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Evaluating the effects of trenching on growth, physiology and uprooting resistance of two urban tree species over 51-months

Alessio Fini ^{a, *}, Piero Frangi ^b, Jacopo Mori ^c, Luigi Sani ^d, Irene Vigevani ^a, Francesco Ferrini ^c

^a Dipartimento di Scienze Agrarie e Ambientali – Produzione, Territorio, Agroenergia, Università di Milano, via Celoria 2, 20133 Milano, Italy

^b Fondazione Minoprio, viale Raimondi 54, 22070 Vertemate con Minoprio (CO), Italy

^c Dipartimento di Scienze e Tecnologie Agrarie, Alimentari, Ambientali e Forestali, Università di Firenze, viale delle Idee, 30, 50019 Sesto Fiorentino (FI), Italy

^d Laboratorio di Studi sull'Albero, via Don Minzoni, 50123 Firenze, Italy

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ABSTRACT

Excavation within the root-zone of urban trees is increasing rapidly in compact cities for the installation and repair of belowground infrastructures, but research on excavation damages is mostly limited to the assessment of their effects on growth and dieback, while effects on physiology and long-term stability are still elusive. This experiment was aimed to understand long-term mechanisms of tree response to root severance. Two urban tree species (*Aesculus hippocastanum* and *Tilia x europaea*) were subjected to two different root damage intensities by digging either one, or two parallel (either side of the root flare) trenches. An equal number of trees were left undamaged as control. Shoot elongation and DBH growth were measured at the end of each growing season for four years after severance. Root system area was measured after the excavation and four years later. Leaf gas exchange, water relations, and chlorophyll fluorescence were assessed during the growing seasons over a 51-month period after severance. The effects on tree stability were evaluated 2 and 44 months after root severance by conducting pulling-tests and by calculating a theoretical uprooting resistance index based on the size of the root system. Results showed that, even at the most severe root damage treatments, which removed up to 70% of the root system, tree survival, growth and physiology were little affected. CO₂ assimilation declined by 16%–25%, mostly due to stomatal limitations, as also supported by a 0.7%–1.9% decrease in the maximum quantum yield of PSII (Fv/Fm). Excavation reduced stem diameter growth rate by 16%–28% and shoot elongation by 30%–41%, compared to control. Although the disturbance to tree physiology induced by excavation had a moderate intensity, the ability to recover from such damage over a 51-month period was scarce, particularly in *Aesculus*. Results indicate that root damage acts as a predisposing factor which reduces in the long term the capacity of trees to withstand co-occurring stresses by decreasing carbon availability for growth and defence. Similarly, the ability of trees to withstand uprooting was reduced by excavation, and no full recovery occurred in the following 44 months, when uprooting resistance was still 20%–66% lower in damaged plants compared to control, depending on the severity of the damage. A strong correlation ($R^2 = 0.822$) was found between results of the pulling test and the uprooting resistance index. This study highlights the importance of integrating physiological parameters for a better prescription of tree preservation guidelines during excavation work.

1. Introduction

Achieving a sustainable management of all types of forests, including the urban forests and improving the capacity to adapt to climate change and enhancing human well-being are among the key goals to be achieved in the forthcoming years (United Nations Sustainable Development Goals n. 11, 13, and 15). Because of their capacity to deliver

a wide range of provisioning, regulation, and cultural ecosystem services (Haines-Young and Potschin, 2018), urban trees are key elements to strengthen the resilience and the adaptive capacity against global change, as well as to strengthen communities and enhance safety and inclusivity in cities. It is long known that tree attributes such as health in the planting site, longevity, and size at maturity are positively correlated with the delivery of ecosystem services (Nowak et al., 2002). On the contrary, early tree decline, physiological stress, stunted

* Corresponding author.

Email address: alessio.fini@unimi.it (A. Fini)

growth and higher carbon emissions for maintenance and replanting can considerably reduce the benefit to cost ratio of urban trees (Nowak et al., 2002).

Excavation damage to tree roots is a stress of increasing importance for trees in the urban environment, where the need to repair belowground infrastructure often takes precedence over tree preservation, particularly since the advent of optical-fiber and cable television (Jim, 2003). In Manion's mortality spiral, root severance was classified as an inciting factor (i.e. stress factors that induce sudden strong biochemical and physiological changes in the energetic balance of the tree), such as drought or severe defoliation (Manion, 1991). Consistently, early research on root severance found that tree losses can increase up to 44% following severance (Morell, 1984) and that leaf wilting can occur within a few hours after roots are damaged (Hamilton, 1988). After reviewing a series of studies on root severance, however, Watson et al. (2014) found that the impact of excavation on tree health was much lower than expected and that symptoms may not be visible for several years after the roots have been severed.

The lack of a deep knowledge about the biological processes involved during tree responses to root injuries (among which physiological processes are included), has been identified as one of the major barriers limiting the adoption of tree preservation practices (Despot and Gerhold, 2003). Most published research has investigated the effects of excavation on tree health using dendrometric parameters, such as above-ground growth responses (Watson, 1998; Pretzsch et al., 2016) and visual tree condition rating (Hauer et al., 1994). These morphological observations have been widely used to develop augering specifications (Morell, 1984), but dendrometric data revealed high variability depending on species, plant age, and site characteristics (including management) where data were collected. Some studies found that short-term reductions in above-ground growth occurred after roots were severed, but they were followed by full recovery of growth rate (Hamilton, 1988; Pretzsch et al., 2016). Authors hypothesized that preferential allocation of resources to roots could temporarily depress growth of above-ground organs (Hamilton, 1988; Pretzsch et al., 2016). Other studies found progressive reductions in growth over time and a low resilience (i.e. the ability to recover to the pre-damage condition) displayed by woody trees to excavation and hypothesized increased sensitivity of trees with severed roots to water stress (Wajja-Musukwe et al., 2008; North et al., 2017). A widespread conclusion of these studies was that root severance presumably caused stress, but neither the stress was measured directly, nor its effects on plant physiology characterized (Watson, 1998; Watson et al., 2014).

Introducing physiological measurements to describe tree responses to root severance may yield a better understanding of how trees respond to this type of damage and allow an accurate stress quantification before visible symptoms appear. This may provide information to structure guidelines for tree preservation based on data not available until recently (Fini et al., 2013; Benson et al., 2019a, 2019b). A recent work on *Quercus virginiana* plants which severed roots at different distances from the trunk by digging circular trenches showed that pre-dawn water potential differed between control and excavated trees when the trench was dug closer than $15 \times$ trunk diameter at breast height (DBH), whereas changes in DBH growth occurred only when trees were trenched at $3 \times$ trunk diameter (Benson et al., 2019b). A limited body of literature explored the effects of root severance on plant physiology, but these studies were conducted on very young plants (Wajja-Musukwe et al., 2008), or were preliminary (Fini et al., 2013) and conducted only in the short term (Benson et al., 2019a, 2019b). Thus, the understanding of the resistance and resilience of physiological traits of mature trees to root damage remains elusive.

As regards tree stability, root damage was suggested to increase the likelihood of uprooting (Hamilton, 1988). Pioneer studies evaluating the uprooting resistance of root-severed trees revealed variable

changes in stability after root damage (Smiley, 2008; Ghani et al., 2009), being tree anchorage reduced by only 13%–47 % after half of the buttress roots were severed (Smiley, 2008; Ghani et al., 2009; Smiley et al., 2014). About 35% of tree failures are root related (International Tree Failure Database, accessed Sept 2019), thus more information is needed to understand how much root loss the different species can withstand without seriously compromising mechanical stability (Ghani et al., 2009). Further, such studies explored the change in tree anchorage before and immediately after root damage, while recovery is unexplored to our knowledge.

To fill these research gaps, a 51-month research was carried out with the aims of: 1) evaluating the long-term effect of two root severance intensities on growth and physiology of two species widely used in urban sites; 2) estimating the early impact of trenching on tree anchorage and the capacity of the two species to recover stability over time.

2. Materials and methods

2.1. Environmental conditions at the experimental site and plant material

The research was carried out in an experimental field at the Fondazione Minoprio (Vertemate con Minoprio, CO, Italy). Average annual rainfall and temperature of the site, measured over the last 30 years, are 1106 mm and 13.3 °C, respectively. Soil is a slightly acidic loam with an organic matter content around 1.8% and no lime (Table 1).

The experiment was conducted from June 2009 to September 2013. Average air temperature and rainfall were measured from January 2009 to December 2013 using a Vantage Pro 2 (Davis, San Francisco, CA, USA) weather station. Volumetric soil moisture was measured during the growing season (May to October) from 2010 to 2013 using three Frequency Domain Reflectometry (FDR) probes (SM100 Watermark, Spectrum technologies, 3600 Thayer Court, Aurora, IL, USA), buried at 15 cm below grade in different parts of the experimental field. Before installation, probes were calibrated using soil samples of known (and equal) volume as described in Fini et al. (2017). Volumetric water contents at field capacity and wilting point were 16% (v/v) and 2.8% (v/v), respectively, resulting in a soil water holding capacity around 13.2%.

