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Adverse effects of air pollution on human health predicted from tree-ring reductions – A conceptualization of a new ecosystem service

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ABSTRACT

Air pollution adversely affects human health, while trees, conifers in particular, growing in areas affected by air pollution, immediately register pollution by developing rings with decreased width. Some diseases in human population, e.g. lung cancer, develop and are diagnosed with a certain delay in relation to the exposure to air pollution, thus, with a certain delay to ring reductions in trees. Therefore, reductions can be recognized as an early indicator that alerts about forthcoming outbreak of adverse health effects in human population. Based on this phenomenon we propose a new approach and a new methodology for assessing threats to human health and lives resulting from air pollution. In this paper we explain the application of new approach by presenting and describing it step by step. We state that data obtained through the new ecosystem service can be applied for early warning against adverse effects of air pollution on human health. This includes improved prediction of hospitalization patterns and financial costs for the healthcare system. The proposed methodology can be useful for decision makers e.g. local governments, state agencies, private enterprises and other stakeholders interested in controlling local emitters of air pollution and the harmfulness of pollution to human health and lives.

1. The impact of air pollution on human health – morbidity and mortality in Poland

More than 90 % of the world's population is exposed to poor air quality with pollution levels exceeding the World Health Organization (WHO) air quality limits (World Health Organization, 2018). Spatial and temporal analyses have shown that ambient air pollution increases human morbidity and mortality (Juginović et al., 2021). For example, a study by Cohen et al. (2017) shows that in 2015 the exposure to PM2.5 caused 4.2 million deaths and 103.1 million disability-adjusted life-years. We observe, an increase in the morbidity for certain diseases and mortality associated with exposure to air pollution in recent years; for example, premature deaths attributed to air pollution increased in 2019 in relation to 2018 (European Environment Agency, 2021). Inhalable particulate matter PM10 and PM2.5 are particularly harmful to human health (Pope and Dockery, 2006; Liu et al., 2019). Also nitrogen dioxide (Gauderman et al., 2005; Hamra et al., 2015), sulphur dioxide (Devalia et al., 1994; Orellano et al., 2021), ozone (Levy et al., 2005; Turner, et al., 2016), Polycyclic Aromatic Hydrocarbons (PAH) (Singh et al., 2018; Aamir et al., 2021) and heavy metals (World Health Organization, 2007; Tsai et al., 2019) are a threat to human life and health. The main human diseases that develop due to air pollution and often cause death are ischaemic heart disease (Finegold et al., 2012), respiratory diseases (Gordon et al., 2014), chronic obstructive pulmonary disease (Andersen et al., 2011), lung cancer (Hystad et al., 2013), cardiovascular disease (Dominici et al., 2006). Long-term exposure to air pollution is linked with an increase in the risk of human mortality (Yazdi et al., 2021). The issue of increased mortality and morbidity due to air pollution mainly affects residents of large cities and people living near large industrial plants that emit large amounts of pollutants into the atmosphere (Traczyk and Gruszecka-Kosowska, 2020; Khomenko et al., 2021). Vulnerable groups: children, the elderly and sick are particularly exposed to the risk of diseases related to air pollution (Orellano et al., 2017; Bekkar et al., 2020; Holst et al., 2020).

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There has been a large emission of pollutants into the atmosphere in Poland in recent years (Nazar and Niedoszytko, 2022; Khomenko et al., 2021), i.e. 36 of the 50 most polluted cities in the European Union are located in Poland (World Bank Group, 2019). Studies have been conducted in numerous sites in Poland to link harmful emissions with adverse human heath effects among people. Zejda et al. (1996) found more frequent attacks of asthmatic dyspnoea as well as the diagnosis of asthma among children aged 7–9, in the city of Chorzów compared to less polluted control area. Children living in polluted areas of Cracow also suffered from allergic rhinitis, and dyspnoea attacks more frequently than reference children (Jędrychowski and Flak, 1997). The total mortality due to exposure to PM10 in 2005 in Cracow was 41 deaths per 100 000 population, compared to 30 in 2013 (Samek, 2016). In Cracow, in 2002–2003 infants with prenatal exposure to polycyclic aromatic hydrocarbons (PAHs) were found to suffer from respiratory symptoms (Jędrychowski et al., 2005). In Warsaw, in 2012 local emissions of PM, NOX, SO_2, CO, C_6H_6, BaP and heavy metals caused approximately 1600 attributable deaths and 29,000 disability-adjusted life-years (DALYs). Additionally, about 80 % of the health burden was due to exposure to PM2.5 (Holnicki et al., 2017). In Warsaw also PM2.5 and PM10 have a significant impact of air pollution in infants and children, it is manifested mainly as respiratory problems (Jakubiak-Lasocka et al., 2015). It was generally found that in Poland, children exposed to PM2.5 have significant lung function deficits in early childhood which may affect foetal lung growth (Jędrychowski et al., 2010). Moderate-term exposure (12 weeks) to air pollution is connected with an increased risk of Upper Respiratory Tract Symptoms among children in Poland in 2018–2019 (Ratajczak et al., 2021). Moreover, ambient PM2.5 and PM10 exposure has increased short-term hospitalizations due to respiratory diseases in big Polish cities: Warsaw, Białystok, Bielsko-Biała, Cracow and Gdańsk in 2014–2017 (Slama et al., 2019). In the Silesian region, in 2016–2017, the increased risk of hospitalization due to respiratory diseases was related to longer exposure to PM2.5 and PM10 expressed by two to four weeks of exposure; outpatient visits were related to a shorter exposure duration of 3 days (Skrzypek et al., 2019). PM2.5 is also responsible for the increase in cardiovascular and respiratory mortality even in north-eastern Poland, in a relatively clean area where research was carried out in 2008–2017 (Kuźma et al., 2020). Living in places close to the main communication routes in Poland also increases morbidity, mainly health problems in children (Porębski et al., 2014; Skrzypek et al., 2019).

