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Broad-Leaved Tree Growth Modulated by Industrial Air Pollution in the Northern Romania (Baia Mare Region)

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Abstract: Atmospheric pollutants over the last century have led to increased negative impacts on the environment, especially on forest ecosystems. In the Baia Mare region of Romania, the influence of pollution on the neighboring forests of the municipality has been reported since 1970, and its negative effects have been reported mainly in the form of reduced tree growth, which implies significant losses of wood biomass. The objective of this study is to analyze the temporal and spatial effect of industrial pollution on the auxological processes of beech trees in this region. Quantification of auxological changes was performed by analyzing the resilience, recovery and resistance indices. The most intense negative effect of local pollution with heavy metal dusts, sulfur and nitrogen oxides, and sulfuric acid vapors, on the auxological processes of beech trees was found in the period 1960–1990, with a maximum in the period 1970–1980, when the mining activity was at its highest intensity. Beech trees responded to the negative effect of pollution by significantly reducing their growth during the period affected by local pollution, and after 1990 they resumed their auxological activity close to normal. In addition, it was noted that the index that best captures the effect of pollution over time is the resilience index. Tree growth resilience, recovery, and resistance assessment and analysis significantly contributes to our understanding of trees response to environment pollution more broadly creating also the base for strategic planning initiatives with valuable insight into the efforts of making the forests more resilient and resistant.

Keywords: air pollution; heavy metals; forest ecosystems; climate change; forest decline

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1. Introduction

Air pollutants have increased negative environmental impacts in the last century with significant economic, ecologic, and social losses. The pollutants act individually or in combination with climate change and affect all ecosystems, especially forests [1]. Air pollutants induce changes in tree physiology processes that can be observed individually and manifest through the discoloration and necrosis of leaves, premature leaf fall, drying of branches, and reduced size of leaves and flowers [2].

At the European level, numerous studies have highlighted the impact of air pollution and climate change on forest ecosystems. Thus, the air pollutant sulfur dioxide, which reacts directly or indirectly in forest ecosystems, was one of the leading causes of forest decline in Poland [3].

Other studies show that, in addition to sulfur and nitrogen oxides, which harm forests, high concentrations of lead and cadmium have been identified in the soil, especially in southern Poland [4]. The concentration of heavy metals in the soil causes a progressive increase in soil acidity with critical effects on forest vegetation [5]. Heavy metal deposits have also been identified in the bark of seven tree species in Nigeria [6]. Heavy metal concentrations higher than the threshold values have been reported in mountain forest soils from the Ukrainian Carpathians; the highest concentrations reported were in oak forests close to sources of pollution. Additionally, some forest ecosystems recorded declines and reduced productivity and defoliation of trees caused by heavy metal pollution [7].

Romania is recognized for its historic mining activities, but these activities have several consequences on the environment. Thus, long-term intensive mining activity, which involved extracting and processing non-ferrous materials, has affected the soil, forest vegetation, water, and air quality [8].

In the Baia Mare region, situated in northern Romania, the influence of pollution on the neighboring forests has been reported since 1970, and the effect on the forest vegetation that has been reported is the decreasing growth of trees, which has resulted in a significant wood volume loss [9].

The copper factory in Baia Mare had its beginnings in 1907 when it was founded by a private company specialized in sulfuric acid processing. In 1925, this company also acquired an existing glass factory in the Baia Mare to expand, and shortly after, in 1927, the factory was renamed Phoenix. From 1925 to 1942, the plant expanded with a copper processing line and a section for melting precious metals, such as gold and silver [10]. Between 1948 and 1980, the plant had a constant production of 5 million tons of ore per year: this is the period in which the plant's activity was the most intense. Also, during this period, many of the technological processes used in the factory were mechanized, the workshops were modernized, and the sewerage system of the industrial platform was built in order to increase productivity. Before 1989, the company had 30,000 employees. Since 1990, all of the mines in the Baia Mare area have reduced their production, reaching 1.4 million tons per year [11]. The negative effect of heavy metal pollution on the forest bordering the Baia Mare area has been reported since 1970, and the primary reported effect on forest vegetation was the loss of wood mass [9].

In 2003, the Phoenix mining plant was acquired by Cuprum, and it became the largest copper producer in Romania. This lasted until 2008, when the price of copper fell sharply, and the company went bankrupt [12]. The mining activity and the extraction and processing of non-ferrous materials in this region strongly affected all parts of the local environment. The pollution is mainly heavy metal powders (e.g., copper, lead, cadmium, and arsenic), sulfur and nitrogen oxides, hydrogen sulfide, and sulfuric acid vapors [9].