In March 2004, 48 uniform balled and burlapped plants of *Aesculus hippocastanum* (3.2–3.8 cm DBH at planting) and 48 plants of *Tilia x europaea* (3.2–3.8 cm DBH at planting) were planted in planting holes as deep and twice as large as the rootball. Trees were planted in 4 rows in quincunx at a density of 476 plants/ha. Planting distance was 6 m within the row and 3.5 m between the rows. Trees were allowed to establish undisturbed for five years, with no fertilization provided. Supplemental irrigation was performed only during the first year after planting using a drip system. No mortality occurred over the five-year period after planting.

Table 1

Soil parameters from laboratory analysis: soil texture, soil actual pH, total lime, organic matter, cation exchange capacity and available macro-elements.

Gravel (w/w)	16%
Sand (w/w)	51%
Silt (w/w)	40%
Clay (w/w)	9%
pH H ₂ O	6.45
Total lime (w/w)	0.0%
Organic matter (w/w)	1.8%
CEC (meq/100 g)	5
Total nitrogen (w/w)	0.13%
Available phosphorus (Bray, w/w)	0.32%
Exchangeable potassium (meq/100 g)	0.26

2.2. Root severance treatments

In June 2009, three different treatments were imposed (Fig. A.1): 1) Severe damage (SD): two parallel trenches (28 m long, 70 cm deep, and 50 cm wide) were dug on two opposite sides (north and south) of the tree, 40 cm apart from the root flare; 2) Moderate damage (MD): one trench (28 m long, 70 cm deep, and 50 cm wide) was dug at one side of the tree (assigned in each row to be either the north or the south side to avoid bias due to light or other environmental factors), 40 cm apart from the root flare; 3) Control (C): no damage. Root severance treatments were imposed using an excavator. Trenches were excavated at a distance about 4.5 times DBH. This distance was about three quarters of the recommended distance for trenching (Costello et al., 2017; Benson et al., 2019c). A depth of 70 cm was chosen as suitable because nearly 100% of tree roots have been found within that depth for several landscape woody species (Gerhold and Johnson, 2003). Visual observations during the trenching activities and during subsequent Air Spade excavation confirmed these hypothesis (see Fig. A.2 in supplemental material).

2.3. Dendrometric measurements

Stem circumference was measured at 1.3 m using a measuring tape on all plants and DBH was calculated from circumference. Measurements were performed immediately after the excavation (June 2009) and at the end of each of four growing seasons after root severance (in detail 8, 20, 32 and 44 months after the excavation). Stem DBH annual growth (Δ DBH) was calculated as the difference in stem diameter between consecutive years. Shoot growth was measured on 20 shoots per 2 species, 3 treatments, 4 blocks and 4 different sampling periods (1920 shoots in total) at the same time as stem diameter, by measuring the shoots from the previous season's terminal bud scar to the apical bud (Fini et al., 2015). Tree height (H_{tree}) was measured using a graduated pole. Trunk height (H_{stem}) was measured as the distance between the root flare and the point where the first order primary branch was attached. Canopy height (H_{canopy}) was calculated as the difference between H_{tree} and H_{stem} . Canopy radii were measured along different directions using the vertical sightseeing method aided by a leveled post (Pretzsch et al., 2015).

Four and 44 months after trenching, the size of the root system was measured after removing the soil using an air-excavator (Airsapade™, Guardair Corp., Chicopee, MA). First, the root flare was exposed to locate structural roots. Then, individual structural roots were excavated starting from the flare and proceeding radially until encountering a root diameter of 2 mm, and their length measured (Stofko and Kodrik, 2008). Finally, the size of the root system (RS_{area}) was calculated as previously reported (Stofko and Kodrik, 2008), with few modifications:

$$RS_{area} = \pi * (RS_{NS}) * (RS_{EW})$$

where RS_{NS} and RS_{EW} are the radii of the root system across the row (N-S orientation) and along the row (E-S orientation). Two independent radii were used, instead of the average diameter reported by Stofko and Kodrik (2008), to account for the oval shape of the root system of trees grown in rows, with longer roots often developed across the row than along it (Gerhold and Johnson, 2003).

The ratio between RS_{area} and stem cross sectional area at 1.3 m was calculated 4 and 44 months after the excavation.

2.4. Physiological measurements

Leaf gas exchange measurements started in June 2009 (1 week after treatments were imposed) and were performed during the growing season (May to September) until 2013. In detail, twelve leaf gas exchange measurements were carried out: 1 week (June 2009), 1 month

(July 2009), 2 months (August 2009), 11 months (May 2010), 12 months (June 2010), 15 months (September 2010), 23 months (May 2011), 25 months (July 2011), 36 months (June 2012), 38 months (August 2012), 48 months (June 2013), and 51 months (September 2013) after the excavation. Measured parameters were: net CO_2 assimilation (A , $\mu mol m^{-2} s^{-1}$), stomatal conductance (g_s , $mmol m^{-2} s^{-1}$), transpiration (E , $mmol m^{-2} s^{-1}$), and CO_2 concentration in the substomatal chamber (C_i , ppm). Stomatal limitations to photosynthesis were estimated as the ratio between C_i and the CO_2 supplied in the leaf cuvette (C_a) (Medrano et al., 2002; Fini et al., 2014). Measurements were conducted on four fully expanded leaves per species, treatment, and block (96 leaves in total) from 9.00 a.m. to 12.30 p.m. Leaf gas exchange parameters were measured on leaves exposed to full sunlight and attached on apical shoots of primary or secondary branches (4 leaves per species, treatment, and block; 96 leaves in total). Measurements were conducted using an infra-red gas analyzer (Ciras 2, PP-System, Amesbury, MA), supplying the leaf in the cuvette with 380 ppm CO_2 (C_a , provided using an external CO_2 cartridge) and saturating irradiance ($1300 \mu mol m^{-2} s^{-1}$, provided using the integrated led unit) (Fini et al., 2015).

Dark-adapted chlorophyll fluorescence parameters were measured on the same leaves as leaf gas exchange using a portable fluorometer (HandyPea, Hansatech, King's Lynn, UK), as previously described (Fini et al., 2016). Immediately after leaf gas exchange measurements, leaves were dark adapted for 40 min using leaf clips to determine F_0 , then exposed to a saturating light pulse of white light ($3000 \mu mol m^{-2} s^{-1}$ for 1 s) to measure F_m (Genty et al., 1989). The maximum quantum yield efficiency of PSII photochemistry (F_v/F_m) was then calculated as: $F_v/F_m = (F_m - F_0)/F_m$, where F_0 , F_m , and F_v are basal, maximum and variable fluorescence, respectively.

Leaf greenness index, a parameter which is highly correlated to leaf chlorophyll content (Percival et al., 2008), was measured once per year in July on the same leaves used for leaf gas exchange measurements using a SPAD-meter (SPAD 502, Minolta, Osaka, Japan).

Leaf water potential (Ψ_w) was measured at pre-dawn (03.00 a.m. to 05.00 a.m.) 15, 23, 36, and 51 months after roots were severed. Measurements were carried out on the same day as leaf gas exchange. Measurements were conducted using a Scholander type pressure chamber at a flow rate of $0.02 MPa s^{-1}$ (Scholander et al., 1965) and were completed within 60–100 s after leaf abscission (Fini et al., 2017). Four leaves per species, treatment and block (96 leaves in total) were sampled for Ψ_w .

2.5. Uprooting resistance

The impact of root severance on uprooting resistance was evaluated using two independent methods: the calculation of the theoretical uprooting resistance index (URI) (Koizumi et al., 2007) and static pulling test (Wessolly and Erb, 1998). URI, i.e. the ratio of the geometrical moment of area for the windward side of a root system to the amount of moment applied on the root flare, was calculated after the excavation (2009) and after 4 years of relief (2013) as reported by Koizumi et al. (2007):

$$URI = G_R / MF$$

where G_R is the geometrical moment of area of the root system and MF is the moment factor applied on the root flare.

$$G_R \text{ was calculated as: } [(RS_{NS})^2 * 2 * RS_{EW}] / 3$$

$$MF \text{ was calculated as: } C_D * W_{canopy} * H_{canopy} * H_w$$

Where C_D is the drag coefficient, estimated 0.25 and 0.35 for *Tilia* and *Aesculus*, respectively (Horacek, 2003), H_{canopy} and W_{canopy} are canopy height and average width, and H_w is the height of the wind pressure center. H_w is calculated as: $H_{stem} + (1/3 * H_{canopy})$, assuming the wind pressure center occurs at 1/3 of canopy height (Koizumi et al., 2007).

Static pulling test was performed 2 months (2009) and 44 months (2013) after root severance as described in Sani et al. (2012). Two inclinometers (PiCUS TreeQinetics, Argus Electronics, Meckenburg, Germany) were positioned horizontally at the north and south sides of the root flare, one at the side undergoing compression stress, the other on the side under tensile stress. A slotted band was tied at the center of gravity of the tree recorded, and its position was recorded with centimeter precision. The slotted band was attached to a load cell (PiCUS TreeQinetics, Argus Electronics, Meckenburg, Germany). Finally, the load cell was tied to a metal cable placed in traction by means of a Tirfor (TU-16, Tractel, www.tractel.com). The Tirfor was anchored on the opposite side from the direction of pull, to 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 5.6 mm 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 flare reached a value of 0.2° , since this value was considered to be sufficiently low not to damage the roots (Wessolly and Erb, 1998). The bending moment required to reach 0.2° inclination of root flare, recorded by the inclinometer under tension (M_T) and under compression (M_C) was calculated according to the methods described in detail by Sani et al. (2012):

$$M = F_w H_w$$

Where F_w is the horizontal component of the tipping force recorded by the load cell.

