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The Accessibility of Post-Fire Areas for Mechanized Thinning Operations

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Abstract: In 1992, in Southern Poland, large areas of Silesian forests were affected by the country's largest forest fire. Stands introduced in the 9000-ha post-fire region are currently undergoing early thinning. Due to the scope of these treatments, the chance for their timely implementation is ensured only by the application of cut-to-length (CTL) technologies, i.e., with the use of harvesters and forwarders. The use of CTL technologies may, however, be difficult due to the fire history of these stands, which could affect the bearing capacity of their soils. The objective of this study is to determine the accessibility of stands for forest machines in relation to the bearing capacity of the soils and changes in soil compaction in the post-fire sites. Soil compaction was measured in terms of penetrometer resistance in the stands introduced in the post-fire area in question, as well as in control stands growing on five different soil types. It was shown that in the topsoil layer—from 8 to 18 cm thick depending on the soil type—differences in soil compaction in the post-fire and control areas were relatively small. The impacts of the forest fire—manifested as a significant increase in the compaction of the forest soils—were still visible, but only in the deeper layers of the soil profile. In all of the compared pairs of forest compartments located in the stands regenerated after the fire, significantly higher values of cone indexes (CI) were found. The average value of this index in the post-fire stands was 2.15 MPa, while in the control stands it was 1.60 MPa, which indicates that in both groups of stands the bearing capacity of the soils should not limit the accessibility for vehicles used for timber harvesting and extraction.

Keywords: soil compaction; cone index (CI); cut-to-length system (CTL); harvester; forwarder

1. Introduction

Rapid weather phenomena and climatic anomalies, clearly visible especially in recent years, cause damage to forest stands due to wind, fires and excessive precipitation, drought or pest outbreaks. The currently observed increased dynamism of weather changes increase the frequency of frequent large-scale destruction of stands [1,2]. In some situations, the more frequent and longer periods of drought, combined with high temperatures and winds, intensify the fire hazard. As a result, as much as 83% of forests (about 7.4 million ha) in Poland are potentially threatened by fires. On average, 5000 fires occur each year, resulting in the destruction of 3000 ha of forest area [3]. Venäläinen et al. [4] and Sousa-Silva et al. [5] link the increase in the number of fires in European forests with global warming and predict that the observed upward trend will continue.

Apart from problems directly related to the clearing of post-fire areas and their regeneration, a significant challenge is the further tending of single-age stands, often introduced in an area reaching thousands of hectares. This is the case of stands introduced mainly artificially, but also a result of natural regeneration, in forest districts located in the southern part of Poland. In 1992, the largest fire in the history of Polish forestry took place here, in which over 9000 ha of forests were burned [6,7].

To start with, rehabilitation of these post-fire areas was established between 1993 and 1995, which now allows for early thinning operations. The performance of thinning based on tree extraction with the use of chainsaws is, due to low efficiency of this technology, impossible to apply because of the very large size of the thinning area and the constantly growing shortage of professional forest workers. In addition, the option to stagger a thinning treatment over a longer period is difficult due to the need for timely performance of that procedure. The solution to this problem is CTL (cut-to-length) technology with use of harvesters and forwarders or farm tractors aggregated with forest trailers. However, the use of machine technologies may be difficult or impossible precisely due to the soil conditions resulting from the fire history of these stands. The fire may have changed the physical properties of the soil or disturbed the water relations so strongly that it influenced the reduction of the bearing capacity of these soils. This, in turn, may limit rational forest management in the areas affected by fires for a long time, due to the limitation of their accessibility, e.g., through swamping.