By considering all these aspects, this study quantifies the growth changes in European beech trees (*Fagus sylvatica* L.) affected by the industrial pollution in the Baia Mare region due to the activity of the Phoenix mining plant.

2. Materials and Methods

A network of experimental plots was established in the Northern part of Romania close to the city of Baia Mare (47°39′ N 23°34′ E), in the beech forest stands affected by industrial pollution. The sampling plots were located at a specific distance from the source of pollution to highlight the different degrees of damage to the stands due to air pollution (Figure 1). Previous studies, in which several stands located at different distances from the source of pollution were analyzed, were taken into consideration, and it was concluded that the distance of 2 km is the approximate distance at which the stands were affected by air pollution in varying degrees of intensity [13]. This distance can be influenced by the direction and intensity of prevailing winds [14]. Thus, twelve experimental plots were placed in the study area: five plots in the intensively polluted area, three plots in the moderately polluted area, and four plots in the unpolluted area.

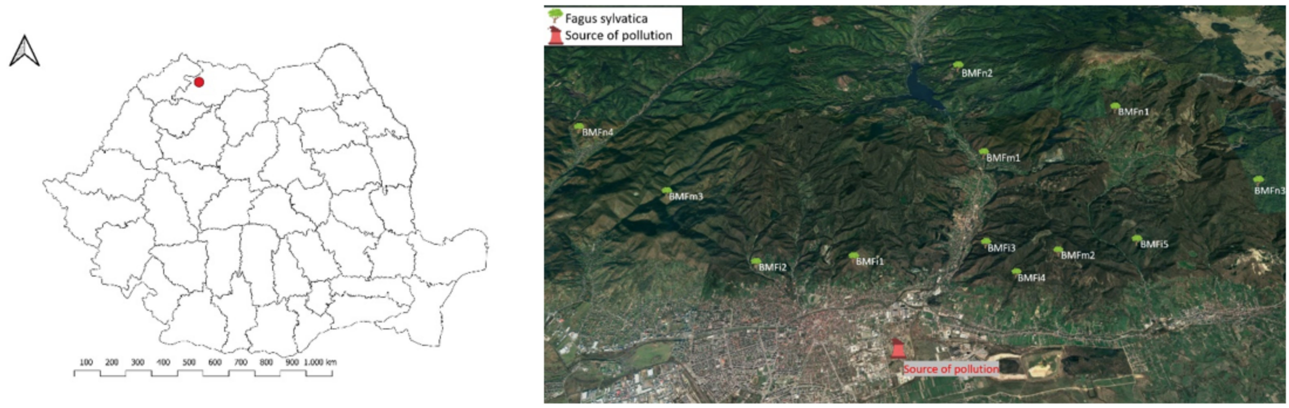

Figure 1. Study location: Spatial distribution of *Fagus sylvatica* sample plots in Baia Mare region.

The selected forest stands included in the experimental network are located from 300 to 650 m asl and aged between 70 and 170 years old (Table 1). They are generally composed by beech trees (*Fagus sylvatica* L.) or mixtures of beech and sessile oak (*Quercus petraea* L.), sweet chestnut (*Aesculus hippocastanum* L.), sycamore (*Acer pseudoplatanus* L.), or hornbeam (*Carpinus Betulus* L.). Stands density varies between 0.5 and 0.9, the age is between 75–140 years, the stands productivity is high and are framed from middle to upper yield classes (2 and 3). The volume per hectare of the studied stands is between 140 and 505 m^3. A minimum of 40 radial growth cores from beech trees has been taken from each sampling plot.

So far, in all studies that examined the impact of local industrial pollution on the auxological processes of trees, the average radial growth has been used as the main indicator. Our study introduced also the basal area increment (BAI) as a parameter, and specific synthetic indicators were calculated (i.e., indices of resilience, recovery, resistance, pointer years). Compared with the average radial increment BAI is an indicator that highlights more accurately the accumulation of tree biomass and stand productivity [15].

Growth sampling, primary processing, measurements, cross dating, standardization, and building of the mean radial growth chronologies were performed in full accordance with the established methodology in the field, using dedicated equipment and software, such as CooRecorder 7.4, CDendro 7.6 [16], TsapWin [17], COFECHA [18,19], R studio [20]. For every growth series, specific statistical parameters were calculated and emphasized [21,22]: the period covered by each stand chronology with a replication of at least ten individual series, the number of trees, the average sensitivity (average percentage change of the annual ring width in relation to the next annual ring, see Fritts 1976), and first-order autocorrelation.

