Forest Resources Management
ORIGINAL PAPER

1 (1) 2026, 5–16

frm.urk.edu.pl

ISSN 3072-4279

BASAL AREA INCREMENT RESPONSE OF SCOTS PINE TO EUROPEAN MISTLETOE INFESTATION IN CENTRAL POLAND

Zuzanna Wilińska[1]✉

Bogdan Wertz[1] 0000-0002-1376-9412

[1] Department of Forest Resources Management, Faculty of Forestry, University of Agriculture in Krakow, Krakow, Poland

ABSTRACT

European mistletoe (*Viscum album* L.) is an increasingly important biotic stressor in coniferous forests, especially under drought and warming. Scots pine (*Pinus sylvestris* L.) is the dominant forest-forming species in Poland, but local evidence on how mistletoe affects tree growth in relation to tree size remains limited. This study aimed to determine whether mistletoe infestation reduces basal area increment (BAI) of Scots pine and whether this effect depends on the relative diameter class of the host tree. A 45 m × 60 m sample plot was established in a 60-year-old pure Scots pine stand in the Piotrków Forest District, Central Poland. Diameter, height, bark thickness and mistletoe infestation were assessed, and increment cores were collected from 172 living pines. Tree-ring widths were measured, cross-dated and converted into annual BAI. Infestation was classified as absent, moderate or heavy, and trees were grouped into standardized diameter classes. Mistletoe occurred mainly on larger and taller trees. Heavily infested trees represented 46% of very thick trees but were absent from the very thin class. Growth reduction was most evident in trees currently classified as heavily infested. Between 2021 and 2025, their mean BAI decreased by 14% compared with 2015–2020, whereas BAI increased by 24% in moderately infested trees and by 11% in uninfested trees. In 2025, average-sized trees currently classified as heavily infested reached only 2.13 $cm^2 \cdot year^{-1}$, compared with 6.32 and 6.21 $cm^2 \cdot year^{-1}$ in moderately infested and uninfested trees. The results suggest that detectable growth reductions were associated mainly with trees classified as heavily infested.

HIGHLIGHTS

- Mistletoe was concentrated on thicker and taller Scots pines.
- Heavy infestation strongly reduced basal area increment.
- Low infestation did not clearly reduce recent growth.
- Current heavy-infestation class showed recent growth decline.
- Tree-size class should be included in mistletoe damage assessment.

KEYWORDS

Viscum album • *Pinus sylvestris* • basal area increment • tree rings • forest health • biotic stress

✉Corresponding author: zuzanna.wilinska@student.urk.edu.pl

DOI: http://doi.org/10.15576/FRM/226029

Accepted: 16.07.2026

© Copyright by Publishing House of the University of Agriculture in Krakow

1. INTRODUCTION

European mistletoe (*Viscum album* L.) is an evergreen hemiparasitic plant that photosynthesizes independently but obtains water, mineral nutrients and part of its carbon resources from the host through haustoria. In forest ecosystems its role is ambivalent. At low abundance, mistletoe may contribute to biodiversity, nutrient cycling and structural heterogeneity. At high abundance, however, it can become a relevant disturbance agent that reduces host vigour, productivity and survival (Glatzel and Geils 2009; Griebel et al. 2017). This dual role is important for forest management, because mistletoe should not be treated only as a botanical curiosity or only as a pest, but as a stressor whose impact depends on host species, infestation intensity, site conditions and climatic context.

The forestry importance of *Viscum album* has increased in Europe during recent decades. The occurrence of mistletoe on forest trees in Poland increased in 2008–2018, especially on Scots pine, silver fir and silver birch (Lech et al. 2020). Climate warming has also been linked with an upward shift in the altitudinal distribution of pine mistletoe in Switzerland, where its upper limit rose by about 200 m over the last century (Dobbertin et al. 2005). These observations are consistent with the view that warmer winters and longer vegetation periods may remove some climatic restrictions on mistletoe distribution, while repeated droughts may reduce the capacity of host trees to compensate for parasitic water losses.

Among European forest trees, Scots pine (*Pinus sylvestris* L.) is particularly relevant. It is one of the most widespread conifers in Europe and the dominant tree species in Poland, where it forms a large share of forest area and timber resources. At the same time, Scots pine is increasingly exposed to climate-related stress. Droughts can reduce radial growth, impair recovery and increase mortality risk in pine stands (Bigler et al. 2006; Galiano et al. 2011; Camarero et al. 2015). Because mistletoe maintains transpiration and draws water from the host xylem, its effect may be especially harmful when water availability is limited (Zweifel et al. 2012; Klamerus-Iwan and Van Stan 2023).

The mechanism of growth reduction is not limited to water extraction. Mistletoe infection can alter the host water and carbon balance, reduce photosynthetic tissue, affect needle size and modify the relationship between leaf area and sapwood area (Rigling et al. 2010; Bilgili et al. 2020a). Studies on Scots pine have shown that heavy mistletoe infection may reduce basal area increment by about 27–29% at stand scale in Germany (Kollas et al. 2018), by 41–64% in a Turkish destructive-sampling study (Bilgili et al. 2018), and by about 24% over the last decade in another Turkish comparison of infected and uninfected pines (Sakici et al. 2023). In Poland, a reduction in radial growth of Scots pine infected by *V. album* subsp. *austriacum* has also been reported (Pilichowski et al. 2018).

Infestation is rarely distributed randomly among trees. Larger, taller and better exposed hosts are often more frequently infected, probably because birds deposit seeds preferentially in prominent crowns and because higher light availability favours mistletoe establishment and growth (Kołodziejek and Kołodziejek 2013; Matula et al. 2015; Bilgili et al. 2020b). This creates a methodological problem: trees with mistletoe may have been more vigorous before infestation, so simple comparisons of infected and uninfected trees may confound parasite effects with initial tree size and social position. Basal area increment is therefore a useful response variable, because it combines radial growth with tree size and is more directly related to volume and biomass increment than ring width alone.

