 1) was established to denote whether an experimental irrigation was carried out 1 day before the beginning of the studied period. This was the case in six of the 25 possible treatment * period combinations;
6. Average daily precipitation within each of the five periods; and
7. Average air temperature within each of the five periods.

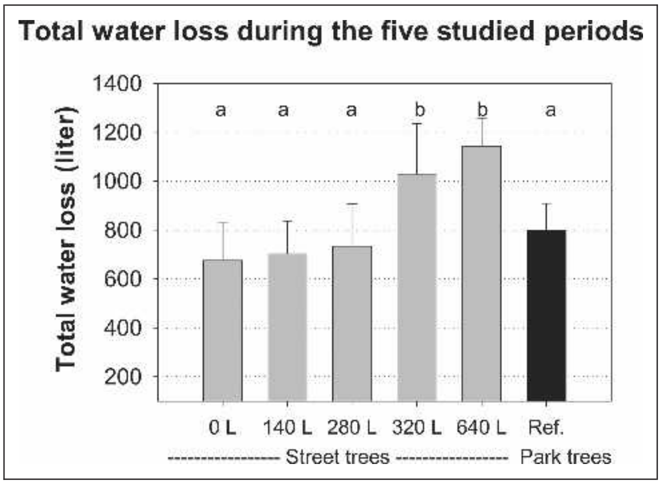

Figure 7. The water loss during five periods of soil water decline is summed and presented treatment-wise. Treatment effects were tested with model 2. The data are not corrected for the methodological problem shown in Figure 6. Thus, the water losses shown are somewhat overestimated.

However, simple correlations between soil water loss and explanatory variables generally revealed low correlation coefficients and a variable and nonsystematic pattern. It also turned out that multiple regression models with the explanatory variables in an additive structure provided a poor explanation (R^2 below 0.4). Thus, a series of multiple regression analyses with various interaction terms were carried out for detection of multiplicative effects (interactions) and a better explanation. Model 3 provided the highest explanation (R^2) and was suitable for quantification of the effects from period length and soil water saturation at the beginning of the periods. Various functions for the declining water loss were tested in model 3, but the chosen reciprocal model provided the best fit and best biologic interpretation.

Results of model 3 are given in Table 4, and predicted values from model 3 are illustrated in Figures 8 and 9. The outcome of model 3 can be summarized as follows:

1. The longer the period, the smaller the average daily soil water loss. (This is the combined effect of the [2] to [4] effect of model 3. This effect is more easily understood from the slope of effect *L* in model 4). Also refer to Figure 8.
2. The higher soil water saturation at the beginning of the period, the larger the average daily soil water loss (the effect of *S* in Table 4 strongly enhances the effect of *RL* in model 3). Also refer to Figure 9.
3. The amount of water irrigated immediately before the investigated periods almost never revealed any significant influence in model 3 and was thus eliminated from the model. The effects of irrigation are accounted for by the *S* effect of model 3.
4. The analysis also revealed that the soil water decline rate was overestimated in five of 25 period * treatment combinations as a result of TDR assessments immediately after irrigation. Model 3 calculated the overestimation in period 216 to 223 to be 0.33, 2.3, 12.3, and 13 L/day (0.09, 0.60, 3.20, and 3.38 gal/day) in the 140, 280, 320, and 640 L (36.4, 72.8, 83.2, and 166.4 gal) treatments, respectively. The correction in period 198 to 214 was 4.2 and –2.5 for treatments of 320 and 640 L (83.2 and 166.4 gal), respectively. The predicted values in Figure 8 were adjusted for these methodological errors.
5. Variables for irrigation before and precipitation during the five periods were not significant. Neither was the air temperature. Thus, these variables were not included in model 3.

Figure 8 also reveals the increasing decline with increasing irrigation in the street tree pits and the straight linear decline in the park trees.

Even if the stem increment effects ($P_i{*}T_j{*}I_{ijk}$) could explain 20% of total variance of model 3 (see Table 4), the sign and significance of the 30 slope estimates varied considerably. There was, however, a clear tendency toward higher and more positive slopes in the 640 and 320 L (166.4 and 83.2 gal) treatments and more frequent negative slopes in the control and the 280 and 140 L (72.8 and 36.4 gal) treatments. The sign of slopes in such complex models cannot be interpreted biologically, because the level of the intercept is strongly influenced by the other model terms. To gain more biologically interpretable signs of slope for the stem basal area increment effect, model 3 was reduced to model 4. Results of model 4 are presented in Table 4. This model produced significant negative slopes for the stem increment variable (*I*) in five of six street tree treatments. The slope in the 640 L (166.4 gal) treatment was not significant.