The degree of reduction and recovery of growth due to the influence of the local industrial air pollution was assessed through resilience, recovery, and resistance indices for every area affected by pollution (intensive, moderate, and unpolluted) for both average radial increment and BAI. These indices have been calculated for moving periods of 3, 5, and 7 years to capture possible differences when the influence of the pollution factors on the stands is considered.

In order to quantify the temporal effect of pollution, indices of resilience, recovery and resistance were calculated along the growth series of the trees, allowing the identification of times when disturbance factors induced changes [23]. The method used for computing the pointer years is the statistical analysis of the normalized values for moving periods of 5, 10, and 15 years [24]. The calculations and analyses were carried out for the period common to all analyzed series between 1900 and 2020.

Table 1. The main characteristics of the experimental plots network from Baia Mare region.

Location (FD/UP/u.a.)	Distance from the Polluting Source (km)	Area (ha)	Age	Composition *	Exposure *	Slope (Centesimal Degree)	Altitude (m)	Canopy Cover	Yield Class	Standing Volume (m^3/ha^{-1})
Firiza/I/89	2.7	14.11	170	7FA 1GO 1CAS 1DT	NE	38	370–530	0.7	3	295
Firiza/VI/63	8.5	13.14	75	9FA 1ME	SW	30	640–860	0.9	3	359
Firiza/I/38	6	26.61	85	10FA	NE	30	380–540	0.9	2	505
Firiza/VI/104B	3.2	13.34	95	10FA	NW	33	330–570	0.7	3	371
Firiza/V/87C	9.5	15.56	150	9FA 1PAM	W	25	500–600	0.6	2	359
Firiza/VI/28A	6.1	9.18	70	10FA	W	30	300–435	0.7	3	288
Baia Sprie/I/3	3	3.47	125	6GO 1FA 1FA 2CA	SE	33	360–560	0.5	3	140
Baia Sprie/I/54B	5.8	4.2	130	10FA	W	24	540–580	0.7	3	367
Baia Sprie/I/73B	9.5	14.46	110	10FA	SE	22	650	0.5	3	215
Baia Sprie/I/11	3.8	1.68	140	9FA 1GO	SW	30	540	0.4	3	258
Tăuții Măgherăuș/III/27A	9.6	35.9	120	9FA 1GO	W	25	350–600	0.6	3	316
Tăuții Măgherăuș/V/29A	7.2	9.72	110	8FA 1GO 1CA	W	28	300–430	0.7	3	335

* Composition—Degrees of participation (in tenths) of the species in the mixed forest stand; European beech (FA), sessile oak (GO), chestnut (CAS), birch (ME), hornbeam (CA), sycamore maple (PAM). * Exposure—NE—North-East; NW—North-West; W—West; SW—South-West; SE—South-East.

3. Results

3.1. Statistical Parameters of the Radial Growth Series

The growth series length varies between 77 and 251 years, while the average radial growth is between 1.762 and 3.898 mm, with lower values for trees in the highly polluted area (Table 2). The average sensitivity varies from 0.140 to 0.233, and the average autocorrelation varies between 0.582 and 0.778. Analysis of the statistical parameters of the radial growth series showed no significant differences between them in relation with the intensity degree of pollution.

Table 2. Statistical parameters of the average radial growth series for European beech from Baia Mare region.

Plot Code *	No. of Cores	Overlapping Period > 10 Core	Average Radial Growth	Average Sensitivity	Autocorrelation Order I
BMFi1	41	1850–2020	2.915	0.144	0.650
BMFi2	42	1826–2020	1.897	0.165	0.778
BMFi3	40	1825–2020	1.762	0.199	0.755
BMFi4	44	1845–2020	3.349	0.140	0.739
BMFi5	40	1769–2020	1.939	0.146	0.754
BMFm1	40	1943–2020	3.898	0.183	0.622
BMFm2	43	1873–2020	2.060	0.185	0.708
BMFm3	41	1905–2020	2.490	0.157	0.682
BMFn1	40	1849–2020	2.478	0.233	0.582
BMFn2	40	1894–2020	2.461	0.148	0.770
BMFn3	40	1870–2020	2.656	0.163	0.764
BMFn4	43	1877–2020	1.802	0.200	0.720

* Plot code: BM—Baia Mare region; F—beech tree; i—intensively polluted area; m—moderately polluted area; n—unpolluted area; 1:5—numbers of plots.

3.2. Analysis of the Auxological Changes of Trees

From the analysis of the average radial growth presented in Figure 2, the beech trees located in the three areas studied (intensive, moderate, and unpolluted) show a relatively constant variation in growth throughout the analyzed period, differing only in the amplitude of their variation during certain time intervals. However, until 1930, the stands in the heavily polluted area had constantly higher radial growth than those in the unpolluted area; after this period, there was a reduction in the average radial growth of the trees in the intensively polluted area until around 1950. After this period, by around 1980, the stands in the area with intensive pollution show constantly lower radial growth compared to the stand in the unpolluted area, an interval which corresponds with high-intensity activity at the plant.

