Water deficiency of little-leaf linden poly-metallic contamination

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Abstract. A high level of environmental pollution identifies Sterlitamak industrial center (PreUral, Russia). Among human-made emissions, particulate matter (including heavy metals), nitrogen dioxide, ammonia and formaldehyde dominate. We studied the water regime of little-leaf linden (Tilia cordata Mill.) trees in habitats with diverse pollution levels from 2010 to 2018. There have been significant changes in the indicators of water deficiency of linden leaves under pollution conditions. Regardless of the category of life state, the linden trees had a slight water deficit under control, while the healthy and weakened linden trees had a high-water deficit under pollution conditions. The results point that under polluted conditions, as the temperature increases and the air's relative humidity decreases, the water consumption of linden leaves increases. The maximum water deficiency is in the daytime (13-15 hours). At night, the flow of water is not covered by the inflow, so the following day, the morning begins with some water lack. Thus, in a polluted environment, significant changes in the water deficit of the linden trees are associated with reduced soil moisture, increased transpiration, and worsened of stand life states.

1. Introduction

Water is involved in the transport of substances, metabolism, and thermoregulation, determining the cell structure and the whole plant's turgor state. Lack of water in the air and soil retards plant growth and development and reduces productivity [1-3]. The volume of water absorbed by trees depends on the intensity of transpiration, which produces more or more minor water deficiency in the plant [4-6]. The primary source of plant water is soil moisture, which is absorbed by root systems. The root systems' role in providing water to plants is primarily that the large absorption surface contributes water uptake from as much soil as possible. Therefore, if part of the root system is suppressed or dead, plants may experience significant water deficiency.

Plants growing in human-made disturbed areas often face complex and even critical water supply conditions, which are accompanied by exposure to various types of toxicants [7-10]. When the tree leaves are polluted, there is almost no full water saturation. Water deficiency is most common in such situations. A water deficit not passing 10% does not cause any damage to the tree plant. Water deficiency of up to 25% or more results in stomatal closures, wilting of leaves, reduced growth rates and photosynthesis.

Little-leaf linden (Tilia cordata Mill. (Tilia genus, Malvaceae family)) represents a deciduous tree which native to much of the European part of Russia. A linden tree grows up to 20-28 m tall, lives up to 200 years, in urban areas up to 80-100. Linden is used in Sterlitamak City's landscaping and grows...
in parks, squares and sanitary protection zones of some industrial enterprises. Due to pollution impact, the linden tree suffers from a lack of moisture in the urban environment. In this study we aim to examine the impact of pollution on leaf linden trees’ water deficiency, taking into account the plant life state.

2. Materials and methods
The climate of the research area is characterized by continentality and insufficient moisture. The average annual temperature is 2.6-2.8 °C. Average annual precipitation 449-469 mm. Sub-zero air temperature occurs in the last decade of October and is held on average until the first decade of April.

The studies were carried out in linden stands located at various distances from the industrial zone of Sterlitamak. The test plots were located directly in the city’s industrial zone, and control plots were placed 20-25 km from the town. The stands studied were of artificial origin and the comparable age (50-55 years old).

The water regime was studied in the field according to Catsky’s technique [11]. The analysis leaves were taken from the top, middle, and bottom of the crown, facing the contamination source. The first weighing of the leaves was carried out immediately after collection. The leaves were then placed in a wet chamber with petioles submerged in water. The re-weighing of the leaves executed two hours later. The water content of leaves was determined in the morning (M1) and the afternoon (M2), with differences (M1>M2) over time indicating a negative water balance. Lack of water during the day (M1 - M2) determines water deficit, expressed as a percentage of leaves’ total water content [12]. Water consumption by plants depends primarily on its content in the soil. Therefore, the determination of soil moisture is essential in assessing plant water deficiency. Soil moisture was defined by applying a standard approach [13]. The life state of trees was determined according to Alexeyev’s method [14].

Studies were conducted from 2010 to 2018, which differed by weather conditions. Rainfall increased in the summer months of 2011, 2013, 2014 and 2015. The summertime of 2010, 2012, 2016 and 2018 are characterized via low precipitation and high temperature.

3. Results and discussions
During the research we established that polluted linden trees have a significantly higher water deficit than plants in control (figure 1). During the study period, maximum values of water deficit were observed in 2010. This year, July was the driest and hottest month compared to other years. During this period, the average relative humidity of the air was only 36-38%. Furthermore, the air temperature reached 29-34 degrees. Against such adverse weather conditions, the linden trees possessed high levels of morning water deficit. July and August of 2012, 2016, and 2018 were also arid, which affected the linden trees’ water regime. Likely, the linden root systems cannot compensate for the transpiration flow, which increases the water deficit both under polluted conditions and in control.