To sum up, a high level of air pollution that has recently been recorded in Poland is closely associated with an increase in mortality and morbidity. The particular cause for that are so-called low-stack emissions from the household sector which produce 88 % of total pollution in Poland (Ministry of the Environment, 2015; Michalak, 2018; Stecuła and Tutak, 2018), with other sources of pollution being transportation, industry, and agriculture (Kryzia and Pepłowska, 2019).

2. The impact of air pollution of the radial growth of trees – growth reduction (suppression)

Atmospheric emissions of phytotoxic compounds lead to serious disturbances in tree physiology and metabolism (Farrar et al., 1977). Under the influence of air pollution, trees develop reduced annual tree rings (Baes and McLaughlin, 1984). These tree rings are much narrower than the rings developed earlier before the emission of air pollution began (Smith, 1990). Different tree species react differently to air pollution (Karolewski et al., 2005), i.e. conifers, including species such as pines, and spruces, are particularly sensitive to air pollution, which causes very deep reductions in their growth rings (Farrar et al., 1977). Reductions in tree rings cover the period of air pollution, however, when pollution disappears, trees start to develop wider rings again (Malik et al., 2012) (Fig. 1). Tree-ring reductions are mainly developed, because the stomata are clogged with dust pollution which suppresses tree growth. Suppressed tree rings resulting from air pollution can develop over large areas, mainly as a result of the impact of heavy industry (Frelich et al., 1989; Elling et al., 2009).

Reductions can develop in trees growing around industrial plants of various types emitting various pollutants into the atmosphere (Stravinskiene et al., 2013). Studies have shown a negative impact of non-ferrous smelter on tree stands growing around (Nöjd et al., 1996), as well as adverse influences of a chemical plant (Jämbäck et al., 1999), metal extraction and processing plant (Ivshin and Shiytov, 1995), and a steel plant (MacDonald et al., 2011). The negative impact of air pollution on tree stands was already observed at the end of the 19th century (Stöeckhardt, 1871). In the second half of the 20th century, industrial production developed on a large scale, and awareness of the negative environmental impact of industrial plants grew. The interest in tree growth suppression as a result of air pollution increased too. Numerous

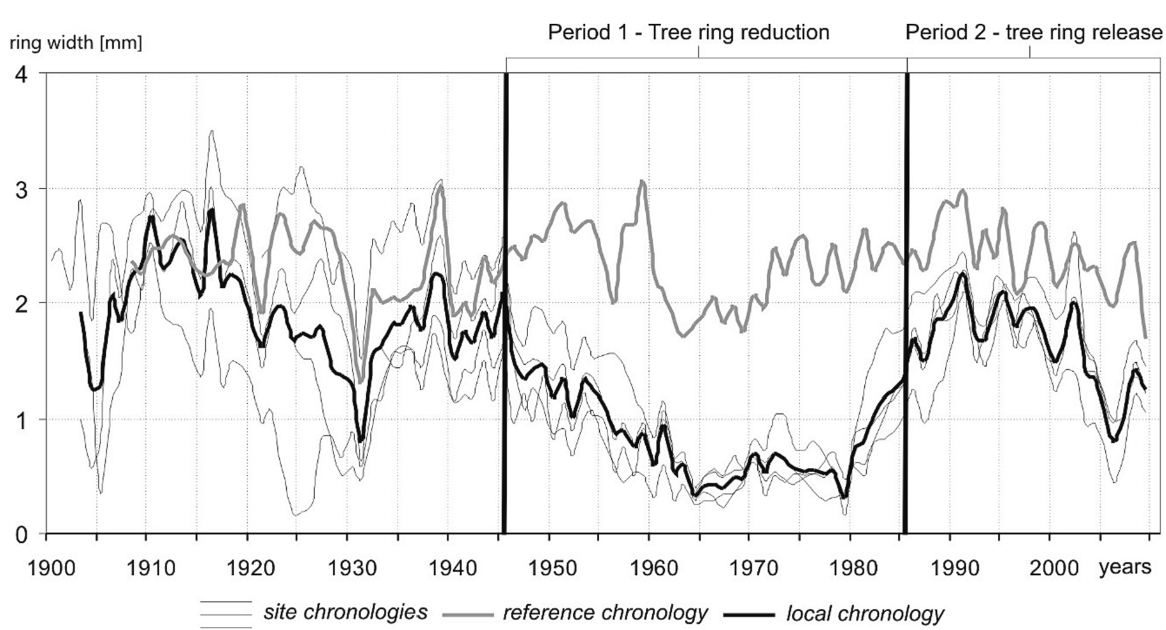

Fig. 1. Tree-ring chronology developed from Scots pine trees (*Pinus sylvestri* L.) growing in the vicinity of the Upper Silesian Industrial District, southern Poland. Period 1 – the tree produced annual narrow rings (growth reduction), Period 2 – the tree produced wider annual rings.

