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# Radial Growth Behavior of Pines on Romanian Degraded Lands

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**Abstract:** More than a third of Romania's surface has low-productive soils, at the same time exposed to risks of climatic phenomena and generating high economic loss. Afforestation with pine has been the most common solution for the recovery of sheet erosion. Many of the pines grown on such land have run down. This paper presents the results of the first dendroecological investigation of degraded lands in Romania, 80 years after the first ecological reconstruction. In this way, the effects of reconstruction were assessed, supporting the adoption of future solutions for the improvement and efficiency of recovered ecosystems. Reconstructed radial growth was set against rainfall, air temperature, and management history. A total of 330 black pine and Scots pine trees (*Pinus sylvestris* L. and *Pinus nigra* Arn.) of different ages and social positions from 11 stands of different densities were cored for retrospective tree-ring analysis. Scots pine has made better use of these sites, with a better growth rate than black pine especially in plantations with lower survival and on dominant trees. The dynamics of radial growth distinguish the two pine species, with Scots pine showing an accentuated juvenile growth spurt and bigger growth range. The growth decline is predominantly a maturation effect that begins when the tree is around 40 years old and seems to be irreversible. After this age, weak or moderated removal is not enough to revive growth. The contribution of climate (air temperature and rainfall) to the last radial increments in decline is 3–57% and is higher than in the previous decades. On moderately degraded land by farming and grazing, the mixture of Scots pine and black pine, rather than monocultures, proved to be a sustainable solution. Dendrochronological surveying of restored ecosystems allows development of management strategies, which becomes critically important in the circumstances of climate warming.

**Keywords:** afforestation; bad lands; black pine; climate change; dendroecology; growth decline; plantations; Scots pine

## 1. Introduction

The large ecological amplitude of pine species [1–4], supported by their geographical distribution [5] and their ability to capitalize lands unsuited to forest vegetation through superior production [6–8], have been long been acknowledged [9]. These characteristics have favored the use of pines as species for afforestation or reforestation of naturally or anthropically degraded fields [10–15].

The diversity of climate, geological substratum, relief, and vegetal cover and their interactions, as well as the effects of the anthropogenic factor, make the natural environment in Romania vulnerable to geomorphologic, hydrologic, and climatic risks [16,17]. The recent national inventory indicates 8.34 million ha of degraded or unproductive land, affected especially by pluvial erosion [18], which amounts to 35% of the country's surface and nearly half of the agricultural land. By 2008, 0.3 million ha of degraded land was reforested, mostly with pine species [18]. Between 4000 and 10,000 seedlings per hectare were used for reforestation, depending on the erosion harshness, densities considerably higher than usual [15]. The postwar ecological reconstruction fulfilled its purpose, managing to eradicate the erosion areas 5–15 years after the afforestation [19].

Using pine in the recovery of degraded land is limited to sheet erosion [10]. The black pine proved to have sustained high growth even on highly eroded lands [20]. Pines can offer good protection of the land and good yields: 3–8 $m^3$ yearly per hectare in forest steppe, 5–10 $m^3$ yearly per hectare in hill mixed hardwood area, 5–8.5 $m^3$ yearly per hectare in oaks and beech area, and 7–12 $m^3$ yearly per hectare in Norway spruce area, at the age of 30 years and on moderately pluvial eroded land [20]. On rock outcrops, the yields are inconspicuous. On heavy soils, the volume of black pine growth is up to 15% less than on coarse-textured soils [10]. Mixes of pines with broad-leaved trees (wild cherry, ash, maple) are the most productive. The yields of Scots pine are superior to those of black pine on degraded fields in the same site [10]. Twenty-five years marks the maximum growth in height of Scots pines on degraded fields that were afforested during the last century [21]. In Romanian natural stands of Scots pine, 50 years is the age of maximum growth of the basal area [22], while black pine crops from the USA accelerate their growth just after this age [23]. The soil's pluvial erosion intensity does not influence the growth of Scots pines in the first 5–10 years [10].

Pines are particularly receptive to annual climate fluctuations [24–27]. In natural stands, for example, the sensitivity of Scots pine to rainfall is above that of Norway spruce and firs [22]. The dry sites accentuate the sensitivity of the trees' growth structure to fluctuations of the environment [28] and their tolerance to drought [29]. However, the pines' tolerance to the stress caused by drought is limited [26]. The limits have become more visible in the last decades through massive and repeated death occasioned by severe droughts [30,31], requiring care in choosing pines [32] and avoiding planting them in forest steppe [20].

However, diagnosing the trees' growth decay is difficult. Dryness, soil scarcity, nutrient deficiency in soil, excessive plantation density, and the biotic stressors incite a decrease in growth [33–37]. Growth depression may also be the symptom of tree maturation [38–40], as a growth increase can be a consequence of not only favorable climatic circumstances, but also a decrease in competition through logging, for example [41–44]. Pollution and fires can have a long-lasting and stimulating effect on the growth of Scots pines [45] respectively of black pine [46]. The contribution of genotype to the radial growth of the Scots pine is low, at least in the first 30 years, allowing for a stronger influence of ontogenetic factors (related to age or resource availability) [47].

Decreasing wood bioaccumulation is also a symptom of tree vitality decline [48]. Consequently, on degraded lands, the survival rate of pines will be lower [11]. Their fragility [49] and low biodiversity [50], as well as the subsequent natural colonization by rustic deciduous trees [51], make pine stands rather temporary solutions [52,53]. After 15–20 years, Scots pine plantations also show reduced density as a result of wind and snow breaking or tearing down the trees [51]. Almost a third of the pine forests on Romanian degraded lands require urgent improvement, promoting deciduous trees as the main species [54].

No dendroecology research has been carried out so far on reforested degraded lands in Romania. Established plantations have been followed for their survival, yield, competition, and health [55]. There has been no species-specific inquiry on radial growth dynamics, especially under different conditions of soil, climate, and vegetation imposed on pine plantations [20]. Increasingly, climatic extremes, deepening of land torrentiality [56], aridity of lands around the steppe, and dieback of pine plantations are a continuing challenge for forest management in choosing sustainable solutions for afforestation [57]. The degradation of plantations through the decline of the tree layer can reactivate erosion processes [58]. Surveillance of plantations with dendroecological methods allows us to predict and check the effects of various solutions for the ecological reconstruction of degraded lands.