The aim of this study was to assess the effect of European mistletoe infestation on the basal area increment of Scots pine in the Piotrków Forest District, Central Poland, with special attention to relative tree diameter classes. We tested the hypothesis that heavy infestation reduces recent basal area increment, while moderate infestation has a weaker or non-detectable effect. We also expected mistletoe to occur more frequently on larger trees, which are more exposed in the canopy and more likely to be visited by seed-dispersing birds.

2. MATERIALS AND METHODS

2.1. Study area

The study was carried out in the Straszów forest range of the Piotrków Forest District, in the south-eastern part of the Regional Directorate of State Forests in Łódź, Central Poland. The district is dominated by fresh forest sites and Scots pine, which accounts for 88.4% of growing stock volume; the investigated stand was a 60-year-old pure Scots pine stand growing on a fresh coniferous forest site.

2.2. Field measurements and infestation assessment

A rectangular 45 m × 60 m sample plot was established in a stand selected after field reconnaissance and consultation with forest staff to include trees representing a wide range of mistletoe infestation. All living Scots pine trees with diameter at breast height above 7 cm were included. In total, 172 Scots pines were measured. Diameter at breast height was measured in two perpendicular directions, tree height was measured with a Vertex hypsometer, and one increment core was collected at breast height from each tree using an increment borer. Bark thickness was additionally measured on 35 trees representing the full diameter range in order to construct a local linear bark-thickness model. Mistletoe infestation was assessed visually in three crown sections: lower, middle and upper. Each section was rated from 0 to 4 according to the proportion of crown volume occupied by mistletoe: 0 – no mistletoe; 1 - up to 25%; 2 - 25-50%; 3 - 50-75%; 4 - more than 75%. The sum of section ratings was then converted into the mistletoe infestation class (MIC): NI - not infested trees, total rating 0; MI - moderately infested trees, total rating 1-3; HI - heavily infested trees, total rating 4-12. Because mistletoe infestation was assessed only at the time of sampling, retrospective BAI patterns were interpreted in relation to the current infestation class of each tree. The section scores were based on a crown-volume assessment approach adapted from Barbu (2009). In this approach, the crown is divided into sections and mistletoe abundance is assessed separately in each part of the crown. In the present study, each of the three crown sections was assigned a score from 0 to 4 according to the estimated proportion of crown volume occupied by mistletoe. The total score therefore ranged from 0 to 12. The final MIC thresholds were adapted to the observed infestation structure in the investigated Scots pine stand. A total score of 0 represented trees without mistletoe (NI), scores 1-3 represented trees with limited or localized infestation, usually restricted to one crown section or occupying only a small proportion of the crown (MI), whereas scores 4-12 represented trees with more extensive infestation affecting a larger part of the crown or more than one crown section (HI). The threshold between MI and HI was set at a total score of 4 because this value indicates a clear shift from localized infestation to more extensive crown infestation. A score of 4 may already represent substantial infestation, for example one crown section occupied by more than 75% mistletoe volume, two crown sections occupied by 25-50%, or a lower but more widespread infestation across several crown sections. Therefore, the HI class was intended to identify trees with a clearly higher mistletoe load, not only trees with extreme infestation throughout the entire crown.

2.3. Tree-ring processing and basal area increment

Increment cores were mounted, dried, sanded and scanned at 2400 dpi. Ring widths were measured with CooRecorder 9.8.0 and cross-dated with CDendro 9.8.0. A local linear relationship between double bark thickness and diameter was used to estimate bark thickness for all sampled trees. Historical diameter without bark was reconstructed backwards using double ring-width increments, and annual basal area was calculated from reconstructed diameter. Annual basal area increment was calculated as the difference between basal area in a given year and in the preceding year. To account for tree size, each tree was assigned to a standardized diameter class (Dst) using z-scores based on the mean and standard deviation of diameter on the plot. Five classes were distinguished: -2 reflecting very thin trees, -1 representing thin trees, 0 representing trees of average diameter, +1 representing thick trees and +2 representing very thick trees. Recent growth patterns were analysed for the whole sample and separately within each standardized diameter class. The main comparison focused on the last 10 years, with special attention to the period 2020-2025, when the separation between MIC groups was expected to be most apparent.

Before statistical testing, the distribution of annual basal area increment (BAI) was assessed. Because BAI did not meet the assumption of normal distribution, differences in annual BAI among the combined MIC and standardized diameter classes were tested using the non-parametric Kruskal-Wallis test. The combined classes were coded as MIC followed by standardized diameter class (for example, NI+1 denotes not infested trees from standardized diameter class +1). For years in which the Kruskal-Wallis test was significant, post-hoc multiple comparisons of mean ranks were used to identify pairs of groups that differed significantly. The analysis was performed separately for each year from 2020 to 2025. Differences in diameter and height among mistletoe infestation classes were tested using the non-parametric Kruskal-Wallis test, followed by post-hoc multiple comparisons of mean ranks when

significant differences were detected. Statistical analyses were performed using Statistica 13.3 software (TIBCO Software Inc., USA). Data preparation and calculation of annual basal area increment were conducted in Microsoft Excel.

We additionally fitted a linear mixed-effects model with tree identity included as a random effect to account for repeated annual observations of the same individuals. The model included diameter class, mistletoe infestation class, year (expressed as years before final assessment), and their interactions. The model was developed in the R v.4.5.3 environment (R Core Team, 2026) supported by RStudio v.2026.01.1 with the help of packages lme4 v.2.0-1 (Bates et al. 2015).

3. RESULTS

3.1. Stand structure and distribution of infestation

The sample included 172 Scots pines. Mean diameter was 20.85 cm and mean height was 19.51 m. At a time of performing measurements 75 trees were classified as not infested (NI), 62 were classified as moderately infested (MI), and 35 were classified as heavily infested (HI). Both MI and HI trees were significantly thicker and taller than NI trees, whereas differences between MI and HI classes were not statistically significant. The differences among MIC groups were statistically significant for both diameter and height. Diameter differed significantly among infestation classes (Kruskal-Wallis test, $H = 27.51$, $p < 0.001$) and post-hoc comparisons showed that both MI and HI trees had significantly larger diameters than NI trees (NI vs. MI: $p = 0.0042$; NI vs. HI: $p < 0.001$), whereas the difference between MI and HI trees was not significant (MI vs. HI: $p = 0.0629$). Tree height also differed significantly among MIC groups ($H = 21.15$, $p < 0.001$), sharing a similar pattern to diameter . Mean diameter increased from 19.60 cm in NI trees to 21.18 cm in MI trees and 22.93 cm in HI trees (Table 1). Mean height showed a similar gradient, from 19.03 m to 19.77 m and 20.08 m, respectively.