2.6. Experimental design and statistics

The experimental design was a randomized complete block with 4 blocks and 4 plants per species and treatment in each block (96 plants in total) (Fig. A.1).

All data were analyzed using a Repeated measures ANOVA where species and root severance intensity were the between-subject factors, and time of sampling the within-subject factor. For parameters which displayed significant species \times root severance interaction, the effects of root severance were analyzed independently per each species (Fini et al., 2010). Means were separated using HSD post-hoc test.

Regression analysis between theoretical and measured resistance to uprooting was performed using the curve estimation tool of the statistical software.

All statistics have been carried out using SPSS software (SPSS v.20, IBM, NY).

3. Results

The experimental years were rainy, with rainfall above the 30-year average in 2009, 2010, 2012, and 2013; only in 2011 rainfall was slightly below average (Fig. 1). Consistently, soil moisture remained above wilting point (2.8%, v/v) throughout the experiment (inset in Fig. 1).

3.1. Dendrometric parameters

All trees survived during the experiment and no mortality or extensive dieback of the canopy was observed over the 51 months after the excavation (data not shown).

Initial DBH was significantly higher in *Tilia* (10.02 cm) than in *Aesculus* (9.30 cm), but did not differ among root excavation treatments (data not shown). Cutting roots reduced DBH growth in both species (Fig. 2A–B). SD plants experienced DBH growth reduction in the

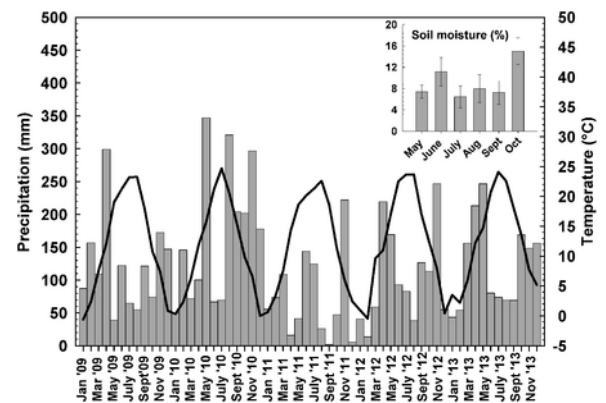


Fig. 1. Monthly average of temperature (line) and rainfall (bars) during the experiment and, in the inset, average monthly soil water content (v/v) during the growing seasons 2010, 2011, 2012, and 2013.

same year the damage was imposed. Conversely, in MD plants, DBH growth was not affected until 20 months after root severance. Interestingly, DBH growth rate in MD and SD trees of both species did not recover to the level of control plants by the end of the experiment.

The effects of root severance on shoot growth were species-specific (Table A.1). In *Tilia*, any degree of root damaged similarly reduced shoot growth (Fig. 2C). Conversely, in *Aesculus*, the more roots were severed, the greater reductions in shoot growth were found (Fig. 2D). Shoot growth of neither species recovered to the normal growth rate of control within 44 months from the damage.

The excavation damage significantly reduced the root system area (Table A.1). Immediately after the excavation, the area of the root system (RS_{area}) was reduced by 40% and 70%, respectively, in MD and SD plants, compared to control, regardless of the species (Fig. 3A–B). Forty-four months after trenching, RS_{area} of MD and SD *Aesculus* was 33% lower compared to control, while RS_{area} of undamaged *Tilia* was 49% and 62% higher than MD and SD *Tilia*, respectively. In the 4 years after severance, the increase in root system area was higher, when expressed in relative terms (i.e. increase in root area per unit existing root area), in SD plant of *Tilia* (+70%) and *Aesculus* (+177%) compared to control (+23% and +31% in control *Tilia* and *Aesculus*, respectively). When root system area growth was expressed on in absolute terms, however, only SD *Aesculus* (6.46 m² increase from 2009 to 2013) displayed higher growth than control (2.36 m² increase). Conversely, control *Tilia* displayed faster absolute root growth (8.20 m² increase from 2009 to 2013) than SD (5.36 m²) and MD (2.36 m²) plants. *Tilia* had, on average, 47% larger root system than *Aesculus*, and this difference was consistent across the years of measurement.

In undamaged plants of *Tilia* and *Aesculus*, each cm² of stem cross sectional area was supported by 1.50 and 0.77 m² of root system area, respectively. Root severance significantly reduced the stem to root system cross sectional area ratio by 40% and 67% in MD and SD plants of both species (Fig. 3C–D; Table A1). Forty-four months after severance, MD and SD plants still had lower root system to stem cross-sectional area ratio than control (Fig. 3C–D). The stem cross-sectional area to root system area ratio was significantly higher in *Tilia* than in *Aesculus*, indicating that the unit stem area in *Tilia* is supported by about 40% larger root system area than in *Aesculus* (Fig. 3C–D).

3.2. Physiological parameters

Pre-dawn water potential (ψ_w) was differently affected by root damage, depending on the species and time after damage (Table A1). Fifteen and 23 months after the excavation, ψ_w of both species was lower in damaged plants than in control, and SD plants displayed either more negative (15 months) or similar (23 months) ψ_w than MD trees (Fig. 4). ψ_w of both MD and SD *Tilia* recovered by the third year after excava-

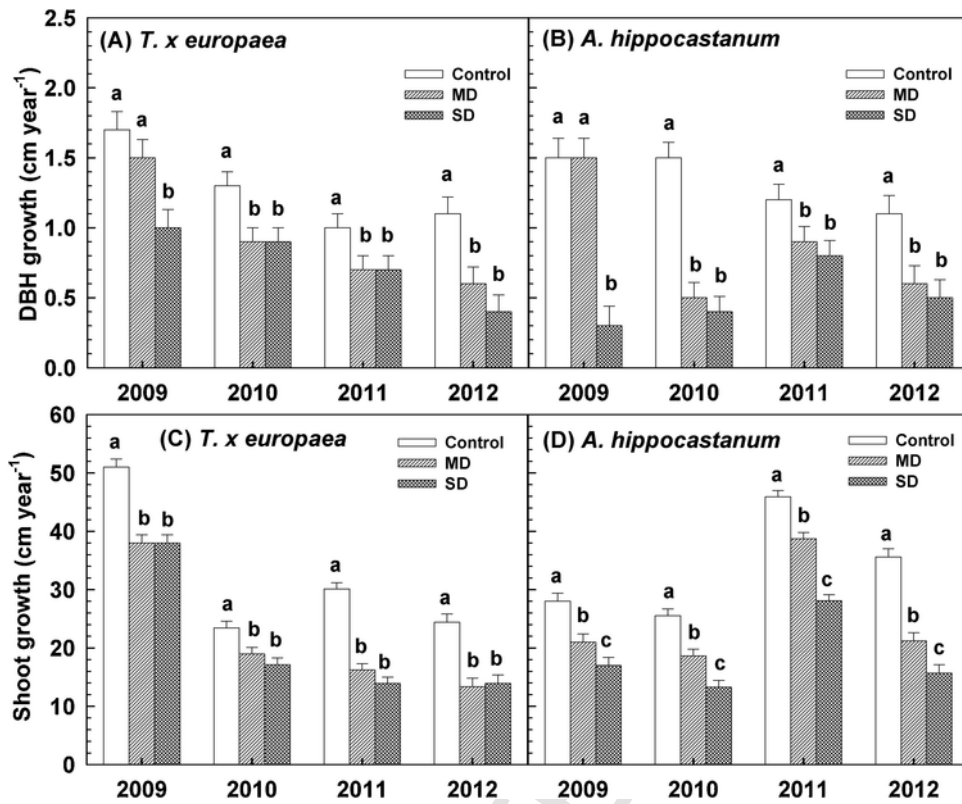


Fig. 2. Above-ground dendrometric parameters measured at the end of the growing seasons 2009, 2010, 2011, and 2012 in *Tilia* (A), (C), (E) and *Aesculus* (B), (D), (F) plants which had been severely damaged (SD), moderately damaged (MD) or left undamaged (control): DBH growth (cm year⁻¹) (A), (B); current year shoot growth (cm) (C), (D). Different letters within the same date of measurement indicate significant differences among root severance treatments at P < 0.05 (see Table A1 for exact P-value).