Above all, the significance and the trend of the regression slopes in model 4 totally reject the *a priori* hypothesis that

Table 4. This table provides statistical results for models 3 to 5.[z]

	Source of variation	Degree of freedom	Sum of squares	Probability	Estimate/slope
Model 3	Dependent variable: W				$R^2 = 0.82$
	A			<0.0001	−13.83
	B	4	271	0.0001	−5.66[y]
	L	1	325	<0.0001	0.38
	RL	1	74	0.05	51.3
	RL*S	1	6020	<0.0001	3.26
	D	6	1021	<0.0001	See text
	I*T*P	30	1922	<0.0001	See text
Model 4	Dependent variable: W				$R^2 = 0.37$
	A			<0.0001	32.67
	B	4	1075	0.0004	−4.54[y]
	L	1	16026	<0.0001	−0.62
	I*T	6	5094	<0.0001	See text
Model 5	Dependent variable: I				$R^2 = 0.36$
	A			<0.0001	18
	L	1	7222	<0.0001	−0.42
	W*T	6	2625	<0.0001	Figure 8

[z] Explanations of model effects: W = water loss per day in a 6.4 m^2 (69.1 ft^2) planting pit (L/day, positive values); A = constant; B = block; P = period; T = treatment; L = length of period (days); RL = 1/L; S = soil water saturation level at the beginning of the periods (%); D = dummy variable (value 0 or 1) describing whether an irrigation was carried out or not on the day before the time domain reflectometry assessment at the beginning of the period; I = average daily stem basal area increment (mm^2/day).

[y] Estimate is average of five blocks.

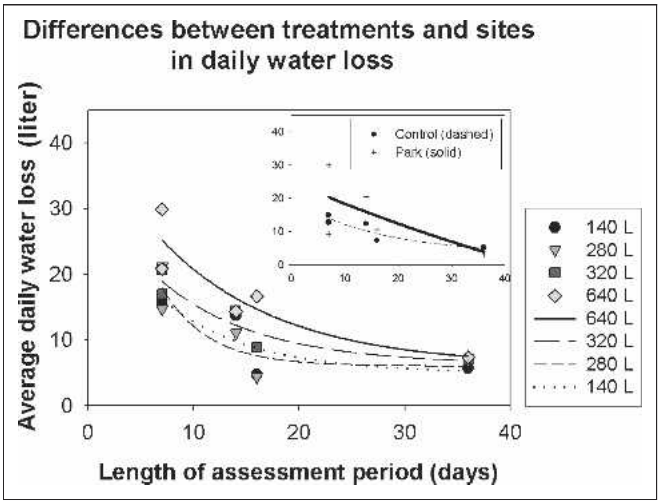

Figure 8. Illustration of model 3 results. The plotted data are period * treatment means of predicted values from model 3, but the plotted data are adjusted for overestimation of the result of irrigations immediately before time domain reflectometry assessments at the beginning of six of 25 period * treatment combinations (by use of the fifth model term in model 3). Thus, the curves are "cleaned" for the methodological error documented in Figure 6. Function of the trend curves: $W = A + B^{*}e^{(-b^{*}L)}$, where A and B are constants and W and L are defined in Table 4. The figure shows that the soil water decline rate increases with irrigation and is highest in short periods of negative soil water fluctuation. This indicates that the soil water loss rate is highest at the beginning of periods with soil water decrease. Precipitation during these periods showed no significant influence.