studies have been carried out to document the negative effects in trees growing around industrial plants (Ashby and Fritts, 1972; Vinš and Mrkva, 1973; Nash et al., 1975). It has been found that sulfur dioxide has a particularly negative effect on forest stands (Rawluk, 2016). High emission of this chemical compound to the atmosphere often caused large-scale dieback of forest stands, e.g. in the Izerskie Mts. (southern Poland) (Godzik and Sienkiewicz, 1990). A varied depth of ring reductions was also investigated depending on the distance from point sources of pollution, wind direction, and terrain morphology (Thompson, 1981; Kennedy-Sutherland and Martin, 1990; Nöjd et al., 1996; Juknys et al., 2003; Borowiec et al., 2005a, 2005b). Recently, tree growth disturbances are more and more often used as an indicator of air pollution (Sawidis et al., 2011; Sensuła, 2016; Putalová et al., 2019).

In Poland, there are several periods of air pollution recorded in annual rings of trees as width reductions (i.e. growth suppressions) (Malik et al., 2012). The development of industry between the First and Second World Wars resulted in ring reductions identified in the trees growing in the southern Poland (Malik et al., 2014; Łuszczyńska et al., 2018). However, the deepest tree-ring reductions were recorded in the post-war period of industrialization in 1960–1990 (Wilczyński, 2006; Barniak and Krąpiec, 2016; Cedro and Cedro, 2018; Barniak and Jureczko, 2019). At that time, trees growing across Poland developed deep ring reductions, particularly strong in the vicinity of large industrial plants (Oleksyn and Fritts, 1991; Szychowska-Krąpiec and Wiśniowski, 1996; Krąpiec and Szychowska-Krąpiec, 2001; Chojnacka-Ożga and Ożga, 2021). Many forests located in Poland were dying out (Fig. 2), and the tree-ring sequences often presents the so-called missing rings, i.e. the years when the trees did not develop an annual increment as a result of a particularly strong influence of air pollution (Danek, 2007; Sensuła et al., 2015a; Sensuła et al., 2015b; Sensuła and Wilczyński, 2017). The next, most recent period of severe air pollution started in the middle of the last decade of the 20th century and lasts until now. It is related to the legal approval of selling and using low-grade coals (often highly sulphated) and flotation waste in home heating systems accompanied with the gradual increase in gas prices (Małkowski and Tymoshenko, 2018). During this period, ring reductions occur in

