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Qualitative and Quantitative Indicators of Foliar Mass of Woody Plants in Urban Greenspaces According to the Level of Air Pollution

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Abstract: The purpose of this study is to conduct a comparative analysis of the leaf fall timing and parameters of fluctuating leaf asymmetry among two commonly used plant species for street landscaping in Detroit city, namely, American elm and American ash. The study was completed between summer and fall for the year 2019 in and around Detroit, US. Phenological leaf fall timing of elm and ash was studied, and the fluctuating asymmetry index of their leaves was estimated within the city limits (80 trees of ash and 40 of elm) and outside the city (control site, 20 trees of each species). Leaf fall in city ash trees was recorded from November 1st to 4th and 5-8 days prior to the leaf fall in elms ($p \leq 0.01$). Elm trees in the control group shed their leaves 10 days later compared to the city trees, i.e., on average, on November 25th ($p \leq 0.01$). Ash trees in the control group shed their leaves earlier than the elm control group, on November 11th ($p \leq 0.001$). In the city streets, the average fluctuating asymmetry ranged from 0.065 to 0.086 (point 1), from 0.049 to 0.078 (point 2) and from 0.063 to 0.082 (control site, near the highway).

Key words: Ash, elm, fluctuating asymmetry, leaf fall, leaves.

Introduction

Among the whole variety of plant species, each plant has a different stress tolerance to the anthropogenic load. In particular, it is manifested in the acceleration of aging processes and longer duration of processes associated with active vegetation (Shadrina et al., 2020). Moreover, under urban conditions, the time required for budding is reduced, and the time for forming generative organs becomes shorter. As a consequence, the timing of pollination of plants, as well as their fertilisation is shifted (Lakatos and Mirtchev, 2014). A known fact is the shift in the timing of leaf shedding (Gebauer et al., 2018). Some plant species experience a decrease in root growth rate and annual diameter. One of the most practical evaluation criteria is the decrease in foliar blade area. Of the foliar blade parameters suitable for a rapid assessment of the level of pollution, including air pollution, its fluctuating asymmetry appears convenient (Milios et al., 2019). This parameter displays small and nondirectional changes in bilateral symmetry. Maintaining stable symmetry values shows the capacity of the body to develop without disturbance and errors.

The advantage of this method of studying the adaptive responses of plants to anthropogenic load is that the data are easy to collect in large quantities, as well as to save the samples and process the material obtained. Besides, leaves grow annually on trees, so different results can be obtained in different years corresponding to various levels of anthropogenic load, which is convenient for comparative analysis (Shadrina and Vol'pert, 2014). At the same time, the applicability of this approach raises some objections. The main arguments are that deviations from symmetry in development are quite small and can be reduced to random deviations within the limits allowed by natural selection (Sandner and Matthies, 2017). Also, under the influence of sufficiently strong (negative) anthropogenic factors, such deviations in symmetry will be quite significant and cannot be explained only by the fact that they are within the backlash allowed by natural selection (Xu et al., 2012).

Likewise, regular processes occur in the atmosphere of most major cities around the world, along with industrial progress. These include increased concentrations of motor vehicle exhaust, smoke, dust and dirt emitted by various industrial facilities, as well as other components of the urban environment. These factors certainly have a poisonous effect on the plants growing in the region, particularly on their leaves (Santos et al., 2013). For roots, an increase in heavy metal content in the soil is devastating. All of these conditions lead to premature leaf necrosis, increased susceptibility to fungal infestations, and other negative consequences for trees. In some countries, like Russia, sodium chloride is still actively used as a spray agent on ice and snow for walking (Zakharov and Krysanov, 1996). This creates an additional load on the plant organism since significant amounts of sodium and other salts penetrate the soil with melting water and go further into the roots of plants. Global warming also plays a significant role in reducing plant sustainability in urban environments. Because of prolonged exposure to unusually high temperatures, some trees drop their leaves, or their leaf mass dries out prematurely and dies, resulting in necrosis (Mendes et al., 2018). Invasive species introduced by other countries may also threaten trees in urban areas. Plants are already weakened in this environment, and the invader in the new habitat still has no natural enemies and can reproduce uncontrollably. Thus, one of the main features of the urban environment is the accumulation of pollutants and wastes, when there is simultaneous pollution of atmospheric air, soil, and water (Murphy and Lovett-Doust, 2004).