The variability of terrain conditions and the varied temperatures generated during forest fires mean that there are no uniform views on their impact on forest soils. The results of numerous studies indicate that forest fires may have adverse effects on soil carbon, nitrogen, phosphorus content and soil alkalization [8–11]. Most likely, these are not the factors that may limit the introduction of forest machines to fire areas. Mechanized harvesting equipment may be limited by other effects of fires: destruction of the ectohumus overlying the organic soil horizon [12], increased water permeability of topsoil layers [13,14] or even changes in the granulometric composition of soils [15]. These factors may affect soil density [16,17] and, thus, influence the bearing capacity of soil and its shear strength. What may change, i.e., either improve or worsen, is the accessibility of post-fire areas for forest machines. For this reason and due to the relatively limited amount of knowledge concerning the impact of forest fires on the accessibility of post-fire areas for specialized forest machinery, an attempt was made to test whether the forest soils in the analyzed post-fire area underwent any changes of the soil's bearing capacity. Such changes may prevent the use of mechanized timber harvesting technologies due to limitation of machine mobility or the occurrence of serious soil damage (e.g., in the form of deep ruts) as well as tearing of the root systems of trees. While these soils will recover, the soil regeneration process can take decades or longer [18], potentially limiting the possibilities to use mechanized equipment. Another problem may lie in soil moisture changes associated with the rise in the level of groundwater after the burning of stands, which are natural water suction pumps [19]. This phenomenon most often occurs on more fertile, wetter sites [20,21]. Increased soil moisture can significantly limit the accessibility of post-fire areas to forest machines, as it is one of the key factors determining the soil bearing capacity [22–24]. An increase in soil water content reduces friction forces between soil particles, thereby reducing the bearing capacity of the soil [25–27]. Soils with low bearing capacity limit the mobility of technological means used for timber harvesting and log extraction and thus reduce their efficiency [28,29]. Work under such conditions is also characterized by an adverse effect of the machines on the soil due to significant soil compaction and rut formation [30,31].

A useful measure for assessing the bearing capacity of soils are data on their compaction, which is correlated with both the density and moisture of soils [23]. Soil in the zone of influence of wheels may be characterized by varying compaction, hence information about the average compaction of this layer is often used, e.g., the cone index (CI). This is a method applied in situ and used for the practical assessment of the possibility of vehicle movement on given soils and the off-road mobility of these vehicles [32–34].

The aim of the study was to determine what changes in soil compaction occur in post-fire areas and to assess of the accessibility of stands growing there for forest machines in relation to the bearing capacity of the soils.

2. Materials and Methods

The research was located in the southern part of Poland (Figure 1), in stands introduced in a post-fire area (F) and in control (C) stands (not affected by fire) situated in the vicinity of the post-fire area. The research area included flat terrain with stands with a predominant share of coniferous trees: Scots pine (*Pinus sylvestris* L.).

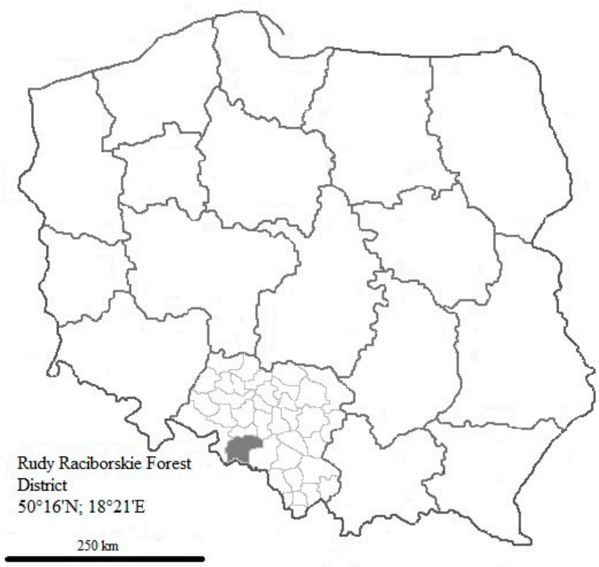

Figure 1. Map of Poland with the research area.

The research covered 3 forest site types and 5 soil types, which reflect 77% of the post-fire area (Table 1). From among the selected forest compartments, 5 pairs with the same soil type were chosen and labeled with the symbols 1F, 1C, 2F, 2C, 3F, 3C, 4F, 4C, 5F and 5C (F if it was a post-fire site or the letter C when it was a control compartment).

Table 1. Characteristics of forest compartments where the research was located.

Symbol	**1F**	**1C**	**2F**	**2C**	**3F**	**3C**	**4F**	**4C**	**5F**	**5C**
Forest site type [1]	Fresh mixed coniferous forest site		Fresh mixed coniferous forest site		Fresh mixed coniferous forest site		Moist mixed broadleaved forest site		Moist mixed coniferous forest site	
Soil type [2]	Podzol		Brunic Arenosol		Albic Brunic Arenosol		Stagnosol		Gleyic Podzol	
Soil textural group [3]	Sand		Loamy sand		Sand		Sandy loam		Sand	
Area (ha)	10.77	0.90	9.35	1.8	0.37	9.44	1.22	7.13	28.59	18.22
Species composition	Pine 80% Larch 10% Birch 10%	Pine 100%	Pine 80% Birch 20%	Pine 100%	Pine 50% Birch 50%	Pine 100%	Pine 70% Alder 20% Larch 10%	Pine 100%	Pine 90% Birch 10%	Pine 60% Birch 20% Larch 10% Alder 10%
Age (years)	24	87	24	70	25	135	23	120	23	27
Growing stock (m^3/ha)	175	237	65	210	65	340	110	340	110	120

[1] Classification based on [35]; [2] classification based on [36]; [3] classification based on [37].