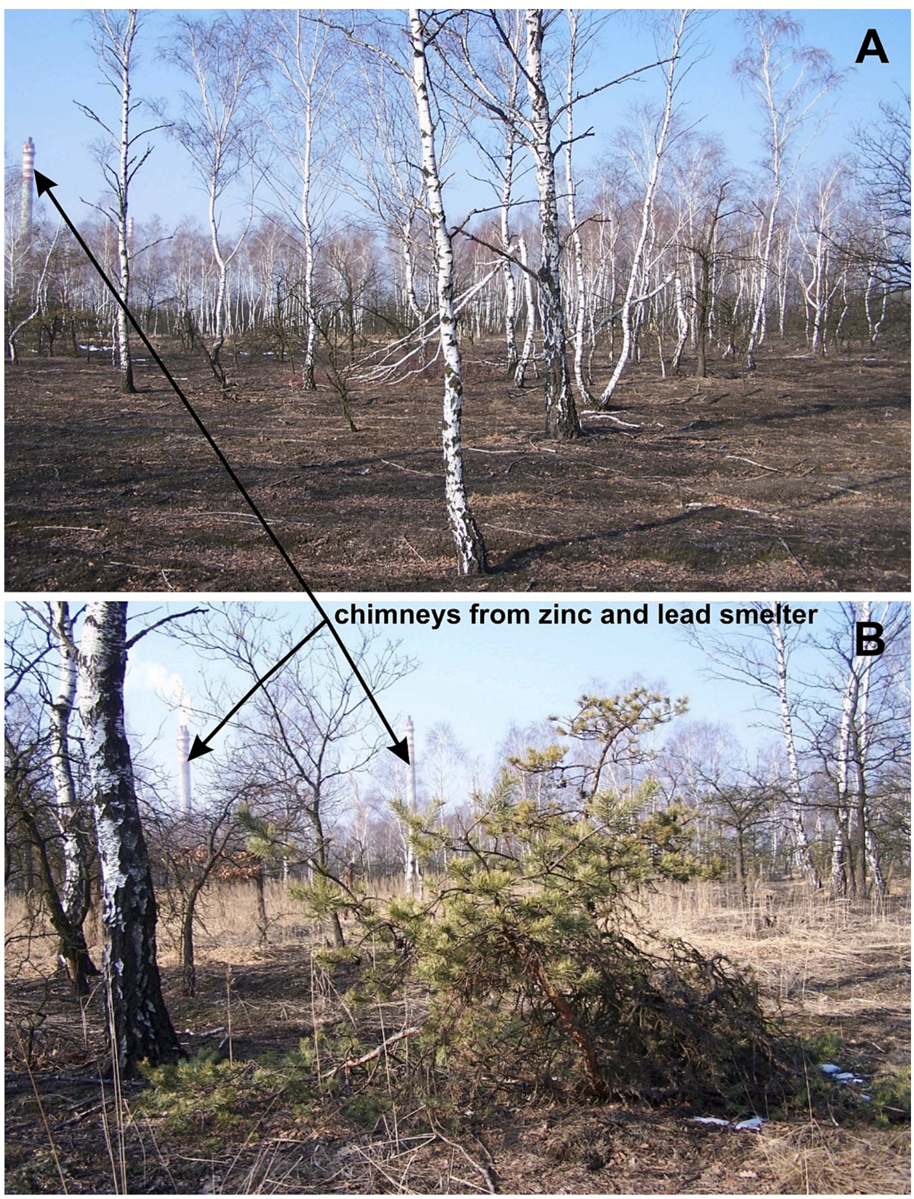

Fig. 2. Forest destroyed as a result of air pollution emitted from zinc and lead smelter (Upper Silesian Industrial District, southern Poland). A – Birch trees resistant to air pollution, which are the only species growing adjacent to the zinc and lead smelter (photo: June 2015), B – Pine tree with a shrub habit developed as a result of air pollution (photo: June 2015).

trees growing near residential areas, most often near single-family houses (Malik et al., 2012).

3. The temporal relation between air pollution, tree-ring reductions and adverse effects for human health

Air pollution negatively affects entire ecosystems and harms organisms, including trees and people (Lovett et al., 2009). It has already been demonstrated that reductions of tree-ring widths develop as a result of the impact of the same compounds, air pollutants that harm human health, e.g. carbon dioxide, sulphur dioxide, and ozone PM (Allen, 1990; Hassan et al., 1994; Legge and Krupa, 2002; Chaudhary and Rathore, 2019). The negative reaction of trees to harmful emissions of pollutants is very quick (Seyyednejad et al., 2011). Gas and dust pollution cause very rapid defoliation of trees, therefore the resulting reduction of tree rings and stand dieback occurs practically simultaneously with pollutant emission (McLaughlin, 1998). Some human diseases, such as respiratory problems, also (similarly to tree growth suppression) appear directly during or immediately after emissions of air pollutants (Peters et al., 1997). However, other diseases, such as lung cancer or infant mortality and malformations, develop longer (Cohen and Pope, 1995). Previous studies have shown that both infant mortality and lung cancer morbidity occur with some delay in relation to adverse effect observed in tree growth (Fig. 3). This relationship was demonstrated by examining temporal relations between air pollution, tree-ring reductions and the occurrence of infant mortality and lung cancer in Poland, in 1960–1990 (Malik et al., 2012). It has also been demonstrated that in Poland, in recent years harmful emissions from heating individual houses caused local reductions of tree rings and increases in human morbidity with adverse impact on human health delayed in relation to growth suppression in trees (Rutkiewicz et al., 2017; Rutkiewicz and Malik, 2018). Similarly, the reduction of tree-ring widths in Japanese cedar and the prevalence of respiratory symptoms in schoolchildren were also investigated in rural districts of Japan (Kagamimori et al., 1990).

Previous research demonstrated that many types of adverse human health effects develop longer after exposure to air pollution and appear with a delay. Thus, we state that increases of human morbidity and mortality caused by air pollution can be predicted from immediate tree-ring reductions. It is possible thanks to the delay of human reaction in relation to emission of air pollution and the growth reaction of trees. Thus, we state that trees, or more precisely, reductions of the width of their growth rings, can serve as predictors of future health decline in human population (Fig. 4). Here we aim to present a new method for application of ring reductions as early indicators of adverse effects of air pollution on human health. We state that reductions can provide a new ecosystem service of early warning and alert about forthcoming outbreak of diseases among humans. This includes improved prediction of hospitalization patterns and financial costs for the healthcare system. We propose a new approach and a new methodology for assessing threats to human health and lives resulting from air pollution. Here we aim to explain the application of this new approach by presenting and describing it step by step, providing guidelines for decision makers e.g. local governments, state agencies, private enterprises and other stakeholders interested in controlling local emitters of air pollution and the harmfulness of pollution to human health and lives.

