Effects of root severance by excavation on growth, physiology and stability of two urban tree species: results from a long-term experiment

A. Fini[1*], P. Frangi[2], G. Amoroso[2], R. Piatti[2], E. Robbiani[2], L. Sani[3], L. Bonanomi[4], V. Blotta[5], F. Ferrini[1]

[1] Department of Plant, Soil and Environmental Science – University of Florence, viale delle Idee, 30, 50019, Sesto Fiorentino (FI), Italy

[2] Centro MiRT – Fondazione Minoprio, viale Raimondi 54, 22070, Vertemate con Minoprio (CO), Italy

[3] Laboratorio di Studi sull'Albero, via del Parione 1, 50123, Firenze, Italy

[4] Demetra Società Cooperativa Sociale Onlus - Via Viscontea 75 - 20842 - Besana Brianza (MB), Italy

[5] Freelance arborist, Studio Tecnoforest, Bologna, Italy

[*]Presenting author: alessio.fini@unifi.it

INTRODUCTION

The presence of trees in urban areas provides several benefits for both the community and the environment (Bernatzky, 1978; Ferrini et al., 2008), with healthy, long lived, big sized trees providing the greatest benefit (Nowak et al., 2002). However, tree health and longevity are threatened by a variety of stresses, caused by both environmental (i.e. drought, excess light, soil compaction) and biotic factors (Florgard, 2000; Fini et al., 2009, 2012). Trees in cities are also subject to intense conflicts with buildings, roads and utility installations, and engineering requirements often take precedence over tree conservation (Jim, 2003). More recently, the advent of optical-fiber and cable television infrastructures has required thousand kilometers of new trenching in the urban environment (Thompson and Rumsey, 1997). Construction activities and trenching near trees commonly cause extensive root damage, often resulting in tree decline and death, thus imposing additional replacement and maintenance cost (Hauer et al., 1994; Matheny and Clark, 1998; Jim, 2003). Root loss can be substantial, because roots usually spread up to 2.9 times beyond the dripline (Gilman, 1988). Therefore, a single trench can remove 18% to about 50% of a tree root system, depending on the distance from the trunk, the age of the tree, and soil characteristics (Watson, 1998; Wajja-Musukwe et al., 2008). Root severance has been reported to increase the risk of premature failing, even if stability loss following trenching was found to be lower than expected (Smiley, 2008; Ghani et al., 2009), but further studies are needed to clarify the relation between root loss and the real loss of stability. Root severance affects plant hydraulic architecture, carbohydrate storage and hormone balance, and consequently, plant physiology (Jackson et al., 2000). Therefore, it is likely that root damage through trenching induces physiological stresses on plants, but this hypothesis has never been tested directly (Watson, 1998).

In fact, several papers focused on root-severance-induced growth reductions, dieback and mortality, and report that visible symptoms may not occur until years after the damage (Watson, 1998; Despot and Gerhold, 2003; Wajja-Musuke et al., 2008), but little attention has been given to the assessment of physiological processes after root damage. The study of plant physiology may be an useful tool for early diagnosis of excavation damage to trees, and may provide a better understanding about the effects of root loss on tree health, long before symptoms become visible. Therefore, the aims of this study were: 1) to evaluate the long-term effects of two different levels of root severance on growth and physiology of two tree species supposed to difference in tolerance to root manipulation; 2) to evaluate the consequences of root severance on both theoretical (calculated) and measured (by pulling test) resistance to uprooting.

MATERIALS AND METHODS

In March 2004, 48 uniform horsechestnuts [*Aesculus hippocastanum*, 10-12 cm (3.9-4.7 in.) circumference] and 48 uniform European limes [*Tilia x europaea*, 10-12 cm (3.9-4.7 in.) circumference] were planted in an experimental plot (Vertemate con Minoprio, CO, Italy), in a sand loamy soil. Meteorological data (i.e. rainfall, air temperature) of the experimental site were recorded using a weather station (Vantage Pro 2, Davis, San Francisco, CA). Trees were allowed to establish undisturbed for five years. In June 2009, when trees were 25-30 cm (9.9-11.8 in.) circumference, the following treatments were imposed: 1) roots were severed only on one side of the tree by excavating a trench [70 cm (2.3 feet) deep and 50 cm (1.64 feet) wide] 40 cm (1.31 feet) apart from the root flare (Moderate Damage - MD); 2) roots were severed on both opposed sides of the tree by excavating two trenches [both 70 cm (2.3 feet) deep and 50 cm (1.64 feet) wide) 40 cm (1.31 feet) apart from the root flare (Severe Damage - SD); 3) roots were not damaged (control). The experimental design was a randomized complete block 4 blocks and 4 plants per species and treatment in each block (96 plants in total).