This study was conducted in one of the most pluvial erosive areas of Romania [59]. We sought to delineate the dynamic behavior of pines (Scots pine and black pine) by means of growth ring time series, queried in relation to rainfall, air temperature, stand density, tree age and social position, and logging. The following hypotheses will be verified: (a) growth behavior is different between the two pines due to higher tolerance of black pine to drought and heavy soil, especially on degraded land [10,60–63]; (b) growth decline is climatically triggered by drought and warming [64]; and (c) human disturbance may have a highly xylogenetic contribution similar to that of the climate, by growth revival due to reduced competition following logging [65].

## 2. Materials and Methods

### *2.1. Erosion Background*

The research was done in the Curvature Carpathians (Figure 1), the second greatest erosion area in Romania [16].

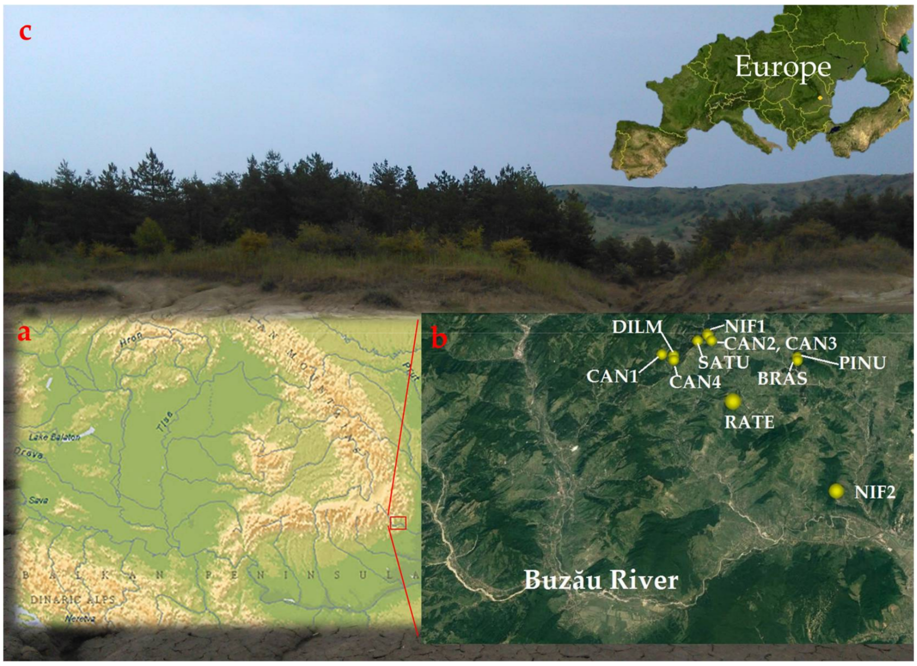


**Figure 1.** (**a**) Geographical location of the study area in the Carpathians area (South-eastern Europe); (**b**) Map of the sample plots area (the yellow dots mark the sampled stands); (**c**) A pine plantation on a Buzau' badland.

The dynamics of the erosion process are so active that it has led to elimination of large areas from agriculture, called Buzau badlands [59]. The erosivity of the pelitic formation in the clay-marl substratum explains the pluviodenudation in the hollows [66].

The sites have a mostly moderate temperate continental climate. The amount of precipitation (665 mm·year$^{-1}$ at 420 m altitude) is exceeded by evapotranspiration (695 mm·year$^{-1}$) [67], so there is a water deficit over the entire vegetation season, totaling 173–195 days. These data confirm the relative aridity of the eroded slopes. Heavy rains are very aggressive: high intensity (1.35 mm·min$^{-1}$ at 420 m altitude) and runoff [68].

Before afforestation, the sites were intensively exploited for agriculture and grazing, which led to the loss of productive capacity and protective functions. The soil-limiting factors for tree growth are shallow depth, weak trophicity, and damage to bioactive horizons.

### *2.2. Study Stands*

The plantations discussed were established between 1935 and 1992 using native seedlings (*Pinus sylvestris* var. *romanica* Svoboda and *Pinus nigra* var. *austriaca* (Höss) Novak), with barren roots, 3 years old, planted at 2 × 1 m spacing, in 30 × 30 × 30 cm holes. All plantations started with 5000 trees per hectare, to achieve the stand closure by the age of 10 [20]. Slopes over 40° were terraced and reinforced with vegetation (especially sea-buckthorn stems, branches, and suckers). Along monocultures, mixtures of hardwoods were also planted. The plantations were followed yearly until they reached canopy closure, which occurred at 8–15 years. Where necessary, gap-filling from the same species was done. In the first decade, there were annual cleanings. After 25 years, some plantations were thinned only once, which led to 2–21% removal from the total volume (Table 1).

**Table 1.** Description of study plots.

| Features | Site Plot | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | RATE | SATU | CAN1 | DILM | CAN2 | NIF1 | NIF2 | PINU | BRAS | CAN3 | CAN4 |
| Altitude (m a.s.l.) | 300 | 295 | 370 | 700 | 325 | 305 | 320 | 665 | 505 | 325 | 340 |
| Exposition | W | NW | N | SE | W | N | N | W | N | NW | W |
| Slope (°) | 15 | 25 | 21 | 20 | 40 | 10 | 10 | 18 | 25 | 40 | 30 |
| Soil substratum | marl | marl | marl | chalky sand stone | marl | clayey marl | marl | sands | loess | marl | marl |
| Soil type * | Cmeu | Cmeu | Cmeu | Cmeu-li | Cmeu | Cmeu | Cmeu | Cmeu-ll | Cmeu | Cmeu | Cmeu |
| Soil physiological thickness (cm) | 42 | 46 | 48 | 32 | 45 | 45 | 54 | 50 | 47 | 47 | 48 |
| Nitrogen in horizon A (%) | 0.28 | 0.26 | 0.22 | 0.18 | 0.30 | 0.47 | 0.36 | 0.20 | 0.15 | 0.21 | 0.14 |
| Carbon in horizon A (%) | 2.95 | 3.76 | 2.05 | 2.37 | 3.52 | 7.03 | 5.08 | 2.78 | 1.80 | 3.21 | 1.63 |
| Base saturation (%) | 57.36 | 55.76 | 56.76 | 53.92 | 58.53 | 39.22 | 53.65 | 54.07 | 54.68 | 58.85 | 56.95 |
| Cation exchange capacity in horizon A (0.01 meq $g^{-1}$) | 16.98 | 17.36 | 18.13 | 16.95 | 17.17 | 23.15 | 16.17 | 16.72 | 16.68 | 17.23 | 17.33 |
| The year of plantation establishment | 1992 | 1962 | 1962 | 1957 | 1952 | 1948 | 1935 | 1935 | 1947 | 1937 | 1937 |
| Stand composition (%) ** | 90BP 10HD | 100BP | 70SP 20BP 10HD | 100SP | 70BP 20SP 10HD | 90SP 10HD | 100BP | 90SP 10BP | 70SP 30BP | 80BP 20SP | 100BP |
| Stand density (trees·$ha^{-1}$) | 1840 | 1680 | 1520 | 740 | 1100 | 1160 | 1080 | 680 | 1280 | 640 | 780 |
| The management of plantations | | | | | | | | | | | |
| Stand age at intervention | - | 31 | 32 | 39 | 43 | 25 | - | - | 42 | 59 | 59 |
| Harvest intensity (% of removal) | - | 3.2 | 3.8 | 2.2 | 7.0 | 6.4 | - | - | 21.1 | 1.5 | 3.2 |