The resilience of plants to anthropogenic stress is therefore associated with several factors. The main ones include the ability to change the physiological processes and stress tolerance of the plant species, the state of the plant itself and its individual characteristics, as well as the severity of the influence of anthropogenic factors.

The experience of using organisms with bilateral symmetry as bioindicators is quite wide and covers a variety of groups: plants and mammals on land, fish and amphibians in aquatic ecosystems (Guo et al., 2017; Lutterschmidt et al., 2016). Among the plant species, the most common bioindicators are the Norwegian maple (*Acer platanoides*), the pyramidal form of the black poplar (*Populus nigra*), the small-leaved lime (*Tilia cordata*), and the weeping birch (*Betula pendula*). These plants are widely introduced into areas where they are not naturally occurring. They are considered not only as landscaping elements in botanical gardens but also planted in the form of alleys in the territories of cities in China and the US.

Detroit (Michigan, the USA) is one of the biggest industrial cities in the United States of America. Its climate depends on the nearby Great Lakes. Moreover, the Detroit River flows through the city, which means that there is a wetter continental climate within the city. Detroit tops the list of Michigan's most polluted cities. However, these numbers vary depending on the time of the year, a particular area of the city, or the presence of a potential air pollutant, such as a factory, in the area. The main sources of pollution are gases emitted by motor vehicles. The Air Quality Index (AQI) may fluctuate significantly due to these factors, with most pollutants being within acceptable limits. The exceptions are two pollutants that are higher than the standard: carbon dioxide concentration and elemental lead content. The city also has a relatively high ozone concentration. Thus, Detroit ranks 34th out of 228 metropolitan areas in this parameter, and 56th out of 217 for the emission of particulate aerosol particles by pollution per day, and 10th out of 203 for average annual pollution as of 2020 (data from the American Lung Association, ALA). Heavy industries are concentrated in the southwest part of the town, and are responsible for the primary source of pollution. There have been no studies devoted to the bioindication of atmospheric air pollution in Detroit with American elm and ash as objects, which determined the relevance of the present work.

This study aims to evaluate the parameters of phenological periods of leaf yellowing and falling and the indicators of fluctuating asymmetry of leaves of American elm (*Ulmus americana*) and American ash (*Fraxinus americana*). The author assumes certain changes in the phases of leaf fall under conditions of increased anthropogenic load and higher values of leaf fluctuating asymmetry in trees of these species in the most polluted areas of the city. The objectives of the study were (a) to estimate the shift in leaf fall periods in two tree species under anthropogenic load and (b) to study changes in the parameters of fluctuating asymmetry under different anthropogenic load factors.

Materials and Methods

Research Design and Sample

The study was completed in the summer and fall of 2019 in Detroit, Michigan, the United States. The first group comprised of 80 ash trees and 40 elms growing in homogenous stands along busy city streets. In the selection of appropriate streets, the level of pollution was taken into account. The two tree species selected are among those currently used in urban landscaping in the northeastern United States and adjacent regions of Canada. The trees selected for observation were of the same age group, determined by comparing their planting dates with 2 control samples for the annual rings taken from both trees. The average age was 30.2 ± 0.2 years for ash and 29.1 ± 0.1 years for elm. Twenty trees of each species were collected at five locations in Detroit (for ash) and three locations (for elm). The trees of both species were also in the same age range. Similarly, a group of trees of the same species (20 elms and 20 ash trees), located in natural conditions (50 km from the city limits) and not experiencing a noticeable influence of anthropogenic factors, was studied.

Experiment

A division was made among the trees of the first group: trees of each species (80 specimens of ash and 40 of elm) located under street lights, and the same number of trees at an equal distance between the lights were examined. During the summer-fall period, trees were reviewed for changes in phenological phases (leaf yellowing, leaf drop).

The fluctuating asymmetry indicators were studied by collecting 15 elm leaves during the period when leaf growth discontinued. The reasons for choosing elm trees are given in the results of the study. Altogether 100 leaves were collected from each tree. The following parameters were examined: (a) width of half a leaf; (b) second order vein length index (the second from leaf base was considered as such); (c) distance between bases and distance between ends of first and second order veins; (d) angle (in degrees) between the main vein and second order vein second from leaf lamina base.