The area of the root plate was calculated 2 and 39 months after root severance by digging the root system with an Airspade™**.** Changes in root plate size induced by the excavation, crown size, and the uprooting resistance index were determined as reported by Koizumi et al. (2007), but considering an elliptical shape of the root system instead of half-ellipse. Stem diameter was measured (at 1.3 m) immediately after the excavation (June 2009) and at the end of the four growing seasons after root severance (in detail 8, 20, 32 and 44 months after the excavation). Shoot growth was measured on 20 shoots per tree, species, treatment and block at the same time as stem diameter. Leaf gas exchange and chlorophyll fluorescence were measured, using an infrared gas analyzer (Ciras 2, PP-System, Amesbury, MA) and a portable fluorometer (HandyPea, Hansatech, King's Lynn, UK), respectively, 12 times during the growing season in the 5 years after damage (from 1 week to 51 months after severance) on 4 leaves per species, treatment and block. Pre-dawn leaf water potential was measured in the 4 years after severance between 3.00 and 5.00 A.M. with a pressure bomb (PMS Instruments, Albany, OR) on 4 leaves per species, treatment and block.

Pulling test was performed 2 months and 4 years after root severance as described in Sani et al. (2012). Briefly, two inclinometers (Picus TreeQinetics, Argus Electronics, Meckenburg, Germany) were positioned horizontally near the root flare, one at the side undergoing compression stress, the other on the side under tensile stress. At a variable height, recorded with centimeter precision, a slotted band was positioned near the centre of gravity of the tree and attached to a load cell (Picus TreeQinetics, Argus Electronics, Meckenburg, Germany), positioned on the pull-line, to determine the pulling force expressed in N. Finally, the load cell was tied to a metal cable placed in traction by means of a Tirfor (TU-16, Tractel, www.tractel.com). On the opposite side from the direction of pull, the cable was connected to the Tirfor and this was connected, using a shackle, to another slotted band attached to the anchorage point the base of a vehicle with sufficient mass and soil adherence. The inclinometer and load cell were then connected to a data acquisition device (TreeQinetics, Argus Electronics, Meckenburg, Germany), for analogue to digital conversion and display of the data on a computer. The test was carried out by progressively and constantly applying the force created by the 56mm advancement of the Tirfor cable and instantly recording the variation of the instrumental stress values. In order to avoid damaging the plants, an attempt was always made to carry out the test within the elastic field, thus interrupting the pulling when the bending of the plate reached a value of 0.20°, since this value was considered to be sufficiently low not to damage the roots.

All data were analyzed with two-ways ANOVA (species and root severance were considered as independent factors) using SPSS statistical software (SPSS v.20, IBM, NY).