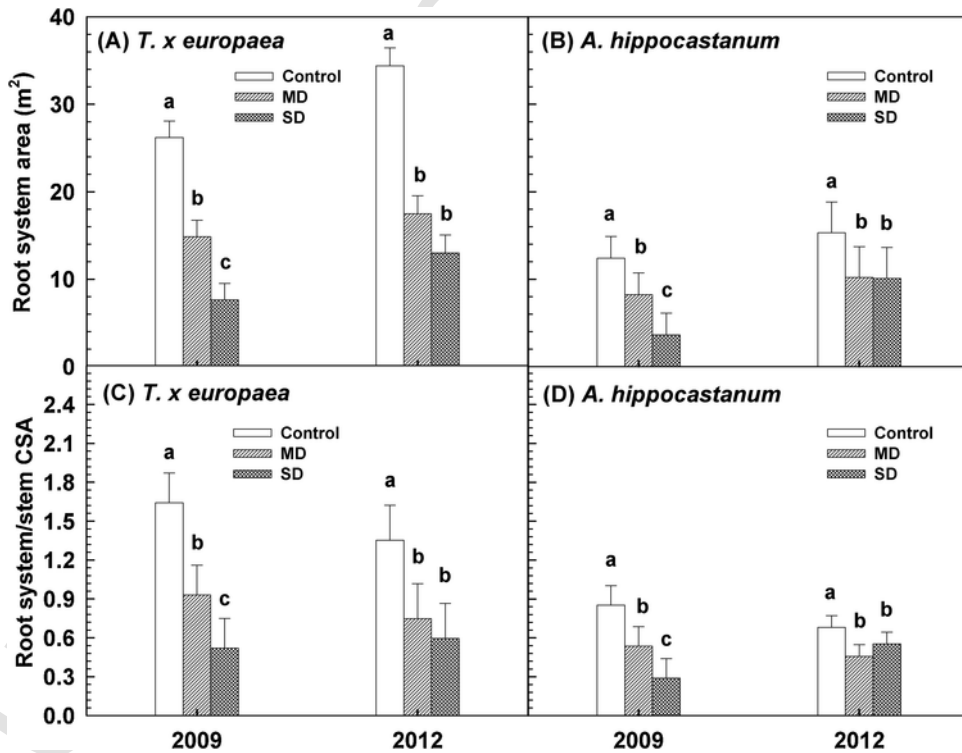


Fig. 3. Below-ground dendrometric parameters at the end of the growing seasons 2009 and 2012 in *Tilia* (A), (C) and *Aesculus* (B), (D) plants which had been severely damaged (SD), moderately damaged (MD) or left undamaged (control): area of the root system (m²) (A), (B) and root system to stem cross sectional area (m²cm⁻²) (C), (D). Different letters within the same date of measurement indicate significant differences among root severance treatments at P < 0.05 (see Table A1 for exact P-value).

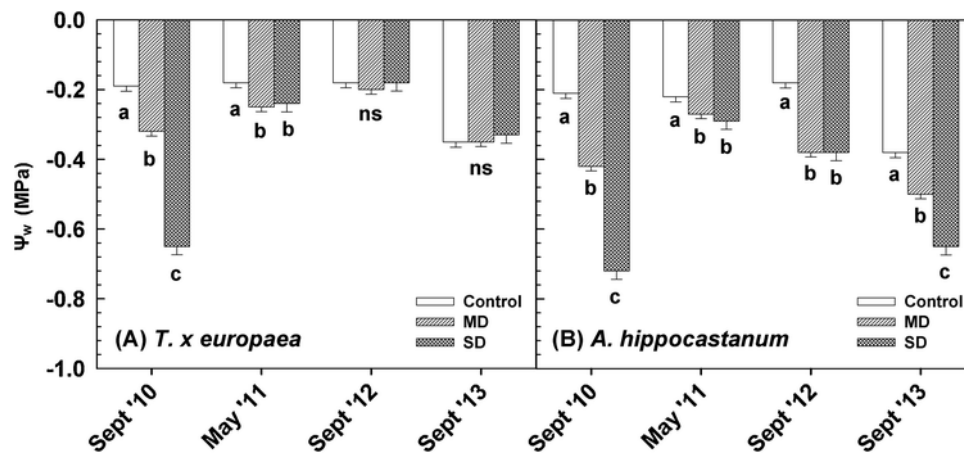


Fig. 4. Pre-dawn water potential measured 15 (sept' 10), 23 (May' 11), 36 (Sept' 12), and 51 (Sept' 13) months after root severance in *Tilia* (A) and *Aesculus* (B) plants which had been severely damaged (SD), moderately damaged (MD) or left undamaged (control). Different letters within the same date of measurement indicate significant differences among root severance treatments at $P < 0.05$ (see Table A1 for exact P-value).

tion (Fig. 4A). Conversely, ψ_w in MD and SD *Aesculus* did not recover to the level of control and, 51 months after trenching, differences in ψ_w were still significant and proportional to the severity of root damage (Fig. 4B).

Stomatal conductance (g_s) was reduced by root severance (-20% and -25% in MD and SD plants, compared to control, average across the entire experiment) (Table A1, Fig. 5A–B). Reductions of g_s as high as 50% were observed in MD and SD plants of both species, compared to control, during the warm season in the first 25 months after severance. Thereafter, g_s fully recovered in MD *Tilia*, while full recovery of g_s occurred after 51 months in SD *Tilia* (Fig. 5A). Conversely, neither MD or SD *Aesculus* showed full recovery of g_s by the end of the experiment (Fig. 5B).

CO_2 assimilation (A) was reduced by root damage, but the effect was slightly delayed compared to g_s : significant differences were not observed earlier than one (*Tilia*) or two (*Aesculus*) months after severance (Fig. 5C–D). Two to 26 months after damage, A of MD and SD *Tilia* declined by 25% and 26% compared to control (Fig. 5C). Two months after severance, reductions as large as 50% were observed, despite precipitation volumes exceeding the monthly average. A of MD and SD *Tilia* recovered to the rate of control after 25 and 38 months, respectively. CO_2 assimilation of severed *Aesculus* did not recover by the end of the experiment (Fig. 5D).

The ratio between leaf internal CO_2 concentration and external CO_2 (C_i/C_a) declined in damaged plants compared to control (Fig. 5E–F). In *Tilia*, the change in C_i/C_a was small and significant differences between control and severed plants were found either only 1 month after trenching (MD plants) or no later than 36 months after trenching (SD plants). In *Aesculus*, instead, changes were large, particularly in SD plants which displayed 30%–50% lower C_i/C_a , compared to control, during June–September 2010 (12 and 15 months after the excavation) and August 2012 (38 months after the excavation) (Fig. 5F). Differently from *Tilia*, MD and SD *Aesculus* were unable to recover C_i/C_a ratio of undamaged plants.

The effects of root damage on the maximum quantum yield of PSII photochemistry (F_v/F_m) were species specific (Table A1). In *Tilia*, excavation at one side of the tree significantly reduced F_v/F_m , compared to control, in two of the twelve measurement days (on average, F_v/F_m decreased by 0.7%). Excavation at both sides of the tree significantly reduced F_v/F_m in four of the twelve measurements (average decrease was 1.3%). F_v/F_m never declined below 0.74, even in SD plants (Fig. 5G). Conversely, SD *Aesculus* experienced lower F_v/F_m than control in 7 of the 12 measurement days, with F_v/F_m approaching 0.72 (1.9% decrease, compared to control) after two months since treatments were imposed (Fig. 5H).

Leaf greenness index was slightly reduced by root damage in both species (-2.7% and -2.2% in MD and SD plants, compared to control), but differences were significant only in 2011 and 2012, 25 and 38 months after severance, respectively (Table A1). *Tilia* had, on average, 8% higher leaf greenness index compared to *Aesculus* (data not shown).

3.3. Uprooting resistance

Root severance reduced the geometrical moment of area of the root system (Gr) in both species (Table A1, Table 2). Gr decreased by 68% and 56% in MD *Tilia* and *Aesculus*, respectively, and by 92% and 90% in SD *Tilia* and *Aesculus*, respectively (Table 2). Four years after the damage was inflicted, Gr was still 64% and 33% lower than control in *Tilia* and *Aesculus*, respectively, in the same treatment (Table 2).

The Moment Factor (MF) calculated immediately after the excavation was higher in *Tilia* than in *Aesculus*, but it did not differ among root pruning treatment (Table 2). Conversely, four years after trenching, MF was 20% and 27% lower in MD and SD *Tilia*, compared to control. In *Aesculus*, MD plants had similar (-7%) MF as control, but SD plants displayed significant reductions (-47%) in MF compared to control (Table 2).

Immediately after the excavation, the Uprooting Resistance Index (URI) decreased by 69% and 55%, respectively, in MD *Tilia* and *Aesculus*, and by 86% and 91%, respectively, in SD *Tilia* and *Aesculus* (Table 2). Four years after trenching, undamaged plants of *Tilia* still had about 55% higher URI than MD and SD plants (Table 2). Conversely, SD and control *Aesculus* displayed higher URI than MD plants.

The bending moment required to reach a 0.2° inclination of the root flare, measured on both the side of the tree under tension (M_T) and under compression (M_C), was on average 1972 and 2322 Nm in control trees of *Tilia* and *Aesculus*, respectively, at the beginning of the experiment (Fig. 6A–B). In *Tilia*, the reduction observed in both M_T and M_C was proportional to the severity of the damage (Fig. 7A). Four years after trenching, M_T and M_C of undamaged *Tilia* plants were about 3950 Nm, but M_T and M_C of severed plants were still about 50% lower, regardless of the intensity of damage. In newly severed *Aesculus*, the response of M_T was consistent with that observed in *Tilia*, but M_C did not decline unless plants were severely damaged (Fig. 6B). Four years after severance, M_T and M_C of control *Aesculus* were on average 2990 Nm. MD and SD plants still showed 21% and 66% lower bending moment, compared to control.