The values of fluctuating asymmetry were calculated according to the formula:

$$FA = 1/5 \sum \left| L - R \right| / (L + R) \qquad (1)$$

where L and R indicate the measurements for the left and right leaf halves, respectively. In order to assess the qualitative influence of the environment on the degree of fluctuating asymmetry of leaves, the V.M. Zakharov scale (a total of 5 points in the scale) was employed. In the scale, one point corresponds to the results of growing the plant in favourable conditions, for example, in the reserve, and 5 points to the extremely depressed state of the plant, i.e., under highly unfavourable conditions. The fluctuating asymmetry index of up to 0.040 corresponds to conditionally normal indicators of environmental quality (1 point), from 0.040 to 0.044 (2 points) – deviations from the norm, but not critical; from 0.045 to 0.049 is an average level, at which deviations from the norm are already more significant (3 points); from 0.050 to 0.054 is 4 points and implies significant deviations from the norm; from 0.055 and above are critical deviations from the norm, i.e., fatal for the majority of tree plant species.

Statistical Analysis

Statistical analysis was performed using Statistica v. 7.0 (StatSoft Inc., USA). According to a database, the arithmetic mean and the error of the mean were computed for each characteristic. Differences between the values were significant at $p \leq 0.05$. Student's t-test was used to check the reliability of differences.

Results

It was found that under the influence of lantern light, American elm ends its growing season later compared to ash trees, and also later compared to trees of the same species that grow in the area between the lanterns (Figure 1A-C).

Leaf fall in ash trees is the earliest, occurring from November 1st to 4th, 5 to 8 days before the same period in elms ($p \leq 0.01$). The difference between elm trees growing under street lamps and those growing between them is significant and averages six days (November 9th to 15th, $p \leq 0.05$). Elm trees growing outside the urban environment shed their main leaf mass later than the urban ones, with an average difference of ten days, i.e., on November 25th ($p \leq 0.01$). Ash trees outside the city shed their leaves two weeks earlier than the elm control group, i.e., on November 11th ($p \leq 0.001$). Thus, the elm is a more suitable species for urban landscaping since even in an urban environment it sheds the leaves later than ash. Hence, elm can retain its foliage mass longer. For this reason, elm trees were chosen as a model to study the fluctuating asymmetry index under different anthropogenic loads (Figure 2).

At the same time, further research into the adaptive responses of American elm in urban conditions is