RESULTS AND DISCUSSION

Results of this study show how root severance affects tree health and stability for several years after damaging, as no complete recovery of physiological processes and in tree stability were found in the 46 months after severance. All intensities of root damage lead to a consistent decline of above-ground tree growth (Tab. 1). However, while in linden growth decreased similarly in MD and SD treatments, in horsechestnut growth was reduced much more in SD than in MD plants which, in turn, showed depressed growth than control (data not shown, but see the significant interactions in Tab. 1). Reduced above-ground growth may be due to greater carbon allocation to roots to compensate for the damage, as reported in previous studies on root manipulation (Amoroso et al., 2010; 2011), but also to lower availability of newly-assimilated carbon because of the decline in leaf gas exchange in severed trees. Consistently, CO_2 assimilation of leaves of both species was reduced by trenching, particularly in SD plants (Fig. 1). Differences in CO_2 assimilation among treatments varied greatly in relation to meteorological parameters, being larger in dry years than in wet years (Fig. 1, Fig. 2). As hypothesized, the ability to recover leaf gas exchange following root damage differed in the two species: CO_2 assimilation of linden recovered 38 months after damage (July 2012) and no significant difference among treatments were found in the following growing season (49 and 51 months after damage, June and August 2013). On the contrary, no complete recovery of CO_2 assimilation was found in horsechestnut, particularly in SD trees. When CO_2 assimilation is constrained by unfavorable environmental conditions (i.e. drought) or human disturbance, leaves may experience excess light stress, leading to oxidative cell damage, membrane disruption and metabolic impairment (Fini et al., 2012). However, as shown by the little change in Fv/Fm (Tab. 2) and the decline in internal to external CO_2 ratio (data not shown), the reduction of CO_2 assimilation appears more related to stomatal limitations (i.e. reduced CO_2 availability in substomatal chamber because of partial stomatal closure) than to biochemical factors (i.e. impairment of Rubisco and Calvin cycle). This results indicate that root damage indirectly (because it is not related to resource availability, but to tree uptake potential) induce a chronic but mild water stress to root-severed trees, even when soil water availability was not limiting. This mild stress may not cause sudden tree death but be a predisposing factor to more severe drought during dry years. This may explain why severed trees may not show visible signs of damage for several years, then die quickly as environmental conditions turn unfavorable. Pre-dawn water potential data support this hypothesis (Tab. 2): in horsechestnut, small but significant differences were found in wet years (year 2, 2010) between control and severed trees, but differences increased in drier seasons (year 3, 2011, and summer 2012 during year 4), as also observed for gas exchange measurements. On the contrary, linden displayed a faster recovery of water relations and, since year 3, differences in Ψ_w among treatments disappeared, confirming higher tolerance to root manipulation in this species than in horsechestnut.

Tree stability was greatly reduced because of root severance (Tab. 3). The uprooting resistance index (URI) calculated after excavation declined in both species, with the maximum reduction in SD trees. The calculated URI was consistent with the results from the pulling test: immediately after excavation, the stress required to induce an inclination of 0.2° to the root plate ($\sigma_{0.2}$) in MD trees was about 30% and 40% lower than in control, in linden and horsechestnut respectively. In SD trees, $\sigma_{0.2}$ declined by 50% in linden and by 70% in horsechestnut. The actual loss of stability, measured by pulling test, was however lower than the calculated value, in agreement with previous investigations (Smiley, 2008). Four years after excavation URI slightly increased in severed trees, and in particular in SD horsechestnut which showed no significant difference with control. URI is the ratio between the contribution of root geometry to tree stability and the moment factor, which depends on crown size and live crown ratio. The increase in URI in SD horsechestnuts was mainly caused by the reduction in moment factor, because of reduced shoot growth and canopy size, rather than to increased contribution of roots to tree stability (data not shown). Consistently, pulling test 4 years after severance confirmed that recovery of tree resistance to uprooting was not complete in SD horsechestnut, as well as in MD and SD linden. Pulling test also revealed that the stress on the compression side and on the tension side were similarly reduced following trenching (Tab. 3).

In conclusion, root severance imposes serious constrains to tree health and stability. The ability of severed trees to absorb water is reduced, and this effect is very long-lasting, thus predisposing trees to drought stress during dry years. Similarly, the capacity of severed trees to stand declines. Despite of the sensitive species showing reduction in above-ground growth if roots are severely damaged, thus reducing the moment factor and the wind load on tree canopy, we show here that the root system do not fully recover, even after several years since trenching, thus predisposing severed trees to failure by uprooting during extreme meteorological events (i.e. strong winds or snow).

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Table 1: Stem diameter ($Ø_{stem}$, cm) and shoot growth (cm), measured at the time of trenching and in the 4 years after excavation, as affected by root severance (MD = moderate damage; SD = severe damage; C = control) and tree species. Different letters within the same column indicate significant differences at P < 0.05 (*) and P < 0.01 using HSD test.

