

The Influence of *Amorpha fruticosa* L. on Natural Recovery of Compacted Vertic Gleysol on Forwarder Trails after a Six-year Period

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ABSTRACT

The study of the natural recovery of the compacted Vertic Gleysol after the period of six years was conducted in the narrow-leaved ash forest (subcompartment 137a, management unit Turopoljski lug, Croatia) by comparing the natural bulk density and porosity of the soil and the cone index, with measurements on and off forwarder trails. The last felling was conducted in the late summer (drier soil) in 2016 using a harvester–forwarder fully mechanised timber harvesting system. Parallel forwarder trails 3 m wide and 20 to 30 m apart were established, which subsequently led to a felling density of 43 m³/ha (~ 12.5 m³/100 m³) and a lower intensity of forwarder traffic per trail, all followed by an invasive false indigo bush (*Amorpha fruticosa* L.) growth. Samples of the surface soil layer in an undisturbed state (Kopecky cylinders), for laboratory analysis of soil physical properties, were taken on trails (8) and off forwarder trails during 2022. In addition to changes in soil physical properties, the determination of forest soil recovery was also investigated by measuring the cone index (penetration resistance) with a penetrometer, during January and September 2022 under wetter and drier conditions of the soil. The impact of false indigo bush on forest soil recovery was investigated on ten square sample plots with dimensions of 3 m × 3m, on which the following measurements were recorded: the number of plants, fresh mass of the aboveground part of the plants, root collar diameter and plant height. A one-way analysis of variance of bulk density and soil porosity for forty soil samples off trails (0.726 g/cm³, 68.4%) and on forwarder trails (0.699 g/cm³, 69.1%) indicated no statistically significant differences. Nevertheless, lower mean values of soil bulk density and higher mean values of soil porosity on trails, as well as the ranges of interval estimates of their values in relation to measurements outside the trails, indicate the natural recovery of compacted soil on forwarder trails over a period of six years. Similarly, a single analysis of variance of the average soil cone index at a depth of 5 to 25 cm, with 60 measurements taken at intervals across the winter and summer periods, indicated statistically significant differences, confirming the natural recovery of compacted soil on forwarder trails. In addition to the passage of time, the obtained results of natural soil recovery were also influenced by the overgrowth of forwarder trails with false indigo, with an average of 833 plants per 100 m of trail and an average fresh mass of the above-ground part of false indigo plants of 208 kg per 100 m of trail, which, through the action of its branched root system, contributed to the improvement of the compacted Gleysol on forwarder trails.

Keywords:

gleysol, timber forwarding, soil compaction, recovery time, false indigo bush

DOI:

<https://doi.org/10.31298/sl.150.9-10.5>

How to Cite:

Bumber, Z. et al., 2026: The Influence of *Amorpha fruticosa* on Natural Recovery of Compacted Vertic Gleysol on Forwarder Trails after a Six-year Period. Šumarski list 150 (9–10): 441–450, 2026. <https://doi.org/10.31298/sl.150.9-10.5>



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INTRODUCTION

During mechanised harvesting operations, high contact pressures and wheel slip of forest vehicles compact the forest soil and form ruts (Picchio et al. 2020, Breinig et al. 2025), often making the natural recovery of soil a long-term process (Labelle and Jaeger 2011, DeArmond et al. 2021).

Soil compaction causes solid particles to come closer together (Pernar 2017), reducing porosity and increasing soil bulk density, while deteriorating water-air relations and the thermal regime. As a result, the soil becomes less supplied with oxygen and water, which disrupts conditions for plant nutrition and development, as well as soil microbiological activity (Cambi et al. 2015). The level of forest soil compaction is influenced by the weight of forest vehicles, the width and inflation pressure of their tyres (Labelle et al. 2022, Brennensthal et al. 2024), vehicles' additional traction equipment (Poršinsky et al. 2011, Poršinsky et al. 2020), the proportion of clay and organic matter in the soil, soil moisture and terrain slope (Sutherland 2003, Lüscher et al. 2019, Latterini et al. 2024). Forest soil compaction increases with the number of vehicle passes, with the first pass causing the greatest compaction (Pandur et al. 2022, Bumber et al. 2024). Soil compaction caused by forest vehicles can significantly affect the growth of aboveground vegetation, especially the underground part of young plants (Cambi et al. 2017, Latterini et al. 2025a).

The natural recovery of compacted forest soil is influenced by natural processes, such as changes in wetting and drying cycles (swelling and shrinking) of clay particles, and freezing and thawing of the soil (Horvat 1995, DeArmond et al. 2021), as well as vegetation (Flores Fernández et al. 2019, Meyer et al. 2014a, Ramineh et al. 2023) and soil fauna (Cambi et al. 2015, Latterini et al. 2025b).

DeArmond et al. (2021) reviewed the natural recovery of compacted soil from skid trails, analysing studies from temperate, boreal, and tropical forests. They concluded that key indicators for assessing forest soil recovery are bulk density, cone index, macroporosity, and fine root content. These were measured and analysed on and off skid trails. Soil recovery generally lasts two to five decades. This duration depends on soil texture, climate, soil sensitivity to compaction at the time of harvesting operations, the characteristics of the forest vehicles used, and the number of vehicle passes.

The surface layers of the soil on skid or forwarder trails with fewer vehicle passes recover faster (Labelle and Jaeger 2011), with complete recovery from only two vehicle passes after three years (Goutal et al. 2012). Clay soils show faster recovery than sandy soils because clay particles swell when they absorb water and shrink when they dry, whereas sandy soils do not exhibit this behaviour (Cambi et al. 2015, DeArmond et al. 2021).

Based on current knowledge, it can be assumed that the properties of Vertic Gleysol favour the natural recovery of compacted soil on forwarder or skid trails, together with the additional help of the branched root system of false indigo (*Amorpha fruticosa* L.), which could contribute to the amelioration of the compacted surface layer of soil. The aim of this paper is to investigate the natural recovery of compacted forest soil on forwarder trails overgrown with invasive false indigo and to assess the contribution of false indigo to soil recovery.

