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Long-term edge effect of strip roads in pine stands (*Pinus sylvestris* L.)

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Crowns of trees neighboring a strip road are exposed to greater amounts of sunlight, which may result in the so-called edge effect, leading to enhanced tree growth. The aim of this study was to assess the edge effect after twenty years since the clearing of strip roads in terms of diameter at breast height (DBH), tree height, crown base height, and crown length. Based on the results of earlier measurements, temporal changes in tree diameters at strip roads were also evaluated. The analyses were conducted in a pine stand, where strip roads 3.5 m or 2.5 m wide had been cleared at a stand age of 31 years, and after eight years the width of the narrow strip roads had been increased to 3.5 m. Measurements were taken on trees growing immediately adjacent to strip roads (edge trees) and those approximately 4.5 m from the road axis, as well as those in the middle of the distance between neighboring strip roads (as a reference). Trees growing at the edge of strip roads had statistically significantly larger diameters at breast height than trees growing farther from strip roads. The differences in tree height were slight and statistically non-significant, whereas the crowns of trees growing at the edges of strip roads had lower bases and were longer than the crowns of other trees. Analysis of DBH data recorded from measurements over 20 years showed a gradual reduction in the effect of strip roads on the diameters of trees growing at their edges.

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Introduction

One of the objectives of multipurpose forest management is to ensure the sustainable utilization of forest resources, considering economic, ecological and social aspects [Martynova et al. 2020; Burov et al. 2021; Timsina et al. 2022]. This refers particularly to timber harvesting, which for many years in Scandinavia [Proto et al. 2018; Lundbäck et al. 2021; Kymäläinen et al. 2021; Holmström et al. 2023; Strubergs et al. 2024], and recently also in Poland [Mederski et al. 2016; Bodył 2022] and in the Baltic countries [Moskalik et al. 2017; Mederski et al. 2021] has been performed by the cut-to-length method using specialist machines, namely harvesters and forwarders. To be able to traverse and operate in the stand, these machines require strip roads. The use of strip roads reduces tree damage and soil disturbance, as has been indicated for many years by researchers [Allman et al. 2016; Cambi et al. 2016; Cudzik et al. 2017; Stempski and Jabłoński 2018; Naghdi et al. 2019; Picchio et al. 2020; Leszczyński et al. 2024]. Decreasing the negative impact of timber harvesting on forests is one of main objectives of sustainable forest management [Tavankar et al. 2022; Latterini et al. 2023; Lee et al. 2024; Yakovenko et al. 2024].

Strip roads are designed and constructed following specific principles, among other things concerning their width and the distances between them. At present

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in Poland the binding Principles of Forest Utilization [ZUL 2019] stipulate that strip roads need to be designed to be approximately 4 m in width at distances of 20 m from one another. According to earlier guidelines issued in 2016 [Zarządzenie/Regulation 2016] the maximum admissible strip road width was 5 m. The parameters of strip roads determine the area covered by these roads in the stand, which is consequently excluded from further timber production. Apart from the reduction in the productive area, strip roads alter growth conditions for trees in their immediate vicinity. They provide greater access to light for the crowns of such trees and enhance access to nutrients for their roots. This may result in the so-called edge effect, in the form of larger growth increments, as indicated by the results of studies. Wallentin and Nilsson [2011] conducted research on the effect of thinning intensity (0%, 30% and 61% of the basal area) on the volume production (in the 3-year period after thinning) of 33-year-old spruce plantations made accessible by 4 m wide strip roads. Their results showed, in the third year after thinning, a statistically significantly greater increase in the volume of trees from the zone near the strip road, containing the first two rows of trees, in comparison with the trees inside the stand, regardless of the degree of thinning intensity. In similar studies on the productivity of 39-year-old spruce plantations, Kuliešis et al. [2018] showed that the annual increase in tree volume was 60–70% greater for trees bordering strip roads than for those in the interior of the plantation. The increase in productivity occurred primarily due to the more intensive diameter growth and higher density of trees in the outer rows. Nuutinen and Miina [2023], in research on the effect of standard and selective thinning on the growth of young pine stands and stands with birch predominant, showed increased values of growth increment in the case of trees on the edge of strip roads.