A strong positive linear correlation was found between bending moment M and URI (Fig. 7A, $P < 0.001$; $R^2 = 0.846$). Also, M and Gr were strongly positively correlated (Fig. 7B, $P < 0.001$; $R^2 = 0.822$).

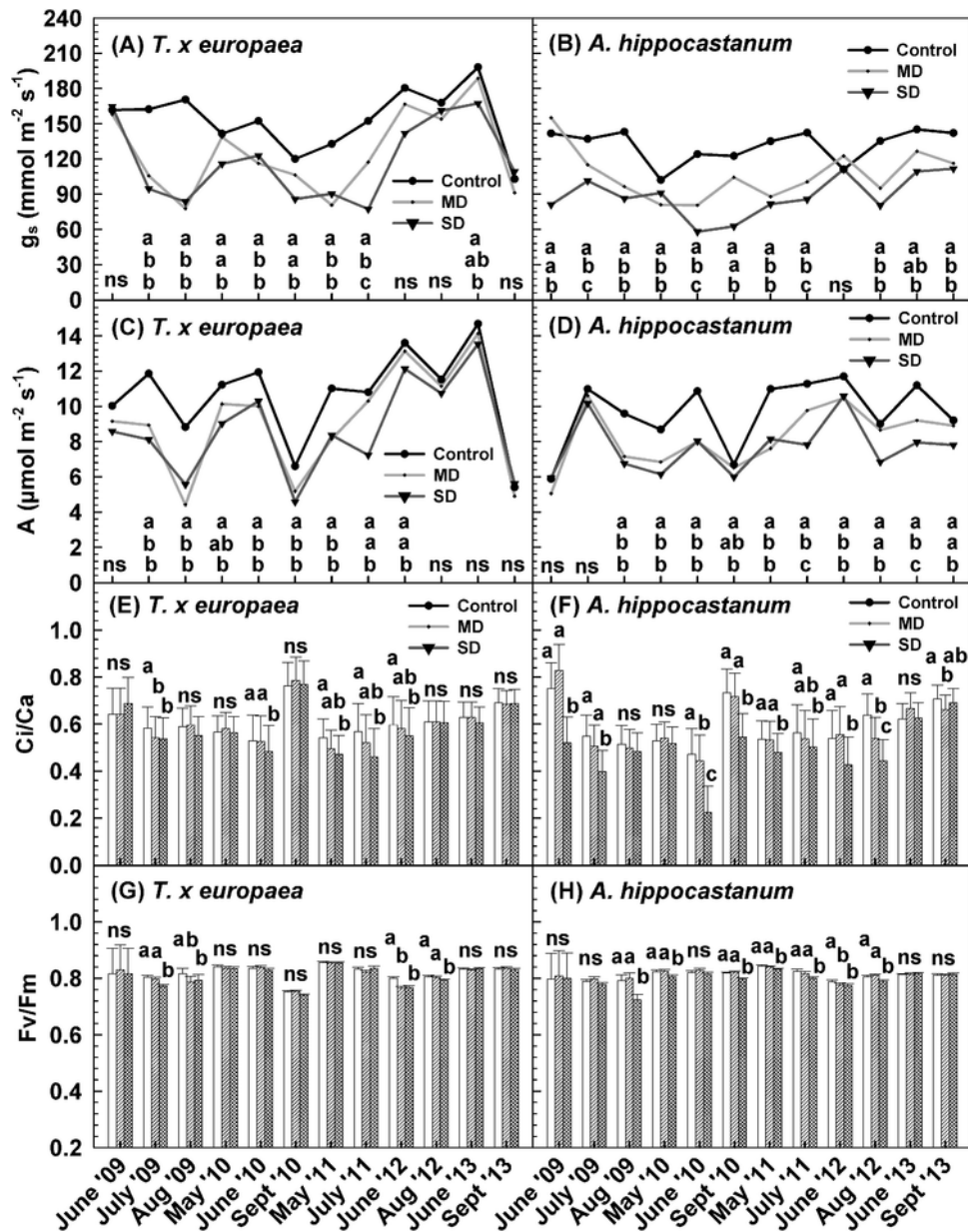


Fig. 5. Leaf gas exchange and chlorophyll fluorescence parameters measured in the 51 months after severance in *Tilia* (A), (C), (E), (G) and *Aesculus* (B), (D), (F), (H) plants which had been severely damaged (SD), moderately damaged (MD) or left undamaged (control): stomatal conductance (g_s , $\text{mmol m}^{-2} \text{s}^{-1}$) (A), (B); net CO_2 assimilation (A , $\mu\text{mol m}^{-2} \text{s}^{-1}$) (C), (D); ratio between internal leaf CO_2 concentration and external CO_2 concentration (C_i/C_a) (E), (F); and maximum quantum yield of PSII photochemistry (F_v/F_m) (G), (H). Different letters within the same date of measurement (top down: C, MD, SD) indicate significant differences among root severance treatments at $P < 0.05$ (see Table A1 for exact P-value).

4. Discussion

This 51-month research evaluated the consequences of two intensities of root severance on growth, physiology, and uprooting resistance of two widely used urban tree species. Trees were severed at a distance from the trunk which poorly fulfills best practices for tree preservation, being about three quarters of the recommended distance for trenching (Costello et al., 2017; Benson et al., 2019c).

Our research results clearly contrast the early-established idea that root severance may cause a sudden and drastic depression in plant health in the absence of co-occurring stresses (Manion, 1991). Rather, they indicate that cutting roots weakens the tree and may increase its long-term susceptibility to co-occurring stresses affecting tree physiology and structural stability. Therefore, this work suggests that root sev-

erance may be reclassified to a predisposing factor in the Manion mortality spiral rather than as an inciting factor as originally identified (Manion, 1991).

In the absence of other co-occurring stresses (e.g. drought) due to favorable environmental conditions which occurred during this experiment (i.e. rainfall above the 30-year average, see Fig. 1), no tree mortality or extensive dieback were observed over the 51 months after the excavation, even at the most severe root severance treatment, which removed about 70% of the root system. These data support and extend to the mid-term previous findings from short-term experiments, which excluded massive mortality or extensive canopy dieback early after severance (Wajja-Musukwe et al., 2008; Benson et al., 2019a), but set the need of understanding the mechanisms that can lead to the mortality observed in root-severed trees in the long run (Morell, 1984; Hauer et al., 1994).

Table 2

Contribution of root geometry to tree stability (Gr, m3), moment factor (MF, m3), and Uprooting Resistance index (URI = Gr/MF) measured 2 months (year 0) and 4 years after root 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	Gr	Gr	MF	MF	URI	URI
		year 0	year 4	year 0	year 4	year 0	year 4
Linden	C	7.5	21.0	74.4	145.6	0.101	0.145
		a	a	a	a	a	a
	MD	2.4	7.7	77.6	116.1	0.031	0.066
		b	b	a	b	b	b
	SD	0.6	6.8	70.0	105.4	0.009	0.064
		c	b	a	b	c	b
Horsechestnut	C	2.5	6.8	33.9	59.1	0.068	0.115
		a	a	a	a	a	ab
	MD	1.11	4.6	33.6	54.3	0.030	0.084
		b	b	a	a	b	b
	SD	0.25	4.4	29.7	30.4	0.009	0.146
		c	b	a	b	c	a

4.1. Effects on physiology

The reduction of pre-dawn water potential observed during the two years after the excavation in severed plants of both species indicate that root damage reduces the capacity of trees to maintain tissue hy-

dration, even when soil moisture availability is not limiting (see Fig. 1 and water potential of control trees being close to zero in Fig. 4). The decline in water potential is due to an abrupt imbalance between absorbing root surface and transpiring leaf area and may lead to root embolism and loss of further functional roots (Sperry et al., 1998). During the first 23 months after excavation, when stress should have been maximum, water potential of excavated plants always remained above -1 MPa, enough to prevent massive embolism of the xylem even in sensitive species (Jackson et al., 2000). Even at the most severe root damage treatments, for example, the drop in water potential in *Aesculus* was much lower than that caused in this species by a typical inciting factor, such as summer drought, which can reduce water potential to about -1.5 MPa (Raimondo et al., 2005). Consistently, droughted *Quercus virginiana* plants had a pre-dawn water potential around -1.7 MPa (Cooper et al., 2018), while water potential was always above -0.51 MPa in live oaks exposed to severe root damage (Benson et al., 2019b).