In the selected forest compartments, soil compaction measurements were performed based on ASAE Standards [38] using the electronic penetrometer Penetrologger 06.15.SA type (Eijkelkamp Agrisearch Equipment, Giesbeek, Netherlands). The cone had a 60° top angle and 1 cm^2 base area with nominal diameter 11.28 mm. Moreover, the cone index (CI) was determined based on ASAE Standards [39]. The CI value was determined automatically when measuring soil compaction with the penetrometer when it reached a depth of 45 cm during a measurement (this is the average of the measured resistance at 1, 15, 30 and 45 cm) [40]. In order to determine the terrain accessibility for vehicles in the analyzed compartments, the obtained CI values were compared with the classification of the bearing capacity of sensitive forest soils as defined in the EcoWood protocol [41,42], according to which on soils with the bearing capacity of 0.3–0.5 MPa wheeled forwarders should be used to a limited extent (only the lightest models on tires of an above-standard width), while on soils with the bearing capacity below 0.3 MPa tracked forwarders should mainly be allowed. All CI data were collected in early September 2018, at a temperature of about 15 °C and rainless weather. Thirty measurements of soil compaction in each of the compartments were made so that the points of subsequent measurements were at least 1 m apart. The measurements were made along a line parallel to the long side of the compartment, designed in such a way as to avoid the proximity of watercourses and old skid trails (Figure 2). If a root or stone was found, the measurement was discontinued and another one was taken at a distance of 1 m. The GPS position of the soil penetration point and the current soil moisture were determined using the ThetaProbe probe ML2x type (DELTA-T Devices, Cambridge, England) with which the penetrometer was equipped.

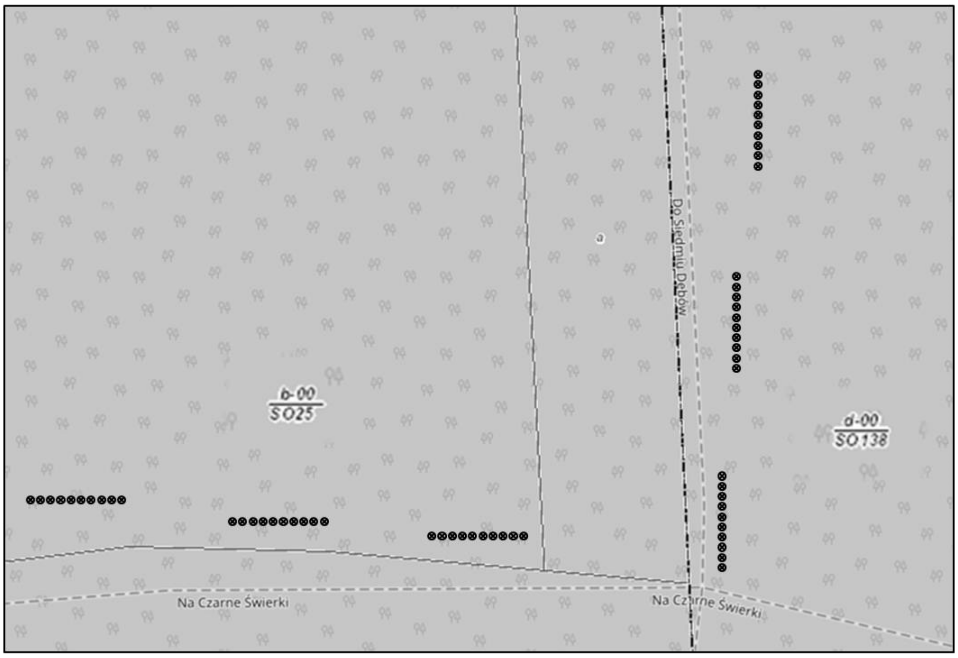

Figure 2. The simplified scheme of measure points layout within the post-fire site 3F (b-00/pine 25 years old) and control compartment 3C not affected by fire (d-00/pine 138 y.o.).

Using Student's *t*-test, the significance of differences in the mean values of CI indexes and moisture in the post-fire stands and the control stands were tested, after checking the index distribution normality on these sites. Statistical analyses were performed using the Statistica 12 package [43].