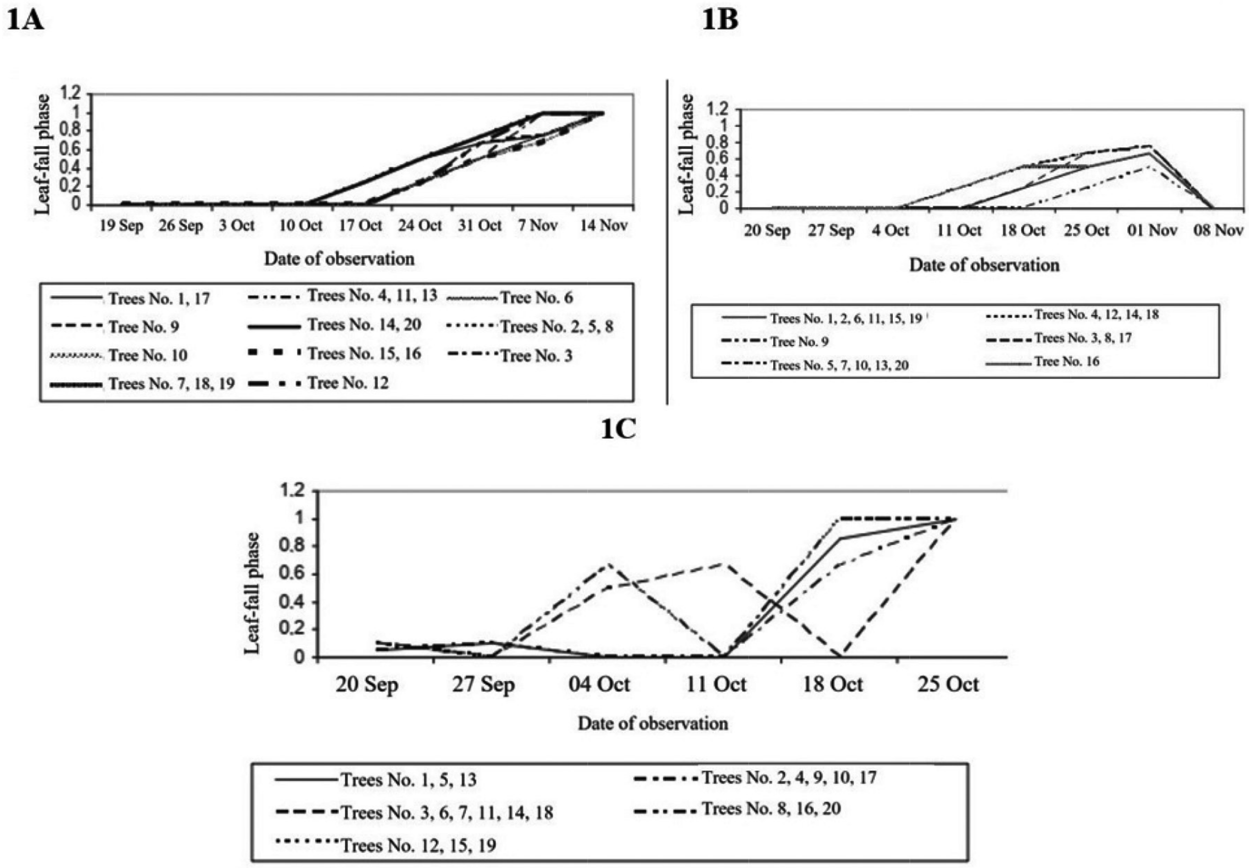

Figure 1: Leaf-fall phases of American elm in the streets of Detroit. (A, B) – locations within the city (group 1), (C) – locations outside the city (control, group 2).

required. Although trees are in the foliage state for a long time, they may be more susceptible to negative factors such as diseases, invaders and environmental effects. Based on the data obtained, it can be argued that in urban conditions, the elm has acquired an adaptive capacity for a longer growing season under the influence of artificial light. In this respect, further research on the stability of its development across fluctuating asymmetry indicators was necessary. This indicator can assist in determining the level of pollution in the area.

The conducted research showed that the American elm trees can respond differently to the level of pollution of the city area, which is accurately reflected through the value of fluctuating asymmetry index (Figure 3). Specifically, under the first location (3B), the mean fluctuating asymmetry index ranged from 0.065 to 0.086. Based on the 5-point Zakharov classification used, this index corresponds to the third and fourth pollution levels. In the second location of Detroit (3D), the situation is somewhat better. Here, the fluctuating asymmetric indices vary slightly less and range from 0.049 to 0.078 ($p \geq 0.05$ with the first location). In this case, it represents the third level of pollution. As for the control site (3F), the index of fluctuating asymmetry was from 0.063 to 0.082, i.e., corresponded to the first location (third to the fourth level of pollution, $p \geq 0.05$ with the first location) and the third to fourth levels of pollution.

Regarding the asymmetric values in the leaves of the American elm, a different expression of the five morphological characteristics of the leaves was observed in the three locations (Figure 3 A, C, E). The maximum values in two of the three cases were 0.11 and 0.1, the distance between the bases of the first and second veins of the second order, which exceeded the other values by 0.5 to 2.0 times ($p \leq 0.05$), except for the distance between the ends of the first and second veins of second order, which even exceeded the distance between bases in the third point (0.11 versus 0.85, $p \leq 0.05$). The least variable indicators were two: the width of the leaf halves and the angle between the veins – they did not exceed the values of 0.04 to 0.05. Thus, among the indicators of fluctuating asymmetry, the distance between the bases and the ends of veins are the most variable, while the