Treatment	$Ø_{stem}$ at excavation	ΔØ 0-8 months	ΔØ 8-20 months	ΔØ 20-32 months	ΔØ 32-44 months	Shoot growth year 1	Shoot growth year 2	Shoot growth year 3	Shoot growth year 4
Effect of root severance									
C	9.7 a	1.4 a	1.3 a	1.1 a	1.8 a	40.1 a	24.5 a	38.0 a	30.0 a
MD	10.0 a	1.5 a	1.0 b	0.8 b	1.3 b	29.4 b	18.8 b	27.5 b	17.3 b
SD	8.9 a	0.9 b	0.9 b	0.8 b	1.3 b	27.9 b	15.2 c	21.0 c	14.8 b
P	n.s.	**	**	*	*	**	**	**	**
Effect of species									
Tilia	10.0 a	1.5 a	1.1 a	0.9	1.5	42.4 a	19.8 a	20.1 b	17.2 b
Aesculus	9.0 b	1.0 b	1.2 a	1.0	1.4	22.6 b	19.1 a	37.6 a	24.2 a
P	**	**	n.s.	n.s.	n.s.	**	n.s.	**	**
Root severance X species									
P	n.s.	n.s.	n.s.	*	n.s.	n.s.	*	*	*

Table 2: Maximum quantum yield of PSII photochemistry (Fv/Fm) and pre dawn water potential (Ψw, MPa), as affected by root loss severity (MD = moderate damage; SD = severe damage; C = control) and tree species. Different letters within the same column and species indicate significant differences at P < 0.05 (*) and P < 0.01 using HSD test.

Specie	Treatment	Fv/Fm year 1	Fv/Fm year 2	Fv/Fm year 3	Fv/Fm year 4	Ψw year 1	Ψw year 2	Ψw year 3	Ψw year 4
Linden	C	0.81 a	0.81 a	0.83 a	0.80 a	-0.19 a	-0.20 a	-0.18 a	-0.35 a
	MD	0.80 ab	0.81 a	0.83 a	0.78 b	-0.32 b	-0.26 b	-0.20 a	-0.35 a
	SD	0.79 b	0.80 a	0.83 a	0.78 b	-0.65 c	-0.27 b	-0.18 a	-0.33 a
Horsechestnut	C	0.79 a	0.80 a	0.83 a	0.80 a	-0.21 a	-0.22 a	-0.18	-0.38 a
	MD	0.80 a	0.80 a	0.82 ab	0.79 ab	-0.42 b	-0.27 b	-0.38 b	-0.5 b
	SD	0.76 b	0.76 b	0.81 b	0.78 b	-0.72 c	-0.29 b	-0.38 b	-0.65 c
$P_{species}$		*	n.s.	n.s.	n.s.	n.s.	n.s.	**	**
$P_{treatment}$		**	*	*	*	**	**	**	**
P_{sXt}		*	*	*	*	n.s.	n.s.	**	**

Table 3: Uprooting resistance index (URI) and stress required to induce a 0.2° bending of the root flare in the side of the tree under tension ($\sigma T_{0.2°}$, N m) and under compression ($\sigma C_{0.2°}$, N m), measured 2 months (year 0) and 4 years after severance. Different letters within the same column and species indicate significant differences at P < 0.05 (*) and P < 0.01 using HSD test.

Specie	Treatment	URI year 0	URI year 4	$\sigma T_{0.2°}$ year 0	$\sigma C_{0.2°}$ year 0	$\sigma T_{0.2°}$ year 4	$\sigma C_{0.2°}$ year 4
Linden	C	0.101 a	0.145 a	1910 a	1972 a	3910 a	3972 a
	MD	0.031 b	0.066 b	1481 b	1656 b	2310 b	2385 b
	SD	0.009 c	0.064 b	967 c	1067 c	2095 b	2145 b
Horsechestnut	C	0.068 a	0.115 ab	2160 a	2172 a	3010 a	2972 a
	MD	0.030 b	0.084 b	1260 b	1372 b	2860 a	2772 a
	SD	0.009 c	0.146 a	659 c	722 c	1060 b	1020 b
$P_{species}$		*	n.s.	n.s.	n.s.	*	*
$P_{treatment}$		**	*	**	*	**	*
P_{sXt}		n.s.	**	n.s.	n.s.	*	*

Figure 1: Carbon assimilation (A, μmol m^{-2} s^{-1}) in linden (*Tilia x europaea*) and horsechestnut (*Aesculus hippocastanum*) subjected to moderate (MD) or severe (SD) root loss. Different letters within the same sampling date indicate significant differences at P < 0.05 (*) and P < 0.01 using HSD test.