In this study, three research hypotheses were adopted:

1. The edge effect of strip roads is still visible after 20 years.
2. The edge effect of strip roads gradually decreases over time.
3. The course of the gradual decrease in the edge effect is not affected by differences in the initial width of the strip road.

The primary aim of this study was to assess the edge effect of strip roads twenty years after they had been cleared, in terms of the diameter and height structure of trees growing in the roads' vicinity. Additionally, based on data from previous measurements, changes in the diameter structure of trees were investigated for the 20-year period since the original clearance of the strip roads. Analysis of these changes in the context of different initial widths of strip roads is a new aspect of research on the edge effect of strip roads.

Material and methods

The biometric characteristics analyzed in this study included diameter at breast height (DBH) and tree height, as well as crown base height and crown length. Investigations were conducted in a pine stand (*Pinus sylvestris* L.) in the eastern part of the Puszcza Notecka forest, Oborniki Forest District, subcompartment 1105i, where the first thinning was performed and the strip roads were cleared when the stand was 31 years old. Thinning was carried out using motor-manual technology (with chain saws), with two methods being applied: the cut-to-length method, with timber extraction performed using a forwarder over 3.5 m wide strip roads, and the tree-length method, with timber extraction using an agricultural tractor over strip roads 2.5 m in width. In both methods the distances between strip roads were equal to 30 m. After eight years a second thinning was performed using the cut-to-length method and the width of the narrower strip roads was increased to 3.5 m.

The analyzed biometric characteristics were measured on trees growing in the vicinity of strip roads in two distance zones, with measurements taken in the middle of the distance between neighboring strip roads used as a control. The first distance zone (I) comprised trees growing in the immediate vicinity of the strip road (edge trees), found at an average distance of 2.5 m from the strip road axis. The second zone (II) consisted of trees growing immediately beyond the edge trees, at an average distance of approximately 4.5 m from the strip road axis, while the third zone, the control (III), was situated approximately 15 m from the strip road axis. Measurements of DBH were taken on trees close to five strip roads that retained the original width of 3.5 m (WR3.5) and five strip roads that had had an initial width of 2.5 m (NR2.5). On each tree the diameter at breast height was measured perpendicular and parallel to the strip road axis using a caliper accurate to 1 mm. In zones I and II measurements were made on both sides of the strip roads, while in zone III it was done only on one side of the road. Overall, for the WR3.5 strip roads, DBH measurements were recorded for 229 trees in zone I, 237 in zone II and 206 in zone III, whereas for the NR2.5 strip roads such measurements were taken for 222 trees in zone I, 235 in zone II and 183 in zone III.

Tree height and crown base height were measured on 16 trees in each distance zone at three WR3.5 strip roads and three NR2.5 strip roads (a total of 48 trees in each zone). Those trees were selected based on the results of DBH measurements (in proportion to the numbers of trees in DBH classes) using a TruPulse 360B rangefinder accurate to 10 cm. The height of the first live branch continuously connected with the crown was assumed as the crown base height.

In the first stage of desk research, for each tree a mean from two DBH measurements was calculated, and then crown length (*dk*) was calculated using the following formula:

$$dk = h - h_k, \qquad (1)$$

where:
h is tree height (m)
h_k is height of crown base (m)

The effect of strip roads on selected biometric characteristics was analyzed based on the results for individual strip roads and for groups of strip roads (all WR3.5 roads and all NR2.5 roads). For data from individual strip roads only mean values were calculated for the analyzed biometric characteristics, whereas for data from a given group of strip roads, means, medians, standard deviations, minimum and maximum values, and coefficients of variation were calculated.

Statistical verification of the results consisted in evaluation of the significance of the differences in values of DBH, tree height, height of crown base and crown length between the distance zones (for individual strip roads and for groups of strip roads). Depending on the character of the distribution of variables (consistency with a normal distribution) either one-way analysis of variance (ANOVA) or the Kruskal–Wallis test was applied. Consistency with a normal distribution was verified by the Shapiro–Wilk test. Hypotheses were tested at the significance level α = 0.05, and calculations were performed using the Statistica 13.0 package [TIBCO Software Inc. 2017].

