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THE IMPACT OF EARTHWORKS ON OLDER TREES IN HISTORICAL PARKS

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Highlights

- Linear excavations are especially dangerous for ageing trees in historical parks.
- Earthworks colliding with root zones cause trees to be doomed to degradation.
- Damage in root zones causes trees to show a three times slowdown of the growth or dying out.
- The reactions of the surviving trees to the stress factor [earthworks] are measurable and long-lasting.

Abstract. The publication aims to investigate the quantitative impact of linear earthworks in urban parks, e.g. during roads' and pavements' modernization in the old trees' root zones, on the increment in their external parameters (e.g. trunk circumference). Pilot studies (Warsaw, Poland) were carried out 2003–2019 in two historical parks: Ursynów and Królikarnia. The dataset of trees' parameters is based on detailed dendrological inventories. Test groups consisted of trees exposed to damage and not exposed to damage (Ursynów) and the control group – trees growing in unchanged site conditions (Królikarnia). Among the three most abundant species of dendroflora, Norway maples (*Acer platanoides* L.) show the most visible difference (>1.8 cm) between the normal and the inhibited growth in trunk circumference. Two other species – black locusts (*Robinia pseudoacacia* L.) and small-leaved limes (*Tilia cordata* Mill.) – also revealed statistically significant differences in the increment of the trunk circumference (respectively: >1.3 cm and >1.4 cm). In general, the reaction of affected trees was a significant reduction of circumference increments from 2.6 to 4.0 times concerning trees not exposed to damage. The verification made with the resistograph in 2019 confirmed a statistically significant decrease in radial increments of trees remaining in the impact zone of the earthworks.

Keywords: historical parks, earthworks, tree growth, root zone, landscape management, environmental sustainability.

Introduction

Mature and ageing trees growing in historic urban parks remain in a delicate biological and ecological balance (Dobbertin, 2005; Mencuccini et al., 2005; Day et al., 2010; Watson & Hewitt, 2012; Stratópoulos et al., 2019). It is because their adaptation ability to environmental changes is very limited (Mencuccini et al., 2005; Fortuna-Antoszkiewicz et al., 2012; Watson & Hewitt 2012; Lonsdale et al., 2013; Dujesiefken et al., 2016). Meanwhile, increasing anthropopression is conducive to a broad spectrum of stress factors. Linear earthworks, incl. excavation, road construction or pavement modernization (Coder, 2000; Randrup et al., 2001; Watson & Hewitt, 2012; Rosłon-Szeryńska et al., 2018) are a frequent cause of damage in the trees' root zone, which translates into the deterioration of their growth rate or even death (Łukaszkiewicz & Kosmala, 2008; Fortuna-Antoszkiewicz et al., 2012; Watson & Hewitt, 2012; North et al., 2015; Rosłon-Szeryńska et al., 2018; Hilbert et al., 2020). In the presented work, a research hypothesis was adopted assuming that such invasive works carried out within tree root systems cause direct (obvious) and indirect (non-obvious) damage. These resulted in a specific reaction of trees: some decline and fall out within a few years others show gradually deterioration of vitality. In the case of the second group – the object of this study – it is assumed that precise measurements

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of dendrometric parameters can statistically indicate the decrease in vitality.

The presented research is based on a case study of two historical parks: Ursynów and Królikarnia in Warsaw. Both objects have many similarities in terms of: the location the edge of the Warsaw Escarpment), the area (4.0–7.0 ha on the upper terrace of the Warsaw Escarpment), origins and the evolution of garden composition (the 18th century suburban residences) and the development of adjacent surroundings (dense urban and traffic development). The plants' habitat conditions are also comparable in both parks: 1) on the upper terrace of the Warsaw Escarpment, there are similar soil, hydrological conditions (water runoff, erosive phenomena, semi-natural water reservoirs at the base of the scarp) and microclimatic conditions (air runoff and ventilation direction); 2) potential plant community is the typical oak-hornbeam forest (*Tilio-Carpinetum typicum*) (Chojnacki, 1990; National Institute of Spatial Policy and Housing, 2018). Both parks, in half of the 20th century, underwent conservation and adaptation to new functions. They included the renovation of road systems and the reconstruction of the parks' stand depleted by the second world war. Currently, apart from a few relics (natural monuments, ancient trees), most of the trees are around 70 years old.

