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Methods of Rut Depth Measurements on Forwarder Trails in Lowland Forest

Mihael Lovrinčević [1], Ivica Papa [1,*], Maja Popović [1], David Janeš [2], Tomislav Poršinsky [1], Tibor Pentek [1] and Andreja Đuka [1]

[1] University of Zagreb, Faculty of Forestry and Wood Technology, Svetošimunska cesta 23, 10000 Zagreb, Croatia; mlovrin@sumfak.unizg.hr (M.L.); mpopovic@sumfak.unizg.hr (M.P.); tporsinsky@sumfak.unizg.hr (T.P.); tpentek@sumfak.unizg.hr (T.P.); aduka@sumfak.unizg.hr (A.Đ.)

[2] Croatian Forests Ltd., Forest Administration Office Delnice, Supilova 32, 51300 Delnice, Croatia; david.janes@hrsume.hr

* Correspondence: ipapa@sumfak.unizg.hr

Abstract: Rutting measurements are a significant part of scientific research on the impact of forest vehicles on the forest soils and damage to the forest transport infrastructure. Although photogrammetric methods of measurement or measurements based on LiDAR (light detection and ranging) data are increasingly being used for rutting measurements, the previous research conducted using these methods indicated the challenge of recording water-filled ruts. For this reason, it is necessary to define a reliable method of rutting field measurement in lowland forest stands characterized by a high level of groundwater that fills the ruts shortly after the passage of forest vehicles. This research analyzed the measurement accuracy using a total station and a GNSS RTK device with a CROPOS correction base in relation to the measuring rod that represented the reference method. Based on recorded and processed data, ruts are displayed in two ways: as net and as gross value of rut depth. The analysis of net rutting revealed a statistically significant difference between the calculated rut depths based on measurements with a GNSS RTK device and other methods. On average, the net rutting measured by the GNSS RTK device was 2.86 cm smaller than that of the reference method. When calculating the gross rutting, which consisted of the net rut depth and the bulge height, no statistically significant difference was found between the measurement methods used. Based on this result, the bulge height was also analyzed, and showed a statistically significant difference between the data recorded by the GNSS RTK device and other methods. It can be concluded that measuring the depth of ruts with a total station gives accurate data and represents the optimal modern field measurement method for the same or similar terrain conditions. In contrast, the GNSS RTK device, which constantly gives higher elevation points, can be used to measure gross rutting.

Keywords: GNSS RTK; total station; measure rod; soil damage; flooded forests; rutting

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1. Introduction

In today's modern, technologically based, eco-efficient, and sustainable forestry, transport infrastructure is one of the key elements of maintaining and improving forest management [1,2]. Forest transport infrastructure, therefore, serves as the basis for the functioning of the entire forest management system. Timber transport is the core of transport in forestry, and there is a constant need to build an optimal forest transport infrastructure network. Timber transport is divided into primary and secondary transport [3]. Primary transport is conducted on a secondary forest traffic infrastructure network from the forest stand to a landing site. Secondary (long-distance) transport continues using forest roads, public roads, railways, or navigable waterways to the end user. Secondary forest traffic infrastructure in the Republic of Croatia is divided into skid roads, skid or forwarder trails, and cable lines. Different timber harvesting systems use skid roads or skid trails (forwarder trails) depending on the terrain where the timber extraction is performed. Skid roads are constructed on sloped terrains with pronounced surface obstacles and heavier construction categories of materials, while skid trails (forwarder trails) are peculiar for flatter terrains without pronounced surface obstacles and lighter construction categories of materials [4]. Forwarder trails represent temporary forest transport infrastructure created by driving a route through the forest and the successive passage of a forest vehicle along that route; they are characteristic of lowland forests and the chainsaw/harvester and forwarder timber harvesting system.

It is a known fact that the continuous passage of vehicles on the forest floor causes damage to the soil [5,6] and, depending on the soil type, on the root system [7]. Soil compaction, or the formation of ruts due to soil compaction, represents forest vehicles' most significant and obvious impact on the soil. The soil on which the appearance of ruts has been recorded is characterized by reduced water and air capacity due to the loss of micro and macro pores, mixing of soil layers, loss of organic layer, and increased amount of CO_2 [6,8,9]. Regeneration of such damaged soil can last for several decades [10–12]. Because of the above, almost every scientific study of the impact of forest vehicles on the forest soil and environmentally acceptable technologies contains rutting measurements. Unfortunately, the methodology of measuring on the ground (terrestrial measurements) using simple measuring instruments, such as a meter, is often insufficiently explained [13–15].