MATERIALS AND METHODS

Study Site

The Turopoljski lug management unit, managed by the Velika Gorica Forest Office, occupies 4407.93 ha of lowland forests located 20 to 30 km southeast of Zagreb (the capital of the Republic of Croatia), in the lowest part of the central Odra plain, at an altitude above sea at 97–104 m (Anon. 2015). The regulated streams Vranić, Buna, and Peščenka flow through the area, and the Sava–Odra drainage channel runs along the northeastern edge, thereby accelerating the outflow of surface water and significantly reducing infiltration into the physiologically active part of the soil profile (Mayer 1995).

The soil of the research area was formed on the quaternary alluvial deposits of the Sava River and its tributaries in the lowest part of the Odra plain. The upper part of the soil profile to a depth of about 1 m is made of heavy clay with low water permeability, below which are texturally lighter deposits – silty clay loams and sands. This textural stratigraphy causes slow percolation through the topsoil and long-term retention of surface water, which, along with seasonal oscillations in groundwater level, is the fundamental pedogenetic factor in the formation of gley soils in this area (Mayer 1995).

The vegetation cover in this management unit directly reflects the microrelief and soil conditions. At higher elevations, where Stagnosol and Stagnic Gleysol occur, forests of pedunculate oak with common hornbeam (*Carpino betuli-Quercetum roboris* (Anić 1959) Rauš 1971) and floodplain pedunculate oak forests (*Genisto elatae-Quercetum roboris* Horvat 1938) are developed. The floodplain pedunculate oak forests also occur at transitional elevations where Gleysol dominates. At the lowest floodplain elevations, where Vertic Gleysol is formed, forests of narrow-leaved ash with autumn snowflake (*Leucojo aestivi-Fraxinetum angustifoliae* Glavač 1959) and forests of black alder with alder buckthorn (*Frangulo-Alnetum glutinosae* Rauš (1971) 1973) predominate (Anon. 2015, Mayer 1995). This differentiated vegetation has a feedback effect on the soil as a pedogenic factor through the input of organic matter, the specific development of the root system, the stimulation of biological activity, and the intensive transpiration of the plant community, directly influencing the dynamics and development of the soil (Pernar 2017).

According to the local meteorological station (Sisak) during the 30-year period (1984–2013) the climate is semi-humid, with a mean annual air temperature of 11.5°C and an average annual precipitation of 924.9 mm (Anon. 2015). According to the more recent reference period of 1991–2020, the mean annual temperature is 12.1°C (Vučetić and Anić 2021), reflecting a documented upward trend in temperatures.

Field measurements were conducted during 2022 in the subcompartment 137a (45°35'55" N, 16°14'45" E) (Figure 1). Subcompartment 137a phytocoenologically consists of a narrowed-leaved ash with autumn snowflake (*Leucojo aestivi-Fraxinetum angustifoliae* Glavač 1959) forest. It is an older mixed stand of narrow-leaved ash (*Fraxinus angustifolia* Vahl) and black alder (*Alnus glutinosa* (L.) Gaertn.), with admixed pedunculate oak (*Quercus robur* L.), established from seed, aged 58 years, and managed within a 100-year rotation period. The area of the subcompartment is 39.9 ha, and

the terrain is flat, with an altitude of 97 m. The growing stock is 280 m³/ha, and the basal area is 29.63 m²/ha with 679 trees per hectare. The mixture is dominated by black alder (37%) and narrow-leaved ash (31%) of the growing stock, with pe-

dunculate oak (13%), while the remaining 19% is accounted for by other soft deciduous species. The current management regulation for this subcompartment is stand thinning with an intensity of 45 m³/ha.

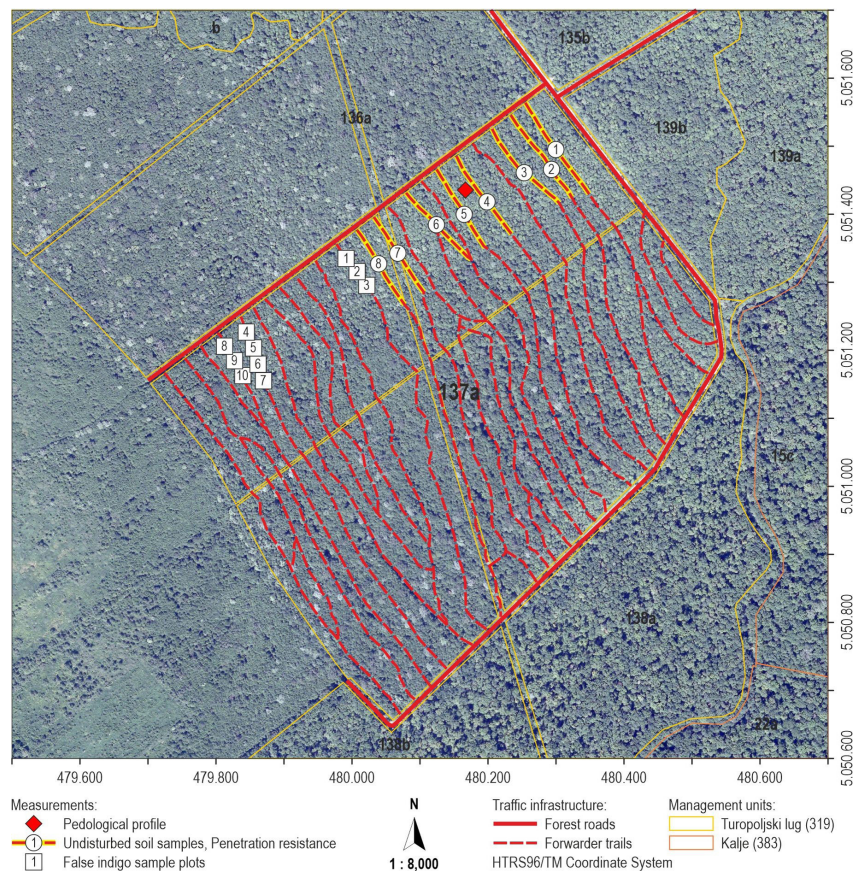


Figure 1 Map of the subcompartment 137a in the Turopoljski lug management unit.