In 2004, the road system in Ursynów Park was modernized, which included the replacement of pavements on pedestrian and drive roads and the conversion of existing ground walkways beneath the canopy to hardened pavements. Unfortunately, the conducted earthworks involved interference with the root systems of trees adjacent to roads (including root reduction to a different extent and increasing the soil compaction). In contrast, no major modernization works have been carried out in Królikarnia since the 1960s.

Knowledge about the impact of such technical works carried out within tree root systems on their condition is essential, taking into account the actual protection of valuable old trees in parks by, for example, selecting the appropriate, least invasive technologies. Concerning historic parks, the problem described in this way is innovative, but dependent on many years of research, taking into account the specificity of tree life – their longevity and the biosocial position.

Reffering to case studies of Ursynów and Królikarnia parks in Warsaw our research aim was to investigate the impact of the earthworks related to modernization of park's pavements, as a specific stress factor affecting basic characteristics of the growth of nearby park trees. The verification, of the results based on the external measurements of tree parameters were compared with the annual increment using a resistograph.

1. Methodology

The authors conducted long-term observations and detailed studies in both sites; hence the essential source of data are dendrological inventories made in the years: Ursynów – 2003 and 2011 and Królikarnia – 2006 and 2013 (materials in the authors' collections). Tree stand inventories were made in similar seasons of the year (summer-autumn), taking into account the following parameters: trunk circumference at the height of 1.3 m, tree height, crown width, assessment of health condition and habit maintenance. The research material was obtained and supplemented with annual observations of the condition of trees in the spring-summer and autumn periods (2003–2019). On this basis, the species structure of the dendroflora was determined. For further analyzes, three species were selected, the most abundant in both parks – Norway maple (*Acer platanoides* L.), locust (*Robinia pseudoacacia* L.), and small-leaved lime (*Tilia cordata* Mill.). The trees selected for research grow in the vicinity of roads, in average light conditions and partial crown closure (40–60%). In order to standardize the results, the analyzes were carried out on mature trees aged 50–70 years. The age of the trees was estimated based on dendrometric parameters, e.g. trunk circumference at the height of 1.3 m (Łukaszkiewicz & Kosmala, 2008).

For each species, a test group A was selected. These were trees exposed to the impact of earthworks (Ursynów park) growing in a strip of soil up to 5.0 m wide from the edges of each modernized road. The test group B contains trees growing outside the works and damage zone (Ursynów park). These were specimens growing at a distance of at least 10.0 m from the edge of any modernized road. Trees representing the control group C grow a strip 0.0–5.0 m wide from the edge of the roads (Królikarnia park) were no earth-works connected to roads or pavements modernization had been conducted for many decades.

The parameter of DBH is widely used in urban tree growth modeling as a useful predictor of examining the growth of dendrometrical parameters over time (age of trees) such as the increase of total tree height, crown radius and leaf area. Especially repeated measurements of the same trees produce critical data for calibration and validation of the tree growth models concerning also factor such as the soil quality and available space in root zone (Randrup et al., 2001; Łukaszkiewicz & Kosmala, 2008; McPherson & Peper 2012; North et al., 2015; Lucke & Beecham 2019; Hilbert et al., 2020).

It was assumed that the deteriorating vitality of trees growing in the vicinity of earthworks, can be assessed by the measurements of tree trunks, although we thought it necessary to confirm these results by the precision method of measuring of the annual rings by drilling with the resistograph. Considering the high precision and invasiveness of this method only 5 tree groups were used which were found statistically sufficient.

For each group (A, B and C), the mean yearly increment of trunks circumference at h = 1.3 m (Z_c [cm]) was estimated based on the inventory data. *Student's T-test* was applied for independent variables. The standard deviation ($\pm s$ [cm]) for the Z_c value and the coefficient of significance (p) were calculated. The analysis was performed with the Statistica 13.0 software.