Under contaminated conditions, the midday water deficit ranges from 14.6% to 28.2%. At midday hours, the air’s maximum temperature and the air’s minimum relative humidity were typically observed. Therefore, maximum values of water deficit were observed in the daytime from 13 to 15 hours. In the evening, from 6 p.m. to 8 p.m., the water deficit is decreasing. In July and August, in contaminated conditions, the morning water deficit of linden leaves ranged from 15.0 to 17.9%, while in control, it changed from 12.0 to 13.0%. The arid nature of the weather also affected the moisture content of the soil. Under pollution conditions, soil moisture in the topsoil (0-20 cm) was only 13.7-14.3%, while in control was higher (on average, 18.8-23.6%). As soil moisture decreases, water becomes less available to plants, increasing the water deficit [15].
Figure 1. Water deficiency (average per growing season) in linden trees within the Sterlitamak industrial center.

Studies of the linden trees' water regime in wet years (2011, 2013, 2014, 2015 and 2017) designated these plants had a significantly smaller water deficit than dry years. Favourable weather conditions contributed to this, with air temperatures rising no higher than 18-20 degrees and relative air humidity of 70-85%. Soil moisture throughout these seasons ranged from 28 to 34%. In this context, the water deficiency of the linden trees equalled 15.8-19.2%.

The intensity of transpiration of linden leaves in the study period is identified by significant variability (table 1). Increased transpiration of linden leaves was observed under contaminated conditions. The transpiration rate of linden leaves is consistent with the water deficit values. An improvement in water deficiency in polluted conditions can be attributed to decreased plant water content to levels that do not support healthy physiological-biochemical processes [16].

Table 1. Transpiration rate of linden leaves under various environmental conditions (mg/g per hour)

| Test plot locations | 2010   | 2011   | 2012   | 2013   | 2014   | 2015   | 2016   | 2017   | 2018   |
|---------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Polluted areas      | 923±23 | 653±17 | 898±33 | 617±18 | 685±34 | 489±17 | 862±24 | 651±28 | 717±38 |
| Control             | 862±24 | 523±14 | 645±38 | 523±13 | 522±36 | 388±12 | 644±31 | 564±22 | 654±26 |

Significant water deficit can cause a decline of trees' life status, especially under contaminated conditions, as all water movement in plants (from soil uptake to transpiration) is directly or indirectly affected by toxicants [17]. Moreover, the decline of life status breaks the tree's water regime, which increases water deficit values. Within the study area, in contaminated conditions, the linden's life state is rated as «weakened» (state index 72.75%) (table 2). Life state decline is caused by significant injury to the leaves by chlorosis and necrosis (up to 20-30% of the leaves' area), which reduces the gross
evaporable surface through damage to the stomata. As a result, degraded trees under pollution conditions possessed more considerable water deficit values than healthy trees. The life state of linden stands in control is valued as «healthy» (state index 88.25%), leaves have slight damage (area of chlorosis and necrosis not more than 10% of total leaf surface). The high life state and the absence of linden leaf damage in control can explain the lower water deficit in the given conditions.

Table 2. Life state of linden trees within the Sterlitamak industrial centre

| Test plot locations | Healthy | Weakened | Severely weakened | Dying trees | Dead trees | Stand life state | State index, % | Category |
|---------------------|---------|----------|-------------------|-------------|------------|-----------------|---------------|----------|
| Polluted areas      | 7       | 9        | 3                 | 7           | 0          | 72.75           |               | Weakened |
| Control             | 14      | 4        | 2                 | 0           | 0          | 88.25           |               | Healthy  |

Thus, increased transpiration, reduced soil moisture content, and decline of trees’ life state in polluted conditions are reflected in more frequent water deficits. Within the industrial territory of the city of Sterlitamak, healthy linden trees have a higher water deficit of 6.0-11.5% than in control. There was no significant water deficit in control. Humid years are distinguished by small water deficit values and their slight fluctuations during the day and growing season dynamics. However, despite more comfortable weather situations, the linden water deficit values in polluted conditions were higher than in control. When comparing dry and wet years, maximum water deficit values (morning, noon and evening) were observed in 2010, 2016 and 2018 (dry years), and minimum values in cool and humid 2015.

4. Conclusion
Consequently, within the Sterlitamak industrial center, there is a high-water deficiency of linden trees under polluted conditions. Variations in the water regime of linden trees under these conditions depend on soil moisture, increased transpiration, and tree life decline. Depending on the weather conditions throughout the year, the amount of water deficit will vary. During arid and hot years (in our case, 2010, 2012, 2016 and 2018), water deficit and transpiration intensity values are higher than in cool and wet years (2011, 2013, 2014 and 2015).

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