To focus on the period when the stands were affected by pollution, BAI series were developed and analyzed (Figure 3). Thus, if until 1960, the stands situated in intensively and moderately polluted areas had similar BAI compared with the stands situated in unpolluted areas, after 1960 and around 1990, they had a significant reduction of BAI to below the normal level, due to the intense mining activity. During the 1960–1970 and 1980–1990 periods, the negative effect of local industrial pollution on the growth processes of beech trees in the Baia Mare region was reduced compared to the 1970–1980 period, which agrees perfectly with the period during which the Phoenix mining plant in the area was operating at full capacity.

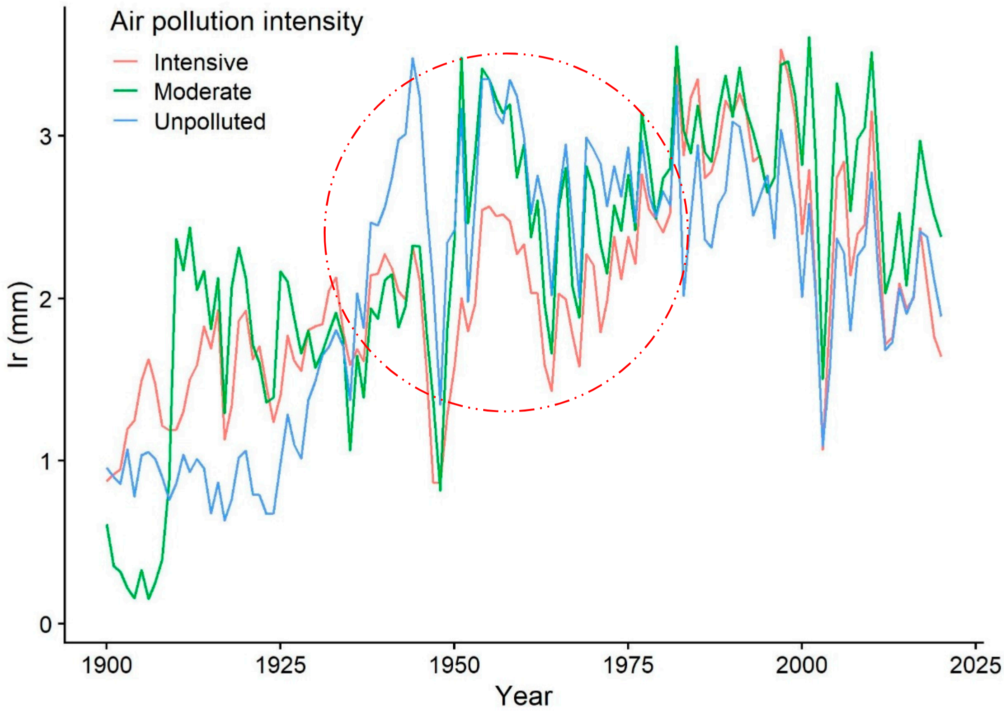

Figure 2. The series of average radial growth of beech in Baia Mare area, presented in relation to the intensity of pollution (intensive-growth series in the area with intensive pollution; moderate-growth series in the area with moderate pollution; unpolluted-growth series in the unpolluted area); dotted area—the period of maximum activity of the plant.