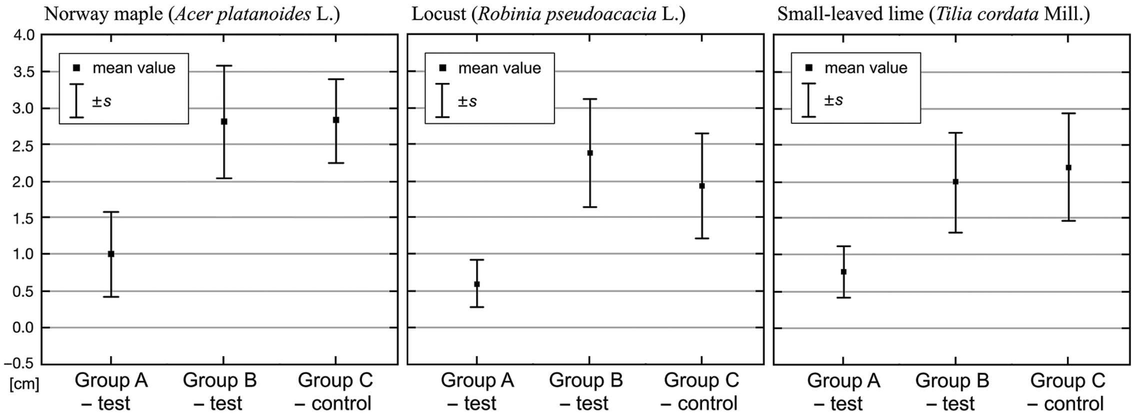

Figure 1. The mean yearly circumference's increment of trunks at h = 1.3 m [cm] and standard deviation (±*s* [cm]) of the three most abundant tree species, where: test group A (Ursynów Park): trees damaged – exposed to earthworks due to roads modernization; test group B (Ursynów Park): trees undamaged – not exposed to earthworks due to roads modernization; control group C (Królikarnia Park): trees undamaged – growing in undisturbed site conditions

The verification of research performed previously in both parks were made with the IML E-400 resistograph during the summer of 2019. Part-invasiveness of resistograph's measurements (drilling) caused, that the basic number of the verification sample was determined as 5 trees randomly selected, separately for groups A and B – test (Ursynów Park) and group C – control (Królikarnia Park), within each of selected tree species abundant in both parks. In this way a total of 45 trees were examined with the resistograph. Each selected tree was drilled twice at a height of 1.3 m in the N-S and E-W directions. The number of annual increments (years) was determined based on the interpretation of the wood resistance curves (from the last 20 years: 2000–2019, read using E-Tools Pro, IML Software). The average annual increment is the quotient of the drilling depth and the number of counted rings from two N-S and E-W repeats. The year 2005 was considered a critical point for tree growth, which separates the periods before and after the completion of earthworks during the modernization of the road system (Ursynów park). For all locations, the average radial growth of the trunks before (reference sample) and after 2005 was compared (test sample). The standard deviation (±*s*) for the Z_c value and the coefficient of significance (*p*) were determined in both locations (Statistica 13.0).

In both parks, soil compaction measurements were additionally carried out at several sites located on lawns under the canopy of trees, in stripes with a width of max. 1.0 m from the edge of the roads[1]. Comparing the average values of soil compaction in the Ursynów Park before and after the road modernization, it was found that they increased in a statistically significant manner – the significance coefficient $p < 0.0001$ (*T-test*, Statistica 13.0): in 2011, the soil compaction at the road edges exceeded ca. 0.5 MPa (5.0 kg/cm^2) but in 2003 it was ca. 0.35 MPa (ca. 3.6 kg/cm^2, ±*s* = 0.30); at a distance of 1.0 m from the edge of roads, the average value of soil compaction under lawns decreased to approx. 0.34 MPa (3.50 kg/cm^2) in 2011; in 2003 it was ca. 0.26 MPa (ca. 2.7 kg/cm^2, ±*s* = 0.60). It means that the compaction of the surface layer of soil in the vicinity of the modernized roads increased significantly and could harm the condition of trees. In contrary in the Królikarnia park, where road reconstruction has not been carried out, the average soil compaction is quite low and values approx. 0.25–0.30 MPa (2.6–3.0 kg/cm^2; ±*s* = 0.40).