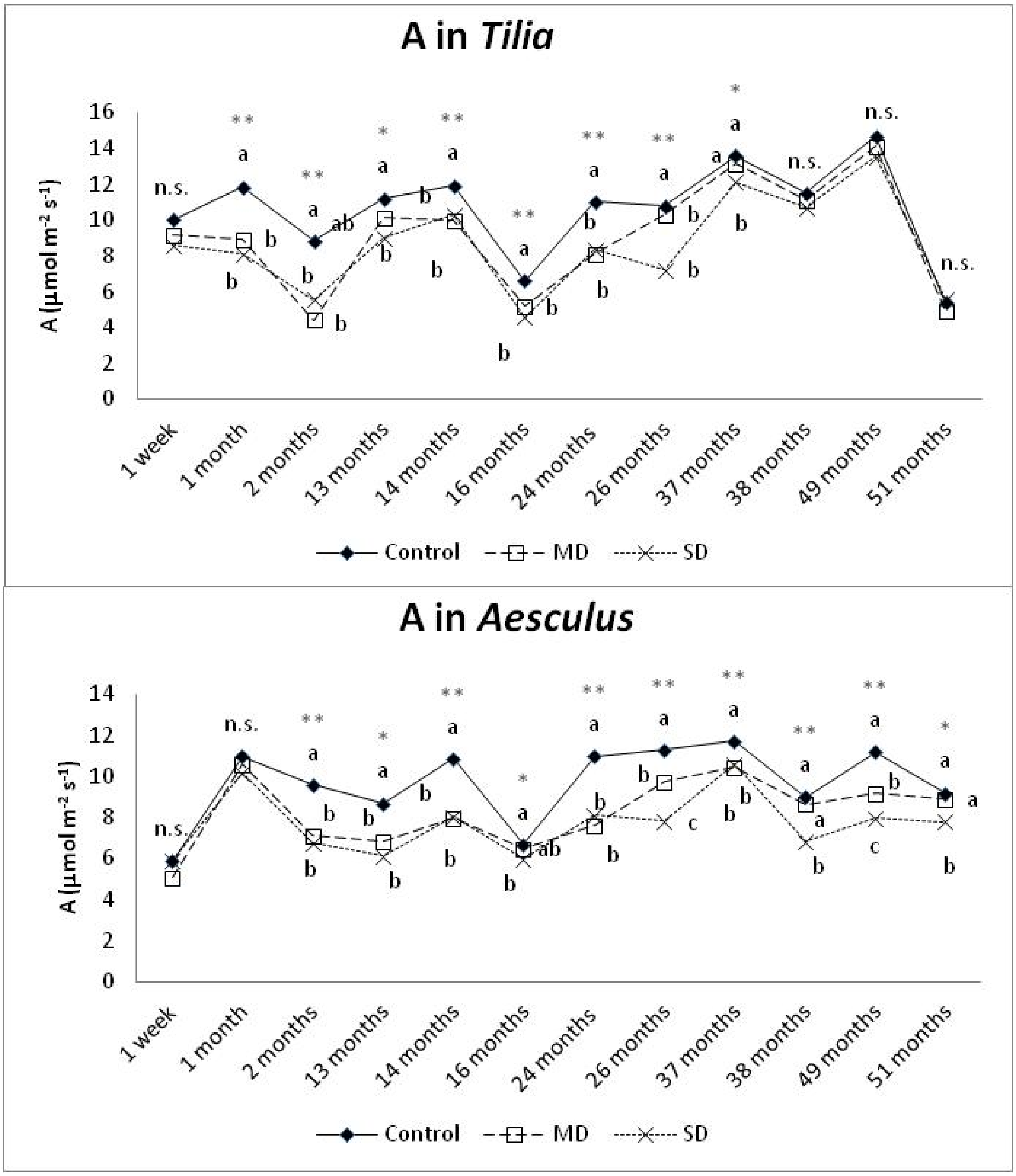

Figure 2: Total rainfall (mm) and average temperature (° C) at the experimental site. 25 mm is equivalent to 1 inch of rainfall.