3. Results

3.1. Cone Index

The average cone index (CI) value in all of the analyzed stands was close to 1.9 Mpa, with the minimum value of about 0.6 and the maximum of 4.8 (Table 2). The mean current soil moisture was 24%, with significant variation from 3 to over 70%. However, moisture of soil didn't show statistically significant differences in compared stands ($p = 0.067$).

In the post-fire stands the mean CI value was higher than at the control sites ($p = 0.000$). The CI variability was also greater, as indicated by their standard deviations.

In all research areas, the CI distribution was consistent with the normal distribution. In all pairs of forest compartments with the same soil (1, 2, 3, 4 and 5), the mean CI values were statistically significantly higher in the post-fire stands (Table 2).

Table 2. The characteristics and significance of differences in the cone index (CI) and moisture indicators in the analyzed stands.

Site	1		2		3		4		5		Together	
CI (MPa)												
	F	C	F	C	F	C	F	C	F	C	F	C
No.	30	30	30	30	30	30	30	30	30	30	150	150
Mean	2.02 [a]	1.59 [b]	2.11 [a]	1.58 [b]	2.33 [a]	1.66 [b]	2.06 [a]	1.41 [b]	2.24 [a]	1.78 [b]	2.15 [a]	1.60 [b]
SD	0.66	0.34	0.70	0.40	1.06	0.55	0.49	0.29	0.80	0.57	0.76	0.45
Minimum	0.95	0.80	1.08	0.88	0.63	0.93	0.88	0.93	1.08	1.00	0.63	0.80
Maximum	3.25	2.53	3.78	2.85	4.80	3.38	3.13	2.03	3.90	3.12	4.80	3.38
Statistics t	3.163		3.617		3.069		6.627		2.503		7.569	
p-value	0.002		0.001		0.003		0.000		0.015		0.000	
Moisture (%)												
Site	1		2		3		4		5		Together	
	F	C	F	C	F	C	F	C	F	C	F	C
No.	30	30	30	30	30	30	30	30	30	30	150	150
Mean	32.23 [a]	29.00 [a]	26.60 [a]	19.67 [a]	22.29 [a]	19.80 [a]	21.00 [a]	25.97 [a]	22.63 [a]	20.56 [a]	24.99 [a]	23.05 [a]
SD	5.44	13.02	12.10	6.96	4.28	7.13	5.18	8.96	7.74	6.48	8.49	9.57
Minimum	21.00	8.00	8.00	8.00	16.00	9.00	10.00	7.00	3.00	8.00	3.00	7.00
Maximum	43.00	73.00	42.00	37.00	34.00	40.00	34.00	42.00	40.00	34.00	43.00	73.00
Statistics t	1.255		1.865		1.596		−1.918		1.092		1.841	
p-value	0.215		0.059		0.116		0.059		0.280		0.067	

[a,b]—different letters mean significant differences.

In the EcoWood protocol, strong soils (class 1) were those with a CI value above 0.5 MPa. In the present research, the lowest mean CI value was found for site 4C, 1.4 MPa and the minimum value of 0.63 MPa was observed on site 3F. It follows that in the analyzed area there were soils with the bearing capacity of class 1. Even on the site with the lowest bearing capacity of soils (4C), the mean CI value was almost three times higher than that of the one recognized in EcoWood as the limit value of strong soil.

3.2. Soil Compaction

The soil penetration resistance, dependent on the measurement depth, for subsequent sites is presented in Figures 3–7.