2. Results

The observed effects of road work on trees were divided into two categories. The first one is the direct (apparent) losses in the park's stand. The trees in this category in the Ursynów Park reacted by quickly dying and falling out. It was found that between 2003 and 2011, 47 inventory items were lost, of which 31 trees (65%) in 2003 did not show symptoms of poor health. In conjunction with the knowledge of their location (trees growing alongside roads), it is reasonable to suppose that they fell out as a result of earthworks during road modernization.

The second category consists of indirect (non-obvious) losses in the park's trees. They could be found based on repeated measurements made during the stocktaking of stands when the average annual increment of trunks circumference (Z_c [cm]) for selected tree samples was determined. The values of the standard deviation (±*s*) showed some natural variability of the increment (Z_c) within individual species. Then, the mean annual growth in trunk circumference (Z_c [cm]) of the test group (A) was compared with the growth of trees in the test group (B). Significant statistical differences were found within species ($p < 0.05$). Detailed results show a clear tendency of trees to react to the stress factor (Table 1). It was found that the increment was 2.6 to 4.0 times smaller (test group A) compared to

[1] Measurement carried out using ELE International, Model 29-3729 (CL-700A) penetrometers. The device provides results in kg/cm^2 with a precision of 0.25 kg/cm^2 in the nominal range of 0.5–4.5 kg/cm^2 for sandy-loam soils in the surface layer (0.0–0.3 m).

Table 1. The response of the mean yearly increment of trunks circumference at h = 1.3 m to the impact of earthworks due to park's road system modernization for the three most abundant tree species in Ursynów and Królikarnia Parks in Warsaw

Trees taken into main research	Norway maple (*Acer platanoides* L.)			Locust (*Robinia pseudoacacia* L.)			Small-leaved lime (*Tilia cordata* Mill.)		
	Z_c [cm]	±s [cm]	p [sample quantity]	Z_c [cm]	±s [cm]	p [sample quantity]	Z_c [cm]	±s [cm]	p [sample quantity]
Group A – test	0.99	0.58	[A vs. B] < 0.000001 [18 psc]	0.59	0.32	[A vs. B] < 0.000001 [35 psc]	0.76	0.34	[A vs. B] < 0.000001 [17 psc]
Group B – test	2.79	0.77	[B vs. C] = 0.925695 [18 psc]	2.36	0.72	[B vs. C] = 0.069426 [16 psc]	1.99	0.70	[B vs. C] = 0.402783 [17 psc]
Group C – control	2.81	0.57	[A vs.C] < 0.000001 [19 psc]	1.92	0.71	[A vs. C] < 0.000001 [21 psc]	2.19	0.74	[A vs. C] < 0.000001 [18 psc]

Note: **Group A – test** (Ursynów Park): trees damaged – exposed to earthworks due to roads modernization. **Group B – test** (Ursynów Park): trees undamaged – not exposed to earthworks due to roads modernization. **Group C – control** (Królikarnia Park): trees undamaged – growing in undisturbed site conditions. Z_c – the mean yearly increment of trunks' circumference [cm]. ±s – standard deviation [cm]. p – coefficient of significance between values of variables represented by independent samples from different locations: $p < 0.05$ = difference between variables means is statistically significant / $p > 0.05$ = difference between variables means is not statistically significant.

the trees of the same species from test group B (Figure 1). The control for the results obtained at this stage of the research was a comparison of the increment (Z_c) of trees growing outside the earthworks zone, i.e. test group B and control group C (Figure 1). It was found that in these groups, despite some discrepancies considered normal; there were no statistically significant differences ($p > 0.05$) between the two parks within each of the three species. In other words, trees from test group B and control group C show a very similar annual growth in trunk circumference (Figure 1).