4. Tree-ring reductions serving as an early indicator of future adverse human health effect caused by air pollution – guidelines for application

Diagnosing adverse effects of air pollution on human health based on analyses of tree-ring widths is only possible in areas, where trees, preferably conifers, occur. The best conditions for the new approach is the presence of forests near pollution sources (e.g. industrial plants, residential areas heated with fossil fuels). The most favourable conditions for using described method occur when forests cover areas leeward in relation to pollutant emitters. Thus, the application of proposed approach is easiest in areas with extensive forest cover, for example in countries with over 50 % afforestation, i.e. Finland, Sweden, Slovenia, Latvia, Estonia. However, for example in Poland forests cover only 30.8 % of country area (of which about 60 % are coniferous stands), but the largest industrial plants and numerous housing areas are located nearby vast forest complexes. Thus, it seems that the proposed methodology for new ecosystem service is universal and can find general application, also in areas where forest cover is limited.

The approach can be used for reconstructing and monitoring air pollution in a specific region or area, near different types of industrial plants, for housing estates powered by conventional fuels. By analysing the width of annual increments in trees and detecting their possible reductions, it is possible to analyse the history of air pollution caused by

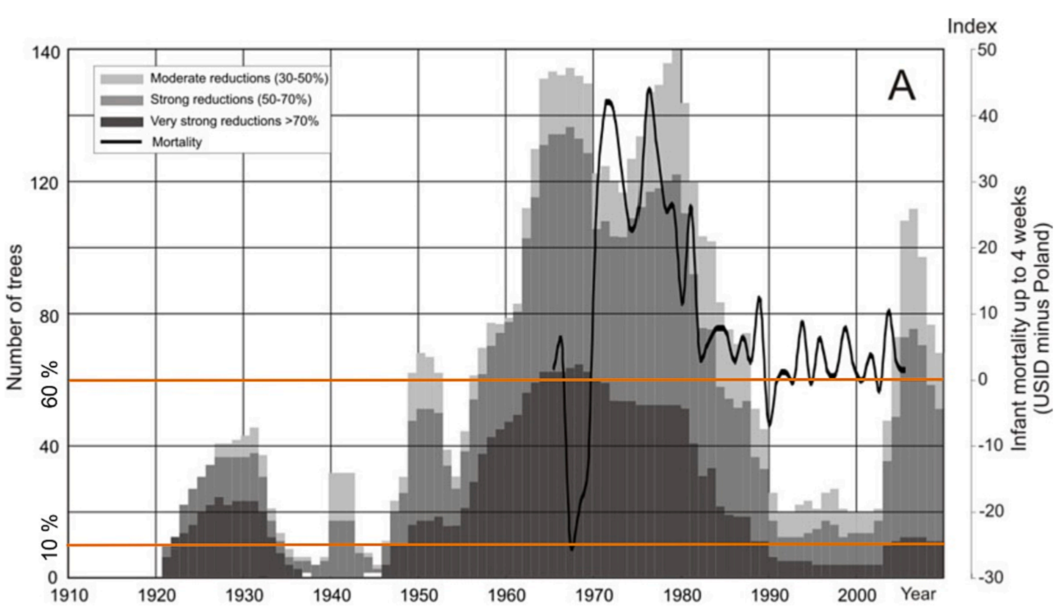

Fig. 3. Tree-ring reductions among Scots Pines and lagged infant mortality in the Upper Silesian Industrial District (USID), southern Poland. Orange lines – threshold amounts of trees with ring reductions (10 % of trees showing very strong reductions and 60 % of trees showing reductions regardless of their strength) which in the 1950s forecasted following increase of infant mortality in the 1960s.