Results

Results for individual strip roads

Twenty years after the strip roads had been cleared, the thickest trees were those growing in their immediate vicinity (Figs. 1, 2), while the thinnest trees were found in zone III (except in the case of one WR3.5 strip road – Fig. 1). Edge trees had statistically significantly larger diameters than the other trees in the case of three WR3.5 and two NR2.5 strip roads (Figs. 1, 2; Table 1). Most often they had statistically significantly greater DBH than trees from the two other zones, although in the case of one WR3.5 strip road this was the case only when compared with trees from zone II (Fig. 1).

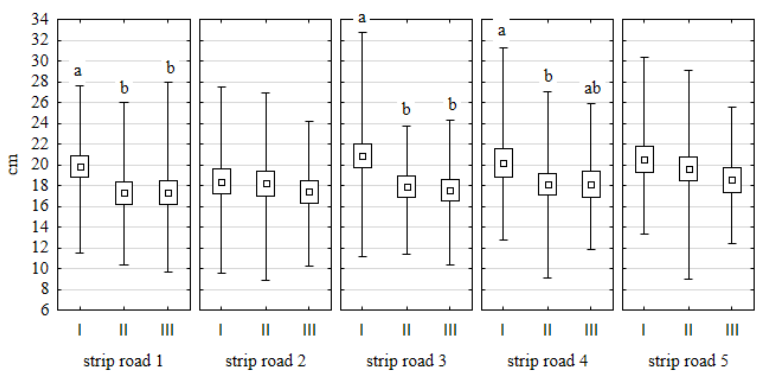

Fig. 1. Mean, 95% confidence intervals (box) and min - max values (whiskers) of tree breast height (cm) at individual WR3.5 strip roads

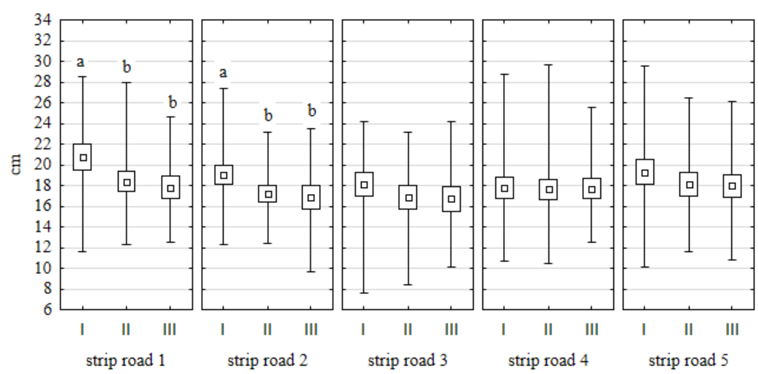

Fig. 2. Mean, 95% confidence intervals (box) and min - max values (whiskers) of tree breast height (cm) at individual NR2.5 strip roads

Table 1. Results of the assessment for differences in DBH values between zones (value *p* of the test)

Strip roads	Strip road No.				
	1	**2**	**3**	**4**	**5**
WR3.5	0.001	0.414	<0.001	0.022	0.078
NR2.5	<0.001	0.003	0.073*	0.955	0.196

* – Kruskal-Wallis test, other results - ANOVA

Table 2. Results of the assessment for differences in tree height, height of crown base and crown length between zones (value *p* of the test)

Strip road No.	WR3.5			NR2.5		
	tree height	**height of crown base**	**crown length**	**tree height**	**height of crown base**	**crown length**
1	0.132*	0.014*	0.008	0.005	0.058	0.005
2	0.242	0.649	0.152	0.512	0.052	0.660
3	0.152	0.732*	0.127	0.083	<0.001	0.007