* Cmeu: Eutric Cambisols; Cmeu-li: Leptic-eutric Cambisols; Cmeu-ll: Lamellic Cambisols. ** SP–Scots pine, BP–Black pine, HD–miscellaneous hardwoods [69].

Erosion was stopped in all the sampled sites. The main type of soils in this area is cambisoil, which makes up 48% of the total forestry soils in Romania [70] and whose features depend on the geomorphological units [71]. In the current state of site recovery, cambisoil exhibits lower volume, slight acidification of the mineral horizons, sandy-loamy texture in the mineral horizon A, and higher content of sand and humus. These are medium-deep soils (physiological thickness 45.8 ± 1.7 cm), poorly stony (the content of rock material 1–9%), high organic carbon (180–210 t/ha [72]), and medium supply of water and nitrogen available to the woody plants (0.25 ± 0.1% in the A horizon). The organic horizon is unbroken only in plantations older than 75 years [73].

### 2.3. Sampling Design and Data Compilation

Before sampling, we screened the degraded land areas afforested with pines in order to cover all the recovery levels of the local sites. Forty plots of 20 × 25 $m^2$ were established in the chosen sites, where we performed full inventories. For cross-dating, a master chronology was also used, from a 108 years old black pine stand grown in sites favorable for pine vegetation, at an altitude of 790–815 m.

The core sampling was drawn from 11 stands, mostly older than 40 years, which facilitated analysis of the long-term growth trend. For comparison, a younger stand was also chosen (Table 1). One sample 5 mm thick was taken from each tree, in the uphill breast height, with an increment borer. We opted for a single drilling direction, following a preliminary study in the CAN4 plot, where it was found that the differences in ring width between breast height radii were not statistically significant ($F = 0.482$, $p = 0.70$). A total of 30 trees in each plot were cored. Each tree was classified according to its top social position (in the Kraft classification), which became the KP variable. KP is a discrete variable with the following values: 1: dominant; 2: codominant; 3: subdominant; 4: suppressed; 5: dying [74].

The climatic data for the dendroecological study came from weather stations in Buzau (45°09′ N, 26°49′ E, 102 m a.s.l.) and Pătârlagele (45°19′ N, 25°91′ E, 390 m a.s.l.) in the research area. The continuous climatic time series have a length of 53 years (1961–2013).

### 2.4. Dendroecological Study

After seasoning, the samples were glued to wooden frames and sanded at a 60–240× granulation [75]. They were then scanned at 1200 dpi resolution using the WinDENDRO Density 2006c device from Régent Instruments [76]. We obtained raw time series for the 5 variables of the annual rings: annual ring width (RW), earlywood width (EW), latewood width (LW), and the corresponding proportions of earlywood (EP) and latewood (LP). For each individual series of RW, we subsequently calculated the range values, designated by the variable ring width range (RWR).

For cross-dating, which was also performed on the WinDENDRO, we used a reference series from the control stand. We kept the growth series with the Gleichläufigkeit nonparametric correlation coefficient with the control series [77] over 0.65.

The series of individuals from the same plot were averaged. At the far end, the average series was truncated at the depth of at least 3 trees [78]. The average series was converted by standardization in series of indices, performed again on WinDENDRO, where the smoothing filter was the spline curve and for which the value of −4 of the Lagrange parameter was chosen [79]. The signal thus extracted (a series of indices) was verified against the climate through the nonparametric test of signs [80]. Age-related and stand dynamics effects were quantified as the difference between the raw series and the standardized series of RW.

In order to identify the events from the average series of RW and the standardized indices, we calculated the moving growth change rates using a 4-year moving window, adapted from [81] and [82]:

$$GC_i = \frac{\sum_{i}^{i+3} X_i - \sum_{i-4}^{i-1} X_i}{\sum_{i-4}^{i-1} X_i} \times 100(\%) \quad (1)$$

where $i$ is the current calendar year and $X_i$ is the RW value of year $i$ (from the raw series) or the value corresponding to the signal (standardized series) or the value of the noise series (the difference between the previous series). Consequently, three types of growth change rate were used. Change rates of radial growth (GC_RW) denote the level of the periodic changes in the annual ring width from the breast height. Change rates of standardized indices (GC_D) indicate the level of fluctuation in the signal. GC_N indicate the level of fluctuation in the noise series.

In order to separate the contribution of the climate from the logging effects, we similarly calculated the change rates for temperature and precipitation (TC and RC, respectively). TC expresses the relative change in average temperature from four consecutive calendar years after the current year as compared to the 4 previous years. The relationship of these climatic indices with the growth change rates was verified by nonparametric correlation.

For the diagnosis of the recent trees' vitality, we extracted the last 10 years from the growth time series [83], thus we obtained the average width of the last 10 years of the series (10 RW variable).

### 2.5. Statistical Analyses

To recognize the influences on growth, we chose a multifactorial design, wherein the dependents were the tree ring variables, the fixed factors were the species of trees and their social position, the covariates were the age of the trees and the current stand density, and the tree was random. To avoid age-related bias in the growth series, we chose analysis of covariance and partial correlation. Thus, to assess the involvement of species and social position in tree growth, independent of their age and of the density of plantation, analysis of variance was replaced by analysis of covariance (ANCOVA) [84]. The variables were previously checked to avoid multicollinearity. In ANCOVA, the tree species and social position were designated as categorically independent variables, the annual growth (RW, RWR, 10R, LP) as dependent, and the age of the trees and density of the stands as covariates. Similarly, in order to remove the age share in the relationship of stand density with tree growth, partial correlations were chosen. To measure the strength of the relationship between climate variables (as predictors) and growth (as dependent variables), multiple correlation was used. Time series synchronization was checked with cross correlation function [85]. Statistical data processing was carried out in Statistica 8.0.