The proportion of HI trees increased strongly with standardized diameter class. No HI trees were found among very thin trees, while this infestation class represented 7.8% of thin trees, 17.0% of average trees, 36.4% of thick trees and 46.2% of very thick trees (Table 2). This pattern confirms that mistletoe was concentrated mainly in larger and probably more dominant individuals.

3.2. Temporal changes in basal area increment

During a large part of the analysed period, trees currently classified as HI showed higher mean annual BAI than NI and MI trees (Fig. 1). This pattern reflects the concentration of mistletoe on larger trees with higher growth potential. However, in the last period, this previous growth advantage weakened and disappeared. The decline in trees currently classified as HI became most visible after year 2021, whereas NI and MI trees maintained or even increased their recent increment. The chronology therefore indicates that trees currently classified as HI were not characterized by chronically low growth throughout the whole period, but rather experienced a recent, abrupt reversal in growth dynamics. In 2015–2020, mean BAI of trees currently classified as HI was 4.89 $cm^2 \cdot year^{-1}$, while it was as high as 4.53 $cm^2 \cdot year^{-1}$ in MI trees and 4.23 $cm^2 \cdot year^{-1}$ in NI trees. In 2021–2025, the mean increment of trees currently classified as HI decreased

Table 1. Biometric characteristics of Scots pine trees by mistletoe infestation class (MIC). Values are means ± standard error unless stated otherwise (Source: Authors' own study)

MIC	n	Mean height (m)	Mean diameter (cm)	Min-max height (m)	Min-max diameter (cm)
All Scots pines	172	19.51 ± 0.09	20.85 ± 0.25	16.00–23.10	13.40–30.15
NI (not infested)	75	19.03 ± 0.14	19.60 ± 0.36	16.00–22.10	14.55–27.00
MI (moderately infested)	62	19.77 ± 0.15	21.18 ± 0.36	17.10–22.40	13.40–27.50
HI (heavily infested)	35	20.08 ± 0.18	22.93 ± 0.51	17.60–23.10	16.10–30.15

Table 2. Number of trees in MIC groups within standardized diameter classes (Dst) (Source: Authors' own study)

Diameter class	n				Share (%)	
	All	NI	MI	HI	NI	MI
Very thin (–2)	11	7	4	0	63.6	36.4
Thin (–1)	51	35	12	4	68.6	23.5
Average (0)	53	18	26	9	34.0	49.1
Thick (+1)	44	12	16	16	27.3	36.4
Very thick (+2)	13	3	4	6	23.1	30.8

to 4.21 $cm^2 \cdot year^{-1}$ (a reduction of 14%) while increment in MI trees increased to 5.63 $cm^2 \cdot year^{-1}$ and to 4.68 $cm^2 \cdot year^{-1}$ in NI trees.

The separation among MIC groups was even stronger when tree size was considered. In the average diameter class, mean annual BAI in 2020 was similar among MIC groups: 4.56 cm^2 in NI, 4.62 cm^2 in MI and 4.45 cm^2 in HI. By 2025, however, trees currently classified as HI had decreased to 2.13 $cm^2 \cdot year^{-1}$, whereas MI and NI trees reached 6.32 and 6.21 $cm^2 \cdot year^{-1}$, respectively. In the thick class, trees currently classified as HI decreased from 5.69 $cm^2 \cdot year^{-1}$ in 2020 to 3.44 $cm^2 \cdot year^{-1}$ in 2025.

3.3. Recent differences among diameter and MIC groups

In 2025, marked differences between trees currently classified as heavily infested and uninfested or moderately infested trees were observed in thin, average and thick diameter classes. Among thick trees, individuals currently classified as HI reached 3.38 ± 0.60 $cm^2 \cdot year^{-1}$, compared with 7.26 ± 0.57 $cm^2 \cdot year^{-1}$ in MI trees and 8.19 ± 0.84 $cm^2 \cdot year^{-1}$ in NI trees. Among average trees, individuals currently classified as heavily infested reached 2.13 ± 0.95 $cm^2 \cdot year^{-1}$, compared with 6.32 ± 0.56 $cm^2 \cdot year^{-1}$ and 6.21 ± 0.68 $cm^2 \cdot year^{-1}$, respectively. Among thin trees, the corresponding values were 1.84 ± 0.55 $cm^2 \cdot year^{-1}$, 3.75 ± 0.46 $cm^2 \cdot year^{-1}$ and 4.72 ± 0.41 $cm^2 \cdot year^{-1}$. Differences between NI and MI trees were not consistent, suggesting that moderate infestation did not yet cause a measurable decrease in BAI. The Kruskal-Wallis test confirmed statistically significant differences in annual BAI among the combined MIC and standardized diameter classes in every analysed year from 2021 to 2025 (Table 3). The strongest overall differentiation was observed in 2023 (H = 76.36), followed by 2021 (H = 70.25), 2022 (H = 67.39), 2025 (H = 64.48) and 2024 (H = 59.00); in all years $p < 0.001$. This confirms that recent annual growth differed significantly among the groups created by combining MIC and standardized tree size.