* – Kruskal-Wallis test, other results - ANOVA

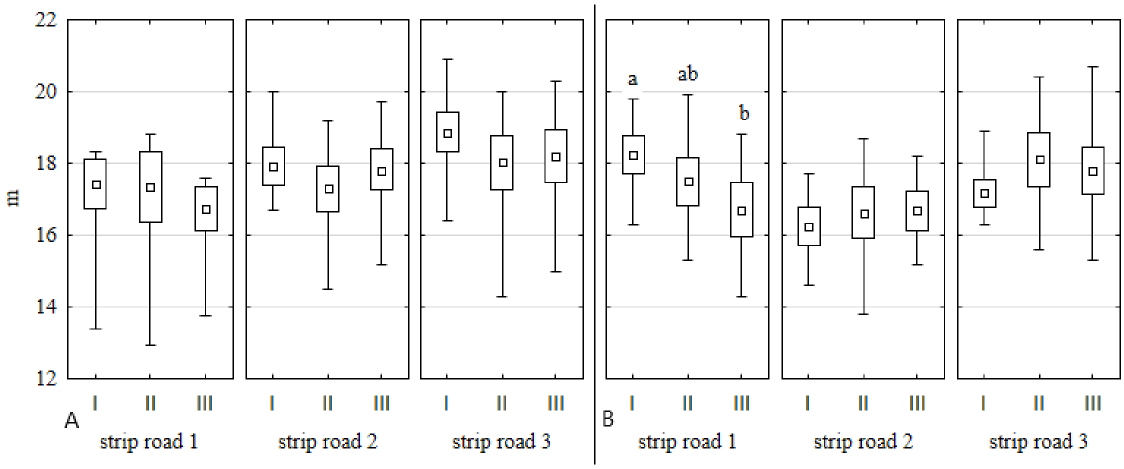

Fig. 3. Mean, 95% confidence intervals (box) and min - max values (whiskers) of tree heights (m) at individual strip roads: A – WR3.5, B – NR2.5

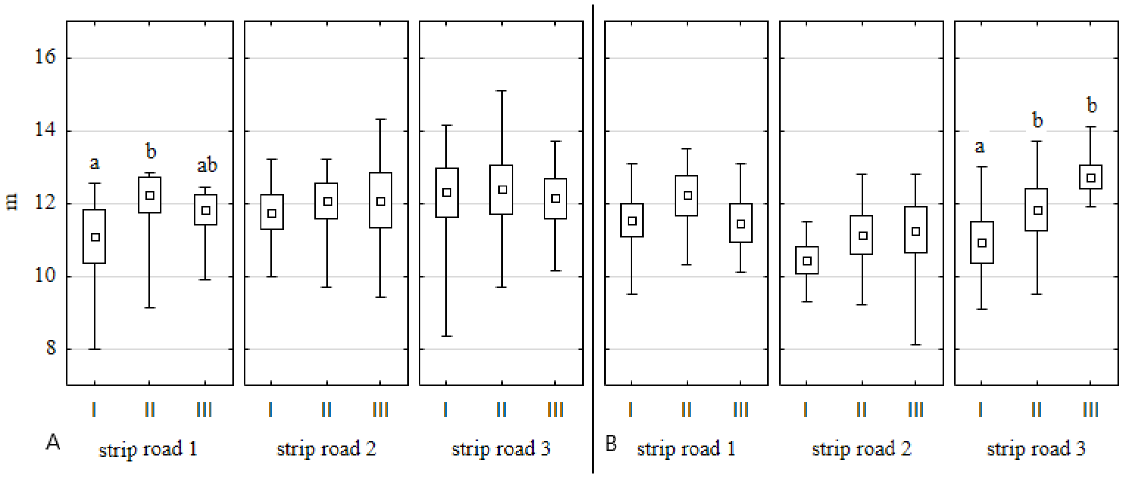

Fig. 4. Mean, 95% confidence intervals (box) and min - max values (whiskers) of crown base height (m) at individual strip roads: A – WR3.5, B – NR2.5