## 3. Results

### 3.1. Differences in Tree Growth between the Two Pine Species

RW ranges from 0.026 to 21.11 mm·year$^{-1}$. At the breast height, the RW reaches its peak in the first 13 years, especially around the age of 7. RW together with LP allow the partition of radial growth into 5–18 juvenile wood rings, followed by a transition to mature wood, which can extend up to the age of 36. The differences between the sampled sites with regards to radial growth occur from the age of 11 years. Starting the age of 40, when all the trees are stucturally mature, the RW stabilizes around an average of 1.1 mm. The width of the annual rings in the last decade of trees growth is 50–80% of the average value over the entire series. In what concern the dominated trees over 40 years old, the width of the rings of the last decade did not reach 20% of the average value per series. Tree age, stand density, and tree social position are factors that influence RW size (Table 2). The contribution of species to growth differences between the trees seems to be small. At the same age, Scots pine grows on average 0.1–0.35 mm·year$^{-1}$ faster than black pine. There are no differences between the two pine species with regards to the age when the annual rings become mature ($\chi^2$ = 0.018, $p$ = 0.89, d$f$ = 1). Even though the radial growth is fairly similar for the two pines, Scots pine shows larger spreading of its annual values (higher values by about 1 mm of RWR). The radial growth from the last decade, which is placed in the decline, also does not distinguish between the two species.

**Table 2.** Analysis of covariance (ANCOVA) of the growth structural traits.

| Dependent Variables | Median | Total Variance between Rings | Predictors (Fixed Effects) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Tree Age | Stand Density | Specie | | Tree Social Position | |
| | | | | | Covariates | | | |
| | | | | | Tree Age | Stand Density | Tree Age | Stand Density |
| | | | *p* Values from *F* Test | | | | | |
| Annual ring width, mm | 1.50 | 2.65 | <0.01 | <0.001 | 0.04 | 0.04 | <0.001 | <0.001 |
| Annual range of ring width, mm | 6.61 | 3.78 | 0.30 | <0.001 | <0.01 | <0.01 | 0.05 | 0.08 |
| Annual average of the last 10 years ring width, mm | 0.97 | 0.34 | <0.01 | <0.001 | 0.53 | 0.57 | <0.001 | <0.001 |

The differences between species is increased for Scots pine, into more sparse stands (Figure 2).

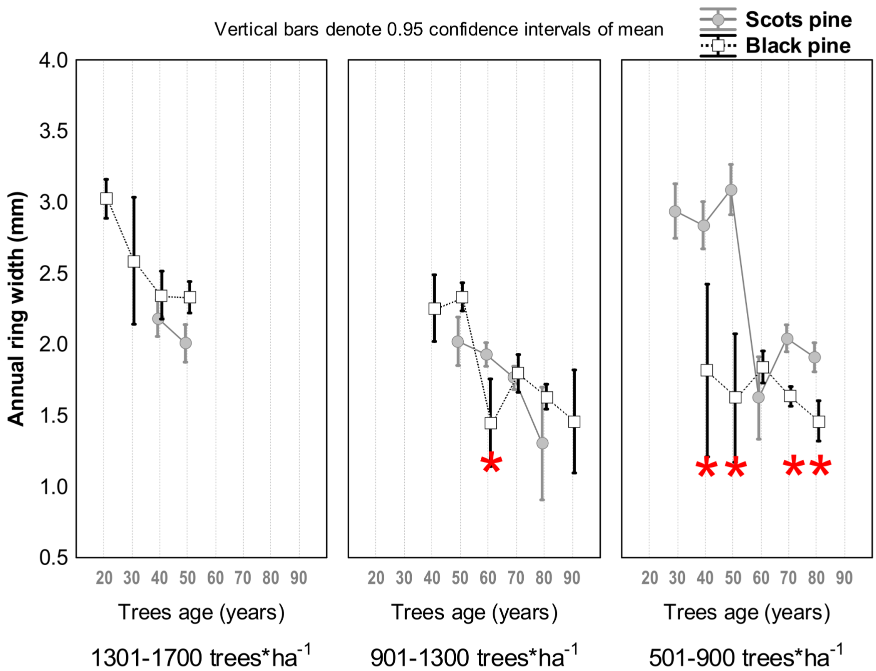


**Figure 2.** Specie x tree age x stand density interaction in pines radial growth at breast height (the asterisks mark significant differences ($p < 0.05$)).

The hierarchical tree position (KP) is an even more important source of annual growth variation. The understories (KP = 4 and 5) emphasize the differences between the two species of pine (Figure 3).

In older plantations, radial growth had a faster start in the Scots pine than in the black pine (Figure 4). Faster growth is supported longer by Scots pine, but a decline in growth usually occurs simultaneously after 39 years. The averages of RW were recorded simultaneously for the two pines without being influenced by the current stand density.

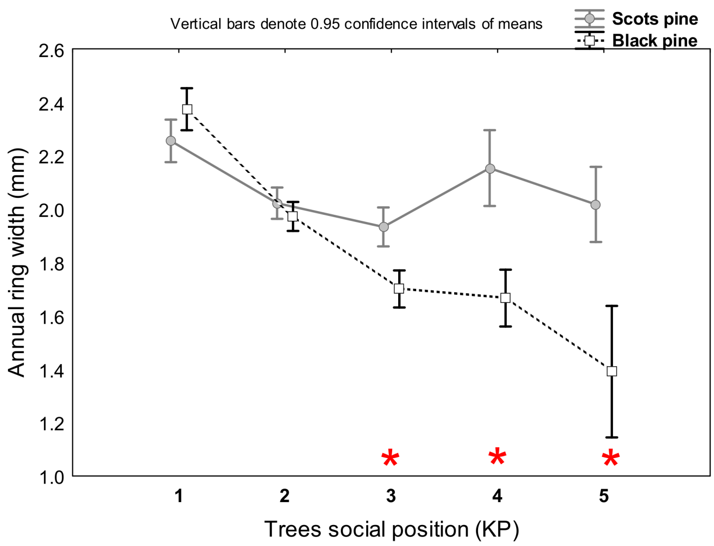


**Figure 3.** Distinguishing between social classes stand in terms of radial growth (1: dominant; 2: codominant; 3: subdominant; 4: suppressed; 5: dying. Stars mark significant differences: $p < 0.001$).