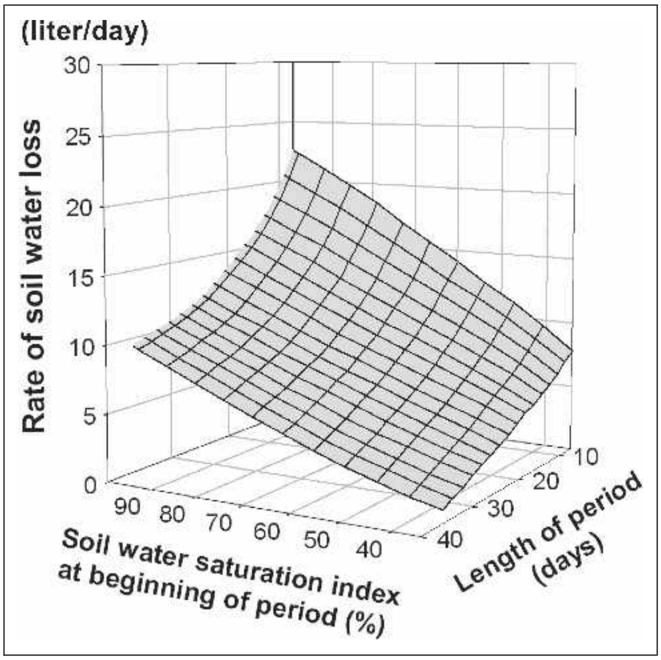

Figure 9. Predictions from model 3 showing the rate of soil water loss as a function of (1) soil water saturation level at the beginning of the water decline period and (2) the length of the water decline period. The mesh plot is smoothed from the predicted values in the control treatment (i.e., street tree without irrigation). The figure indicates that the average rate of water decline decreases with falling initial soil water saturation level and with increasing length of the water decline period. The figure also indicates the multiplicative effect of the two independent parameters.

enhanced tree growth might contribute to depletion of the soil water resource in the street planting pits.

The Effect of Soil Water Decline on Tree Growth

In contrast to the hypothesized contribution of stem growth rate and crown transpiration to soil water decline, results of model 4 indicate the opposite causality. The previous section gave rise to an *a posterii* hypothesis that stem basal area increment may decrease with decreasing soil water retention capacity (here expressed by an increasing rate of soil water decline). Thus, the order of dependent and independent variables from model 4 was reversed and tested in model 5, which reflects the new hypothesis.

Results of model 5 are shown in Table 4. The effects from the rate of soil water decline on the tree growth are expressed by the treatment-specific slopes, $\beta_{j,}$ from model 5. These slopes are shown in Figure 10. A negative slope means that a drop in soil water content led to a decrease in stem increment. A positive slope means that a drop in soil water content was related to an increase in stem increment. Figure 9 shows that an increase in daily water loss of 1 L (0.26 gal) from the 6.4 m^2 (69.1 ft^2) planting pits during drier periods reduced the stem basal area increment 0.37 mm^2/day (0.00056 in^2/day) on average in the control sample. In the 640 L (166.4 gal) irrigation treatment, the reduction in stem basal area was only 0.14 mm^2/day (0.00021 sq in^2/day).

The positive slope for park trees in model 5 is not biologically logical. The data show that the relationship between soil water changes and tree growth differed between park trees and street trees. It seems more logical to reverse the causality for the park trees, which indicates that stem growth rate, as an indicator of crown transpiration, actually was a driving factor in the soil water balance below park trees.

DISCUSSION

Methodological Discussion

A number of problems arose with the TDR technology during the project. A large problem was the systematic overestimation of soil water content when assessments were carried out

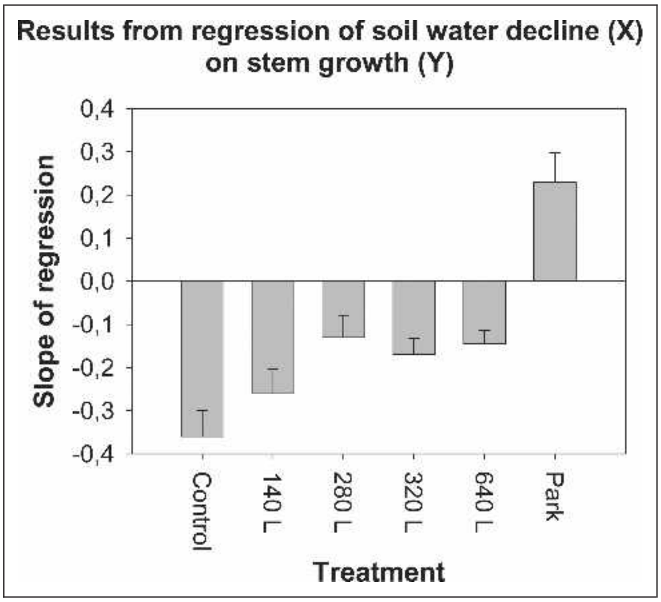

Figure 10. Effects of the soil water decline rate on tree growth are tested in model 5. The treatment specific regressions slopes (β_i) of model 5 are presented in this figure. The water decline rate is expressed in positive values. The figure shows that the increasing rate of soil water loss causes tree growth to decline in the street tree samples. The causality seems to be the reverse in park trees, in which it is assumed that growth and transpiration of the trees contribute to reduction of the soil water resource.

shortly after precipitation or irrigation. This problem was particularly obvious after irrigation events (Figure 6). In 16 of the 19 TDR assessment days, the preceding precipitation amount was close to zero. On only three occasions (days 184, 208, and 238) was the precipitation between 4 and 11 mm (0.16 and 0.44 in) on the day before a TDR measurement, which was reflected in the 0 to 25 cm (0 to 10 in) soil horizon curve of the street control planting pits in Figure 4.