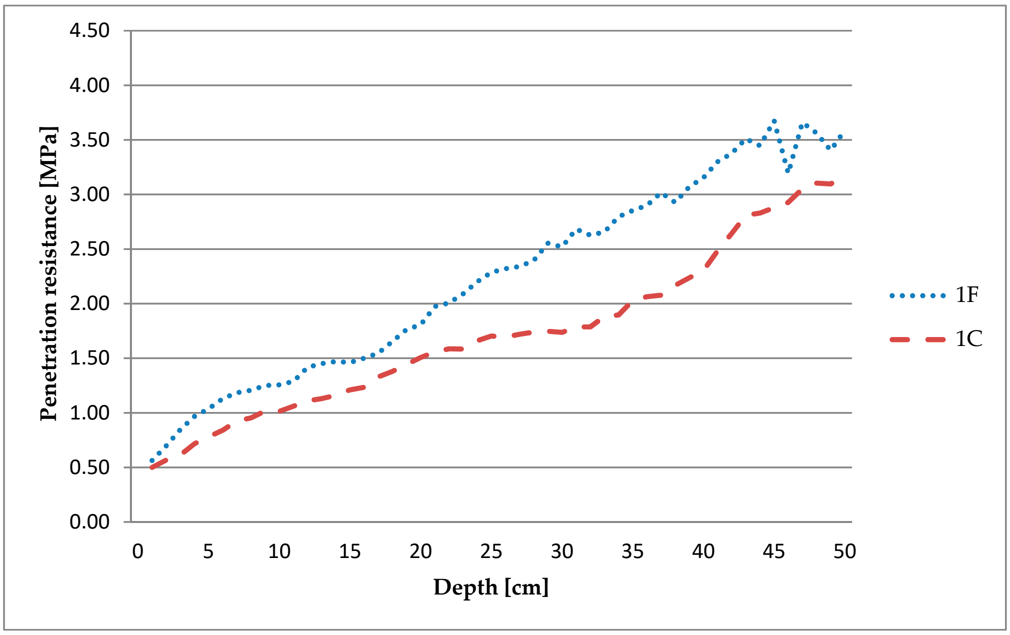

Figure 3. Soil compaction at sites 1F and 1C.

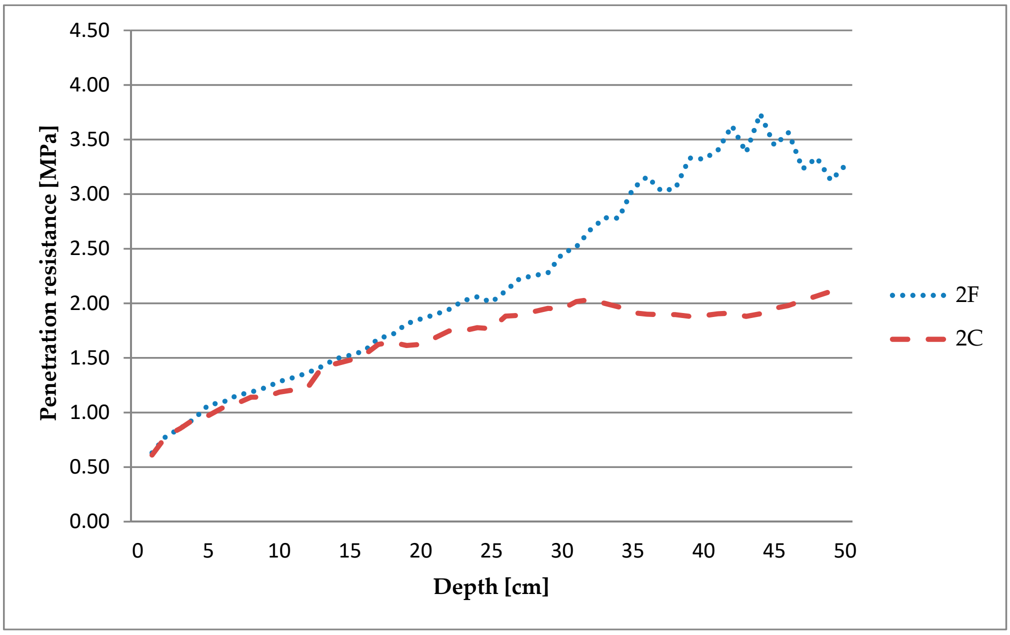

Figure 4. Soil compaction at sites 2F and 2C.

At sites 1 and 2, in the entire analyzed soil profile, soil compaction in the post-fire stands was greater than in the control ones. To a depth of about 18 cm, the differences between soil penetration resistance on both sites were stable; at site 1 they amounted to about 0.2–0.3 MPa, while at site 2 they were smaller, 0.1–0.15 MPa. From a depth of 19 cm, soil compaction in the post-fire stands was significantly higher than in the control stands. The maximum difference in soil compaction at site 1, amounting to 0.94 MPa, was found at a depth of 37 cm, while at site 2 (1.83 MPa) it was a depth of 44 cm.