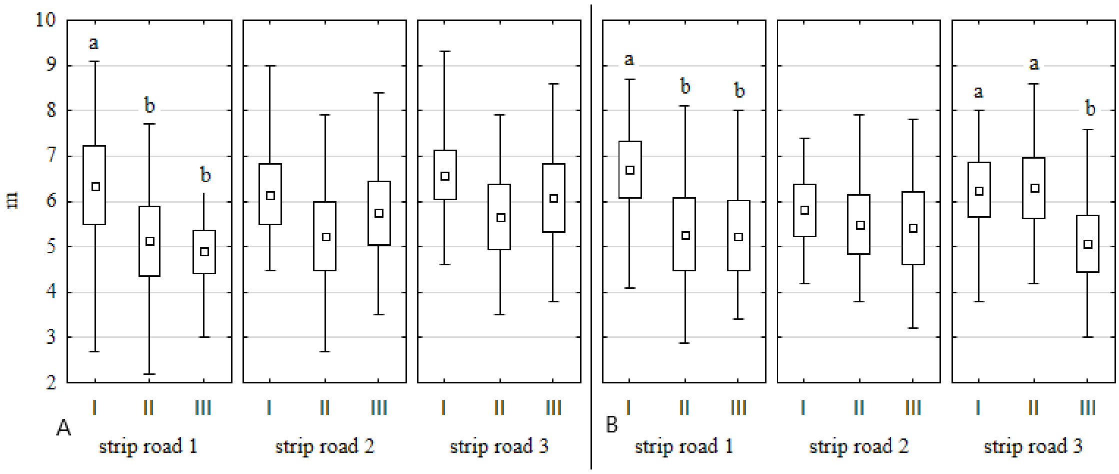

Fig. 5. Mean, 95% confidence intervals (box) and min - max values (whiskers) of crown lengths (m) at individual strip roads: A – WR3.5, B – NR2.5

A slightly different situation was observed in the case of tree height. For all of the WR3.5 strip roads and one NR2.5 strip road the edge trees were taller than those growing in the other zones (Fig. 3). These differences were slight and were statistically significant only for one NR2.5 strip road (Table 2), where the edge trees were significantly taller than trees from zone III (Fig. 3B).

The crown base height of edge trees was generally lower than that of trees from the other zones (Fig. 4); only in the case of one WR3.5 and one NR2.5 strip road was it minimally greater than for trees from zone III. Statistically significant differences were recorded for one WR3.5 and one NR2.5 strip road (Table 2): in the former case the edge trees had crown bases located significantly lower than trees from zone II (Fig. 4A), while in the latter case they were lower than trees from both other zones (Fig. 4B).

Generally edge trees had longer crowns than trees from the other zones (Fig. 5). Statistically significant differences were found for one WR3.5 and two NR2.5 strip roads (Table 2).

Results for groups of strip roads

The values of diameter at breast height calculated based on measurements of trees by all WR3.5 and NR2.5 strip roads followed similar patterns as the results for individual strip roads (Table 3).

Regardless of the initial width of a given strip road, the largest diameters at breast height were found in edge trees, and the smallest in trees from the control zone (Table 3). The differences were statistically significant; the diameters at breast height of edge trees in each case were significantly greater ($p < 0.001$) than those of trees from zones II and III (Table 3). Also, the differences between the minimum and maximum values were the largest in the case of edge trees, amounting to over 10 cm. The variability of the results was small, with slightly greater values of the coefficient of variation recorded for the WR3.5 strip roads.

In the case of tree height the differences between the zones were smaller than those recorded for diameter at breast height, and they were statistically non-significant

Table 3. Descriptive statistics of DBH (cm)

Zone	Mean	SD	Median	Min	Max	$V_{\%}$
			WR3.5 (ANOVA: p<0.001)			
I	19.93[a]	4.13	19.95	9.55	32.75	20.72
II	18.25[b]	3.80	18.20	8.85	29.10	20.83
III	17.76[b]	3.59	17.58	9.65	28.00	20.22
			NR2.5 (Kruskal-Wallis test: p<0.001)			
I	18.95	3.73	18.45[a]	8.00	29.50	19.71
II	17.65	3.41	17.15[b]	8.85	29.65	19.35
III	17.41	3.32	17.15[b]	9.65	26.10	19.08

SD – standard deviation, $V_{\%}$ - coefficient of variation, different lowercase letters - statistically significant differences

Table 4. Descriptive statistics of tree height, height of the crown base and crown length (m)