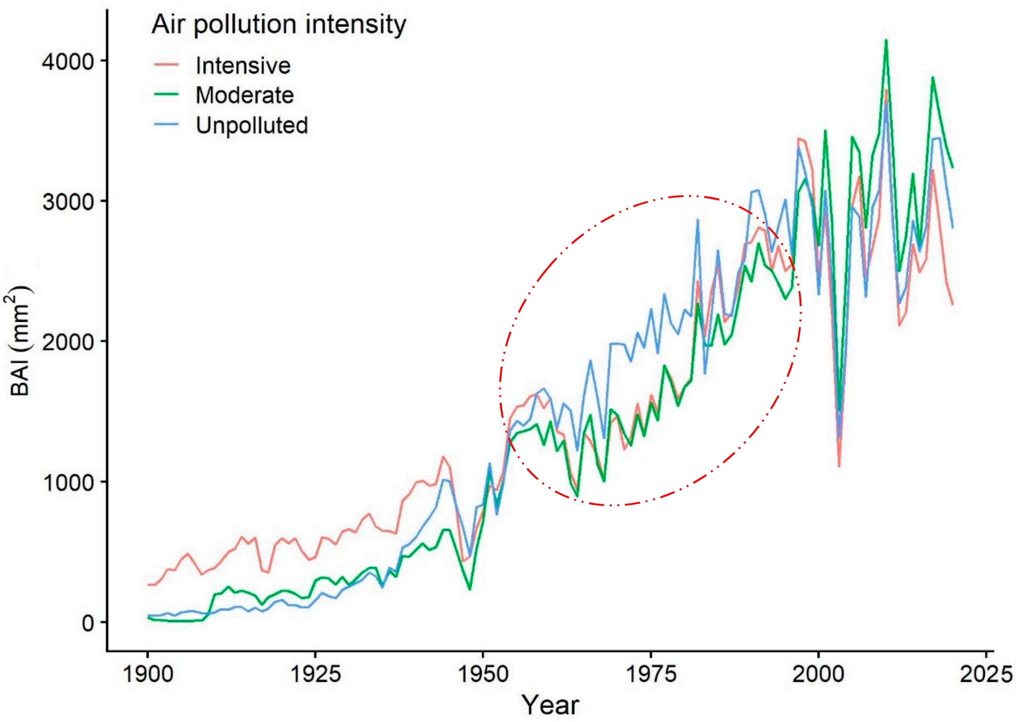

Figure 3. Mean BAI series of beech in Baia Mare region, presented in relation to the intensity of pollution (intensive-growth series in the area with intensive pollution; moderate-growth series in the area with moderate pollution; unpolluted-growth series in unpolluted area); dotted area—the period of maximum activity of the plant.

After 1990, there is a normal recurrence of the BAI of the stands in the two affected areas, following the same trend of the average radial growths. These variations of the average radial increment and average BAI after 1990 (Figure 3) are explained by the significant reduction in the activity of the plant. The pollutants that were affecting these increments were significantly reduced, so the trees resumed their normal physiological activity.

From the analysis of Figures 2 and 3, it can be observed that, compared to the radial growth of trees, the BAI captures more accurately the pollution impact on the auxological processes of beech trees in the Baia Mare area, with regard to the period and the impact of the industrial pollution.

Regarding the BAI resilience indices from the period 1960–1990, when the trees were affected by the industrial pollution, when it is used for the mobile periods of 5 and 7 years the influence of pollution is better highlighted comparing with 3 years of mobile periods (Figure 4). After 1990, the mining activity was significantly reduced and trees returned to their almost normal auxological activity, as they were no longer exposed to intensive pollution.

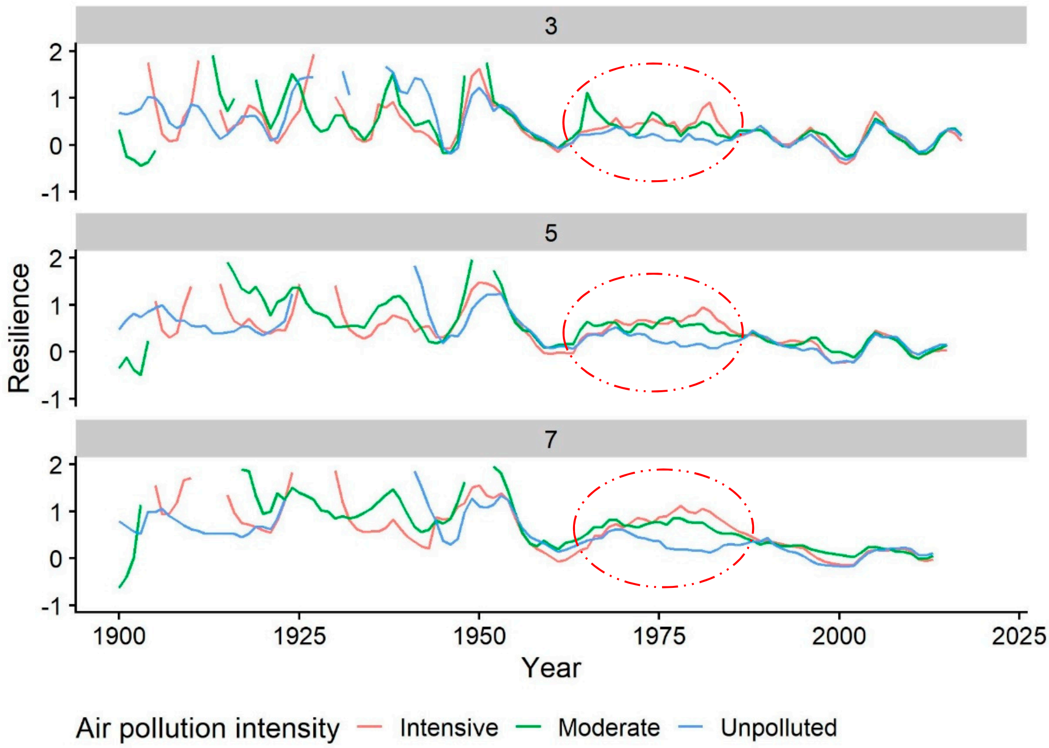

Figure 4. Resilience indices of the average BAI series for beech in Baia Mare region (dotted area—the period of maximum activity of the plant).