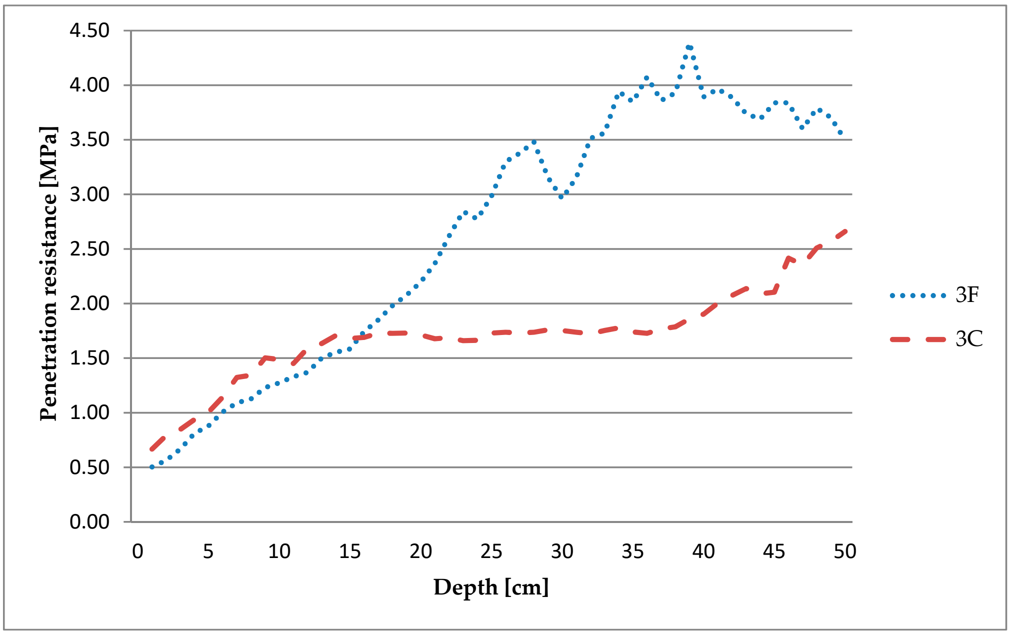

Figure 5. Soil compaction at sites 3F and 3C.

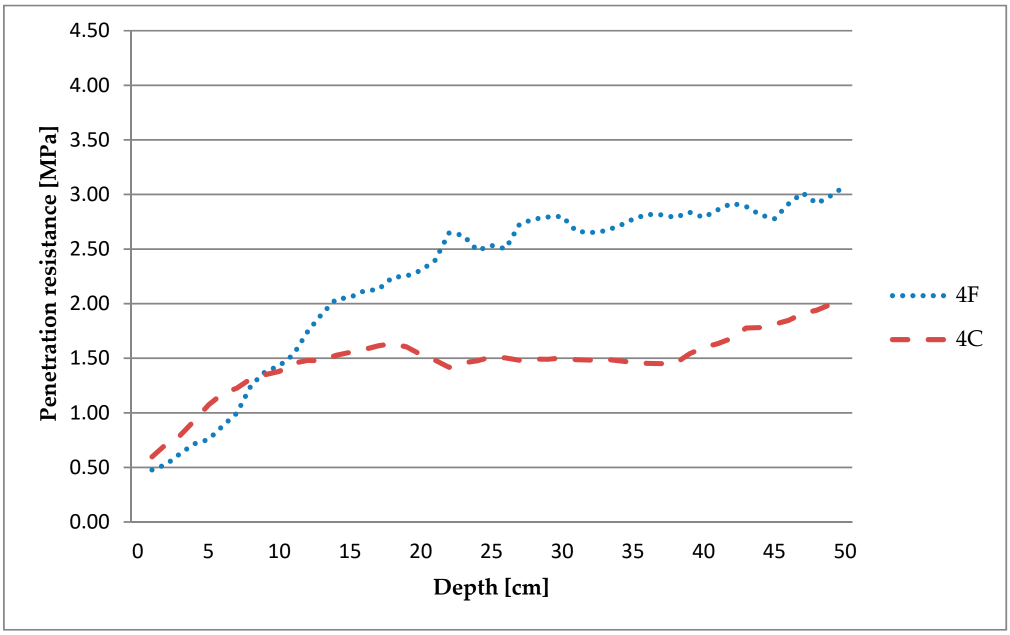

Figure 6. Soil compaction at sites 4F and 4C.