Despite the impact of excavation on leaf water relations remaining below the limits to avoid xylem embolism, the recovery of water potential was extremely slow and required more than 2 years in the tolerant species *Tilia* (Fig. 4). Full recovery, instead, did not occur in the sensitive species *Aesculus*, regardless of the intensity of root loss (Fig. 4). The slow and incomplete recovery which follows root severance differs substantially compared to recovery from inciting stressors. For instance, a large body of literature reports a prompt recovery of leaf water relations occurring in several woody species after relief from se-

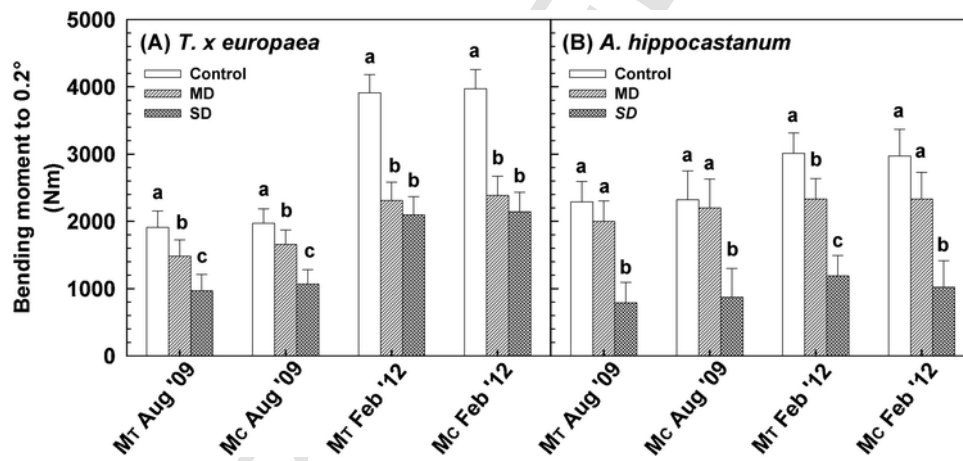


Fig. 6. Bending moment (M, Nm) required to reach an inclination of 0.2° at the sides of the root flare under tension (M_T) and under compression (M_C) in *Tilia* (A) and *Aesculus* (B) plants which had been severely damaged (SD), moderately damaged (MD) or left undamaged (control). M_T and M_C were measured 2 and 44 months after the excavation. Different letters within the same date of measurement indicate significant differences among root severance treatments at $P < 0.05$ (see Table A1 for exact P-value).

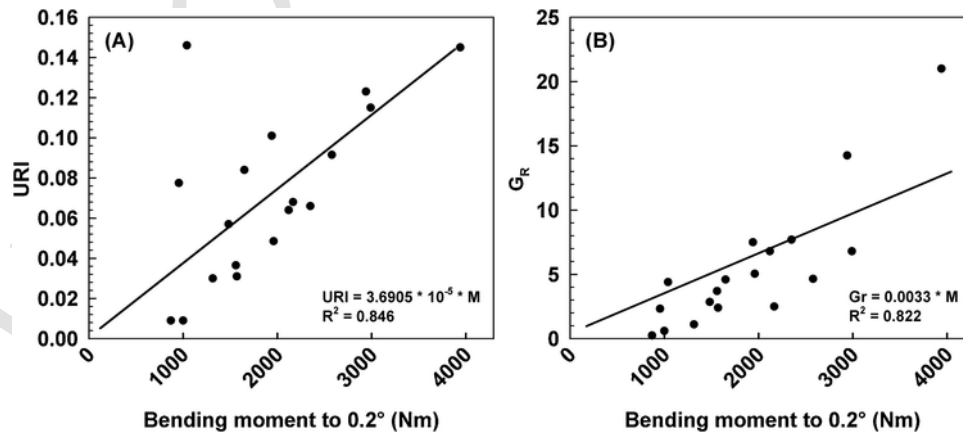


Fig. 7. Correlation between average tension and compression bending moments (M) measured by pulling test and the uprooting resistance index (URI) (A), and the contribution of root geometry to tree stability (G_R) (B).

vere drought and salinity stresses (Cermak et al., 1993; Tattini et al., 2002; Massai et al., 2004; Gallé et al., 2007; Tattini and Traversi, 2009; Fini et al., 2013).

Stomata are the pressure regulators of plants: they regulate water flow through the soil-plant continuum to match atmospheric demand with the maximum supply capacity by tree roots and prevent xylem pressure and tissue water status from reaching damaging values (Jackson et al., 2000). Thus, any disturbance that influences the hydraulics of the continuum also impacts leaf gas exchange through hormonal and hydraulic signaling (Jones et al., 2010; Brunetti et al., 2018). Consistently, we found that root severance triggered a 20% and 28% decline in stomatal conductance in MD and SD plants of both species, compared to control. Despite showing a similar decline in stomatal conductance and transpiration, the two species displayed a different capacity to recover from the damage. In tolerant species to root damage such as *Tilia*, stomatal conductance took about 36 months to recover, upon the severance of about 40% of the roots, while 51 months were required to recover stomatal conductance for a plant which had 70% of roots severed. Conversely, in sensitive species such as *Aesculus*, full recovery was observed in none of the severed treatments throughout the experiment. Recent evidence suggesting ABA as a driver of stomatal re-opening after relief from stress, rather than stomatal closure (Tombesi et al., 2015), allows us to posit that the different capacity of tolerant and sensitive species to recover from trenching damage may be partly explained by differences in ABA-signaling.

Changes in leaf conductance affect the influx of CO₂ from the atmosphere to the sites of carboxylation and, in turn, net carbon assimilation. In fact, chloroplastic CO₂ is a highly conserved trait in C3 woody plants, and photosynthetic rate is tightly modulated to match CO₂ diffusion across the stomata and the mesophyll with CO₂ fixation by Rubisco (Fini et al., 2016). Consistently, carbon assimilation declined by 16%–25% and 23%–26% in moderately and severely damaged plants, respectively, compared to control (Fig. 5). We did not measure mesophyll conductance to CO₂ diffusion and CO₂ concentration in the chloroplast, so a quantitative analysis of limitations to photosynthesis (*sensu* Grassi and Magnani, 2005) could not be performed. Nonetheless, we used the ratio between CO₂ concentration in the substomatal chamber to atmospheric CO₂ to estimate factors contributing to the observed reduction in photosynthesis caused by root severance (Medrano et al., 2002). We observed that plants of both species subjected to excavation damage had, in general, lower Ci/Ca than control plants (Fig. 5), suggesting that stomatal factors are prevailing over mesophyll and biochemical limitations to photosynthesis (Medrano et al., 2002; Fini et al., 2014). These findings are corroborated by the maximum quantum yield of PSII, which remained above 0.77 (except for SD *Aesculus* 2 months after severance) and fully recovered by the end of the experiment, suggesting a down-regulation, rather than a permanent impairment of the photosynthetic apparatus in leaves of excavated plants (Murchie and Lawson, 2013). Prevailing stomatal limitations are associated with mild stress, which can be quickly recovered as soon as stress is relieved and stomata can re-open and restore the CO₂ influx in the leaf (Medrano et al., 2002). For example, mature beech trees exposed to years of chronic mild water stress could recover within minutes after an irrigation event (Cermak et al., 1993). Recovery of photosynthesis after excavation damage was instead extremely slow and required from 25 to 38 months in the tolerant species *Tilia*, depending on the intensity of root severance. *Aesculus*, instead, was unable to recover net assimilation rate within 51 months from trenching, regardless of the intensity of root severance. A possible explanation to such slow and incomplete recovery lies in the fact that demand components (*i.e.* the capacity of the tree to absorb available water), rather than supply components (*i.e.* soil water availability), affected gas exchange in severed trees, and recovery may require a change in allocation of photosynthates between above and below ground organs, to restore the ratio between absorbing and conducting or transpiring areas (Ledo et al., 2018; Benson et al., 2019a).

4.2. Effects on growth

Compensatory growth after root severance may be hindered by a chronically lower amount of photosynthates available for growth (Hamilton, 1988). Consistently, in our work, excavation depressed above-ground growth in both species for the 4 years after excavation (Fig. 2). In agreement with Benson et al. (2019b), shoot extension was the above-ground growth parameter most sensitive to root damage. Declines in shoot extension were observed within six months from the excavation in both species. DBH growth also declined in severed plants: differences in DBH growth were evident after 6 months following excavation on severely damaged plants, and after 18 months on moderately damaged trees, irrespective of the species. Recovery of pre-damage growth rates is controversial. Pretzsch et al. (2016) found that large mature beech trees growing in a high-quality forest site recovered growth rate within three years after up to 40% of their roots had been severed by a single trench. Conversely, Wajja-Musukke et al. (2008) found that stem diameter growth decreased over time after about 18% of tree roots were severed by a single trench. Similarly, other studies report long-lasting reductions in growth of trenched trees, compared to undamaged ones, only partially mitigated by exceptionally wet growing seasons (Rook, 1971; North et al., 2017). Our study conforms to these latter findings: none of the above-ground dendrometric parameters measured on severed plants recovered to the values displayed by undamaged trees within four years after the excavation.

Preferential allocation of photosynthates to below-ground organs to produce new roots and compensate for root loss may further explain the reduction in above-ground growth observed after root severance (Amoroso et al., 2010; North et al., 2017; Ledo et al., 2018). Trenching damage removes root tips, which are rich in cytokinin, thus promoting root branching and fine root production, but at expenses of above-ground growth (Hamilton, 1988; Amoroso et al., 2010). Consistently, severely damaged plants of *Aesculus* showed higher root system expansion both in relative and absolute terms, when compared to control plants. Such prompt reallocation of resources to roots may be important in the acclimation to root severance in species, such as *Aesculus*, with small rooting areas and a narrow root to stem area ratio, whereas species with a higher root system to stem cross sectional area ratio, such as *Tilia*, may be more tolerant to root loss. We are aware that root system area may not directly correlate to root absorbing surface, because changes in fine root densities between severed and control plants may result in different exposed root surface per unit root system area. Nonetheless, root system area may still reflect tree ability to grow and absorb in unexplored soil, rather than being forced to regenerate new absorbing roots back in soil portions which had already been exploited, and where auto-toxic allelochemicals may depress root physiology (Reigosa et al., 2006).