Last harvesting operations in the subcompartment 137a were in late summer 2016 using a harvester–forwarder harvesting system during the dry season, with parallel forwarder trails 3 m wide and 20 to 30 m apart (Figure 1), at a cutting density of 43 m³/ha, or ~12.5 m³ per 100 m³ of forwarder trail. The density of forwarder trails was 343 m/ha, and due to the possible two-sided timber forwarding, the average forwarding distance was 140 m, which accounted for two forwarder passes per trail. In the meantime, the trails were not used and were overgrown with invasive false indigo

(Figure 2), and subsequently the narrow-leaved ash in the stand was attacked by a parasitic fungus (*Hymenoscyphus fraxineus* (T. Kowalski) Baral, Quelo & Hosoya), causing the dieback of the narrow-leaved ash. The first appearance of false indigo in the area of this management unit was recorded in 2008, and its intensive spread across the entire area of the management unit was observed after the harvesting operations in 2012, which is attributed to the transfer of seeds by uncleaned forest vehicles during their relocation from other forest working sites and locations.



Figure 2 Forwarder trails in subcompartment 137a – A) covered with false indigo bush, and B) after the cutting of false indigo bush plants.

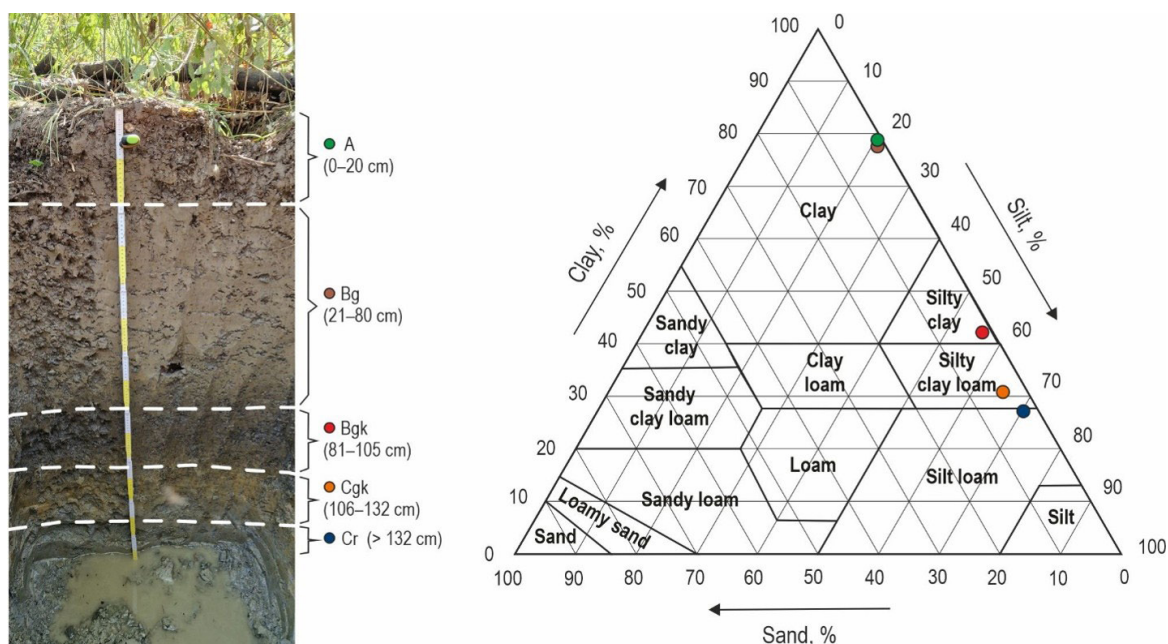


Figure 3 Soil profile and textural triangle of Vertic Gleysol in subcompartment 137a.

A soil profile was opened in subcompartment 137a to determine the pedophysiological characteristics of the soil at the research site (Figure 3). The soil is classified as an Eutric Gleysol (Clayic, Vertic) according to the IUSS Working Group WRB (2022), with the horizon sequence A – Bg – Bgk – Cgk – Cr. The surface humus-accumulative horizon A is dark brown in colour, with a crumbly structure with abundant roots, sharply delimited from the lower horizon. The upper two horizons (A and Bg) are non-carbonate and have a medium to very weak acidic reaction (Pernar 2017). The distinctly clayey texture of the upper horizons determines the soil's vertical properties (alternation between swelling during wetting and shrinkage during drying), which are morphologically manifested as deep cracks and a bumpy soil surface. The profile with a developed Bg horizon in the upper part is specific to heavy clayey soils with an impermeable surface layer, in which precipitation and floodwater are retained for a long time. As a result, in this part of the profile, reduction processes prevail over oxidation; oxidation occurs only during a short dry period after the water has receded, leaving a morphological trace as rusty mottles on the surfaces of structural aggregates. From the Bgk horizon

onwards, carbonates appear, and their content increases with profile depth, resulting in a transition towards a basic soil reaction. Carbonate concretions are visible in the zone reached by capillary water. Fe/Mn concretions are also present in the same horizon as a morphological indicator of the alternating change of reduction and oxidation conditions. With increasing profile depth, soil porosity progressively decreases while bulk density increases (Table 1), reflecting a decrease in organic matter content and biological activity with depth, as well as compaction of deeper horizons due to the pressure of the upper soil layers. The surface horizon A is characterised by an elevated organic matter content (Table 1), which is characteristic of lowland Gleysols in which long-term anaerobic conditions slow down its mineralisation. The deepest horizon, Cr, represents a zone of permanent reduction, as confirmed by its predominantly greyish colour and the presence of groundwater at the bottom of the profile at the time of opening. The physical and chemical characteristics of the studied soil by genetic horizons are shown in Table 1. The morphological description of the profile is fully consistent with earlier soil observations by Mayer (1995) in the Turopoljski lug management unit.