In the case of the recovery indices of BAI, as in the case of the resilience indices, the period between 1960–1990 is very prominent, especially in the case of the mobile periods of 5 and 7 years (Figure 5). An interesting aspect is that after 1950, for a short time, the trees showed low values of recovery rates, a phenomenon that is generated by more favorable environmental conditions. This may be because, at that time, the mining plant was in its full development, and new technologies that significantly reduced the pollution factors for a short period were introduced.

In the case of the resistance indices, the period in which the beech trees were affected by local pollution factors is not as clearly evident as in the cases of the resilience and recovery indices. However, differences in the variations of these indices in relation to the intensity of pollution in the period 1960–1990 can be observed (Figure 6).

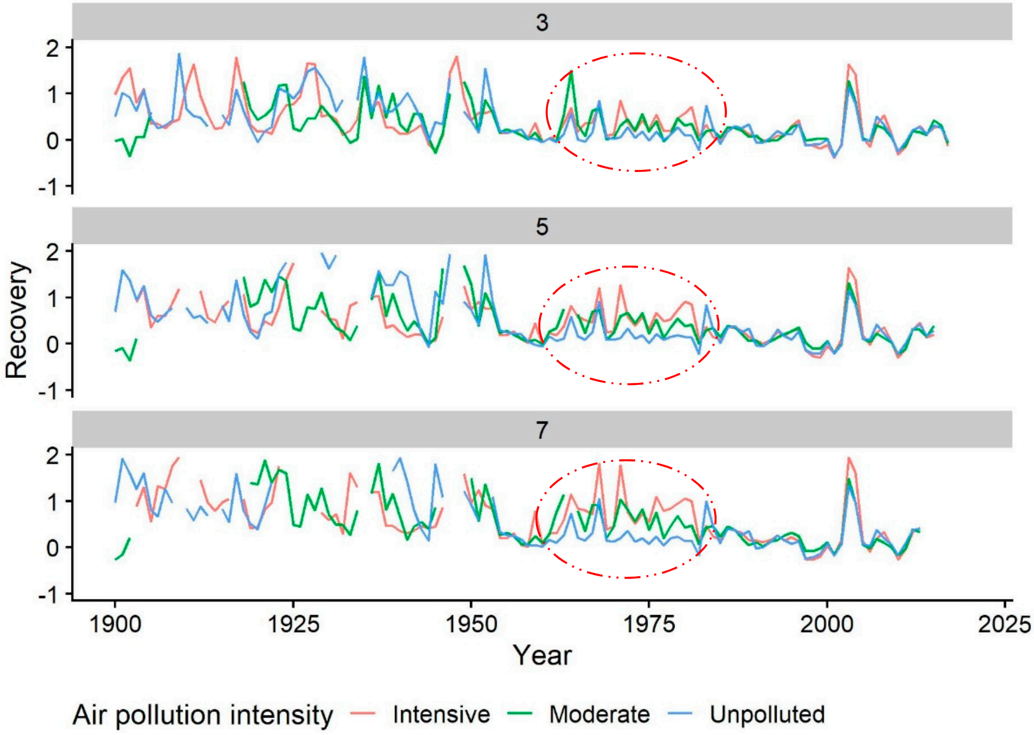

Figure 5. Recover indices of the average BAI series for beech in Baia Mare region (dotted area—the period of maximum activity of the plant).