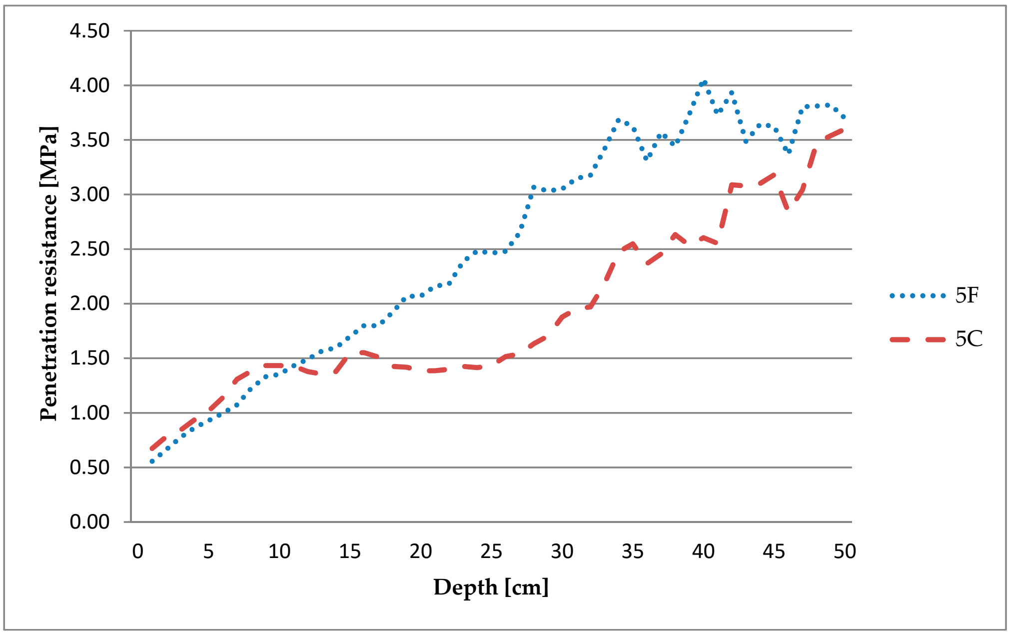

Figure 7. Soil compaction at sites 5F and 5C.

At sites 3, 4 and 5, soil compaction was slightly different. In the top layer at these sites in the stands where the fire had not occurred, amounting to 16, 8 and 10 cm, respectively, slightly higher soil compaction was observed: up to 0.23 MPa greater than the post-fire stands. In deeper layers, the trend became the opposite: soil compaction became higher in the post-fire stands than in the control ones. The maximum difference in soil compaction between a post-fire stand and a control stand was found at site 3 (2.53 MPa) at a depth of 39 cm. At site 4, the maximum difference occurred at a depth of 42 cm (1.24 MPa), while at site 5 it was a depth of 40 cm (1.46 MPa).

All of the analyzed stands showed a decrease of the difference in soil compaction between the sites located in the post-fire area and the control sites at depths close to the maximum (50 cm) for which soil compaction measurements were performed.

4. Discussion

Fully mechanized timber harvesting in the post-fire areas in the region under analysis is essentially associated with two threats in terms of its feasibility. The first of them consists in the fact that, in relatively young, 20-year-old stands, the performance of thinning based on mechanized technologies may be associated with low efficiency and, consequently, with low profitability of the work. This results from higher time consumption of harvesting of 1 m^3 of timber, among others related to the relatively small volume of individual trees harvested in this age class.

The other threat is the likely low bearing capacity of the soil in the post-fire area, limiting the accessibility of this area for forest machines. This is due to a possible increase in the level of groundwater in the deforested area. An increase in soil water content reduces friction forces between soil particles, thereby reducing the bearing capacity of the soil [25–27]. In the analyzed stands, however, this phenomenon probably did not occur—no statistically significant differences in soil moisture were found between the post-fire and the control stands. For this reason, it is probably the field conditions that will significantly limit selection of the means applied in timber harvesting processes in a given area [44,45], the technology of their use [46] or at least the period of performance of the scheduled treatments [32].

The soils in the areas where the fire had not occurred were characterized by a bearing capacity that was satisfactory, i.e., did not limit the possibility of movement mechanized harvesting and extraction vehicles. The average cone index (CI) value for the sites without the fire was 1.60 MPa, while for the post-fire ones it was 2.15 MPa, the fire had additionally raised the CI value, further increasing the bearing capacity of the soils. Since moisture is a factor that significantly affects the bearing capacity of the terrain, its seasonal increase, e.g., after heavy rains or during spring thaws, often causes a temporary reduction in the bearing capacity and thus limits the accessibility of such areas for machines used in the timber harvesting process [47]. In the analyzed post-fire areas, characterized by a high bearing capacity, it will probably be possible to use mechanized timber harvesting even in the case of increased soil water content, which means that the work will not have to be limited to dry periods or to winter with the frozen soil cover [24].