Table 1 Selected soil properties of Vertic Gleysol by genetic horizons.

Genetic soil horizons and their depth	Bulk density* (g/cm ³)	Soil porosity* (% volume)	Particle size distribution (% mass)				pH (H ₂ O)	CaCO ₃ (g/kg)	Organic carbon (g/kg)	Total nitrogen (g/kg)
			Sand (0.063–2 mm)	Silt (0.002–0.063 mm)	Clay (<0.002 mm)	Soil texture				
A (0–20 cm)	0.82 ± 0.05 (0.75–0.88)	62.6 ± 2.4 (60.9–66.5)	0.28	21.19	78.53	Clay	5.84	–	60.6	6.1
Bg (21–80 cm)	1.15 ± 0.03 (1.12–1.18)	50.1 ± 1.7 (47.5–52.1)	0.21	22.23	77.56	Clay	6.73	–	29.4	3.3
Bgk (81–105 cm)	1.59 ± 0.02 (1.56–1.62)	37.5 ± 1.0 (36.0–38.5)	1.62	57.04	41.34	Silty clay	8.29	20.7	3.3	0.5
Cgk (106–132 cm)	1.62 ± 0.01 (1.61–1.64)	37.8 ± 0.9 (36.9–39.2)	4.40	64.79	30.81	Silty clay loam	8.44	27.9	0.9	0.4
Cr (>132 cm)	1.64 ± 0.02 (1.62–1.67)	36.4 ± 1.0 (35.2–37.6)	2.37	70.48	27.15	Silt loam	8.51	15.5	1.3	0.5

* values of five undisturbed soil samples (rolls) for each genetic soil horizon – mean ± standard deviation (minimum–maximum)

Data Collection

Field data collection (Figure 1) included the following steps: i) opening the pedological profile to determine soil type and morphological properties, and sampling soil by genetic horizons and depths; ii) taking undisturbed soil samples (Kopecky cylinders) from eight forwarder trails, with five samples from the surface on each trail and five off each trail; iii) collecting disturbed soil samples to determine granulometric composition, pH value, carbonate content (CaCO_3), organic carbon and total nitrogen; iv) measuring the soil cone index with a penetrometer on eight forwarder trails, with 15 measurements on and 15 off each trail; v) sampling false indigo on the surfaces of forwarder trails (Klanica 2023), on ten sample plots of 3×3 m, to record the number of plants, fresh mass, root collar diameter, and plant height to determine the possible amelioration effect on forest soil recovery. Field surveys were conducted during January and early September 2022.

The soil cone index (penetration resistance) was measured with an Eijkelkamp Penetrolgger digital penetrometer with a cone area of 2 cm^2 and a top angle of 30° , and the results are expressed as a standardised average value of cone penetration resistance measurements at a soil depth of 5 to 25 cm, in accordance with the ASAE EP542 (1999) standard.

Laboratory analysis was carried out in the Laboratory of Forest Ecology and Pedology at the Institute of Forest Ecology and Silviculture, Faculty of Forestry and Wood Technology, University of Zagreb. Soil samples in a disturbed state were prepared in accordance with ISO 11464 (2006), and the soil granulometric composition (ISO 11277, 2020), pH value (ISO 10390, 2021), carbonate content (ISO 10693, 1995), organic carbon (ISO 10694, 1995) and total nitrogen (ISO 13878, 1998) were determined. Soil bulk density (ISO 11272, 2017) and soil solids density (ISO 11508, 2017) were determined on soil samples in an undisturbed state (Kopecky cylinders), from which soil porosity was calculated.

The natural recovery of the compacted Vertic Gleysol of the narrow-leaved ash forest in the subcompartment 137a of the Turopoljski lug management unit was investigated six

years after the last felling operations, by comparing the soil bulk density and porosity, and the soil cone index on forwarder trails and off the trails (undisturbed ground).

Statistical data processing was carried out in the Statistica v. 14.0.0.15 program, with testing for data normality and performing descriptive statistical analysis. To determine the statistical significance of the differences in the mean values of forest soil recovery indicators (on forwarder trails and off the trails), as well as the measured false indigo properties on exemplary plots, a one-way analysis of variance (ANOVA) was used. In the case of statistically significant differences between the indicators being compared, a post hoc test was performed. In all analyses, an error of 5% was considered statistically significant.

RESULTS

Soil bulk density outside forwarder trails (control measurement) ranged from 0.609 to 0.877 g/cm^3 , with an average value of $0.726 \pm 0.063 \text{ g/cm}^3$ (median 0.718 g/cm^3), and on forwarder trails from 0.562 to 0.830 g/cm^3 , with an average value of $0.699 \pm 0.067 \text{ g/cm}^3$ (median 0.685 g/cm^3). One-way analysis of variance did not reveal statistically significant differences between samples collected outside and on the surface of forwarder trails – $F(1,78) = 3.5095$; $p = 0.06476$ (Figure 4A).

Soil porosity outside forwarder trails (control measurement) ranged from 62.83 to 73.17% , with an average value of $68.42 \pm 2.65\%$ (median 69.42%), and on forwarder trails from 62.90 to 75.22% , with an average value of $69.06 \pm 2.78\%$ (median 69.42%). One-way analysis of variance did not reveal a statistically significant difference between samples collected outside and on the surface of forwarder trails: $F(1,78) = 1.1027$; $p = 0.29691$ (Figure 4B).