The verification confirmed the negative impact of earthworks on trees in the form of slower annual stem increments in all three species in group A (Figure 2; Table 2). It was found that for each of the species, the difference between trees located in the earthworks zone and those with undisturbed habitat is statistically significant ($p < 0.05$). Norway maples (*Acer platanoides* L.) from the test group A reacted particularly clearly, showing in the period following the damage (2004–2019) an average decrease of radial wood increment by more than 4.0 mm per year compared to the condition before the damage

Table 2. The verification of the effectiveness of the circumference measurements (Table 1): the response of radial wood increment [resistograph] to the impact of earthworks due to park's road system modernization for the three most abundant tree species in Ursynów and Królikarnia Parks in Warsaw

Trees taken into verification	Relation to damage	Mean annual radial wood increment								
		Norway maple (*Acer platanoides* L.)			Locust (*Robinia pseudoacacia* L.)			Small-leaved lime (*Tilia cordata* Mill.)		
		Z_c [mm]	±s [mm]	p [sample quantity]	Z_c [mm]	±s [mm]	p [sample quantity]	Z_c [mm]	±s [mm]	p [sample quantity]
Group A – test	before	10.3	2.5	< 0.0000 [5 psc]	7.6	1.9	< 0.00000 [5 psc]	9.3	1.9	< 0.0000 [5 psc]
	after	6.1	1.9		5.4	1.6		6.2	1.9	
Group B – test	before	8.2	2.7	= 0.0026 [5 psc]	4.8	1.9	= 0.00002 [5 psc]	8.5	2.1	= 0.6822 [5 psc]
	after	6.7	2.0		3.4	1.3		8.3	2.3	
Group C – control	before	7.3	2.2	= 0.5845 [5 psc]	5.8	1.5	= 0.1681 [5 psc]	9.7	2.6	= 0.3488 [5 psc]
	after	7.5	1.5		5.3	1.5		9.2	2.5	

Note: **Group A** – **test** (Ursynów Park): trees damaged – exposed to earthworks due to roads modernization. **Group B** – **test** (Ursynów Park): trees undamaged – not exposed to earthworks due to roads modernization. **Group C** – **control** (Królikarnia Park): trees undamaged – growing in undisturbed site conditions. **Relation to damage** – comparatively registered tree radial increments in groups A, B and C in the periods before and after the time, when the road modernization in the Ursynów park was performed in 2005. Z_c – mean annual radial increment of the trunk [mm]. ±s – standard deviation [mm]. p – coefficient of significance between values of variables represented by independent samples from different locations: $p < 0.05$ = difference between variables is statistically significant / $p > 0.05$ = difference between variables is not statistically significant.

(reference test). During the same period of time the average annual radial wood increment of Norway maples from the test group B showed only a slight decrease by 1.5 mm and in the control group C – even a slight increase by 0.2 mm (Figure 2; Table 2).

The verification results for black locusts (*Robinia pseudoacacia* L.) confirm the tendency observed in the case of Norway maples (Figure 2; Table 2). Trees collected in the test group A, showed in the period following the earthworks an average decrease of radial wood increment by more than 2.0 mm as compared to the state before the damage. The average annual increases in group B after 2005 showed a decrease by 1.4 mm and in group C a slight decrease by 0.5 mm (Figure 2; Table 2).

In the case of small-leaved limes (*Tilia cordata* Mill.) exposed to damage (test group A), the verification after 2005 showed an apparent decrease in the average annual radial growth of a trunk. 3.0 mm, compared to the state before 2005 (Figure 2; Table 2). The average annual increments of limes in the test group B after 2005 showed a slight decrease by 0.2 mm and in the control group C a slight decrease by 0.5 mm (Figure 2; Table 2).