This problem may be the result of uneven spatial distribution of irrigated water within the pits or the result of fast infiltration along the TDR rods followed by a slower elimination of water gradients through the soil pores. This problem could be corrected for in model 3 but not in most other analyses. Thus, the treatment effects on soil water content are likely to be smaller than shown in Figure 5. It is concluded that TDR assessments should not be carried out until 2 days after irrigation or heavy rainfall.

Another problem was the difficulties of installing 80 cm (32 in) deep TDR rods; these rods would have provided us with information on the fate of soil water, which was lost in the upper 50 cm (20 in) horizon. On the other hand, the TDR method has many advantages; it is fast, cheap, and largely nondestructive.

A statistical problem exists in model 3, because the five periods per street tree planting pit are not statistically independent. Hence, the significance levels in this model should be interpreted very conservatively. On the other hand, the ability of model 3 to accurately describe the data is beyond any discussion. This is illustrated in Figure 11, which shows very good correspondence between observed values and model prediction.

Biological Interpretation of the Results

Not surprisingly, the irrigation treatments were reflected by the soil water level. The soil water saturation level increased with increasing irrigation up to 26% above the street tree control (Figure 5), but these responses are somewhat overestimated as a result of the methodological bias described here and shown in Figure 6. Still, growth responses of the street trees on irrigation were significantly positive (Bühler et al. 2006). The drop in soil water during the dry spring period (days 130 to 160) was particularly strong in the park soil, and we attribute this to the intense weed vegetation on the park site. The bark mulch prevented evaporation and weed development in the street tree pits in this period. Also, in accordance with our expectations, the soil water fluctuation was much less in the 25 to 50 cm (10 to 20 in) horizon than in the 0 to 25 cm (0 to 10 in) surface layer (Figure 4). The horizontal differences in soil water content (Figure 3) were very significant but difficult for us to interpret. Still, they are presented to show the difference between park and street trees.

The major benefit of this study is the comparison of park and street tree soil water dynamic. Despite above-average precipitation, the soil water resource in the street planting pits was generally reduced during the summer (Figure 4). This is contrary to that of the park soil, whose water content gradu-

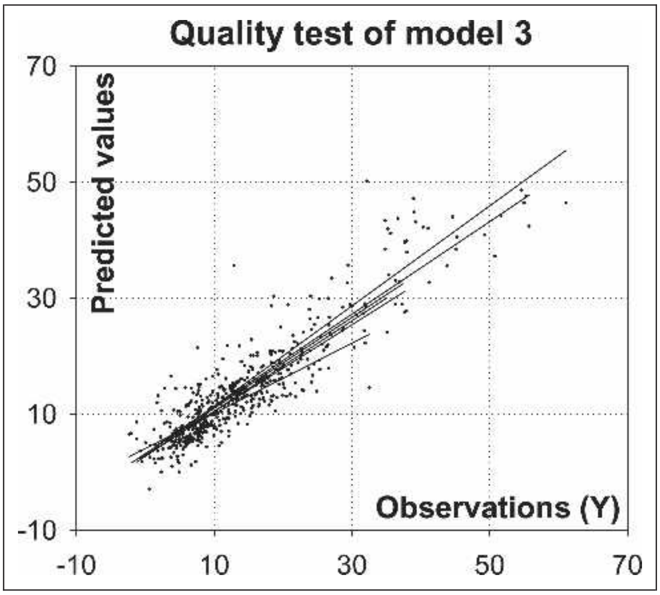

Figure 11. Test of the predictability of model 3. The units of both axes are liters per day.