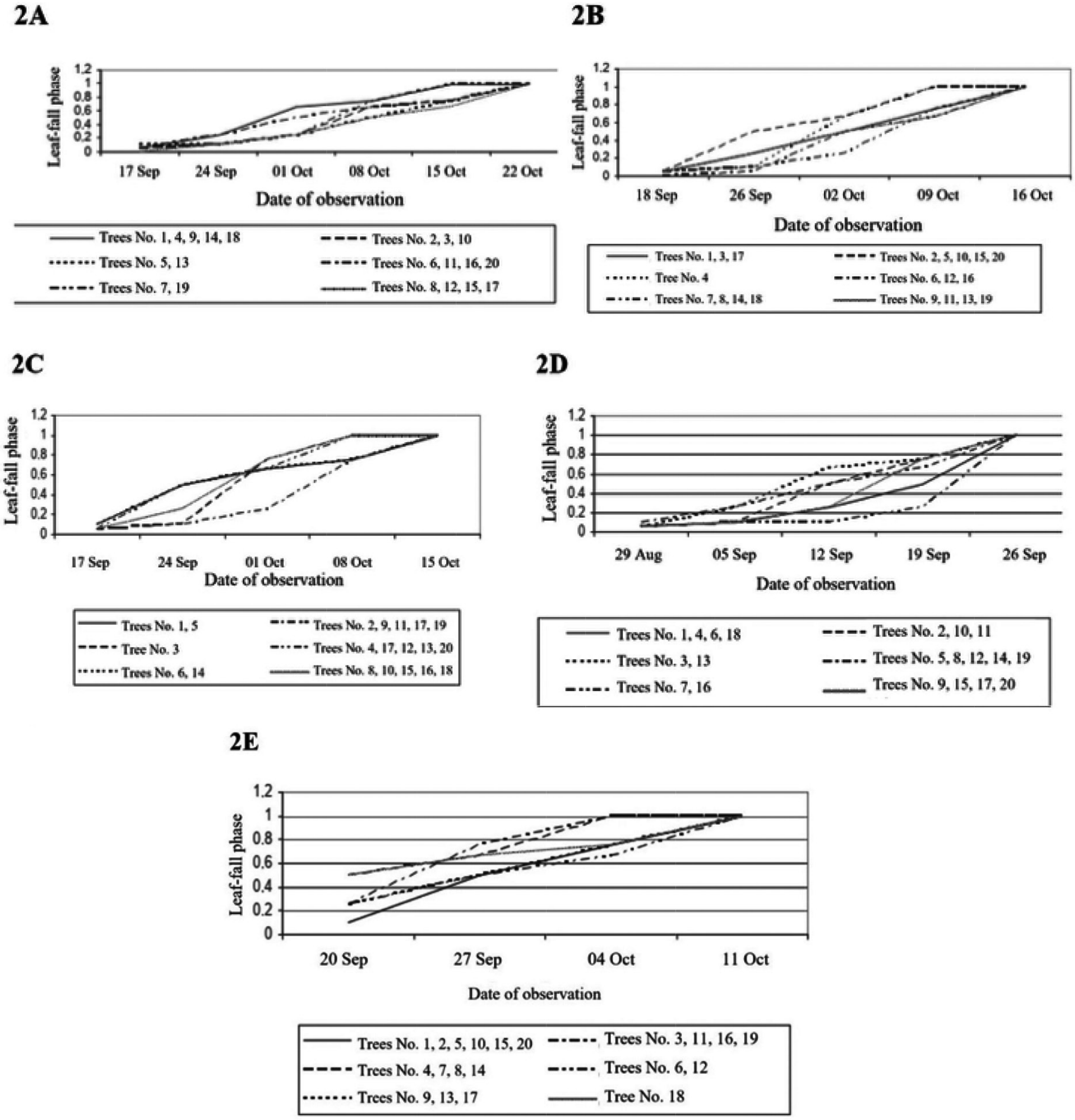

Figure 2: Leaf-fall phases of the American ash tree within Detroit (A–D, group 1), and outside Detroit (E, group 2).

width of halves and the angle between veins are the least variable.

Discussion

Leaf fluctuating asymmetry indicators have their own models, depending on the distance to the source of pollution. As known from numerous works, this dependence is inverse, i.e., asymmetry decreases with increasing distance (Ambo-Rappe et al., 2007; Zverev et al., 2018). In particular, the intake of heavy metals from the atmosphere with industrial emissions is related to prevailing wind direction and the concentration of these metals in the composition of soils. From there, they penetrate the root system of the plant and extend further towards the leaves. The leaves also