Zone	Mean	SD	Median	Min	Max	$V_{\%}$
tree height – WR3.5 (Kruskal–Wallis test: p=0.171)						
I	18.08	1.24	18.00	14,10	20.90	6.85
II	17.56	1.50	17.75	13.60	20.00	8.57
III	17.59	1.33	17.80	14.50	20.30	7.59
tree height – NR2.5 (ANOVA: p=0.437)						
I	17.22	1.21	17.15	14.6	19.8	7.02
II	17.41	1.45	17.35	13.8	20.4	8.35
III	17.06	1.32	17.30	14.3	20.7	7.72
height of the crown base - WR3.5 (Kruskal-Wallis test: p=0.108)						
I	11.71	1.29	11.70	8.40	14.90	11.03
II	12.22	1.04	12.40	9.60	15.90	8.48
III	12.01	1.10	11.95	9.40	14.40	9.13
height of the crown base – NR2.5 (ANOVA: p<0.001)						
I	10.97^{a}	0.98	11.05	9.10	13.10	8.94
II	11.72^{b}	1.12	11.80	9.20	13.70	9.53
III	11.81^{b}	1.13	11.95	8.10	14.10	9.60
crown length – WR3.5 (ANOVA: p<0.001)						
I	6.37^{a}	1.30	6.35	2.70	9.30	20.49
II	5.34^{b}	1.38	5.35	2.20	7.90	25.86
III	5.78^{b}	1.30	5.50	3.00	8.60	23.37
crown length – NR2.5 (ANOVA: p<0.001)						
I	6.25^{a}	1.15	6.20	3.80	8.70	18.31
II	5.69^{ab}	1.37	5.60	2.90	8.60	24.01
III	5.25^{b}	1.34	5.15	3.00	8.00	25.54

SD – standard deviation, $V_{\%}$ - coefficient of variation, different lowercase letters - statistically significant differences

(Table 4); in the case of WR3.5 strip roads the edge trees were the tallest, while in the case of NR2.5 strip roads the tallest were trees from zone II. The variability of the results for this characteristic was markedly smaller than that obtained for diameter at breast height (Table 4).

Regardless of the initial strip road width, edge trees had the lowest crown base height; in the case of NR2.5 strip roads the differences between the zones were greater and were statistically significant (Table 4). In this case edge trees had significantly lower crown base heights than trees from both zone II ($p = 0.002$) and zone III ($p < 0.001$) (Table 4). The smaller differences observed in the case of WR3.5 strip roads were statistically non-significant. The variability of the results for this characteristic was slightly greater than that recorded for tree height.

The smaller crown base height for the edge trees resulted in greater crown lengths in those trees (Table 4). Differences relative to trees growing deeper within the stand ranged from approximately 0.6 to 1.0 m. Edge trees by WR3.5 strip roads had statistically significantly longer crowns than trees from both zone II ($p < 0.001$) and zone III ($p = 0.010$), whereas in the case of NR2.5 strip roads this was the case only in comparison with trees from zone III ($p < 0.001$). The variability of data for this characteristic was markedly greater than that recorded for crown base height (Table 4).

Discussion

The results confirmed the first research hypothesis – twenty years after the cutting of the strip roads, the edge effect was still evident. The larger diameters at breast height recorded for the edge trees indicate that during that period those trees were characterized by diameter growth. In terms of timber production this may be considered a beneficial effect of strip road construction. The greater thickness of edge trees at strip roads is confirmed by literature data. For example, the Finnish researchers Isomäki and Niemistö [1990],

Table 5. Mean DBH (cm) in the zones 5, 10 and 15 years after cutting down the strip roads