ally improved after the dry spring period (Figures 4 and 5). This basic difference in long-term trends was not changed by irrigation. Irrigation elevated the soil water level during the application period, but thereafter, irrigated planting pits exhibited the same trend as the control sample (Figure 5). The declining time trend of the water saturation index in street tree pits is more serious than indicated in Figure 4, because street planting pit soils also have a poorer water retention capacity than the park soil (Figure 2). Obviously, street tree planting pits are subjected to severe net water losses during the summer period, whereas the opposite was found for park trees. The fact that the daily water loss rate was slightly lower in nonirrigated street tree planting pits than in the park soil (Figures 7 and 8) suggests that the declining time trend of the planting pit water resource is caused by a severely reduced amount of precipitation infiltrating into the soil of the street tree planting pits. Sealed soil surfaces outside the planting pit lead to surface runoff (into sewers). Thus, it becomes difficult for tree roots to find water outside the planting pit. Interception of precipitation by buildings, bark mulch, and the tree crown itself limit the water input further. Taking the very wet summer period (with precipitation 55 mm [2.2 in] above the average) into consideration, it is likely that the soil water resource in the planting pit will be totally depleted during a normal growing season. This conclusion concurs with the facts that the growing season of the street trees was 28 days shorter than that of the park trees and that irrigation significantly prolongs the growing season of street trees (Bühler et al. 2006). The negative effect of decreasing water content on the length of the growing season was also found by Nielsen and Jørgensen (2003).

Reduced infiltration of summer rain (water input) is part of the problem. However, the fate of soil water in the planting pits (water output) is, according to the presented results, a major issue also. Because the investigated planting pits are surrounded by curbstones, surface runoff is widely negligible, and soil water is primarily lost through evaporation, transpiration, and drainage. The generally elevated air and soil temperature in urban environments (Kuttler 1993; Meyer 1982) and the proximity to asphalt covers tend to increase evaporation from the soil surface, but the layer of bark mulch is likely to reduce evaporation. This is supported by the slower water loss rate during the dry spring period compared with the park soil (Figure 4). Soil hydrology and tree hydrology normally constitute a mutual feedback system, but the traditionally large impact of tree transpiration in old forest ecosystems (Holstener-Jørgensen 1958/59) was not found to be a driving mechanism in the soil hydrology in the street planting pits. As opposed to the park trees, where growth (and transpiration) of the trees was shown to significantly contribute to the soil water decline, the soil water dynamics of street tree pits seemingly were not driven by growth of the trees (Figure 10). This does not suggest that street trees did not transpire water, but it shows that street trees adapt to the soil hydrology rather than influence it.

Estimates based on data from Holstener-Jørgensen (1958/59) show that 23 m (75.9 ft) tall beech trees on a soil type similar to the park soil in our study had an average daily transpiration of 150 L/day (39 gal/day) during the growing season. As shown in Figure 4, the park subsoil was not saturated during the growing season, which strongly indicates that downward drainage was close to zero during the growing season, which also concurs with common hydrologic behavior in undisturbed soils (Pedersen 1993). Thus, a daily transpiration rate of 10 L/day (2.6 gal/day) for the park trees in our study seems fairly reasonably (Figure 7). The linearly decreasing water loss for park trees (Figure 8) is also in accordance with transpiration as the major cause of water loss in the park trees. Even if it deviates from current experience with undisturbed soils (Pedersen 1993), it is judged that drainage from the planting pit is an important cause of water loss, which is also true during the summer period. The soil texture of the planting pits is coarse, which provides good drainage but poor water retention capacity. The surface of the planting pit surroundings was sealed with asphalt and bricks, which caused the precipitation to run off and the soil around the planting pit—and most likely also the soil below the planting pit—to be comparatively dry. It is likely that the gradient in soil water content between the planting pit and the dry soil around and beneath it tends to level out. This explanation concurs with the exponential shape of the water loss curves for street trees (but not for park trees; Figures 8 and 9), and it concurs with basic theory of water movement from moist to dry soil (Brady 1974; Figure 7).

Further investigations into the fate of planting pit soil water seem promising. We believe that the linear water loss curve of the park soil in Figure 8 is facilitated by "normal" hydrology in the surrounding soil and by undisturbed subsoil with higher clay content. Because the soil beneath asphalt and bricks around street pits is generally heavily compacted, the contained water is strongly bound by capillary and adsorptive forces. This soil compaction will further drive the smoothing of soil water gradients between the planting pit and the surrounding soil. Furthermore, water that is lost from the planting pit to the surrounding soil will often not be available for tree roots, because roots do not grow in this compressed soil (Kristoffersen 1998, 1999).

One further problem with the street planting pits is the large variation among pits in water retention capacity. Whether this is the result of different soil texture in the pits or the result of different water exchange conditions with the surrounding soil is not clear.