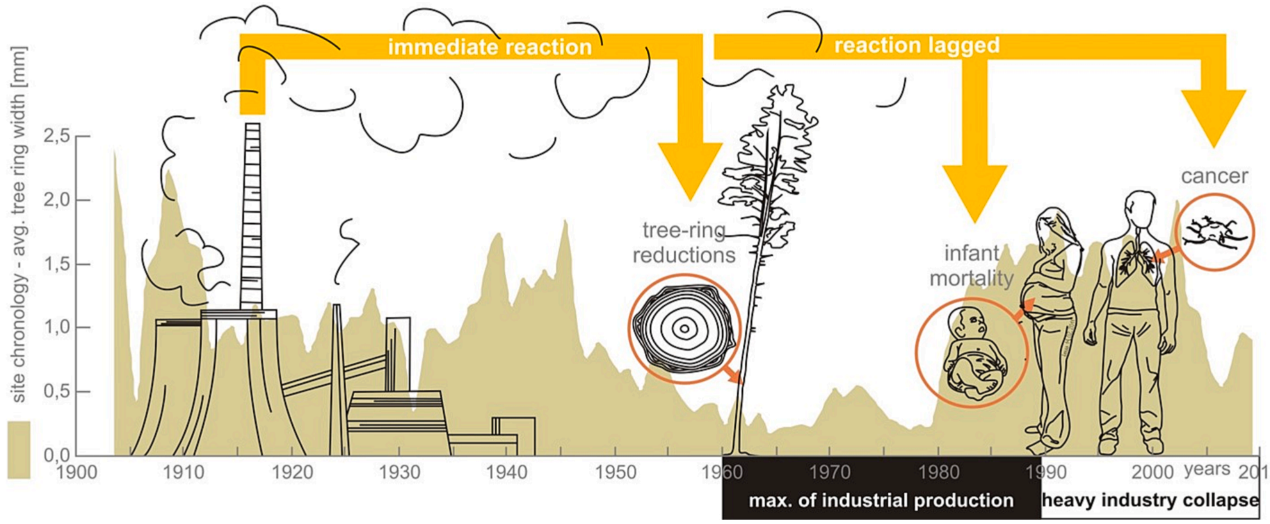

Fig. 4. A Diagram showing the immediate negative reaction of trees to air pollution and the delayed onset of diseases in human population (based on the results by Malik et al., 2012 from the Upper Silesian Industrial District, southern Poland).

a specific emitter. It is possible to determine the exact onset of harmful emissions from industrial plants, residential areas or any other source of pollution. It is also possible to determine how the pollution lasted and possibly also when it stopped (Malik et al., 2012).

The methodology also offers possibility to monitor current levels of air pollution by sampling trees adjacent to pollution source in subsequent years (by collecting increment cores year after year). Such approach allows continuous, up-to-date assessment whether harmful atmospheric emissions occur and how far the pollutants reach from their source in each subsequent year. Such data obtained from trees constitute an ecosystem service of pollution monitoring and can be used for improved prediction of hospitalization patterns and financial costs for the healthcare systems, Such monitoring can be used by decision makers, including local governments and state agencies, and also other stakeholders (private enterprises, NGOs, etc.) interested in controlling local emitters of air pollution and their impact on environment and health.

Other potential applications of trees as providers of ecosystem services of environment quality monitoring (and, indirectly, monitoring also human welfare and health) include, for instance, monitoring thermal and chemical pollution of surface waters that is frequent near wastelands in post-industrial area (Chmura et al., 2011; Chmura and Molenda, 2012) or in other so called novel ecosystems, where woody plants grow (Hobbs et al., 2006; Woźniak et al., 2022).

In order to assess air pollution from the analysis of tree-ring reductions and to indicate potential hazard for human health and lives, the following steps should be followed:

1. Forest stands (or groups of trees) suitable for sampling increment cores and ring-width analysis should be identified based on orthophotos or other cartographic materials, where forested areas are presented. Forest stands selected for sampling should be located close to the air pollution sources. In the case of industrial plants, the distance between trees providing the monitoring ecosystem service and a plant should not exceed 5 km (Malik et al., 2012). In the case of emissions from heating systems of residential areas it should not exceed 0.5 km, due to much lower height of emitters potentially limiting the spatial extent of pollution impact. It is the most beneficial, if several sampling sites (forest stands or groups of trees) located at different distances from the source of pollution are tested. Such situation offers opportunity for analyses of tree-ring reductions of diverse depth, usually with strength decreasing with the distance from the source of the air pollution (Fig. 5). For each studied pollution source, one control forest stand should also be analysed outside the area affected by harmful emission. Areas not

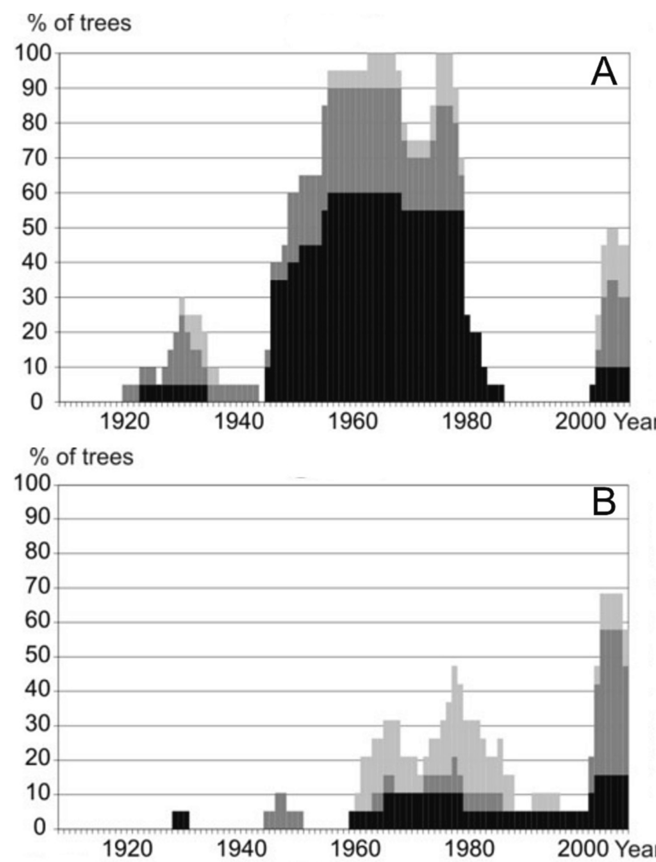

Fig. 5. Annual tree-ring reductions produced by Scot Pines growing at different distances from air pollution emitter (black– very strong reductions, dark grey – strong reductions, light grey – moderate reductions). A – Annual ring reduction in trees growing in the vicinity of the industrial plant in the Upper Silesian Industrial Distinct. B – Annual ring reductions in trees growing further far from the same industrial plant, but closer to residential areas.

affected should be identified by taking the control samples from trees (2–3 trees per one distance) located 5, 6,7…10 km from the pollution source. Trees which not record ring reduction designate a control area. Trees which not record ring reduction designate control area. The control site should be located in forest stand as similar as possible to the diagnostic forest, i.e. represent the same tree species and age structure, forest habitat type and soil type.