Time since cutting the strip roads (years)	WR3.5			NR2.5		
	zone I	zone II	zone III	zone I	zone II	zone III
5	13.1	11.7	11.2	12.3	10.9	11.1
10	15.9	14.2	13.7	15.5	13.7	13.8
15	18.4	16.8	16.0	17.3	16.2	16.0
20	19.9	18.3	17.7	19.0	17.7	17.4

in a study of the impact of strip roads with a width of almost 4 m on the growth of spruce stands after the first thinning, showed increased growth increment in edge trees even in the first year after the roads were cleared. In a Swedish study, Eriksson [1987] showed increased growth of edge trees at strip roads 3.5 and 5 m in width. Similarly, Wallentin and Nilsson [2011], who studied the growth increments of trees in pine stands subjected to thinning operations of varying intensity, reported greater growth increments in trees adjacent to strip roads regardless of thinning intensity. In Germany, an increase in the growth increments of spruces aged 27–43 years at strip roads was reported by Kremer and Matthies [1997]. In more recent studies, Gencal et al. [2018] showed that silver linden trees (*Tilia tomentosa* Moench) growing at a distance of up to 5 m from a 4 m wide forest road had a statistically significantly larger basal area than trees growing deeper in the stand. However, literature data indicate that the phenomenon of increased diameter growth increment in trees at the edge zone of a strip road does not always occur. In Poland, Suwała [2007] reported that DBH was 10% smaller for trees next to a strip road than for trees growing deeper within the stand. That study analyzed the diameter at breast height of Scots pine (*Pinus sylvestris* L.) trees growing at distances of 0–5 m, 5–15 m and 15–30 m from strip roads 3.5 m in width, which had been cleared using technologies that included chainsaw felling and timber extraction using a forwarder. Bembenek et al. [2013] generally found no difference in growth increments between edge trees and trees from the middle of a 39-year-old spruce (*Picea abies* (L) H. Karst) stand five years after strip roads 5 m in width had been cleared. Similarly, Turski et al. [2023] showed the absence of an edge effect from forest roads in a 60-year-old pine (*Pinus sylvestris* L.) stand. Elsewhere, a lack of increased growth in edge trees of Turkish fir (*Abies bornmulleriana* Mattf.) growing in a plantation was reported by Yilmaz et al. [2010].

In this study, diameters at breast height of edge trees were almost 9% and 7.5% greater (for the WR3.5 and NR2.5 strip roads, respectively) than those of trees growing in zone II, which were in turn 2.8% and 1.7% greater, respectively, than the DBH of trees in the control zone (III). These results indicate that the effect of strip roads is found not only for edge trees, but also for trees growing farther away, at an average distance of approximately 4.5 m from the strip road axis (that is, almost 3 m from the strip road margins). These results are consistent with literature data; for example, the Finnish researchers cited above [Isomäki and Niemistö 1990; Mäkinen et al. 2006] observed the effect of a strip road up to a distance of approximately 3 m from its margin. In turn, the markedly greater percentage difference in DBH between the control zone and zone II in the case of WR3.5 strip roads compared with NR2.5 (2.8% vs. 1.7%) indicates a relationship between strip road width and the distance at which this effect occurs (that distance is larger for WR3.5 strip roads). This phenomenon was already reported in the 1980s by Eriksson [1987].

The investigations leading to the results presented in this paper were the fourth during the 20-year period of existence of strip roads in this stand (with measurements taken every 5 years). This made it possible to assess changes in the analyzed biometric characteristics over time. In this study this evaluation was limited to diameter at breast height, as this was the tree characteristic on which strip roads had the greatest effect. It should be noted that from the point of view of timber production, the degree and duration of this effect is the most important, since increased diameter growth of edge trees may offset (partly or even fully, depending on the duration of the edge effect) losses in volume caused by the clearing of strip roads [Kuliešis et al. 2018; Stempski et al. 2021]. Results of earlier studies in the same stand also showed markedly (statistically significantly) greater diameters at breast height in edge trees (Table 5).