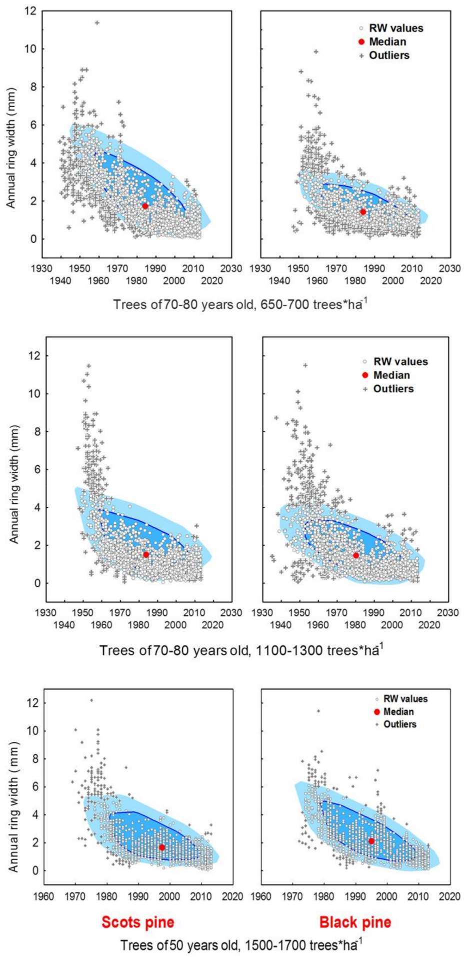


**Figure 4.** Ring width dynamic: comparisons between the black pine and the Scots pine for densities level.

In Table 3 we presented the density of the tree stands whose growth depression is in fact irreversible. The mixtures of black pine and Scots pine, rather than pure tree stands, survived better on degraded land.

**Table 3.** The current density of plantations with the age of more than 40 years.

| Stand Composition | No of Trees·ha$^{-1}$ (Mean ± Standard Deviation) |
|---|---|
| Scots pine stands | 1193 ± 228 |
| Black pine stands | 1109 ± 468 |
| Pine mixtures | 1364 ± 344 |

### 3.2. Climate Share in Radial Growth

Multiple correlations of detrended growth change rate with climate change rate (rainfall together with air temperature act to separate the climate share from radial tree growth (Figure 5). We started from the assumption that any change in temperature and precipitation (shown by RC and TC) would cause a corresponding shift in growth (reflected by the GC from the signal). The hypothesis was verified in the sequence of recent and very narrow rings (with an average RW per plot <1 mm).

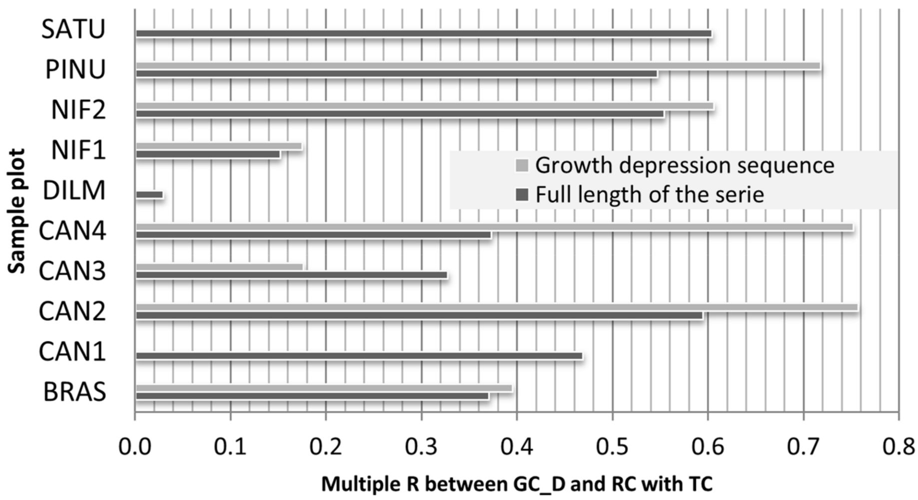


**Figure 5.** Verifying the growth response to the climate.

The multiple correlation coefficients, varying from one plot to another, between 0.175 and 0.757, show a sound affinity of the growth regime to the climate regime. Therefore, the contribution of climatic range to the latest narrow ring widths can be 57% at most. The differences among plots originate from the time lags between them. Improving correlation coefficients with temperature x precipitation in the growth suppression phase (Figure 5) argues that the climate maintains and accentuates the decline. The local climate trend over the past 50 years shows a warming of 0.24 °C per decade ($R^2$ = 0.26; $p$ < 0.001)), more pronounced since 1994. The precipitations have suffered an insignificant decrease by 0.3 mm·year$^{-1}$ ($R^2$ = 0.002, $p$ = 0.77), being more consistent in the dry decade 1981–1990. By consequence, in the researched area, we cannot talk about the climate becoming arid which means that the decline of growth is not an argument for this.

Growth response to rainfall varies from one plot to another (Figure 6). The drought from the ninth decade of the last century did not seem to have any influence on the RW oscillations. An improvement in the water supply in 1998 was not able to revive the trees' growth. Crosscorrelations in time series analysis indicate a growth rate delay of 1–3 years versus rainfall change rate. It has been noted that the site with highest delay in growth as a response to rainfall (lag = 3 years) is distinguished by the highest carbon content and the lowest base saturation in the top soil layer. The correlation between growth change rate and temperature change rate is poor (simple nonparametric correlation coefficients which in the modulus do not exceed 0.198) and not significant ($p > 0.19$).