3. Discussion

The presented research, although being a pilot for a narrow group of objects (*case study*), showed an adverse reaction of trees – limitation of growth – in connection with

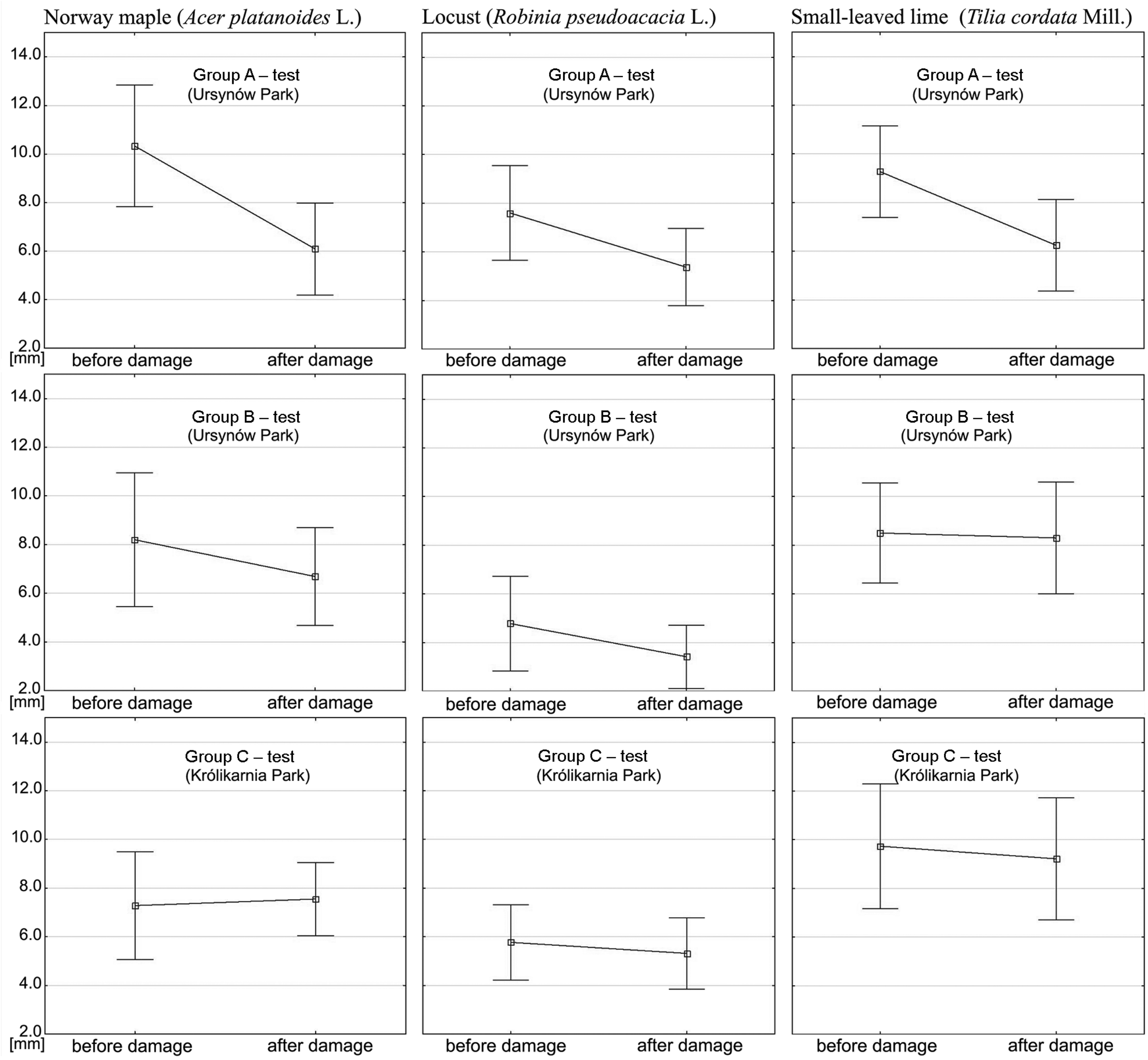

Figure 2. The verification of the effectiveness of the circumference measurements (Figure 1). The standardization of the average annual radial wood increment [mm] and the adequate values of the standard deviation ±*s* [mm] before and after the certain point of time, when earthworks around trees in Ursynów Park were completed. The results: the response of average annual radial wood increment obtained for groups A and B – test (Ursynów Park) in comparison with the group C – control (Królikarnia Park), within each of selected tree species abundant in both parks