During laboratory processing of samples, significant soil shrinkage was observed upon drying, ranging from 24 to 55% , with an average of approximately 41% , providing morphological confirmation of the vertic properties of the studied soil.

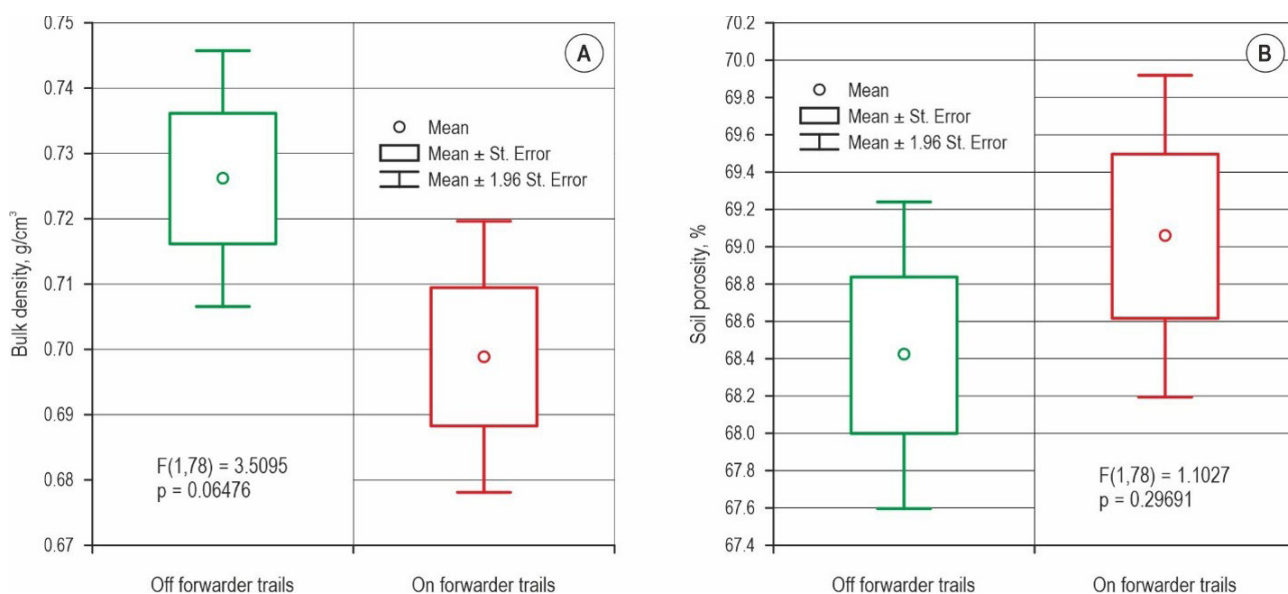


Figure 4 Comparison of soil bulk density (A) and soil porosity (B) off and on the surface of forwarder trails.

The mean values of soil bulk density and soil porosity on and off forwarder trails are comparable to each other, with no statistically significant differences (Figure 4).

In addition to physical soil characteristics, the recovery of forest soil on forwarder trails was assessed by comparing the cone index measurements on and off forwarder trails. The results are expressed as a standardised average cone penetration resistance at depths of 5–25 cm. The cone index measurements depend on the current soil moisture, which differed between winter and summer measurements (Figure 5).

During the winter measurement, the current soil surface moisture (Figure 5A, trails 1–4) averaged $64 \pm 2\%$ (median 64%) and ranged from 55% to 70%. The soil cone index outside the trails ranged from 0.324 MPa to 1.243 MPa, with an average value of 0.655 ± 0.176 MPa (median 0.626 MPa), and on the trails from 0.238 MPa to 0.795 MPa, with an average value of 0.516 ± 0.130 MPa (median 0.529 MPa). One-way analysis of variance revealed statistically significant differences between measurements off and on the surface of the forwarder trails: $F(1,118) = 24.134$; $p = 0.000003$ (Figure 5A).

During the summer measurement (Figure 5B, trails 5–8), the current soil surface moisture averaged $26 \pm 10\%$ (median 25%), ranging from 12% to 49%. The moisture at the bottom of the humus-accumulative horizon, determined by the gravimetric method, averaged $58 \pm 7\%$ (median 59%), ranging from 44% to 72%. The soil cone index at a depth of 5 to 25 cm outside the forwarder trails ranged from 0.400 MPa to 3.486 MPa, with an average value of 1.803 ± 0.682 MPa (median 1.807 MPa), and on the trails from 0.320 MPa to 3.148 MPa, with an average value of 1.490 ± 0.631 MPa (median 1.429 MPa). One-way analysis of variance revealed statistically significant differences between measurements off and on the surface of forwarder trails: $F(1,118) = 6.7995$; $p = 0.010296$ (Figure 5B).

The soil cone index on forwarder trails was lower than the values measured off the trails at both measurement times, and the differences were statistically significant for both winter and summer soil moisture conditions (Figure 5). The same trend in differences was observed for soil bulk density, although it was not statistically significant (Figure 4).