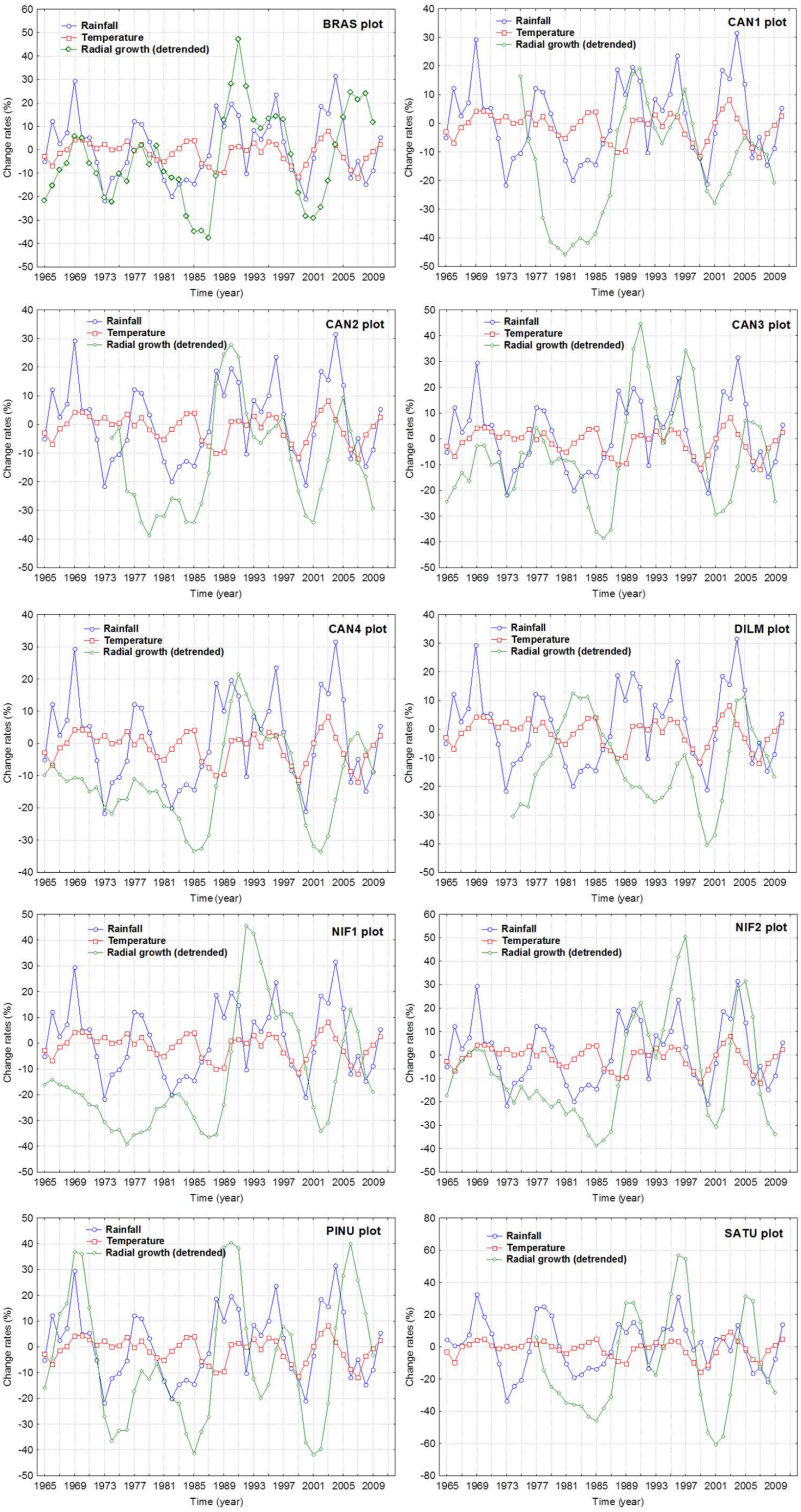


**Figure 6.** The dynamic of the change rates of detrended ring width, temperatures, and rainfall in the examined sample plots.

### 3.3. Logging Effects

Only logging from the BRAS and CAN3 stands seemed to stimulate radial growth (Table 4). In order to customize the logging effects, the nonclimatic noise series of radial growth was employed.

By comparing the GC values with the multiannual climatic regime, we noticed several aspects. The increased growth following the relative powerful thinning in the BRAS plot (GC = 294%) could have been caused, to some extent, by rainfall (RC = 10.5%). Indeed, the amount in the year prior to the intervention exceeded the multiannual average by 84.4 mm and was reached especially in May and June. In the following years, it oscillated a great deal, from 818.5 mm in 1991 to 461.7 mm in 1992. After 1989, the year of the intervention, the temperature increased again until 1994.

In order to delimit the contribution of climatic factors, we verified the multiple correlations between the detrended growth series and the temperature along with precipitation. For the eight-year sequence around the intervention, multiple *R* (0.774) shows a contribution to RW of up to 55.4% from temperature and rainfall from the period following the intervention. The sudden increase of GC_N was prepared in the previous year, when it became positive (Figure 7). Consequently, the revival of growth after 1989 in the BRAS plot was arranged by rainfall, but was actually allowed by thinning. The increase rate lasted only nine years, with GC subsequently returning to negative values.

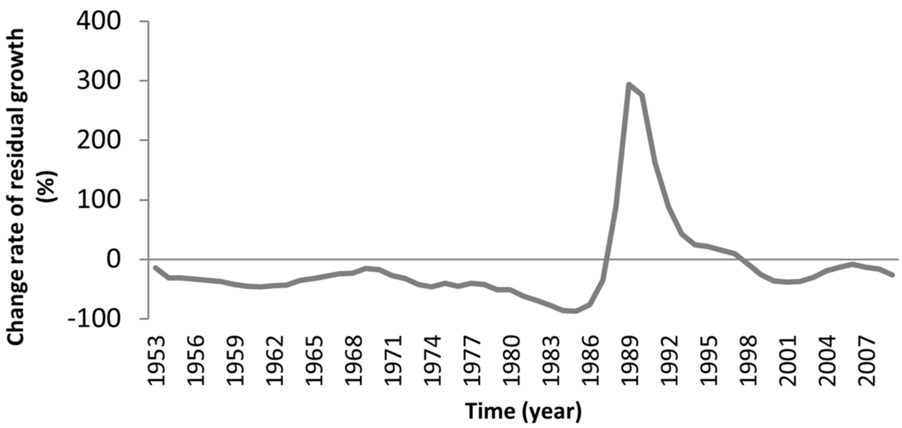


**Figure 7.** The variation of the growth change rate in the residual series of the ring width on the plot intensively managed.

The moderated logging on CAN2 seems to have had no bearing on growth (Table 4), despite the climatic incitement. The logging effects from the NIF1 plot on growth (Table 4) seem to be neutralized by temporary dryness. Actually, the RC value was on account of the low amount of rainfall during the year of logging, the surrounding seasons being normally supplied with water.