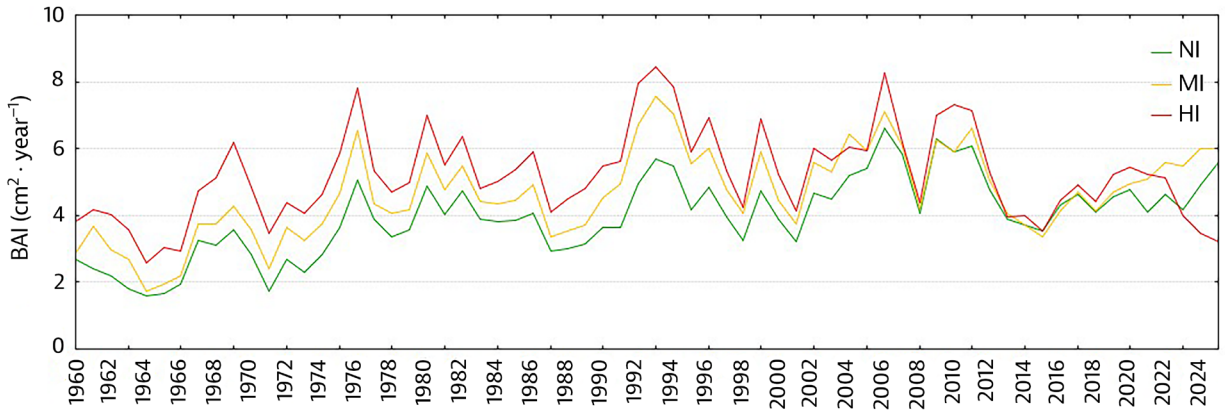
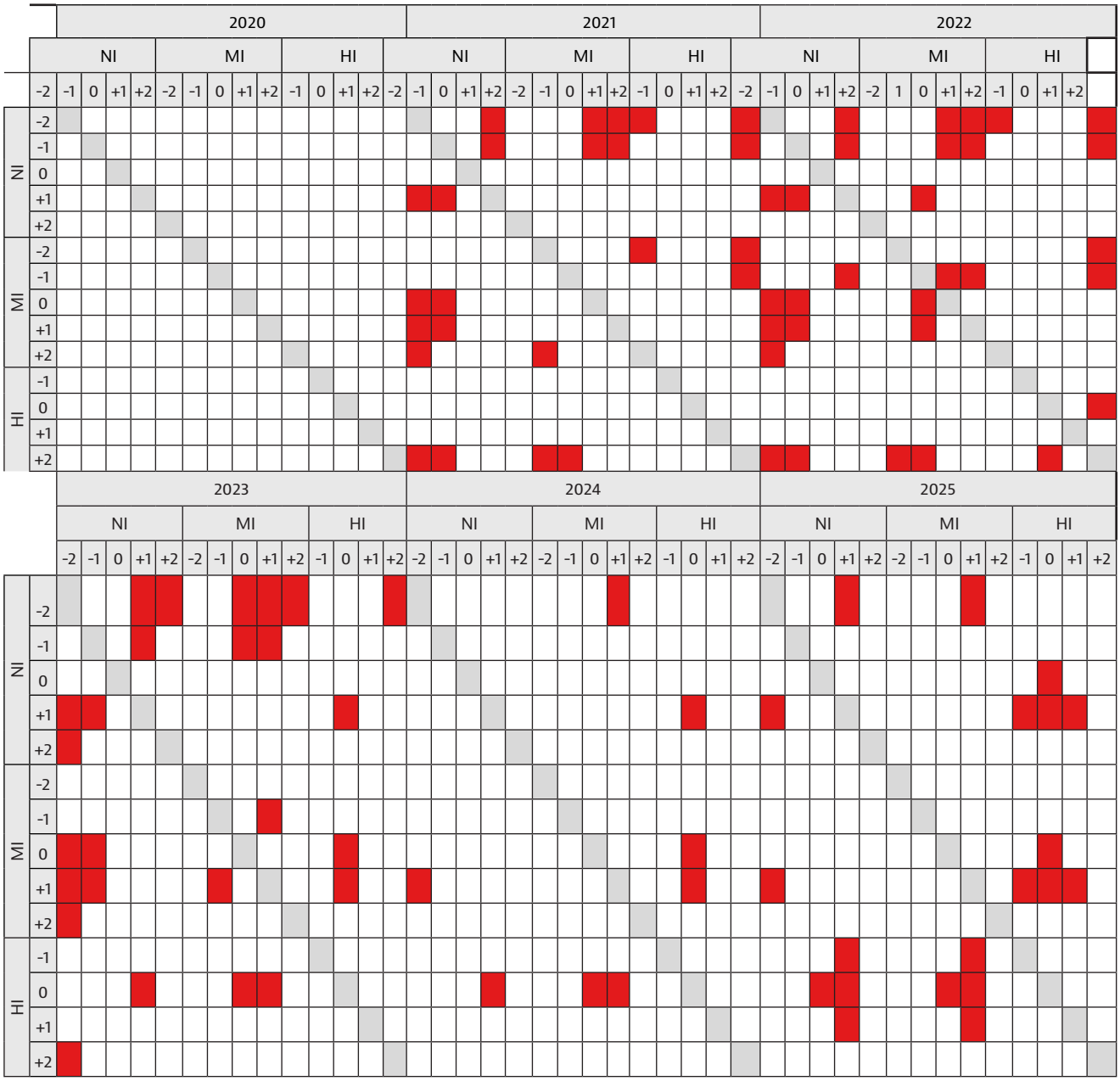


Fig. 1. Long-term chronology of mean annual basal area increment (BAI) of Scots pine trees according to mistletoe infestation class (MIC): NI - not infested, MI - moderately infested, HI - heavily infested (Source: Authors' own study)

Table 3. Pairwise post-hoc differences in annual basal area increment (BAI) among combined mistletoe infestation class (MIC) and standardized diameter class categories in years 2020–2025. Red cells indicate significant differences at $p < 0.05$ following post-hoc multiple comparisons after the Kruskal-Wallis test (Source: Authors' own study)