4.3. Effects on uprooting resistance

This research revealed that trenching significantly reduced uprooting resistance, both measured by pulling test and using a theoretical uprooting resistance index. The reductions observed in this research conform to previous studies (Smiley, 2008; Smiley et al., 2014), where the removal of 30% and 50% of roots resulted in 20%–35% and 33%–47% lower moment required to bend the buttress. Such similar changes, with respect to previous works (Smiley, 2008; Smiley et al., 2014) where winching was stopped at an inclination of 1°, suggest that stopping the pulling test at an inclination of 0.2° of the buttress may yield sound estimates of uprooting resistance without the need of applying large loads, thus with a high confidence of being in the elastic range of the trunk (Sani et al., 2012). In our study, the pulling line was set perpendicular to the direction of the trenches, in order to have the severed side of the tree under tension, because roots loaded in tension were shown to be crucial for uprooting resistance of broadleaved

trees (Smiley et al., 2014). Such pulling tests revealed a similar inclination recorded by the inclinometers loaded under tension and compression, indicating the absence of torsional stress. Nonetheless, previous experiments which used winching tests to investigate the reductions in rotational stiffness of trenched trees confirmed the little short-term effect of excavation damage on uprooting resistance, mostly due to the contribution of sinker roots to tree stability (Ghani et al., 2009).

Few studies have evaluated so far the early impact of root severance on tree mechanical stability, but none, to our knowledge, has clarified the capacity of trees to re-establish their safety factor after a relief period that allowed trees to recover the severed roots (Forcaud et al., 2008; Watson et al., 2014). When the winching test was conducted again, four years after severance, differences in bending moment between control and severed trees were maintained or even increased. This latter case was common in moderately damaged trees, which displayed 22%–41% lower bending moment than control at year 4 (i.e. the delta between control and MD trees increased 2–4 folds from 2009 to 2013). Thus, our data show that the spread in uprooting resistance imposed by excavation damage, compared to undamaged trees, more likely increases over time, rather than recover.

The calculated uprooting resistance index (URI) confirmed this finding. Trenching depressed URI mainly due to a sudden change in the size and symmetry of the root area paralleled by an unchanged moment acting on the tree canopy. Despite Gr increasing over time after excavation, as expected (Koizumi et al., 2007), severed trees failed to recover Gr of control trees, even after 4 years. Nonetheless, growth reductions occurring to canopies in severed trees resulted in a smaller moment factor compared to control. This was clear in plants of the sensitive species *Aesculus*, where severe root damage reduced moment factor more than proportionally compared to Gr, resulting in a full recovery of URI. The high correlation observed between bending moment measured by pulling test and both the uprooting resistance index and the contribution of root geometry to tree stability (Fig. 8) confirms the lateral extension of the root system as a major component of tree anchorage (Stofko and Kodrik, 2008; Ghani et al., 2009), particularly in urban trees which systematically lose the taproot at transplant (Gilman et al., 1992). Gr overestimated stability loss, compared to pulling test, possibly because of the contribution of secondary sinker roots, developed from lateral roots near the flare, and of the little impact of conducting roots to tree stability (Mickovski and Ennos, 2003; Ghani et al., 2009).

5. Conclusions

This research investigated the early consequences of root severance at two different intensities and capacity to recover growth, physiology, and stability of two urban tree species over a 51-month period. Results highlighted root damage as a latent stress factor, which may not cause visible consequences to trees for years, while chronically affecting plant physiology, as well as capacity of the tree itself to stand. Under favorable environmental conditions, such as the non-limiting water availability occurring during this experiment, changes in plant growth parameters and leaf gas exchange were little, even at the most severe root severance treatments, which reduced root system size by 70%. The observed changes, however, were long-lasting and the stress-recovery pattern after root damage clearly differs from those described for other inciting stresses such as drought and defoliation. Little resilience by urban trees to root severance may explain why after several years of lack of visible symptoms, trees may suddenly decline, as soon as environmental conditions turn unfavorable. Thus, based on our data, we propose that root severance acts as a predisposing, rather than inciting factor. Species with larger root area supplying the unit of stem cross sectional area, such as *Tilia*, showed a faster recovery than species with small root area per unit stem cross sectional area, such as *Aesculus*, which was not able to recover by the end of the experiment.

The resistance of trees to uprooting significantly declined after root severance, as shown by theoretical calculations and by the pulling test experiments. Both species could not recover the reduction in tree anchorage induced by root severance by the end of the experiment, supporting the idea that safety factor to uprooting becomes chronically reduced after roots have been damaged, thus predisposing severed trees to failure by uprooting during extreme meteorological events. Above-ground growth depressions occurring in tree species sensitive to root manipulation can, however, reduce the bending moment acting on the flare and compensate, in the long-run, to reduced anchorage by roots.

CRedit authorship contribution statement

Alessio Fini: Conceptualization, Investigation, Formal analysis, Writing - review & editing. **Piero Frangi:** Conceptualization, Resources, Investigation, Writing - review & editing. **Jacopo Mori:** Investigation, Writing - review & editing. **Luigi Sani:** Resources, Formal analysis. **Irene Vigevani:** Formal analysis. **Francesco Ferrini:** Conceptualization, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.ufug.2020.126734>.

References

- Amoroso, G., Frangi, P., Piatti, R., Ferrini, F., Fini, A., Faoro, M., 2010. Effect of container design on plant growth and root deformation of little-leaf linden and field elm. *HortScience* 45 (12), 1824–1829.
- Benson, A.R., Morgenroth, J., Koeser, A.K., 2019. The effects of root pruning on growth and physiology of two *Acer* species in New Zealand. *Urban For. Urban Green.* 38, 64–73.
- Benson, A.R., Koeser, A.K., Morgenroth, J., 2019. A test of tree protection zones: responses of *Quercus virginiana* Mill. Trees to root severance treatments. *Urban For. Urban Green.* 38, 54–63.
- Benson, A.R., Morgenroth, J., Koeser, A.K., 2019. Responses of mature roadside trees to root severance treatments. *Urban For. Urban Green.* 46, 126448.
- Brunetti, C., Loreto, F., Ferrini, F., Gori, A., Guidi, L., Remorini, D., Centritto, M., Fini, A., Tattini, M., 2018. Metabolic plasticity in the hygrophyte *Moringa oleifera* exposed to water stress. *Tree Physiol.* 38, 1640–1653.
- Cermak et al., 1993. J. Cermak, R. Mattysek, J. Kucera, Rapid response of large, drought stressed beech trees to irrigation, *Tree Physiol.* 12 (1993) 281–290.
- Cooper, C.E., Vogel, J.G., Muir, J.P., Moore, G.W., 2018. Leaf functional trait responses to changes in water status differ among three oak (*Quercus*) species. *Plant Ecol.* 219, 1463–1479.
- Costello, L.R., Watson, G.W., Smiley, E.T., 2017. Best Management Practices: Root Management, 1 ed. International Society of Arboriculture, Champaign, Illinois, USA, 17.
- Despot, D., Gerhold, H., 2003. Preserving trees in construction projects: identifying incentives and barriers. *J. Arboricult.* 29, 267–280.
- Fini, A., Ferrini, F., Frangi, P., Amoroso, G., Giordano, C., 2010. Growth, leaf gas exchange and leaf anatomy of three ornamental shrubs grown under different light intensities. *Eur. J. Hortic. Sci.* 73, 111–117.