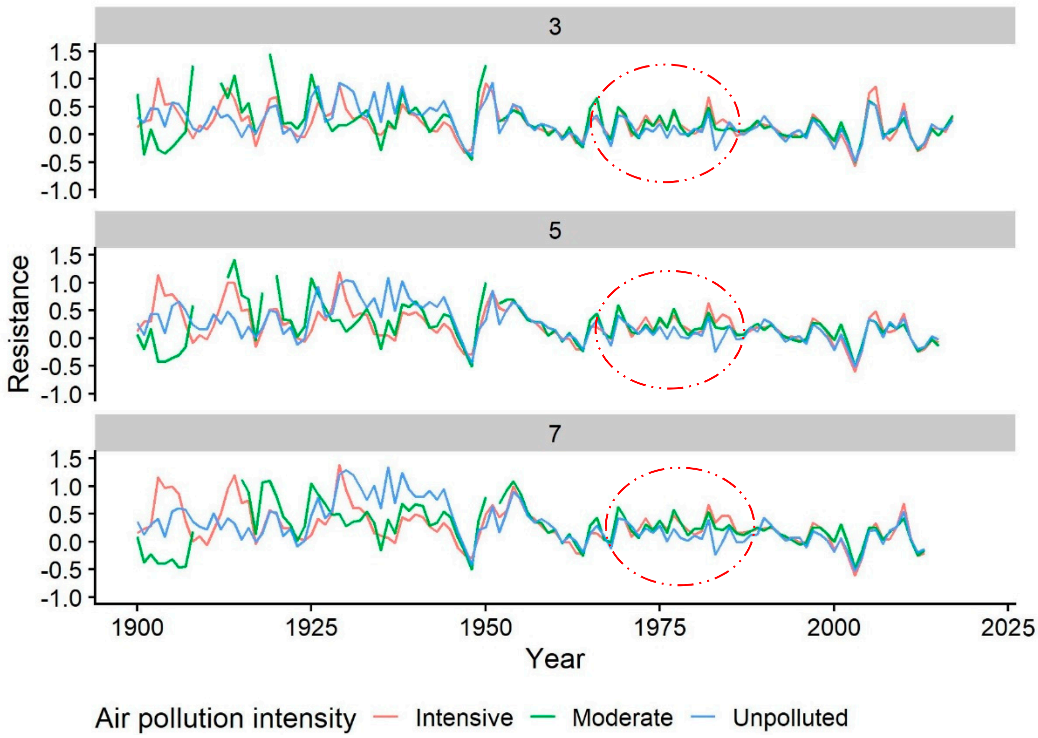

Figure 6. Resistance indices of the average BAI series for beech in Baia Mare region (dotted area—the period of maximum activity of the plant).

In the case of the average BAI series, the variation of the characteristic years is random until around 1970 (Figure 7). Analyzing the period when the trees were affected by local pollution (1960–1990), we observed high amplitude for these years for trees in the intensively polluted regions. In the case of the trees located in the moderately polluted region, this amplitude is lower, and in the case of the unpolluted area trees, the variation of the characteristic years of pollution decreases after 1950, a sign that these areas were not affected by pollution. After 1990, the variation of the characteristic years follows the same trend, regardless of the area affected by pollution, due to the significant reduction of activity at the mining plant and the resulting decrease in the pollution factors. Hence, the trees resumed almost normal auxological activity.