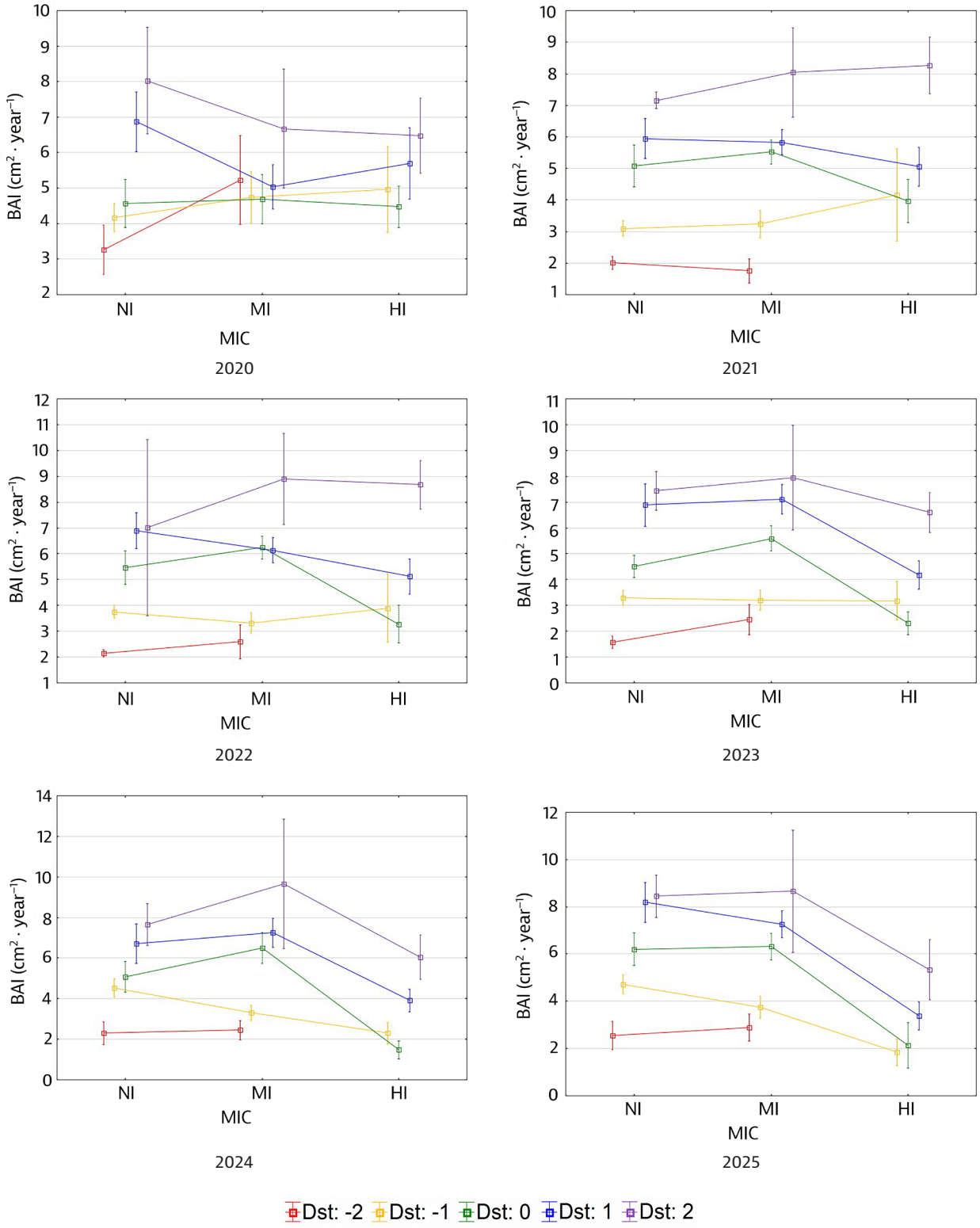


Fig. 2. Mean annual basal area increment (BAI) in years 2020–2025 according to mistletoe infestation class (MIC): NI - not infested, MI - moderately infested, HI - heavily infested and standardized diameter class (Dst). Points represent means and whiskers indicate ±1 standard error (Source: Authors' own study)

In all analysed years, BAI generally increased with standardized diameter class, which confirms the strong effect of tree size on this variable (Fig. 2). Trees from the highest standardized diameter classes, especially Dst+1 and Dst+2, usually showed the greatest mean increment values, whereas the lowest values were observed in the thinnest trees from Dst−2 and Dst−1. However, the pattern changed depending on mistletoe infestation intensity. In 2020–2022, differences among MIC groups were less consistent, and the effect of tree size was dominant. In these years, trees from higher diameter classes maintained relatively high BAI even when they were classified as HI. From 2023 onwards, the negative effect of heavy mistletoe infestation became more visible. In particular, HI trees showed a clear decrease in mean BAI compared with NI and MI trees within similar diameter classes. This decline was especially evident in 2024 and 2025. In these years, the mean BAI of HI trees from Dst 0 and Dst+1 was markedly lower than that of NI and MI trees. The reduction observed in HI trees suggests that heavy mistletoe infestation increasingly limited radial growth in the final years of the analysed period. At the same time, HI trees from Dst+2 still maintained relatively higher increment than thinner HI trees, indicating that the negative effect of mistletoe was partly modified by tree size and previous growth potential.

Overall, the graphical pattern supports the results of the Kruskal-Wallis test and the post-hoc comparisons summarized in table 3. In 2021 and 2022, significant pairwise differences were mainly associated with standardized diameter class rather than with a clear negative effect of mistletoe. In these years, HI very thick trees still belonged to the high-growth group, indicating that tree size and previous growth potential dominated over infestation effects. From 2023 onwards, the pattern changed and contrasts involving HI average-diameter trees became evident. In 2023 and 2024, HI trees from Dst0 had significantly lower BAI than several NI and MI groups of comparable or higher diameter classes. In 2025, the negative effect of heavy infestation was most pronounced: HI trees from Dst0 and Dst+1 showed significantly lower BAI than corresponding NI and MI trees. This indicates that the recent growth reduction was mainly associated with heavy infestation and became clearly visible in average and thick trees during the final years of the chronology.