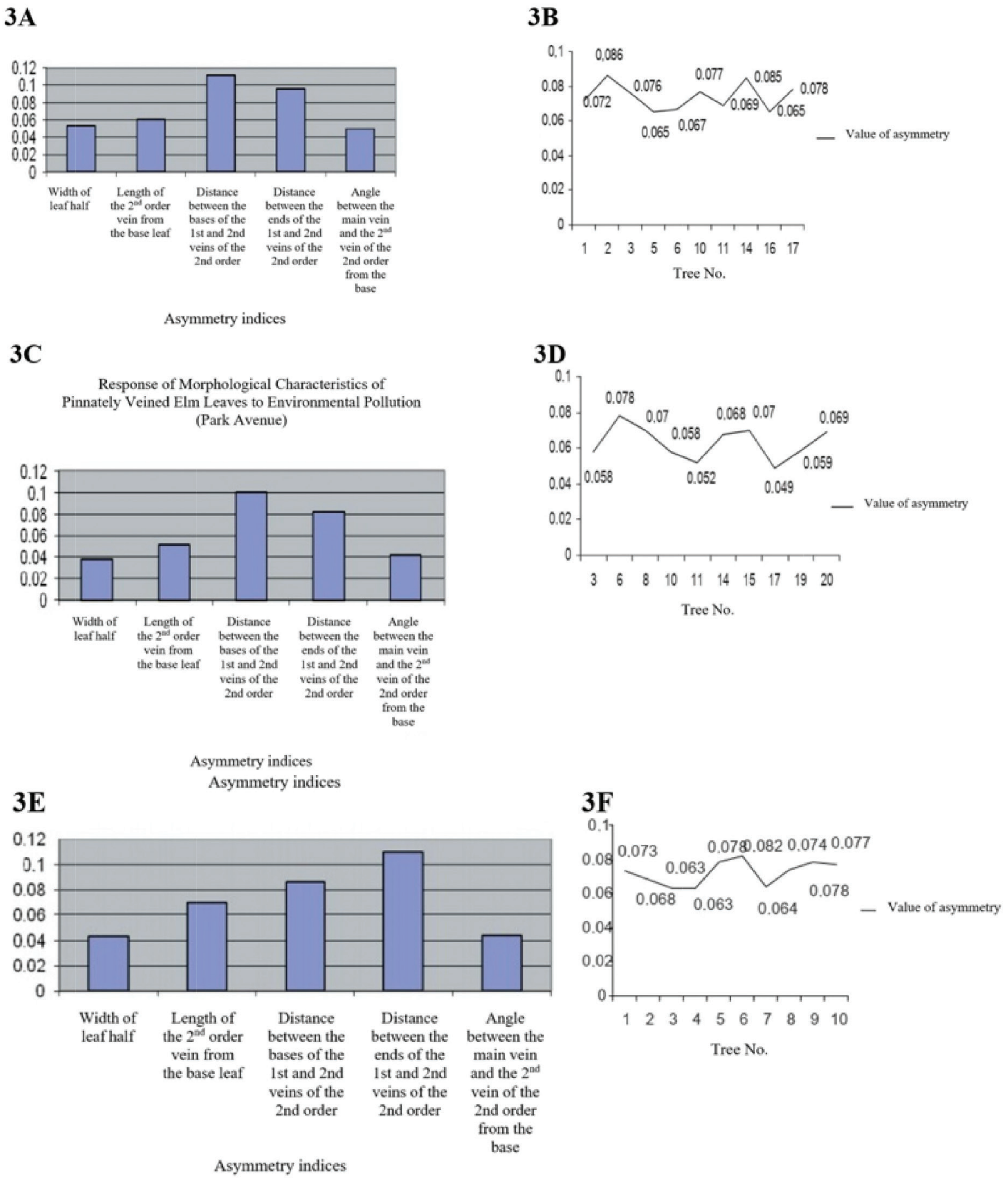

Figure 3: The asymmetry values of the American elm leaves at three Detroit locations (B, D, F) and the values of the fluctuating asymmetry index of the American elm leaves at the same locations (A, C, E). On the left and right, the first two points are Detroit streets (A to D), the third point (E, F) – the control site (suburban areas next to the highway).

receive heavy metals and other toxicants, which are deposited on them together with particulate matter from the ambient air (da Silva et al., 2020; Graham et al., 2010; Hassan et al., 2013). Once adsorbed on cell surfaces, toxicants penetrate the cells and can cause changes in physiological processes and biochemical metabolism patterns (Celiktas et al., 2019; Milewska-Hendel et al., 2017; Singh Suwal et al., 2019). Different toxic compounds can accumulate differently in plant tissues. In pine needles, fluorides may accumulate at concentrations varying from 7.7 to 21.3 mg per 1 kg dry weight. This exceeds the average concentration of fluoride by 4 to 10 times (Bell et al., 2011).