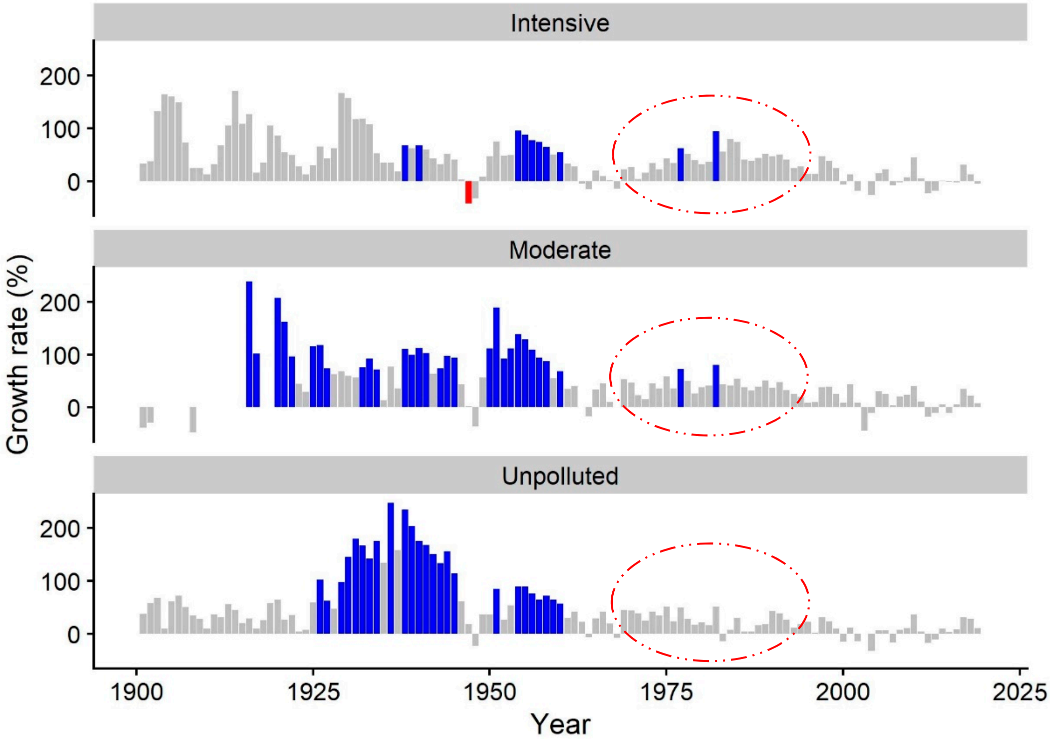

Figure 7. The pointer years of the series of average BAI growth indices of the beech trees in Baia Mare region, affected by pollution, for a moving period of 15 years (dotted area—the period of maximum activity of the plant).

As with the resilience, recovery, and resilience indices, the characteristic years of the BAI series highlight the period analyzed, where beech trees were affected by local pollution over longer mobile periods. Figure 7 shows the variation of the characteristic years of the BAI over mobile periods of 15 years.

4. Discussion

The study confirms the influence of local pollution factors on the radial growth of beech trees in the Baia Mare area, as in the previous studies. The closer the trees are to the pollution source, the more obvious the influence of the pollution on the increment becomes [13]. The most intense negative effect of the local pollution, which includes heavy metal dust, sulfur and nitrogen oxides, and sulfuric acid vapors, on the auxological processes of beech trees was in 1960–1990, with a maximum in 1970–1980, the period when the mining plant operated at the highest intensity.

This period, when the beech trees were affected by the local pollution, can also be observed in the resilience, recovery, and resistance indices. It is very prominent when the indices are calculated for long mobile periods of 5 and 7 years. Moreover, the local pollution in the Baia Mare area has also been quantified in the soil, where high concentrations of lead, copper, zinc, cadmium, and arsenic have been found [10]. These high concentrations directly influenced the vegetation, including the forests, as shown by the results of this study. Beech trees responded to the negative effect of pollution, significantly reducing their increments between 1960 and 1990, and after 1990 they resumed nearly normal auxological activity. As in this study, the reduction of BAI due to NO_2 and SO_2 pollution has been reported in both beech and spruce trees [25]. Heavy metal pollution also negatively influenced beech, sessile oak, Austrian pine, and spruce trees in the Copșa Mică area [26], and spruce and common silver fir trees in the Tarnița area [27]. Pollution has also had negative influences on other species of trees, such as pine trees in Lithuania, where the burning of fossil fuels has led to the decline of trees and, thus, to the reduction of increments [28].

For the first time, the tree growth analysis showed that the BAI emphasized more clearly than the radial tree growth the impact of pollution on the auxological processes of beech trees in the Baia Mare area, both in terms of the timing and the level of impact. The same comparison has been made between these indices with respect to the tree biomass and the tree productivity, and it has been concluded that the BAI captures tree growth much more accurately [15].

In addition, for the first time in the analysis of the three resilience, recovery, and resistance, the most accurate index for emphasizing the period when beech trees in the Baia Mare area were affected by local pollution proved to be the resilience index, especially for the series with average BAI. This period becomes more evident for the indices that were quantified for longer mobile periods of 5 and 7 years. The resistance is the least representative index for showing the period when the beech trees were affected by local pollution. Although there are differences between the three areas affected differently by pollution, they are not as obvious as in the case of the resilience and resistance indices.

The pointer years are another parameter that can be used as an indicator of the effect of pollution on forest ecosystems. This parameter has mainly been used to highlight the reactions of trees to climate changes [29] and sudden changes in environmental conditions [30]. In the Baia Mare area, the calculation of the characteristic years of the radial growth series shows the period 1960–1990 prominently, when the trees were affected by pollution, with clear differences between the intensively polluted and unpolluted areas.

5. Conclusions

It is very well known that the high industrial activity developed in the last decades of the 20th century negatively influenced the forests ecosystem status worldwide increasing air, water and soil pollution. Our study confirms the influence of local pollution factors on the radial growth of beech trees in the Baia Mare area.

For the first time the analysis of radial growth indices and BAI showed that compared to the radial tree growth, the BAI emphasized more clearly the impact of pollution on the auxological processes of beech trees in the Baia Mare area both in terms of the timing and the level of impact.

Additionally, analyzing the resilience, recovery, and resistance indexes of the basal area and radial growth it has been observed that the period when beech trees in the Baia Mare area were affected by local pollution is best pictured by the resilience index, especially for the series with average BAI. The outcomes of this research provide important information and significantly contributes to our understanding of trees response to environment pollution more broadly creating also the base for specific strategic planning initiatives with valuable insight into the efforts of making the forests more resilient and resistant.

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