The linear mixed-effects model fitted to further quantify the effects of tree size, temporal trends and mistletoe infestation intensity while accounting for repeated observations of individual trees with tree identity included as a random effect confirmed a strong positive relationship between stem diameter and basal area increment (BAI), indicating that larger trees maintained higher growth rates (Fig. 3). The temporal pattern of BAI was nonlinear, with significant polynomial components describing changes in increment during the analysed period. Significant interactions between diameter and time indicated that temporal changes in BAI differed among tree size classes, consistent with the observed divergence of growth trajectories among standardized diameter groups. Mistletoe infestation status significantly affected BAI only in HI trees. Compared with NI trees, individuals currently classified as HI showed significantly lower BAI ($\beta = -1.75$, $p < 0.001$), whereas MI trees did not differ significantly from NI trees. The interaction between infestation class and diameter was not significant, suggesting that the effect of infestation severity was not restricted to a particular size class. However, significant interactions between infestation class and time indicated different temporal trajectories of BAI among infestation groups. In particular, the decline in BAI over the recent years was considerably stronger in HI trees, supporting the pattern observed in the annual comparisons. The random effects revealed substantial variability among individual trees, both in average BAI (SD = 3.17 $cm^2 \cdot year^{-1}$) and in temporal changes in increment (SD of random slope = 0.65), demonstrating that tree-specific growth history contributed considerably to observed variation. Overall, the mixed-effects model supported the descriptive analyses, indicating that the recent reduction in growth was primarily associated with heavy mistletoe infestation, while tree size remained an important determinant of growth potential.

4. DISCUSSION

The results support the hypothesis that mistletoe reduces recent growth of Scots pine mainly when infestation becomes heavy. The lack of a clear difference between not infested and moderately infested trees indicates that the host can probably compensate for low parasite loads, at least in the short term and under the conditions of the investigated stand. This is consistent with studies on fir and pine, where the strongest reductions in radial or basal area increment were observed only in higher MIC groups (Barbu 2009; Bukowiec and Bednarz 2017; Pilichowski et al.

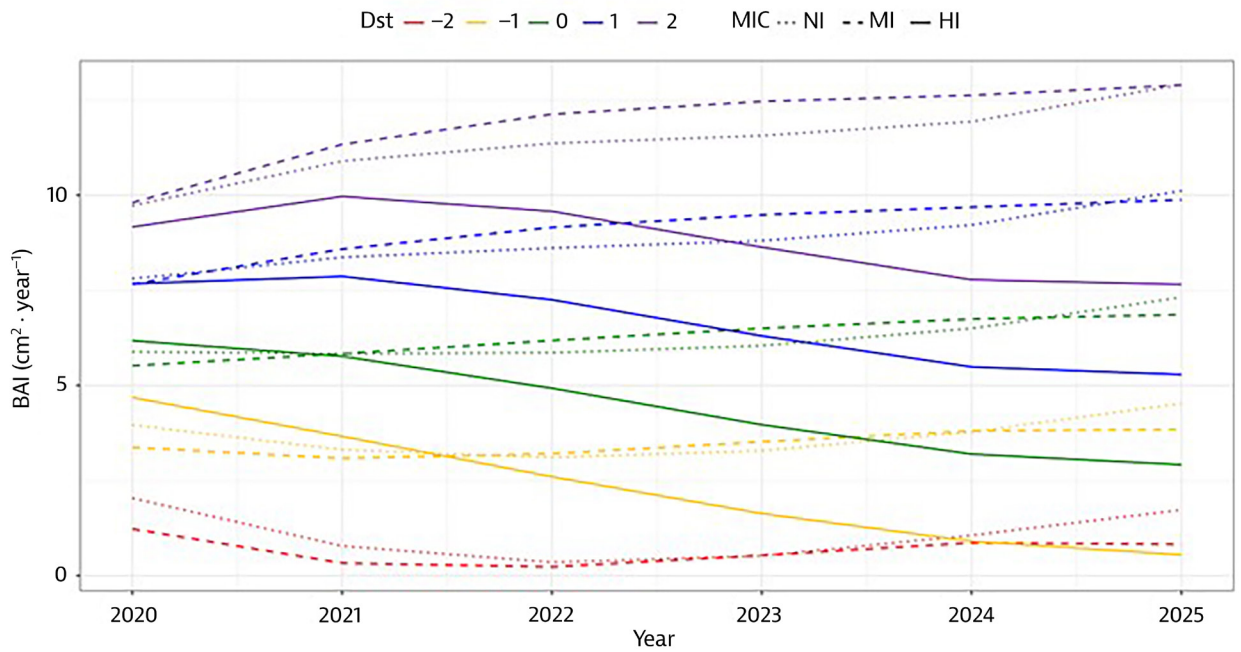


Fig. 3. Predicted mean annual basal area increment (BAI) derived from the linear mixed-effects model (LMM) for 2020–2025 across mistletoe infestation classes (MIC) and standardized diameter classes (Dst) (Source: Authors' own study)

2018). The present study adds that this threshold-like pattern is also visible when growth is expressed as BAI and compared within relative tree-size classes. The use of BAI is important because ring width alone may underestimate the contribution of larger trees to stand production. A narrow ring on a thick stem can represent a larger addition of wood area than a wider ring on a small stem. Since mistletoe was concentrated on larger trees, analysing only mean ring width could lead to an incomplete interpretation of production losses. BAI is also closer to volume and biomass increment, which are central variables for forest management, timber production and carbon sequestration. However, this approach requires reconstruction of historical diameter and therefore depends on assumptions about bark thickness, pith position and within-stem eccentricity. These limitations should be considered when interpreting exact numerical values, but they do not change the general direction of the observed recent decline in trees currently classified as HI.

The concentration of mistletoe on thicker trees is consistent with earlier work from Central Poland and other regions (Kołodziejek and Kołodziejek 2013; Matula et al. 2015; Bilgili et al. 2020b). Several non-exclusive mechanisms may explain this pattern. Larger trees offer a greater target area for seed deposition, more perching sites for birds and better light conditions for mistletoe development. They may also be older, giving mistletoe more time to establish and spread within the crown. From a management perspective, this distribution pattern is unfavourable, because HI trees are often the most valuable crop trees and the individuals contributing strongly to stand basal area increment before infestation becomes severe. The sharp divergence after about 2021 suggests that mistletoe effects may become visible only after a period of apparently normal growth. Similar delayed or cumulative responses have been reported in Scots pine exposed to drought and mistletoe, where reduced growth, crown degradation, altered water-use efficiency and lower resilience may interact over several years (Rigling et al. 2010; Sangüesa-Barreda et al. 2012; Camarero et al. 2019). In this study, trees currently classified as HI had previously shown the highest growth but then shifted to the lowest recent increment. This reversal may reflect a situation in which vigorous dominant trees initially tolerate infestation, but as mistletoe biomass increases, the additional demand for water and carbon exceeds the host's compensatory capacity. The mixed-effects model provided additional support for these patterns by accounting for repeated observations of individual trees and separating tree-specific variability from the effects of diameter, time and infestation status. The

model confirmed that tree size remained a major determinant of basal area increment, with larger trees maintaining higher growth potential. However, after accounting for this size effect, trees currently classified as HI showed significantly lower BAI than NI trees, whereas MI trees did not differ significantly. This supports the interpretation that growth reduction is associated primarily with advanced infestation rather than with the presence of mistletoe itself. Significant interactions between infestation status and temporal trends further indicate that the negative effect of heavy infestation was not constant throughout the analysed period but became increasingly evident during recent years, corresponding to the divergence observed in annual BAI trajectories.