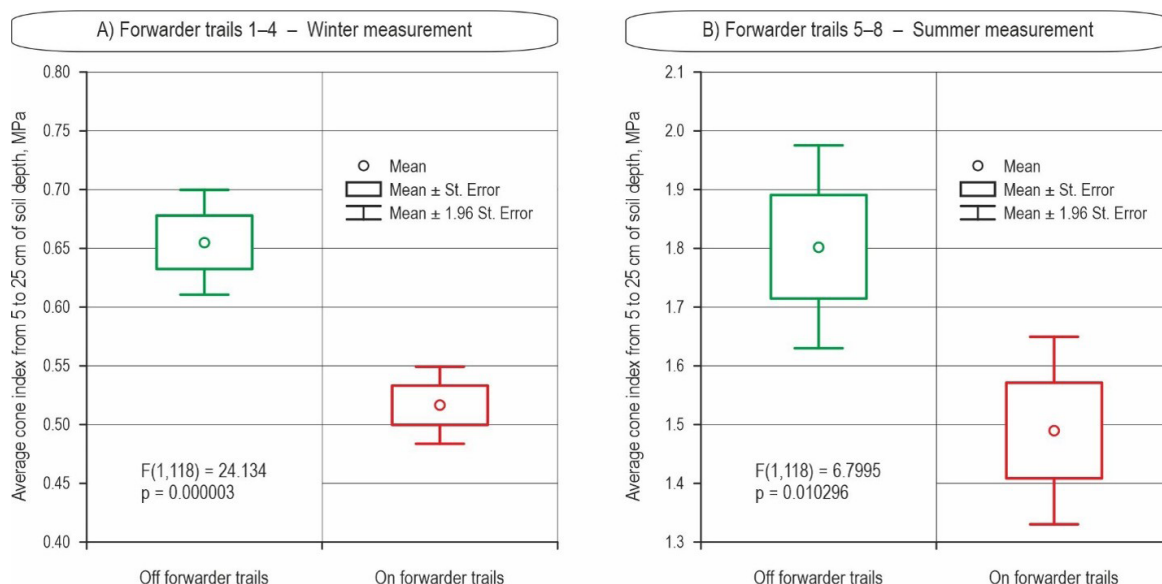


Figure 5 Comparison of average soil cone index off and on the surface of forwarder trails.

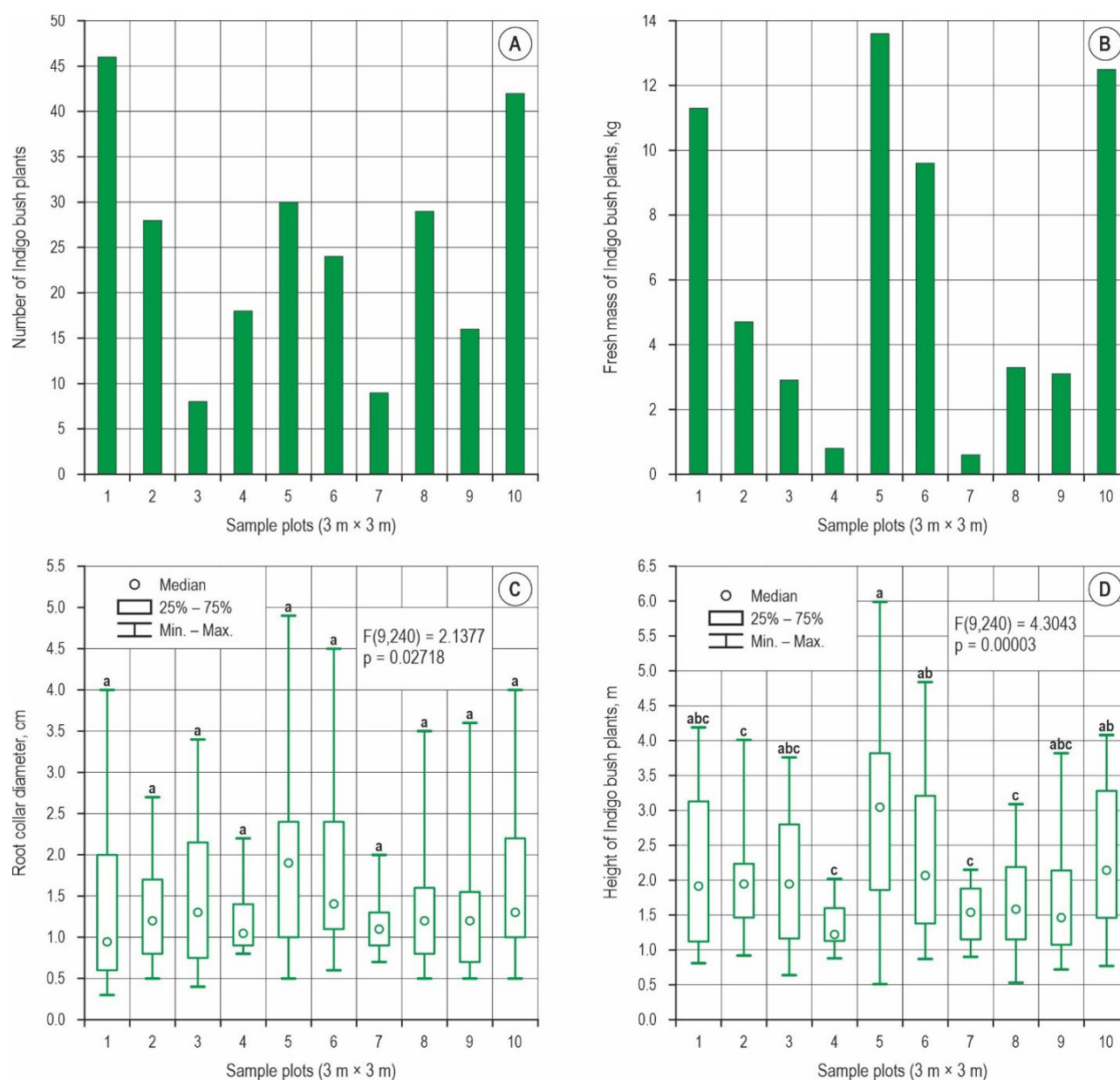
The number of false indigo plants per sample plot ranged widely from 8 (Plot 3) to 46 plants (Plot 1), with an average value of 25 ± 13 (median 26) plants per 9 m^2 (Figure 6A). The sample plots with the highest canopy closure (Plots 3, 4, 7, and 9) had <20 false indigo plants per plot (Figure 6A). Variability in canopy closure between sample plots was due not only to the cleaning of forwarder trails but also to local loss of canopy because of the drying of ash trees caused by the fungus *Hymenoscyphus fraxineus*.