earthworks in the root zone. It is consistent with the hypothesis adopted at the outset a priori, which assumed the occurrence of the so called "concealed" damages to park's tree stand due to severe transformation of soil conditions in tree root zones. Trees subjected to such stress have a reduced average annual growth in trunk circumference (Z_c) compared to their counterparts growing in undisturbed site conditions. It is known that mature or ageing trees are more susceptible to stress factors than young trees. Should such stressors be too strong or chronic (e.g. damages, open wounds, pathogen infection) the energetic resources of the tree get depleted and a so called "death spiral" is initiated (Day, 2010; Watson & Hewitt, 2012; North et al., 2015; Hilbert et al., 2020).

Of the three analyzed species, the most decisive response to the stress factor was shown by Norway maples, in which the difference between the normal and the slower growth in trunk circumference (Z_c) exceeded 1.8 cm. In the two other studied species – black locust and small-lived lime – the differences in the increment of the trunk circumference (Z_c) are smaller, but still statistically significant and amount to: >1.3 cm and >1.4 cm, respectively. A transparent reaction of trees to adverse changes in the habitat in the root zone is expressed by a reduction in the increment of trunks circumference during the research period (2003–2019) from 2.6 to 4.0 times concerning trees of the same species, growing outside the impact of earthworks (Ursynów Park) or under unchanged conditions (Królikarnia Park). Of course, naturally mature trees show a gradual slowdown in the growth of dendrometric parameters over the years (e.g. Mencuccini et al., 2005; Łukaszkiewicz & Kosmala, 2008; Hilbert et al., 2020). However, in the case of trees subjected to the stress factor mentioned above, this process was much more rapid, as shown by the obtained results. Resistograph measurements, 15 years after the completion of earthworks in Ursynów Park, showed a statistically significant decrease in the radial increments of trees concerning the specimens distant from the modernized roads. When analyzing the obtained results, it can be assumed that earthworks could also have a slight deterioration in the growth rate of trees (group B) growing outside the technical works zone (Ursynów Park). It is confirmed by the comparison of the results with the control group (C) of trees from the Królikarnia park, where modernization road system wasn't carried out for many years.

Conclusions

1. It was found that in historic parks, the negative impact of earthworks on the vitality of neighbouring trees is manifested by an average 3-times slowdown in the annual growth of trunks circumference compared to trees growing in undisturbed conditions.
2. It was shown that the trunk circumference in this case is a parameter which adequately reflects tree's vitality, as confirmed by resistograph measurements, which shows a good approximation of results of dendrological inventories.
3. Tree growth decrease is a natural phenomenon in aging trees, however the stressor – in all three investigated species – caused a dynamic decrease in trunk growth compared to control group: Norway maple (*Acer platanoides* L.) showed the greatest decrease in growth, while the growth decrease of black locust (*Robinia pseudoacacia* L.) and small-leaved lime (*Tilia cordata* Mill.) was visible but, not as rapid.
4. The results obtained in the presented case study are indicative, showing that the effects of indirect ("concealed") damage to trees in parks due to linear earthworks are measurable and long-lasting – persisting many years after the stressor ceased.
5. In cities, there are many problems related to the preservation of older trees, exposed to damage and degradation during the necessary modernization of technical infrastructure. Research on the impact of this type of work on trees needs to be continued. It may be used to minimize the adverse effects of earthworks, e.g. by selecting the appropriate, least invasive technologies, which should contribute to the real protection of the most valuable, historic tree stands.

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Author contributions

JŁ and BFA conceived the study and were responsible for the design and development of the data analysis. JŁ, BFA and JB were responsible for data collection. JŁ, BFA and JB were responsible for the data analysis. JŁ and BFA were responsible for data interpretation. JŁ wrote the first draft of the article and was responsible for the translation process.

Disclosure statement

The authors declare no conflict of interest.

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