Water relations are probably a key mechanism behind the observed growth reduction. Mistletoe acts as a persistent leak in the host water transport system, maintaining transpiration and water uptake from the host xylem even when the tree attempts to reduce water loss by stomatal closure (Zweifel et al. 2012). Recent work also indicates that mistletoe can add another form of water loss at the canopy level by intercepting rainfall and increasing evaporative losses from infected crowns (Klamerus-Iwan and Van Stan 2023). These processes may be particularly important in Scots pine stands growing on fresh or poor coniferous sites, where soil water reserves can become limiting during warm and dry periods. Mistletoe effects are also linked to carbon balance and crown condition. Reduced needle length, needle area and altered leaf area-sapwood area relationships in infected Scots pine indicate that the host assimilatory apparatus may decline as infestation increases (Bilgili et al. 2020a). At the same time, the parasite may affect host metabolism, phytohormone profiles and oxidative stress processes in bark and wood (Hu et al. 2017). The combination of lower photosynthetic capacity, water stress and additional carbon demand may explain why trees currently classified as HI in this study showed a recent decline in basal area increment while NI and MI trees continued to increase their increment.

The findings have direct implications for forest management. First, monitoring should record not only the presence of mistletoe, but also infestation intensity and the size or social position of the host tree. Methods based on crown sections or sample plots can support early detection and comparable assessments across stands (Kędziora et al. 2020). Second, moderate infestation should not automatically be interpreted as immediate production loss, but it should be treated as a warning stage requiring repeated observation. Third, because heavy infestation affects dominant and thick trees, delayed intervention may lead to a loss of the most productive component of the stand. Removing severely infested trees, regulating light conditions and reducing the number of seed sources may be justified in stands where production and sanitary objectives dominate (Iszkuło et al. 2020). At the same time, management decisions should not ignore the ecological role of mistletoe. Mistletoe can support biodiversity and influence nutrient cycling, and its complete elimination is neither realistic nor always desirable (Griebel et al. 2017). The practical objective should therefore be to prevent severe infestation and associated growth losses rather than to remove every infected tree. The study was based on one sample plot, which might limit the generality of the results; however, the consistent pattern within diameter classes indicates that heavy mistletoe infestation was associated with a recent and substantial reduction in basal area increment. An additional limitation is that mistletoe infestation intensity was assessed only at the time of sampling, whereas growth patterns were reconstructed retrospectively from tree rings. Therefore, the results should be interpreted as relationships between past BAI dynamics and the current infestation class, rather than as a direct record of infestation intensity in each previous year. Future research should aim to define operational thresholds: for example, infestation levels at which basal area increment loss becomes economically relevant under specific site and drought conditions. Multi-plot studies combining tree-ring analysis, crown condition, microclimate and stand density would be especially useful for translating the threshold concept into silvicultural guidelines.

5. CONCLUSIONS

Mistletoe infestation in the investigated Scots pine stand was concentrated mainly on larger and taller trees; the share of HI trees increased from 0% in the very thin class to 46% in the very thick class.

Heavy infestation was associated with a clear recent decrease in basal area increment, whereas MI trees did not show a consistent reduction compared with NI trees. This pattern was confirmed by a linear mixed-effects model accounting for individual tree variability, indicating that the observed decline was not solely a consequence of differences in tree size or growth potential.

Assessment of mistletoe damage in pine stands should combine infestation intensity with tree size or social position, because the strongest economic impact may occur in dominant trees.

Further studies should define site-specific infestation thresholds and include drought indices, stand density and crown condition to support forest management decisions.

Acknowledgements and funding

The authors thank the staff of the Piotrków Forest District for assistance in selecting the study stand and access to field information. No external funding was received.

Declaration of competing interests

The authors declare no competing interests.

Data availability statement

The data underlying this study are available from the corresponding author upon reasonable request.

REFERENCES

Barbu, C. 2009. Impact of mistletoe attack (*Viscum album* ssp. *abietis*) on the radial growth of silver fir. A case study in the North of Eastern Carpathians. Annals of Forest Research, 52(1): 89–96.

Bates, D., Mächler, M., Bolker, B., Walker, S. 2015. Fitting Linear Mixed-Effects Models Using lme4. J. Stat. Softw. 67. https://doi.org/10.18637/jss.v067.i01.

Bigler, C., Bräker, O.U., Bugmann, H., Dobbertin, M., Rigling, A. 2006. Drought as an inciting mortality factor in Scots pine stands of the Valais, Switzerland. Ecosystems, 9(3): 330–343. https://doi.org/10.1007/S10021-005-0126-2

Bilgili, E., Ozturk, M., Coskuner, K.A., Baysal, I., Serdar, B., Yavuz, H., Eroglu, M., Usta, Y. 2018. Quantifying the effect of pine mistletoe on the growth of Scots pine. Forest Pathology, 48(4): 1–9. https://doi.org/10.1111/efp.12435

Bilgili, E., Coskuner, K.A., Ozturk, M. 2020a. Leaf area-sapwood area relationship in Scots pine (*Pinus sylvestris* L.) under mistletoe (*Viscum album* ssp. *austriacum*) infection. Dendrobiology, 84: 1–11. https://doi.org/10.12657/DENBIO.084.001

Bilgili, E., Coskuner, K.A., Baysal, I., Ozturk, M., Usta, Y., Eroglu, M., Norton, D. 2020b. The distribution of pine mistletoe (*Viscum album* ssp. *austriacum*) in Scots pine (*Pinus sylvestris*) forests: from stand to tree level. Scandinavian Journal of Forest Research, 35(1–2): 20–28. https://doi.org/10.1080/02827581.2020.1729402

Bukowiec, G., Bednarz, B. 2017. Wpływ jemioły pospolitej jodłowej (*Viscum album* ssp. *abietis*) na przyrosty roczne jodły pospolitej (*Abies alba*). Acta Scientiarum Polonorum, Silvarum Colendarum Ratio et Industria Lignaria, 16(2): 77–83.