The arithmetic mean values of the root collar diameter of false indigo plants in ten sample plots ranged from 1.2 ± 0.4 cm (Plot 4) to 1.9 ± 1.0 cm (Plot 5). The smallest individual value of 0.3 cm was recorded in Plot 1 (which also had the largest number of plants), and the largest of 4.9 cm in Plot 5. A one-way analysis of variance determined statistically significant differences between sample plots: $F(9,240) = 2.1377$; $p = 0.02718$ (Figure 6C). The average root collar diameter was 1.5 ± 0.9 cm (median 1.2 cm).

The arithmetic mean values of the heights of false indigo bush plants in the sample plots ranged from 1.33 ± 0.32 m (Plot 4) to 2.79 ± 1.28 m (Plot 5). The lowest individual value of 0.64 m was recorded in Plot 3 (which also had the lowest number of plants), and the highest value of 5.99 m in Plot 5. One-way analysis of variance determined statistically significant differences between the sample plots: $F(9,240) = 4.3043$; $p = 0.00005$. Tukey's post-hoc test indicated the differences shown in Figure 6D. The average height of false indigo bush plants was 2.09 ± 1.04 m (median 1.85 m).

The fresh mass of the above-ground parts of false indigo bush plants in representative plots of 9 m^2 (Figure 6B) ranged from 0.8 kg (Plot 4) to 13.6 kg (Plot 5), with an average value of 6.2 ± 5.0 kg (median 4.0 kg).

By calculating the average values per representative plots per 100 m forwarder trail (3 m wide), false indigo bush on average covered the trails with 833 plants and an average fresh mass of above-ground parts of 208 kg per 100 m trail.



* Letters denote the statistical difference between individual plots for root collar diameter and plant height (Tukey HSD), respectively, at $p < 0.05$.

Figure 6 Number of plants (A), fresh weight of aboveground parts (B), root collar diameter (C) and height (D) of false indigo bush plants on ten sample plots of forwarder trails in subcompartment 137a.

DISCUSSION

The condition of the surface soil layer on forwarder trails six years after timber felling and forwarding, in terms of natural recovery, is most comparable to that reported by Horvat (1995), who investigated the recovery of compacted Stagnic Gleysol on forwarder trails in lowland floodplain forests. Based on the cone index measurement with a penetrometer, the author concluded that approximately ten years were required for the natural recovery of the compacted soil. The results of this study indicate a faster natural recovery of the studied soil than that reported by Horvat (1995). Such a difference can be attributed to several factors: the vertic properties of the studied soil, the lower intensity of vehicle traffic on the forwarder trails during the last harvesting operations, and the possible ameliorative effect of the false indigo bush organic matter input on the forwarder trails. Horvat (1995)

conducted his research on a Stagnic Gleysol with a lighter texture – silty loam, whereas this study deals with a soil with an extremely high clay content – above 77% to a depth of 80 cm (Table 1). A high clay content does not necessarily indicate faster recovery – the mineralogy of the clay fraction is the key. The classification of the soil as a Vertic Gleysol, morphologically confirmed by deep cracks, a bumpy soil surface, and significant shrinkage of the samples during drying (24–55%), indicates the predominance of clay minerals with swelling and shrinkage properties, likely dominated by smectite-group minerals (Pernar 2017). It is precisely these cycles in the surface layer of the studied soil, exposed to seasonal wetting and drying, that trigger the natural mechanism of loosening the compacted structure, known as self-mulching (DeArmond et al. 2021, Goutal et al. 2012). In addition to the soil's vertic properties, the structure's rapid rehabilitation was significantly influenced by the extremely

low intensity of forestry vehicle traffic during the felling in 2016, which consisted of only two passes of the forwarder along the trail. A review by DeArmond et al. (2021) confirms that skid trails with such low traffic intensity in the temperate zone can largely recover within a decade, primarily in the soil's shallowest surface layer. An additional factor that mitigated the initial damage was the summer drought. The drier surface layer of the studied soil provided the soil with greater bearing capacity and mechanical resistance, which limited the depth and intensity of soil compaction and reduced the possibility of deep rutting in the profile, thus confirming the justification for planning harvesting operations in the dry season (Labelle and Jaeger 2011, Goutal et al. 2012).

Two common methods have been used to determine the natural recovery of the studied soil from forwarder trails: the comparison of soil bulk density and porosity (Labelle and Jaeger 2011, Latterini et al. 2025b) and the cone index (Horvat 1995, Mohieddinne et al. 2019) between forwarder trails and control plots. The method for determining soil bulk density and porosity provides direct indicators of the soil's physical properties and requires laboratory analysis of undisturbed samples, which is more expensive and time-consuming. However, on this soil, this method is methodologically limited by the pronounced shrinkage of the samples upon drying, with a volume contraction of 24 to 55% recorded in this study, averaging approximately 41%. Such soil behaviour calls into question the suitability of the standard procedure for determining soil bulk density as an indicator of the degree of compaction and recovery on vertic soils. The cone index, although dependent on the current soil moisture, measures the in situ penetration resistance without laboratory artefacts, and therefore showed greater sensitivity in distinguishing the soil condition in forwarder trails and control plots on this soil type, as confirmed by statistically significant differences between the trail and the control at both measurement dates. Therefore, when interpreting the level of soil recovery, the cone index measurements were considered more reliable indicators of soil recovery than soil bulk density and porosity determinations.