Applied Discussion

As stated in the introduction, poor water input is a common problem for urban trees, and the results from this Copenhagen study show that the water resource in 1.5 × 4 m (4.95 × 13.2 ft) planting pits is close to becoming depleted during a normal growing season. Furthermore, the variation among planting pits showed that tree growth was reduced with an increasing rate of water loss.

How can we deal with this from a practical point of view?

The long-term and best solution is to avoid or reduce the water problems in the design phase. If the trees could be placed further away from the street, salt deposition would be reduced and the roots might have room for expansion in uncompressed and nonpolluted adjacent soil volumes. Deposition of deicing salt intensifies the effects of drought (Dobson 1991; Sieghardt 2000; Czerniawska-Kusza et al. 2004), and the possibility for further root extension will reduce the risk of sublethal storm damage to roots and root ball, thereby also conserving a well-functioning root system (Nielsen 1990; Nielsen and Hansen 2004).

Technical solutions for improved water balance could also be considered in the design phase. The most obvious solution is to enlarge the surface of the planting pit, because this enhances the amount of precipitation infiltrating into the pit. An enlargement of the planting pit surface (beyond the crown drip zone) by 1 m^2 (10.8 ft^2) would theoretically enhance the water input by 265 L (68.9 gal) during the growing season (100 dm^2 * 2.6 L/dm^2, assuming 265 mm [10.6 in]) rain during the growing season). Put in other words, the increase in relative stem growth from 10.9% in the control street trees to 15.1% for the trees under the 640 L (166.4 gal) irrigation treatment (see Bühler et al. 2006) might have been achieved by a 2.4 m^2 (25.92 ft^2) enlargement of the planting pit (from 6.4 to 8.8 m^2 [69.12 to 95.04 ft^2]). Managers in the large German cities recommend a permeable surface of between 8 and 14 m^2 (86.4 and 151.2 ft^2) (Klaus Schröder, park manager, City Osnabrück, pers. comm. 2005), which is in accord with our findings. Kristoffersen (1998) described the possibility of expanding the rooting zone of street trees by establishing root-friendly load-bearing layers under sealed surfaces carrying only light traffic as, for example, structural soils. Furthermore, Schröder (2004) described how to extend the rooting zone downward and below traffic lanes by use of a "subsoil" substrate, which is a root-friendly composition of stones (lava), sand, brown coal, and clay granules. This substrate can be compacted to a degree enabling the construction of bicycle lanes and parking lots on top. It is obvious that expansion of the root-friendly soil volume and increased infiltration of water will reduce the effects of drought and thus the need for costly irrigation. However, it is also important to use a soil or substrate with sufficient water retention capacity. The topsoil used in the planting pits in this study was very coarse because sand was added to facilitate good drainage, but the result was an exponential water loss rate during the first days after rainfall or irrigation. Examples for soil mixtures are provided by Schröder (2004) and the recent German standard for soil substrates (FLL 2004).

Most urban tree managers in European cities have a large stock of trees that do not have proper soil and tree water balance. For some of these plantings, a "tree health irrigation" program might be a reasonable course of action to improve survival and the quality of tree function. Two goals for irrigation programs are discussed: (1) survival on a short-term basis, and (2) normal growth and development and/or high longevity (50 to 80 years).

Survival

Trees adapt to drought by means of architecture, morphology, anatomy, and biochemistry (Parker 1968; Lyr et al. 1992; Nielsen 1990). Thus, trees may have poor growth but survive under "normal" dry conditions. A survival problem arises after extreme droughts (Mar:Møller 1965) or if additional stress factors arise. Year-ring analysis showed that drought reduced root growth three times that of stem growth and that forest trees continued to die for up to 3 years after the severe drought in 1976 (Nielsen 1990). Even if trees have adapted to low water supply, strong drought will cause mortality in the root system and, as a result of poor growth conditions, the trees often will not recover. Even if survival is the only goal, a monitoring system should be used to determine when irrigation is necessary for tree survival. It is obvious that urban tree managers would need to assign their trees to various risk groups with various thresholds of precipitation deficiency. TDR equipment with remote reading could be used for such a monitoring system. An emergency irrigation system, in which irrigation is carried out only to prevent root dieback, would doubtlessly reduce tree mortality as well as crown deformations in urban trees.