Camarero, J.J., Gazol, A., Sangüesa-Barreda, G., Oliva, J., Vicente-Serrano, S.M. 2015. To die or not to die: Early warnings of tree dieback in response to a severe drought. Journal of Ecology, 103 (1): 44–57. https://doi.org/10.1111/1365-2745.12295

Camarero, J.J., González de Andrés, E., Sangüesa-Barreda, G., Rita, A., Colangelo, M. 2019. Long- and short-term impacts of a defoliating moth plus mistletoe on tree growth, wood anatomy and water-use efficiency. Dendrochronologia, 56, 125598. https://doi.org/10.1016/J.DENDRO.2019.05.002

Dobbertin, M., Hilker, N., Rebetez, M., Zimmermann, N.E., Wohlgemuth, T., Rigling, A. 2005. The upward shift in altitude of pine mistletoe (*Viscum album* ssp. *austriacum*) in Switzerland – the result of climate warming? International Journal of Biometeorology, 50(1): 40–47. https://doi.org/10.1007/S00484-005-0263-5

Galiano, L., Martínez-Vilalta, J., Lloret, F. 2011. Carbon reserves and canopy defoliation determine the recovery of Scots pine 4 yr after a drought episode. New Phytologist, 190(3): 750–759. https://doi.org/10.1111/J.1469-8137.2010.03628.X

Glatzel, G., Geils, B.W. 2009. Mistletoe ecophysiology: Host-parasite interactions. Botany, 87(1): 10–15. https://doi.org/10.1139/B08-096

Griebel, A., Watson, D., Pendall, E. 2017. Mistletoe, friend and foe: Synthesizing ecosystem implications of mistletoe infection. Environmental Research Letters, 12(11): 115012. https://doi.org/10.1088/1748-9326/aa8fff

Hu, B., Sakakibara, H., Takebayashi, Y., Peters, F.S., Schumacher, J., Eiblmeier, M., Arab, L., Kreuzwieser, J., Polle, A., Rennenberg, H. 2017. Mistletoe infestation mediates alteration of the phytohormone profile and anti-oxidative metabolism in bark and wood of its host *Pinus sylvestris*. Tree Physiology, 3(5), 676–691. https://doi.org/10.1093/treephys/tpx006

Iszkuło, G., Armatys, L., Dering, M., Ksepko, M., Tomaszewski, D., Ważna, A., Giertych, M.J. 2020. Mistletoe as a threat to the health state of coniferous forest. Sylwan, 164(3): 226–236. https://doi.org/10.26202/sylwan.2019121

Kędziora, W., Bobińska, A., Wójcik, R. 2020. Proposition of a large-scale mistletoe inventory method. Sylwan, 164(7): 568–575. https://doi.org/10.26202/SYLWAN.2020034

Klamerus-Iwan, A., Van Stan, J.T. 2023. Rainfall interception by common mistletoe (*Viscum album* L. ssp. *album*): An additional water loss from infected forests. Ecohydrology, 16(4): 1–7. https://doi.org/10.1002/eco.2485

Kollas, C., Gutsch, M., Hommel, R., Lasch-Born, P., Suckow, F. 2018. Mistletoe-induced growth reductions at the forest stand scale. Tree Physiology, 38(5): 735–744. https://doi.org/10.1093/treephys/tpx150

Kołodziejek, J., Kołodziejek, A. 2013. The spatial distribution of pine mistletoe *Viscum album* ssp. *austriacum* (Wiesb.) Volmann in a Scots pine (*Pinus sylvestris* L.) stand in Central Poland. Polish Journal of Ecology, 61(4), 705–714.

Lech, P., Żółciak, A., Hildebrand, R. 2020. Occurrence of European mistletoe (*Viscum album* L.) on forest trees in Poland and its dynamics of spread in the period 2008-2018. Forests, 11(1): 83. https://doi.org/10.3390/f11010083

Matula, R., Svátek, M., Pálková, M., Volařík, D., Vrška, T. 2015. Mistletoe infection in an oak forest is influenced by competition and host size. PLoS ONE, 10(5): e0127055. https://doi.org/10.1371/journal.pone.0127055

Pilichowski, S., Filip, R., Kościelska, A., Żaroffe, G., Żyźniewska, A., Iszkuło, G. 2018. Influence of *Viscum album* ssp. *austriacum* (Wiesb.) Vollm. on tree radial growth of *Pinus sylvestris* L. Sylwan, 162(6): 452–459.

R Core Team. 2026. R: A Language and Environment for Statistical Computing.

Rigling, A., Eilmann, B., Koechli, R., Dobbertin, M. 2010. Mistletoe-induced crown degradation in Scots pine in a xeric environment. Tree Physiology, 30(7): 845–852. https://doi.org/10.1093/treephys/tpq038

Sakici, O.E., Özcan, G.E., Seki, M., Sağlam, F. 2023. The effects of pine mistletoe (*Viscum album* subsp. *austriacum*) on the growth of Scots pine and Crimean pine in Turkey. Forest Pathology, 53(2): 1–11. https://doi.org/10.1111/efp.12802

Sangüesa-Barreda, G., Linares, J.C., Camarero, J.J. 2012. Mistletoe effects on Scots pine decline following drought events: Insights from within-tree spatial patterns, growth and carbohydrates. Tree Physiology, 32(5): 585–598. https://doi.org/10.1093/treephys/tps031

Zweifel, R., Bangerter, S., Rigling, A., Sterck, F.J. 2012. Pine and mistletoes: How to live with a leak in the water flow and storage system? Journal of Experimental Botany, 63(7): 2565–2578. https://doi.org/10.1093/jxb/err432