2. Selected forest stands or groups of trees should be analysed on-site to verify the species composition and age of the stand. For air pollution monitoring, it is recommended to use conifer trees older than 15 years (Malik et al., 2012). In general, it is best to use older trees, because the longer the sequence of tree rings, the longer is the history of pollution recorded in their growth rings. Trees younger than 15 years do not have ring sequences long enough for reliable identification of ring width reductions. In addition, juvenile trees develop growth rings under the influence of numerous environmental factors that are less important for adult trees, e.g., browsing, limitations related to access to light (Szwagrzyk et al., 2020). Importantly, deciduous trees influenced by air pollution do not develop as clear ring reductions as conifers, due to their lower sensitivity to atmospheric emissions (Seyyednejad et al., 2011).

3. Environmental factors (other than air pollution) which may cause ring reductions should be analysed. Suppression of radial growth can often be caused by various environmental factors, e.g., climate conditions, insect outbreaks, fires (Pohl et al., 2006). Environmental factors causing ring reductions other than air pollution often occur simultaneously with the latter. As a result, tree-ring reductions caused by air pollution become more severe (deeper) (Malik et al., 2014). Depending on the available information, years with extreme environmental events (other than air pollution) that may reduce tree-ring widths should be identified. These include, among all, particularly harsh winters, particularly dry summers, years with outbreaks of insects attacking specific tree species. The source of this information are most often meteorological agencies, forestry agencies, scientific publications and reports.

4. Increment cores should be sampled from previously selected forest stands or groups of trees, and sampled increments should be processed. Pressler borers should be used to collect cores from selected trees (Fig. 6A, 6B). Dominant and co-dominant trees without sloping trunks, wounds and scars on trunks should be selected for sampling cores. Cores should be sampled at the breast height of trees (approximately 1.3 m above ground level). Two cores should be collected from every tree. Each core should be c 5 cm longer than the radius of tree cross-section to ensure that a complete sequence of growth rings is obtained (comprising all rings between pith and bark. At each study site (forest stand or group of trees) cores should be taken from at least 15 trees (Malik et al., 2012). Sampling at control sites located outside of harmful air pollution should be conducted in the same way. Next, cores taken from all trees should be glued to custom wooden holders, dried, sanded with sandpaper with decreasing grit (preferably 250, 500, and finally 1000). This way, the structure and anatomy of wood will be revealed, which will allow for precise measurement of tree-ring widths. Usually, after sanding, tree-ring reduction are already clearly visible in increment cores (Fig. 6B).

5. Tree-ring widths should be measured. A tree-ring measuring station (e.g. LinTab measuring tool) should be used to measure the tree-ring widths. The standard station consists a shift table, a counter, a binocular and software for recording tree-ring widths. By measuring subsequent rings, a set of their widths is obtained with the accuracy of 0.01 mm. From tree-ring width series derived from individual trees sampled on one sampling site, a site chronology can be developed (Speer, 2010). The easiest way to developed site chronology is to average the width of tree rings for subsequent calendar years. The averaged values are the widths of successive tree rings from all trees sampled on and individual site (Schweingruber, 1988). Sometimes severe air pollution affects the lack of tree ring production (missing ring formation) in an individual tree, so we need to identify missing rings in tree ring series using Cofecha software or a visual technique called skeleton plot (Grissino-Mayer, 2001; Grundmann et al.,2008). In case of significant differences in tree age on one site, it is possible to use detrending of ring series in ARSTAN application (Grissino-Mayer et al., 1992), which eliminates tree age trend (Cook and Kairiukštis, 1990). Both within individual series of ring widths, and within site chronologies, it is already possible to determine the occurrence of growth reductions.

6. Reductions of tree rings should be determined. Mathematical recalculation of ring widths into growth reduction values should be done for each calendar year separately (Schweingruber et al., 1985). Reduction values were calculated as the total tree ring width of all rings in a reduction period (for following 3 rings) in relation to the total tree ring width of all the same number of rings from the period preceding the reduction period (for following 3 rings). Finally, obtained reduction values are divided into three levels of depth: moderate reductions: 30–50 %, strong reductions: 51–70 %, and very strong reductions: >70 %. Reductions weaker than 30 % and shorter than 3 years should not be considered (Malik et al., 2012).