The effect of pollutants may initially seem insignificant. In particular, some increase in the concentration of green pigment in the composition of leaves is recorded. This leads to the necrosis processes becoming increasingly widespread, which make up to 40% of all leaves on the tree in the final stage (Khalid et al., 2018). At the same time, the chlorophyll content is comparable to that of healthy leaves until the pollutant accumulates at a critical level. It should be noted that the critical level of a pollutant can be different not only for leaves of different ages but even for leaves located at the top or bottom of the same tree (Rashidi et al., 2012).

Urban trees are extremely important for many animal species, some of which may serve as consorts. This is illustrated by the example of English oak (*Quercus robur*) in broad-leaved forests and parks in Kyiv, Ukraine (Stukalyuk et al., 2020). This tree species had an insect presence (ants) which exceeded the other species 2 to 10 times. As shown by Stukalyuk et al. (2020), the most invasive woody plant species, as well as introduced species, are not attractive to native species of ants, aphids, and possibly other invertebrates. This means that when green spaces are created in urban areas, native plant species should be favoured over introduced species. This will allow for stable trophic links with native invertebrate species and further stabilise the state of the urban ecosystem.

Data from this study showed that local plant species have unequal tolerance to urban conditions, i.e., different leaf fall periods. At the same time, within the same species, the timing of leaf fall can differ even between trees growing near artificial light sources and between them, similar to the example of American elm. An urban environmental state can create different growing conditions for plants, depending on factors such as (a) traffic load – determines the level of air pollution and the content of aerosol particulate matter suspended in it; (b) lawn width (determines more favourable growing conditions for planted trees); (c) peculiarities of planting tree seedlings (the method of planting “in a glass” worsens the chances of a tree to survive under urban conditions, because conditions are created for stagnant water in the root system and its rotting). Trees that have been under unfavourable conditions for a long time may be more susceptible to necrosis as well as cancer (Saltan et al., 2020). For instance, among linden trees, tyrostromic necrosis was observed in 41% cases.

Large industrial plants, particularly metallurgical ones, can have a detrimental effect on a wide range, from 10 to 100 km. In this area, fluctuating leaf asymmetry values are always high and correspond to 4-5 points on the Zakharov scale (Hodar, 2002). For this study, a moderate level of 3 points and a severe level of 4 points on the Zakharov scale were recorded. The main contribution comes from motor transport because there are no large plants in the Detroit area. For example, fluctuating leaf asymmetry can be an appropriate sign for assessing the level of air pollution.

In China, the variability of leaf asymmetry parameters of dwarf bamboo (*Chimonobambusa utilis*, *C. utilis*) in natural high-mountain forests at different altitudes and canopy densities was studied (Li et al., 2020). Canopy altitude and density have been found to facilitate ecological stress, resulting in the adaptation of morphological traits and oscillatory asymmetry of *C. utilis* leaves to the habitats in mountain forests. As a result, asymmetry may also occur to a greater or lesser extent in natural conditions.

Conclusions

The sites studied in the city of Detroit exhibited moderate levels of air pollution. Detroit showed moderate and strong degrees of atmospheric pollution, which is the result of high values of fluctuating leaf asymmetry. These levels correspond to 3 and 4 out of 5 possible points on the pollution scale. Consequently, based on the absence of large industrial plants in the vicinity of the surveyed sites, motor transport is the main source of air pollution in Detroit. Of the two tree species studied, which are widely used in urban landscaping, leaf fall periods were found to be significantly different. The ash comes earlier than elm by 6-10 days, hence, ash is less suitable for urban landscaping as it is less capable of retaining the green mass of leaves for a long time. On the other hand, during its longer growing season, elms are more vulnerable to undesirable factors, such as invaders and the influence of anthropogenic stress. First, the negative impact is reflected in high values of fluctuating asymmetry index in the leaves. Among the five considered parameters of fluctuating leaf asymmetry, most variable and the maximum value of the asymmetry index were the distance between the bases and the distance between the ends of veins. The least variables were the width of the leaf half and the angle between the veins. According to these data, the first two parameters can be recommended as model parameters to analyse the degree of fluctuating asymmetry variability under the influence of anthropogenic factors in urban conditions. Furthermore, a comparison of the asymmetry indices between different years is necessary to correlate them with the level of air pollution and to look for possible regularities.

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Conflict of Interest

The authors declare that they have no conflict of interests.

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Contents