Proper Development and High Longevity

The prerequisite for a proper appearance and a long lifespan is absence of severe degeneration events. Ontogenetic degeneration is accelerated if the carbohydrate or water balance is disturbed over a long period. Root dieback from drought or storm damage, severe crown pruning, or defoliations may initiate the self-reinforcing degeneration cycle (Nielsen and Knudsen 2004), because damage to either the carbohydrate or the water balance is interacting: A disturbed water balance will effect carbohydrate production negatively and vice versa (Figure 12).

If longevity and vital tree development is the goal, it is important to maintain a reasonable growth rate in the tree. Among other things, this is a prerequisite for good compartmentalization and encapsulation of wounds, and it helps the tree protect itself against insects and fungi. A suitable and inexpensive way to monitor the "degeneration status" of trees is by regular diameter or circumference assessments, because the stem increment reflects the carbohydrate status of the tree.

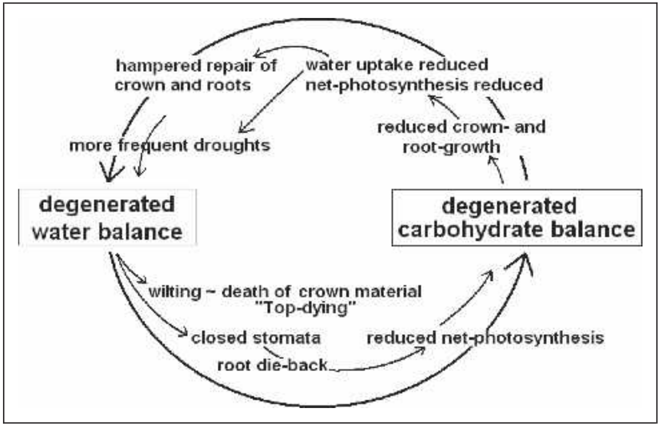

Figure 12. Illustration of the self-reinforcing cycle of tree degeneration.

For optimal monitoring, diameter assessments should be carried out on a yearly basis. Monitoring of growth should be accompanied by soil water assessments to determine when supplemental irrigation is required for proper long-term development of urban trees.

It is our belief that establishment of an "irrigation alarm system" is economically justified, because it is likely to reduce tree mortality rates. Such a system will slightly increase the maintenance costs but strongly reduce the costs of tree establishment.

CONCLUSIONS

Both absolute and relative growth were considerably lower in nonirrigated street trees than in park trees of similar age (Bühler et al. 2006). To a wide extent, this finding is attributed to differences in the soil water dynamic. Our results indicate that a large part of the precipitation never enters the mineral soil matrix in these 1.5 × 4 m (4.95 × 13.2 ft) planting pits because of extensive interception by buildings, bark mulch, and by the tree crown itself.

We think that a marginal expansion of the planting pit surface outside the crown drip zone would distinctly improve water infiltration. The water retention capacity of the planting pit substrate was variable but generally poor. One of the consequences was a high rate of water loss during the first days after precipitation or irrigation. It is recommended to improve the topsoil substrate with clay granules to counteract the excessive drainage caused by the coarse soil texture. Expanding the planting pit vertically with a subsoil substrate will likely help retain some of the drained water within reach of the roots. Furthermore, efforts to reach a higher homogeneity in water retention within a series of planting pits will result in more homogenous long-term development of the trees.

We suggest using maintenance irrigation to prevent death and degeneration of trees. Monitoring of stem diameter growth and of soil water content will provide a proper knowledge base to improve irrigation plans.

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Zusammenfassung. An 100 Straßenstandorten mit 6,9 m^2 Standfläche in der Nähe von 5 Parkbäumen wurde die Dynamik der