At WR3.5 strip roads the differences in diameters at breast height between zones I and II after 5, 10, 15 and 20 years were respectively 1.4, 1.7, 1.6 and 1.6 cm, while between zones I and III the differences were 1.9, 2.2, 2.4, and 2.1 cm. In the case of NR2.5 strip roads the respective differences were 1.4, 1.8, 1.1, and 1.3 cm between zones I and II, and 1.2, 1.7, 1.3, and 1.6 cm between zones I and III. These data indicate that the differences expressed in absolute values generally did not decrease

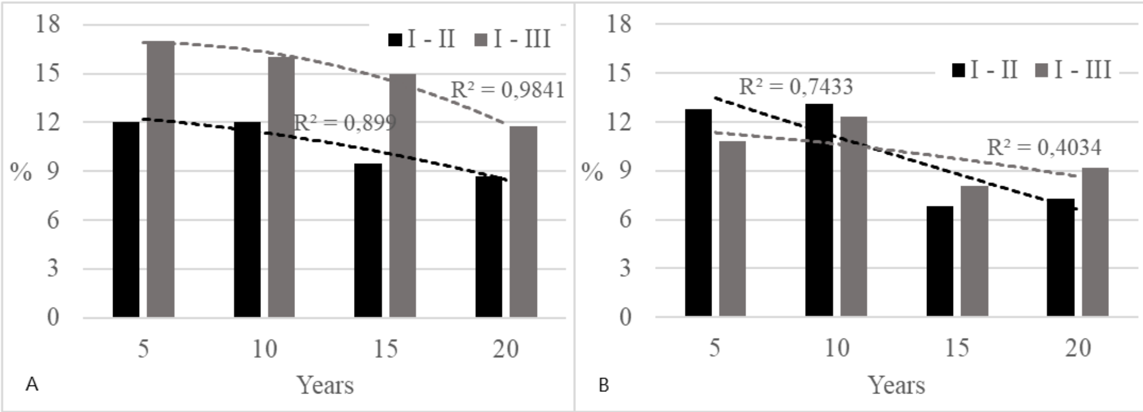

Fig. 6. Percentage differences in DBH values between zones I–II and I–III after 5, 10, 15 and 20 years since clearing of strip roads: A – WR3.5, B – NR2.5

with time after the strip roads were cleared. However, a downward trend was evident in differences expressed as percentages (Fig. 6), particularly in the case of WR3.5 strip roads (Fig. 6A). These results confirm the second of the initial research hypotheses, concerning a gradual decrease in the edge effect over time. Moreover, it is seen from Fig. 6A that the effect of WR3.5 strip roads during the entire 20-year period following their clearance concerned not only edge trees, but also trees from zone II (as indicated by the much smaller percentage differences between zones I and II than between zones I and III). In the case of NR2.5 strip roads this pattern was evident only in the results after 15 and 20 years; earlier the relationship had been reversed (Fig. 6B).

The reasons for this are linked to the fact that the width of NR2.5 strip roads was increased to 3.5 m only after 8 years, which means that the effect of road width enlargement was not manifested in data recorded after 10 years, but only after 15 years. Also in the case of the NR2.5 strip roads the differences were greater after 10 years than after 5 years, and were greater after 20 years than after 15 years (this applies both between zones I and II and between zones I and III, while a general downward trend was observed over the entire 20-year period) (Fig. 6B). In the case of the WR3.5 strip roads such a situation was not found (only the difference between zones I and II after 10 years was identical; Fig. 6A). Generally the WR3.5 strip roads exhibited a much more regular downward trend in percentage differences in DBH values, both between zones I and II and between zones I and III, than was the case for the NR2.5 strip roads (Fig. 6A). The reason for this should be sought in the different initial widths of the strip roads. This means that the third research hypothesis, which stated that this width would have no effect on the course of the gradual decrease in the edge effect, was not confirmed.

Limitation of the study

The main limitation of the research was the use of a single study area. Although DBH measurements were taken on trees at ten strip roads (five WR3.5 and five NR2.5), they were all located in one subcompartment.

Conclusions

1. The edge effect of the strip roads 20 years after they had been cleared was still evident in most of the analyzed biometric characteristics of trees in their vicinity.
2. Edge trees had statistically significantly greater diameters at breast height than trees growing deeper within the stand. There were no differences in tree height, whereas crown base heights of edge trees were lower and the crowns were statistically significantly longer.
3. Analysis of 20-year measurement data for diameter at breast height showed a gradual reduction in the effect of strip roads on the diameters of edge trees. This phenomenon occurred in a much more regular fashion for strip roads of greater initial width.

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