The results of the study indicate the ameliorative effect of false indigo bush plants on the recovery of the physical characteristics of the soil on forwarder trails. False indigo bush overgrew exclusively on forwarder trails where as an invasive species it displaced the surrounding vegetation by forming a dense structure and through allelopathic activity, inhibiting the development of other plant species (Radovanović et al. 2017, Bakacsy et al. 2024). The lower values of soil bulk density and cone index determined on trails compared to control measurements can be partially associated with the presence of a dense structure of false indigo bush and the activity of its branched root system. A similar ameliorating effect of vegetation on trails has been documented for grey alder (*Alnus incana* (L.) Moench) by Flores Fernández et al. (2019), black alder (*Alnus glutinosa* (L.) Gaertn) by Meyer et al. (2014b) and Ramineh et al. (2023), and Caucasian alder (*Alnus subcordata* C.A. Mey.) and velvet maple (*Acer velutinum* Boiss.) by Jourgholami et al. (2019). The positive impact of vegetation on the recovery of compacted soil is most often associated with the mechanical action of roots, the input of organic matter and the stimulation of soil biological activity, which contributes to the development of macropores

and the gradual regeneration of soil structure (Meyer et al. 2014a, 2014b; Flores Fernández et al. 2019; Ramineh et al. 2023). However, for false indigo bush, the aforementioned positive effects on soil physical properties cannot be considered in isolation from its invasive nature. The spread of false indigo bush is associated with the suppression of native vegetation and the difficulty of natural regeneration of lowland forests, and the spread of invasive species by uncleaned forest vehicles poses an additional ecological risk (Blinn et al. 2019, Snyder et al. 2021).

The mass settlement and extremely dense cover of false indigo bush on the studied forwarder trails can be linked to the impaired health and structure of this floodplain stand. The activity of the fungus *Hymenoscyphus fraxineus*, which caused extensive dieback of ash trees, led to a strong opening of the crown, loss of the forest cover and increased light inflow to the soil surface, which, according to recent European research, is the main trigger for the invasion of non-native species in ash forests (Pautasso et al. 2013). Since false indigo bush is a pronounced heliophyte that does not have special soil requirements and aggressively occupies open and unvegetated spaces, these ecological conditions enabled its rapid expansion along the forwarder trails, resulting in an extremely dense cover of as many as 833 plants and 208 kg of fresh aboveground biomass per 100 meters of trail length. Such dense overgrowth and progressive changes in stand structure have a feedback effect on the dynamics and development of the soil itself through the input of organic matter and the specific development of the root system (Pernar 2017).

False indigo bush is a shrub native to eastern and south-eastern North America and was introduced to Europe at the beginning of the eighteenth century (Schnitzler et al. 2007). The first record of this allochthonous species in Croatia dates to 1889 (Ettinger 1889). Some authors conclude that riverine ecosystems are specifically susceptible to the invasion of false indigo because they are usually exposed to strong anthropogenic modifications (Catford et al. 2011, Eschtruth and Battles 2011). Also, during the construction of railways in the past, false indigo bush was planted on embankment slopes for their stabilization, from where it aggressively spread into the area of Croatian lowland floodplain forests (Petračić 1938). Although the results of this research indicate the ameliorative properties of false indigo in terms of physical recovery of the compacted surface layer of soil, the forestry profession must take a firm and critical stance towards this invasive species. Its historical course, from its appearance at the end of the 19th century in Europe (Schnitzler et al. 2007) to a globally dispersed species, with occurrences in Central Asia, China, Japan, and South America (GBIF 2026) has turned into a serious ecological threat. Due to its pronounced amensalism and secretion of allelopathic compounds (Radovanović et al. 2017, Bakacsy et al. 2024), it completely suppresses indigenous vegetation and weeds in young areas. This makes natural forest regeneration more difficult, threatening, and expensive, which is a persistent problem documented over decades of forestry practice (Spaić 1957, Liović and Halambek 1988). All observed positive physical effects of false indigo bush on the soil cannot therefore be viewed separately from the permanent ecological damage and economic costs it causes. However, its large

fresh biomass (7.4–13.2 t of fresh biomass per ha) potentially represents a raw material for energy production in short-rotation crops (Krpan et al. 2014, Krpan et al. 2015), which can partially offset the costs of its removal.

CONCLUSIONS

Based on the conducted research on the natural recovery of compacted Gleysol on forwarder trails, the following conclusions can be drawn.

The research results indicate the ameliorative impact of invasive false indigo bush (*Amorpha fruticosa* L.) on the physical properties of the soil on forwarder trails, which is reflected in statistically significantly lower values of the cone index and lower values of soil bulk density compared to control measurements after a six-year period. Despite the possible positive impact on the physical recovery of the soil, the forestry profession in natural forest management procedures must maintain a firm and critical attitude towards this species due to its aggressive suppression of autochthonous vegetation and the difficulty of natural forest regeneration.

A methodological limitation of the standard method for determining soil bulk density by taking soil samples in an undisturbed state (100 cm³ Kopecky cylinders) on this soil type has been established. The pronounced volume contraction of the samples when dried at 105°C (24–55%, on average about 41%) calls into question the suitability of soil bulk density as an indicator of the degree of compaction and recovery on this soil type. In contrast, measuring the cone index with a digital penetrometer has proven to be a more sensitive indicator of the differences between forwarder trails and control plots and a more suitable indicator of the state of compaction and recovery of the soil in situ.

When managing ash stands on soils with a heavy textural composition, it is advisable to plan harvesting operations in late summer when gley soils reach their lowest moisture content. This makes better use of the soil's natural bearing capacity and reduces the risk of more serious structural damage, as recognised in the current Croatian Ordinance on the Tree Marking, Timber scaling, Consignment Notes (Accompanying Documents) and Slash Stacking (NN 71/2019), which can also be characterised as an example of a best practice on a national level. By making maximum use of the existing primary and secondary traffic infrastructure network at the felling site, soil disturbance must be minimised, and the number of vehicle passes along trails must be limited, thereby reducing the intensity of soil compaction and creating more favourable conditions for its natural recovery.

FUNDING

The research was carried out as a part of the project "Conservation of narrow-leaved ash stands (*Fraxinus angustifolia* Vahl) in the Republic of Croatia with an emphasis on harmful biotic factors" funded by the Ministry of Agriculture of the Republic of Croatia from the Funds for The Multifunctional Role of Forests.

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