Bodenwassers untersucht. Die Erweiterung der Stammdurchmesserfläche wurde ebenfalls wöchentlich untersucht. Von den 100 Straßenbäumen wurden bei 4 X 20 Pflanzflächen 4 verschiedene Bewässerungen installiert. Eine Winteruntersuchung bei Feldkapazität zeigte, dass die Wasserrückhaltefähigkeit bei Standorten im Straßenbereich niedriger waren als bei Parkstandorten. Dies wurde unterstützt durch das ziemlich grobe Substrat in den Pflanzlöchern. Extrem hohe Variabilität unter den Pflanzlöchern bei der Wasserrückhaltefähigkeit kann mit der schwachen Normung der Substrate zusammenhängen, aber es kann auch durch die variierenden Drainage-Bedingungen beeinflusst werden. Die Wasserverlustrate bei den Straßenstandorten war sehr hoch nach Regenfall oder Niederschlag und nahm exponential ab während der ersten 10 Tage nach der Wasserzufuhr. Wir führten dies auf eine sehr schnelle Drainagewirkung zurück, welche sowohl vertikal als auch horizontal wirkt. Die Wasserverlustrate im Parkboden war durchschnittlich etwas höher als bei den Kontrollflächen in der Straße, aber zeigte über die Zeit einen mehr linearen Verlauf. Wir schlossen daraus, dass der Wasserverlust in den Parkböden während des Sommers primär durch die Transpiration der Bäume (etwa 10 l/Tag) verursacht wurde, was mit den Erfahrungen in dänischen Wäldern übereinstimmt. Die Beziehung zwischen Wasserverlust und Baumwachstum war bei den Straßenstandorten genau umgekehrt. Sicherlich verbrauchten die Bäume Wasser für ihr Wachstum, aber Wachstum und Transpiration der Straßenbäume waren nicht die treibenden Kräfte in der Hydrologie der Pflanzflächen. Die großen Zuwachsunterschiede bei Straßenbäumen können begünstigt sein durch die Standortunterschiede und ihrer Fähigkeit, Wasser zu halten. Je schneller die Wasserverlustrate, desto langsamer das Baumwachstum. Die Bewässerung konnte nicht die finale Depletion der Bodenwasserresourcen verhindern, aber die Bewässerung hob den Wassergehalt für einen begrenzten Zeitraum während der Wachstumsperiode und begünstigte daher das Wachstum. Neben den offensichtlichen Möglichkeiten für verbesserte Wasserbalance durch horizontale und vertikale Ausdehnung der Wurzelzone schlagen wir auch eine Verbesserung der Wasserrückhaltefähigkeit der Pflanzlöcher durch das Einbringen von Tonteilen vor. Hier werden Möglichkeiten diskutiert, den gegenwärtigen Degenerationsstatus der Bäume und den Bodenwassergehalt zu überwachen, um die Erhaltung zu optimieren.

Resumen. Se estudió la dinámica del agua del suelo en 100 sitios de plantación de 6.4 m^2 (69 ft^2) y el suelo adyacente en cinco parques urbanos. El incremento de la sección trasversal del tronco fue también evaluado semanalmente. Se implementaron cuatro niveles de riego en sitios de 4 x 20 de 100 árboles urbanos. Las mediciones a capacidad de campo en invierno mostraron que la capacidad de retención fue más baja en los sitios de plantación que en el suelo del parque. Esto fue atribuido al sustrato usado en los sitios de plantación. La extremadamente alta variabilidad entre los sitios de plantación en cuanto a capacidad de retención hídrica puede estar relacionada a la pobre estandarización de los sustratos, pero puede también ser afectada por la variación de las condiciones de "drenaje". La tasa de pérdida de agua en los sitios de plantación en la calle fue muy alta inmediatamente después de la lluvia o precipitación y disminuyó exponencialmente durante los 10 días siguientes. Se atribuye esto a un "drenaje" muy rápido, el cual puede ser tanto horizontal como vertical. La tasa de pérdida de agua en el suelo del parque fue en promedio levemente más alta que en los sitios de control, pero mostró una disminución más lineal sobre el tiempo. Se concluye que la pérdida de agua en el suelo del parque durante el verano fue dirigida primariamente por la transpiración de los árboles (arriba de 10 litros/día ~ 2.2 gal/día), lo cual cumple con la experiencia común del bosque danés. La relación entre pérdida de agua y crecimiento del árbol fue lo opuesto en los sitios de plantación. Por supuesto, los árboles consumieron agua para el crecimiento, pero el crecimiento y la transpiración de los árboles del parque no fue notablemente un mecanismo dirigido hidrológicamente en los sitios de plantación. La gran variación en el incremento de los árboles de la calle pudo ser atribuida a la variación entre los sitios de plantación en su habilidad para retener agua. A tasa más rápida de pérdida de agua, más lento crecimiento de los árboles. El riego no previno la pérdida final del agua del suelo en los sitios de plantación, pero el riego elevó el contenido de agua por periodos limitados durante la estación de crecimiento y contribuyó de esta manera al crecimiento de los árboles. Además de las posibilidades obvias para mejorar el balance de agua por expansión horizontal y vertical de la zona de raíces, se sugiere también mejorar la capacidad de retención de agua del suelo en los sitios de plantación añadiendo nódulos de arcilla. Se discuten opciones para el monitoreo de los estados y contenidos de agua del suelo para optimizar el mantenimiento.