**Table 4.** The logging effects on the radial growth of trees.

| The Managed Plots | The Growth Changes after the Intervention | | | |
|---|---|---|---|---|
| | Change Rate of Undetrended Ring Width (%) | Change Rate of Residual Serie of Ring Width (%) | Change Rate of Air Temperature (%) | Change Rate of Rainfall (%) |
| BRAS | +18.93 | +294.23 | −9.60 | +10.46 |
| CAN1 | −7.03 | −25.61 | −0.90 | +4.51 |
| CAN2 | −2.69 | −15.98 | +3.49 | +10.16 |
| CAN3 | +16.47 | 7.72 | +2.46 | +23.56 |
| CAN4 | +2.37 | +86.64 | +2.46 | +23.56 |
| DILM | −12.18 | −18.86 | +2.46 | +23.56 |
| NIF1 | −30.62 | −36.74 | +2.43 | −21.63 |
| SATU | −17.36 | −26.65 | +3.00 | +8.49 |

## 4. Discussion

In the present study, the retrospective analysis of time series of the radial increments allowed the reconstruction of the behavior of pines planted on pluvial eroded land, at 80 years after the first afforestation. We have identified the sources of variation of the radial growth size, among which the age, the species and the fluctuations of rainfall, together with the temperature, have the greatest impact. The radial growth trends were analyzed in relation to the particular soil conditions. We diagnosed, at the same time, the effect of tending operations (cleanings and thinnings) on the rate of growth in relation to their intensity and climatic context.

Despite the adequate fitting and the relevant contribution of this research, we speculate that these multifactorial models could get more resolution with dendroecological data using individual tree models based on other studies [40]. For a better estimate of radial growth, the model should be strengthened with other variables related to vegetation, such as competition indices, spatial distribution indices, trees quality and health [86–92]. These should be tracked in dynamics, which extends research over time. The model could be improved with other climate variables as fixed effects, such as sunshine hours, soil temperature, relative air humidity, vapour pressure deficiency, as well rainfall and air temperature extremes [93,94].

### *4.1. Scots Pine vs. Black Pine in Terms of Radial Growth and Survival*

The size and the dynamics of tree growth are specie, genotype and age specific. In previous studies, growth rate differences have been reported between the two pine species, which are usually in favor of the black pine (on carbonate soils [95], on rendzinic leptosols [96], on deep soils on limestone [97], on the sunny slopes and on superficial soils in steppe [10], and in the tree nursery [98]), sometimes in favor of the Scots pine (on degraded land in the dry areas [99]). In the natural tree stands vulnerable to fires from the Dinaric Alps [100], as well on the well sunny slopes or on superficial soils in the Carpathians [51], the differences of growth between the two pin species are insignificant. In the present study, the differences in growth between the two species became perceptible only after stratification of the values according to the social positioning of the trees and the actual density of the plantations (Table 2, Figures 2 and 3).

If we take as starting point the assumption of physiological similarities of pine species, especially the photosynthetic ones, then the differences between black pine and Scots pine in terms of net production are due to a different level of climatic sensitivities [101]. Out the investigations we carried so far, it has been demonstrated that black pine is more resistant to drought [97]. The Scots pine is more sensitive to heat and drought [102], even after irrigation [103], due to the more drastic limitation of photosynthesis and transpiration, in the soil water deficit [104], by a stronger stomatal control [97]. Pines resistance to drought is due to their isohydric behavior [105], to the reduction of crown conductivity [106,107] and to a more efficient way to use the water [108] that leads to a diminished water loss. In relation to the pines, the dryness leads to cell walls becoming thinner and to tracheid's lumen becoming larger, with positive impact on the conductivity of the water [97]. The accelerate juvenile growth of the Scots pine comparing to the black pine (Figure 4) it was noticed shortly after planting pine trees on the degraded lands [99].

In our sites, it may be the reaction of pines to soil conditions rather than their different climatic sensitivities. The sandy cambisoils, with a high level of humus and a small level of stone, in a climate where rainfalls sometimes exceed 800 m·year$^{-1}$, have a positive influence on Scots pine [109]. The Scots pine also makes better use of the favorable microclimatic conditions in the under storey (Figure 3). Limiting factors such as shading or heavily declivous slopes, as well as the reduced physiological thickness of soils affects the two pine species equally.

In plantations established on degraded lands, more the erosion is advanced, more the black pine turned out to be competitive at a higher level than the Scots pine, in terms of the survival [10]. In our sites, moderately affected by pluvial erosion, 80 years after planting, only 13–22% of the initial trees (5000 trees·ha$^{-1}$) survived. The mixture of black pine and Scots pine, rather than pure tree stands, survived better on degraded land (Table 3). Scots pine in Romanian plantations proved to be vulnerable to wind and breaks caused by the snow [51]. It is, moreover, one of the most important causes of the reduced survival rate (Table 3). In these plantations, Scots pine grew faster (Figure 2), also because it is more shade-intolerant than the black pine [109]. The trees that survived have a good health. When they occur, the defoliations do not exceed 25% of the crown and are more pronounced to Scots pine than to black pine [110].

### *4.2. Age-Dependency against Climate-Related Trends in Growth*

The ontogenetic exponential decay of radial increments in sampled plantations (Figure 4) has the appearance of dynamics generated by the age of cambium. In Scots pine, the rapid decline in growth with age is a characteristic of trees with low wood quality of trunks [111], and the delay in mature wood formation is a result of difficult growing conditions [112]. Some sample plots from the present study showed a linear decline in radial growth, which is similar with a delay in maturation. The Scots pine stands from our plots are located on soils with very low level of nitrogen (0.15–0.20% nitrogen in mineral horizon A). The depletion of nitrogen occurred by sustaining an increased growth level of the trees for over 40 years. In fact, it is known that intensive land use with coniferous plantations, particularly pine, leads to alteration of soil fertility [113,114]. The length of the juvenile wood formation period in the examined trees corresponds to the values from the literature–between 6 and 16 years [115].

From 14–18 years, growth in the analyzed stands is declining. The decline of growth is primarily an aging process, physiologically and genetically controlled, which can be maintained by the environment [38].