- Fini, A., Ferrini, F., Frangi, P., Piatti, R., Amoroso, G., 2013. Effects of root severance by excavation on growth, physiology and uprooting resistance of two urban tree species. *Acta Hort.* 990, 487–494.
- Fini, A., Ferrini, F., Di Ferdinando, M., Brunetti, C., Giordano, C., Gerini, F., Tattini, M., 2014. Acclimation to partial shading or full sunlight determines the performance of container-grown *Fraxinus ornus* to subsequent drought stress. *Urban For. Urban Green.* 13, 63–70.
- Fini, A., Frangi, P., Faoro, M., Piatti, R., Amoroso, G., Ferrini, F., 2015. Effects of different pruning methods on an urban tree species: a four-year-experiment scaling down from the whole tree to the chloroplasts. *Urban For. Urban Green.* 14, 664–674.
- Fini, A., Loreto, F., Tattini, M., Giordano, C., Ferrini, F., Brunetti, C., Centritto, M., 2016. Mesophyll conductance plays a central role in leaf functioning of Oleaceae species exposed to contrasting sunlight irradiance. *Physiol. Plant.* 157, 54–68.
- Fini, A., Frangi, P., Mori, J., Donzelli, D., Ferrini, F., 2017. Nature based solutions to mitigate soil sealing in urban areas: results from a 4-year study comparing permeable, porous, and impermeable pavements. *Environ. Res.* 156, 443–454.
- Forcaud, T., Ji, J., Zhang, Z., Stokes, A., 2008. Understanding the impact of root morphology on uprooting mechanisms: a modelling approach. *Ann. Bot.* 101, 1267–1280.
- Gallé, A., Haldimann, P., Feller, U., 2007. Photosynthetic performance and water relations in young pubescent oak (*Quercus pubescens*) trees during drought stress and recovery. *New Phytol.* 174, 799–810.
- Genty, B., Briantais, J., Baker, N., 1989. The relationship between the quantum yield of photosynthetic electron transport and quenching of chlorophyll fluorescence. *Biochim. Biophys. Acta* 990, 87–92.
- Gerhold, H.D., Johnson, A.D., 2003. Root dimensions of landscape tree cultivars. *J. Arboricult.* 29, 323–326.
- Ghani, M.A., Stokes, A., Fourcaud, T., 2009. The effect of root architecture and root loss through trenching on the anchorage of tropical urban trees (*Eugenia grandis* Wight). *Trees* 23, 197–209.
- Gilman, E.F., Beeson Jr, R.C., Black, R.J., 1992. Comparing root balls of laurel oak transplanted from the wild with those of nursery and container grown trees. *J. Arboricult.* 18, 124–129.
- Grassi, G., Magnani, F., 2005. Stomatal, mesophyll conductance and biochemical limitations to photosynthesis as affected by drought and leaf ontogeny in ash and oak trees. *Plant Cell Environ.* 28, 834–849.
- Haines-Young, R., Potschin, M., 2018. Common International Classification of Ecosystem Services (CICES) V5.1. And Guidance on the Application of the Revised Structure. In: www.cices.eu.
- Hamilton, W.D., 1988. Significance of root severance on the performance of established trees. *J. Arboricult.* 14, 288–292.
- Hauer, R.J., Miller, R.W., Ouimet, D.M., 1994. Street tree decline and construction damage. *J. Arboricult.* 20, 94–97.
- Horacek, P., 2003. Introduction to tree statics and static assessment. In: *Proceedings of the Tree Statics and Dynamics Seminar: Interpreting the Significance of Factors Affecting Tree Structure and Health*. Westonbirt, UK.
- Jackson, R.B., Sperry, J.S., Dawson, T.E., 2000. Root water uptake and transport: using physiological processes in global predictions. *Trends Plant Sci.* 5, 482–488.
- Jim, C.Y., 2003. Protection of urban trees from trenching damage in compact city environments. *Cities* 20, 87–94.
- Jones, T.J., Luton, C.D., Santiago, L.S., Goldstein, G., 2010. Hydraulic constraints on photosynthesis in subtropical evergreen broad leaf forest and pine woodland trees of the Florida everglades. *Trees* 24, 471–478.
- Koizumi, A., Oonuma, N., Sasaki, Y., Takahashi, K., 2007. Difference in uprooting resistance among coniferous species planted in soils of volcanic origin. *J. For. Res.* 12, 237–242.
- Ledo, A., Paul, K.I., Burslem, D.F.R.P., Ewel, J.J., Barton, C., Battaglia, M., Brooksbank, K., Carter, J., Haakon Eid, T., England, J.R., Fitzgerald, A., Johnson, J., Mencuccini, M., Montagu, K.D., Montero, G., Ancelm Mugasha, W., Pinkard, E., Roxburgh, S., Ryan, C.M., Ruiz-Peinado, R., Sochacki, S., Specht, A., Wildy, D., Wirth, C., Zerihun, A., Chave, J., 2018. Tree size and climatic water deficit control root to shoot ratio in individual trees worldwide. *New Phytol.* 217, 8–11.
- Manion, P., 1991. *Tree Disease Concepts*. Prentice-Hall, Englewood Cliffs, New Jersey.
- Massai, R., Remorini, D., Tattini, M., 2004. Gas exchange, water relations and osmotic adjustment in two scion/rootstock combinations of *Prunus* under various salinity concentrations. *Plant Soil* 259, 153–162.
- Medrano, H., Escalona, J., Bota, J., Gulias, J., Flexas, J., 2002. Regulation of photosynthesis of C3 plants in response to progressive drought: stomatal conductance as a reference parameter. *Ann. Bot.* 89, 895–905.
- Mickovski, S.B., Ennos, A.R., 2003. Anchorage and asymmetry in the root system of *Pinus peuce*. *Silva Fenn.* 37, 161–173.
- Morell, J.D., 1984. Parkway tree augering specifications. *J. Arboricult.* 10, 169–175.
- Murchie, E.H., Lawson, T., 2013. Chlorophyll fluorescence analysis: a guide to good practice and understanding some new applications. *J. Exp. Bot.* 64, 3983–3998.
- North, E.A., D'Amato, A.W., Russel, M.B., Johnson, G.R., 2017. The influence of sidewalk replacement on urban street tree growth. *Urban For. Urban Green.* 24, 116–124.
- Nowak, D.J., Stevens, J.C., Sisinni, S.M., Luley, C.J., 2002. Effects of urban tree management and species selection on atmospheric carbon dioxide. *J. Arboricult.* 28 (3), 113–122, 28(3).
- Percival, G.C., Keary, I.P., Noviss, K., 2008. The potential of a chlorophyll content SPAD meter to quantify nutrient stress in foliar tissue of sycamore (*Acer pseudoplatanus*), English oak (*Quercus robur*), and European beech (*Fagus sylvatica*). *Arboric. Urban For.* 34, 89–100.
- Pretzsch, H., Biber, P., Uhl, E., Dahlhäuser, J., Rotzer, T., Caldentey, J., Koike, T., van Con, T., Chavanne, A., Seifert, T., du Toit, B., Farnden, C., Pauleit, S., 2015. Crown size and growing requirement of common tree species in urban centers, parks, and forests. *Urban For. Urban Green.* 14, 466–479.
- Pretzsch, H., Bauerle, T., Haberle, K.H., Matyssek, R., Schultze, G., Rotzer, T., 2016. Tree diameter growth after root trenching in a mature mixed stand of Norway spruce (*Picea abies* [L.] Karst) and European beech (*Fagus sylvatica* [L.]). *Trees* 30, 1761–1773.
- Raimondo, F., Trifilò, P., Salleo, S., Nardini, A., 2005. Seasonal changes of plant hydraulics, water relations and growth of *Aesculus hippocastanum* seedlings infested by the leaf-miner *Cameraria ohridella*. *Ann. For. Sci.* 62, 99–104.
- Reigosa, M.J., Pedrol, N., Gonzales, L., 2006. Allelopathy: a Physiological Process With Ecological Implications. Springer, Dordrecht, The Netherlands, 637.
- Rook, D.A., 1971. Effect of undercutting and wrenching on growth of *Pinus radiata* D. Don seedlings. *J. Appl. Ecol.* 8, 477–490.
- Sani, L., Lisci, R., Moschi, M., Sarri, D., Rimeidiotti, M., Vieri, M., Toffanelli, S., 2012. Preliminary experiments and verification of controlled pulling tests for tree stability assessments in Mediterranean urban areas. *Biosyst. Eng.* 112, 218–226.
- Scholander, P.F., Hammel, H.T., Bradstreet, E., Hemingsen, E.A., 1965. Sap pressure in vascular plants. *Science* 148, 339–346.
- Smiley, T.E., 2008. Root pruning and stability of young willow oak. *Arboric. Urban For.* 34, 123–128.
- Smiley, T.E., Holmes, L., Fraedrich, B.R., 2014. Pruning of buttress roots and stability changes of red maple (*Acer rubrum*). *Arboric. Urban For.* 40, 230–236.
- Sperry, J.S., Adler, F.R., Campbell, G.S., Comstock, J.P., 1998. Limitations of plant water use by rhizosphere and xylem conductance: results from a model. *Plant Cell Environ.* 21, 347–359.
- Stofko, P., Kodrik, M., 2008. Comparison of the root system architecture between wind-thrown and undamaged spruces growing in poorly drained sites. *J. For. Sci.* 54, 150–160.
- Tattini, M., Traversi, M.L., 2009. On the mechanism of salt tolerance in olive (*Olea europaea* L.) under low- or high-Ca²⁺ supply. *Environ. Exp. Bot.* 65, 72–81.
- Tattini, M., Montagni, G., Traversi, M.L., 2002. Gas exchange, water relations and osmotic adjustment in *Phillyrea latifolia* grown at various salinity concentrations. *Tree Physiol.* 22, 403–412.
- Tombesi, S., Nardini, A., Frioni, T., Soccolini, M., Zadra, C., Farinelli, D., Poni, S., Palliotti, A., 2015. Stomatal closure is induced by hydraulic signals and maintained by ABA in drought-stressed grapevine. *Sci. Rep.* 5, 12449.
- Wajja-Musukwe, T.N., Wilson, J., Sprent, J.I., Ong, C.K., Deans, J.D., Okorio, J., 2008. Tree growth and management in Ugandan agroforestry systems: effects of root pruning on tree growth and crop yield. *Tree Physiol.* 28, 233–242.
- Watson, G.W., 1998. Tree growth after trenching and compensatory crown pruning. *J. Arboricult.* 24, 47–53.
- Watson, G.W., Hewitt, A.M., Custic, M., Lo, M., 2014. The management of tree root systems in urban and suburban settings II: a review of strategies to mitigate human impact. *Arboric. Urban For.* 40, 249–271.
- Wessolly, L., Erb, M., 1998. *Handbuch Der Baum Statik Und Baum Kontrolle*. Patzer Verlag, Berlin, 288.