7. Threat to human health by air pollution should be determined through the analysis of tree-ring reductions. Based on previously

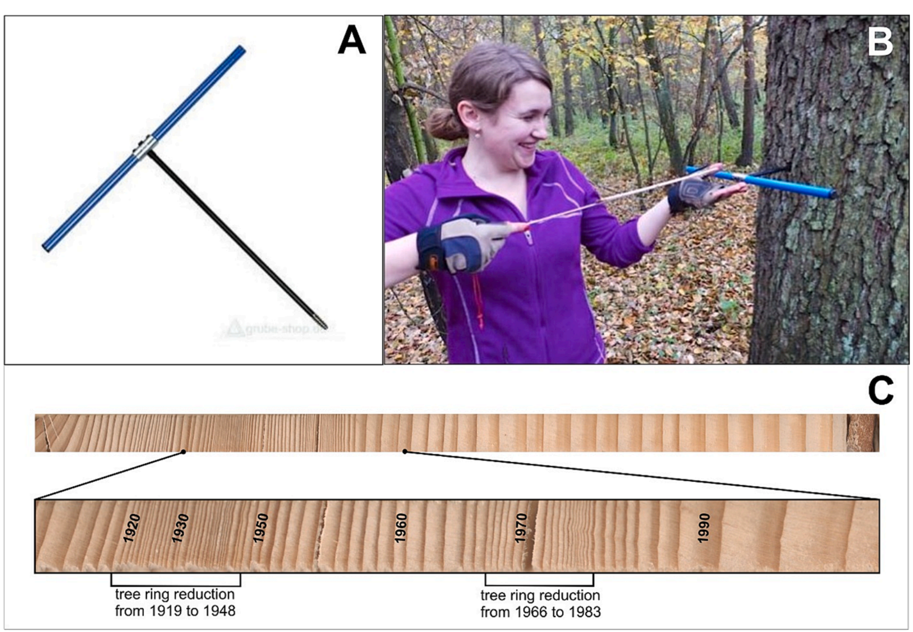

Fig. 6. A Pressler borer (A) used for sampling an increment core from a tree (B), and annual tree-ring reductions of Spuce (*Picea abies)* visible in a sanded increment core (C).

conducted analyses (Malik et al., 2012), if more than 60 % of trees reduce tree rings in the same year and if more than 10 % of trees develop very strong reductions (>70 %) in the same year, then the pollution threats human health and lives. This assumption results from the comparison of temporal variability of infant mortality and the tree-ring reductions (Fig. 3). The comparison shows that the increase in infant mortality occurs, when more than 60 % of trees reduce tree rings and, at the same time, more than 10 % of trees develop very strong reductions (Fig. 3). However, so far there is 6–8 years lack of analyses of the temporal relationship between the reductions of tree rings and escalations in the morbidity for diverse diseases in human populations (Malik et al., 2012). In the future, such analyses should provide information on the types of adverse human-health effects that can be forecasted from monitoring reductions in tree-ring widths. Future studies should also focus on the length of delay between the appearance of growth suppression in trees and the incidence of certain diseases in human population.

5. Summary

1. Different types of air pollutants (for example particulate matter PM10 and PM2.5, nitrogen dioxide, sulphur dioxide, ozone, Polycyclic Aromatic Hydrocarbons (PAH), heavy metals) cause adverse human health effects. The main diseases that develop and increase mortality among people due to air pollution are ischaemic heart disease, respiratory diseases, chronic obstructive pulmonary disease, lung cancer, cardiovascular disease, general human mortality. Under influence of the same air pollution trees suppress their radial growth and produce rings with reduced widths. A negative health reaction among trees occurs immediately after air pollution begins, while numerous human diseases develop longer and are diagnosed with a delay in relation to harmful emissions. Therefore, reductions of tree rings can be used as an early indicator for the appearance of some diseases (for example lung cancer) among people.

In order to assess air pollution from the analysis of tree-ring reductions and to indicate potential hazard for human health and lives, the following steps should be followed:

a. Forest stands (or groups of trees) suitable for sampling increment cores and ring-width analysis should be identified based on orthophotos or other cartographic materials, where forested areas are presented;

b. Selected forest stands or groups of trees should be analysed on-site to verify the species composition and age of the stand;

c. Environmental factors (other than air pollution) which may cause ring reductions should be analysed;

d. Increment cores should be sampled from previously selected forest stands or groups of trees, and sampled increments should be processed;

e. Tree-ring widths should be measured;

f. Reductions of tree rings should be determined;

g. Threat to human health by air pollution should be determined through the analysis of tree-ring reductions.

3. The proposed methodology allows the reconstruct past levels of air pollution and the impact of this air pollution on human health. It also allows for on-going monitoring of air pollution and obtaining information about the future appearance of adverse health effects among human population. We state that data obtained through the new ecosystem service of monitoring environment quality and related human welfare can be applied for early warning against adverse effects of air pollution on human health. This includes improved prediction of hospitalization patterns and financial costs for the healthcare system. The proposed methodology can be useful for decision makers e.g. local governments, state agencies, private enterprises and other stakeholders interested in controlling local emitters of air pollution and the harmfulness of pollution to human health and lives.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ireneusz Malik reports financial support was provided by University of Silesia in Katowice.

Data availability

Data will be made available on request.

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