The decline of radial growth is primarily an aging process, physiologically and genetically controlled, which can be supported by the environment [38]. Separating factors becomes even more difficult with maturation because the genetic control of wood formation gradually decreases [116]. The decline of growth closely followed the decline in the efficiency of water use [117]. Thus, it is not a random coincidence that the water intake in pine trees peaks at the age of 30–35 years [31], ie the age at which the transition to mature wood ends and the decline in growth is inevitable. In the internal silvosteppe, the decline of pine plantations is even faster at 25 years [21]. On degraded lands, the growth suppression phase ends with the die-back of Scots pine at 30 years, and black pine at 40–45 years [30].

Quantitatively, the climate (rainfall and temperature) contributed 3.1–57.3% to tree radial growth from the last decade variance in our plots. The contribution of rainfall seems to be greater than that of temperature (Figure 6), proving the xeric character of the sites. Temperature smooths the growth fluctuation with rainfall. The contribution of rainfall to black pine radial growth was estimated to be 54% [24], very similar to the cumulated contribution of rainfall and temperature to our BRAS plot. In black pine marginal populations, smaller contributions were reported (34% from rainfall and 27% from temperature) [118].

The temporal instability of the climate-growth link (Figure 5) was also noticed by Johnson et al. [64] and Pärn [119]. In an analysis of the red spruce's decline after 1960 in the eastern USA, this instability advocates the hypothesis that the causes of the recent auxologic regress are different from those in past centuries [38].

At the stage of decline, increased rainfall is no longer able to revive tree growth (Figure 6). Thus, the decline seems irreversible. In these conditions, the constancy of growth in the last decades seems to be mostly the physiological age effect, and the growth amount due to the effect of inhospitable soil conditions.

### *4.3. The Management of the Ecological Reconstruction on Land Degraded by Pluvial Erosion*

The degraded lands are unable to recover spontaneously, requiring human interventions through ecological reconstruction [13]. In the ecological reconstruction of eroded land, pines are only a supportive solution, the vegetation makeup being directed toward restoring local biodiversity [13,53,120,121]. Moreover, in the pine plantations made on degraded lands on the outskirts of the Carpathians, we observed that, after the age of 40, the stands were invaded by rustic deciduous trees [51]. Pine plantations have managed to recover degraded stations (Figure 1) and remain models to follow for similar actions, especially in climate warming. On the soils well supplied with water, the Scots pine and the black pine mixes are better than monocultures (Table 3).

The first technical measure for achieving this should be thinning. Failing a remedial management response, denser crops are more vulnerable to drought [35] and very low in biodiversity [122], due to the physiological inhibition of the understorey [35]. However, the authors argued that the dense forest microclimate can mitigate climate excesses, which have escalated in the past 50 years [123]. The thinned stands can be subsequently cut for regeneration and hygiene [124], and thus gradually substituted by local mixtures that are more effective from a hydrological and protective point of view. The pine monocultures can become functionally and productively unfit after only 15–20 years, being exposed to breakage and windthrow [19].

The former recovery solutions for eroded land in Romania were directed toward optimizing anti-erosion protection with the gain of maximum biomass. Overstressing the forest productive potential cannot be a long-term solution [125]. Our previous inquiries [73] stated that pine sites with greater physiological thickness of soil are not the most productive (partial correlation of the soil's physiological thickness with the site class: −0.899, $p < 0.05$). We can therefore infer that the recovered sites we studied were not well exploited by pines. Thus, they represent a reserve of resources available to future late-successional vegetation. The yield availability of our crops does not look promising, since the vegetation successional trend toward the climax leads to reduced productivity [126].

The most influential management measures distribute the competition in the trees' layer. The density of pine plantations on degraded lands must be optimized to reduce runoff by avoiding water stress on individuals [35]. In the dense pine forests of Romania, the drought was felt more strongly, with the decline it caused stopped only by a radical intervention, heavy thinning [127]. All the examined plantations in this study had the same initial density (5000 seedlings·ha$^{-1}$), and so the same competitive start. In the inhospitable sites where they were founded, the low survival demanded periodical gap-filling, which sometimes lasted up to 20 years. The behavior of the black pine understory (Figure 3) did not recommend it in gap-filling, which will use Scots pine or local hardwood, which is less light demanding.

### *4.4. Trees Response to Management*

The tree growth answer to thinning is according to its intensity [128]. At Scots Pine, it was found that the thinnings stimulate the division of cambium [39]. In our stands, the moderate thinning had a slight effect on tree growth for nine consecutive years (Figure 6). The weak interventions were not able to counteract the temporary deficit of rainfall and stop the decline (Table 4). In our findings, the effects of the release of competition on growth are biased toward climate. According to the results obtained for other species, following heavy thinning, the responsiveness of the subjects to temperature increased [128]. For ponderosa pine, the competition does not affect climatic sensitivity in the overstory [78].

A forcible management on degraded land would be likely to be risky, especially in the warming of the local climate. As a matter of fact, in Scots pine heavy thinnings do not generate a surplus of growth compared to moderate ones, on the contrary [129]. Pine plantations from recovered sites can be managed, with moderate intensities, also after the age at which growth enters declining, depending on the state of tree health. For Scots pine, for example, the prolonged decline in radial growth precedes mortality by 15–40 years [130]. However, it needs to be taken into account that the longevity of pine trees on eroded land is lower [10] and postponing the renewal of the vegetation layer could compromise ecological reconstruction. Because the degraded sites in the area we studied have not heavily treated, the present study can provide only suggestions for forest management, requiring further experimental research.

## 5. Conclusions

In the sites moderately affected by sheet erosion from Buzau, Scots pine showed a slightly greater increase in radial growth than black pine.

Moderately eroded lands in Buzău under the Carpathians (Eastern Romania) have been systematically afforested for 80 years. A retrospective analysis of the radial growth time series revealed several differences between the two pine species used for afforestation. In comparison with black pine, Scots pine had (1) stronger youth growth, (2) a higher growth range over time, and (3) a significant growth advantage for the plantations with lower survival rates and trees from the understory.

A decline in growth occurs in both species after 39 years. Declining growth rates are similar for both pines. Climate (air temperature together with rainfall) has a global contribution that can reach 57% in tree growth. The contribution is higher in the growth decline sequence. The response to rainfall can be prompt or delayed by 1–4 years. By analyzing the reaction to drought and improving rainfall in individual sample plots, the conclusion is that climate has allowed the decline or even accentuated it, without causing it.

Management of the pine plantations on degraded land in Romania has been quite mild. Slight to moderate logging did not have a substantial impact on the growth of standing trees. The largest growth rate after logging occurred with rainfall assistance. In this case, the growth increase after logging lasted nine years.

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