A practical assessment of the bearing values of soils from the post-fire area and the control compartments was performed with the use of the Eco Wood protocol. In the protocol, the best bearing capacity characterizes soils with the CI value above 0.5 MPa, where harvesters and forwarders with pressures above 80 kPa can be used. On the analyzed sites, the CIs were higher and even vehicles with significantly higher pressures can be used under those conditions, i.e., 6- and 8-wheeled forwarders of medium or large class with the bearing capacity of, respectively, 6–12 t and 12–15 t, equipped in front tires of at least 600/55-26.5 and rear tires of at least 710/45-26.5 (Table 3).

Table 3. Nominal ground pressure (NGP) of selected forwarders. Based on [48].

Forwarder Class	Weight (Tones)	Number of Wheels	Front Tires (Without Band Tracks)	Rear Tires (Without Band Tracks)	Load Capacity (Tones)	NGP (kPa)
Medium	12.9	8	600/50-22.5	600/50-22.5	9.0	76
	12.7	6	28L-26	710/40-24.5	12.0	83
	14.4	6	710/55R34	710/45-26.5	12.0	84
	16.2	8	600/55-26.5	600/55-26.5	12.0	86
Large	15.9	6	28L-26	800/40-26.5	13.0	85
	17.8	8	710/45-26.5	710/45-26.5	13.0	80
	15.1	6	710/55R34	800/40-26.5	15.0	89
	16.9	8	710/45-26.5	710/45-26.5	15.0	82

The soil compaction analyses, carried out in a deep soil profile of up to 50 cm, showed that up to a depth of several centimeters that the differences in soil compaction between the post-fire and the control stands were small, not exceeding 0.3 MPa. It seems that such a trend may be linked to site fertility or soil preparation before planting, but this requires further research. In deeper layers, soil compaction was always higher in the post-fire area than in the control stands, and this difference was significantly greater (0.9–1.8 MPa) than the one observed in the topsoil layer of several centimeters. In this context, the use of the CI to assess the bearing capacity of the soils after the fire and in the control, stands could have given inconsistent results. This is because the cone index is based on average soil compaction at depths of 1, 15, 30 and 45 cm. Considering the similar soil compaction value in the post-fire area and the control stands at a depth of 1 and 15 cm, it is the significantly increased soil compaction values in the deeper layers (30 and 45 cm) that essentially affect the significantly higher CI values obtained in the post-fire area. In practice, one should expect a similar bearing capacity of the soils in the post-fire area and the control stands because, considering the large compaction of those soils, the impact of vehicle wheels on the ground should be limited to the top several centimeters, whose compaction in the compared areas was similar. A similar conclusion was reached by Saarilahti [32], who proved that the first 15 cm below the surface is the most important soil layer from the point of view of the movement of vehicles used in the timber harvesting process. Numerous studies [49–51] concerning the depth of ruts formed in the harvesting process clearly confirm that, under conditions present in Europe, the impact of machines on forest soils is really limited to the top 10–15 cm layer.

The fire, which over 25 years ago destroyed several thousand hectares of forests in the Rudy Raciborskie Forest District, has had such a strong impact on the soil structure that its effects are still visible. This is evidenced by the fact that even at the maximum analyzed depth of 50 cm, increased soil compaction is visible in measurements made in the post-fire area. The process of regeneration of the topsoil layer has already begun, as evidenced by similar compaction of the topsoil layer in the post-fire area and the control stands. Most likely, this is due to natural processes involving the deposition of the humus layer, more powerful on more fertile sites, or to loosening of the topsoil layer due to changes in its volume during the winter freezing and thawing [52]. However, the reason for this phenomenon requires further research. The results presented here show that the effects of the fire are currently the most visible in deeper soil layers.

5. Conclusions

Statistically significant higher values of the cone index (CI) were found in all of the compared pairs of forest compartments in stands regenerated after fire. The mean value of this index in the post-fire stands was 2.15 MPa, while in the control stands it was 1.60 MPa. In both groups of stands, the bearing capacity of the soil did not limit the accessibility of those areas for vehicles used for timber harvesting and extraction. In the present research, the lowest mean CI value for the entire study area was 1.4 MPa, while the minimum value of this index for a single measurement was 0.63 MPa. Detailed soil compaction analyses, performed at every 1 cm, up to a depth of 50 cm, showed that, in forest practice, differences in the bearing capacity of soils from a post-fire area and control areas could be imperceptible. It was shown that in the top several centimeters of soil, which is the most important for forest area accessibility for machine timber harvesting, differences in soil compaction between the post-fire and the control sites were relatively small. The impact of the forest fire, shown as a significant increase in the compaction of forest soil, is still visible, but only in the deeper layers of the soil profile.

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