Based on the review of the available literature, it can be concluded that the manual measurement of ruts, using a measuring stick or similar, is still the most often used method [16,17]. As an alternative to the measuring rod, Toivio et al. [18] use a self-leveling construction laser device, a leveling rod, and a laser beam detector to monitor the change in the depth of the rut, and the authors have no objections to the system used. One possible alternative is using GNSS (Global Navigation Satellite System) RTK (real-time kinematic) devices to measure the rut depths. GNSS RTK devices or systems enable the measurement with centimeter accuracy [19,20]. However, the precision of GNSS devices in forest conditions and the applicability of such systems depend on several factors: (1) the canopy structure and its density; (2) the type of trees; (3) the terrain of the area; and (4) the season of field measurements [21–24]. While investigating adequate soil protection from compaction resulting from timber extraction operations, Ring et al. [15] also measured the depth of ruts using a GNSS RTK device (Topcon GRS-1) and a switch meter. Rutting measurements were not the primary goal of the research, and the methodology itself was not described in detail. The estimated error of the GNSS RTK device was 4 cm, and, based on this, the authors concluded that the GNSS RTK method of field measurement of rut depth represents a valuable substitute for the classic measurement method. At the same time, the authors reported that certain illogicalities were recorded during the measurement of the rut depth with the GNSS RTK device, which was manifested by a decrease in the value of the rut depth between two passes of the machine. The authors also highlighted the unresolved issue of determining the ground's reference zero/initial state when calculating the rut depth.

With the advancement of technology, it is possible to measure the depth of ruts using photogrammetry or LiDAR (light detection and ranging) systems [25–27]. The measurement of the rut depths based on photogrammetric methods, especially based on aerial photographs taken by an unmanned aerial vehicle, enables an accurate representation of the terrain and the calculation of rutting that do not differ statistically significantly compared to the reference methods used [28,29]. Photogrammetric processing and depth analysis of ruts are related not only to unmanned aerial vehicles but also to using a camera on a pole. Pierzchała et al. [30] compared different software tools for photo processing. The authors emphasized that the photogrammetric method of measuring the depth of ruts is as accurate as manual measurement. Salmivaara et al. [31] investigated the applicability of the 2D LiDAR system when measuring ruts and determined that the average error of this system is 3.5 cm. Water in the ruts makes it difficult to use photogrammetric methods and LiDAR technology and is a prominent problem in the studies mentioned and others [32–34]. Depending on the water depth, the error can be up to 15 cm [28]. One of the characteristics of lowland forests is the high water level, occasionally flooded land, along with stagnant water that usually remains throughout the winter and spring periods [35]. For this reason, it is necessary to use other methods that guarantee accurate measurement of rutting, especially in lowland forests with high water levels.

Depending on the authors, the constituent parts of the ruts and their calculations are performed in several ways. Haas et al. [36] divided rutting or deepening into net-deepening and gross-deepening. Gross-deepening is made up of bulge height and net-deepening. Meek [37] and Poršinsky [8] measured the rut depth as the difference between the original ground surface and the ground surface after the vehicle has passed, not including the bulge height in the calculation.

This research describes the method of measuring and calculating ruts in detail. The hypothesis is that the depth of ruts on forwarder trails in lowland forests can be accurately measured using a GNSS RTK device with a CROPOS (CROatian POsitioning System) correction base and a total station.

2. Materials and Methods

2.1. Research Area

The research was conducted in January 2022 in a 58-year-old ash forest stand (*Leucojo aestivi-Fraxinetum angustifoliae* Glavač 1959) (45°36′10.812″ (N), 16°14′48.150″ (E)) (Figure 1). The forest stand of the researched area is managed by Croatian Forests Ltd., the Forest Administration Zagreb, Forest Office (FO) Velika Gorica, Management Unit (MU) Turopoljski lug, subcompartment 137a. According to the forest management plan, the stand's structure is characterized as dense, and the soil as amphigley. The altitude of the research area is 98 m a.s.l. The researched forest stand represents the Republic of Croatia's characteristic lowland flood forest. Narrow-leaved ash (*Fraxinus angustifolia* Vahl) habitats in the Republic of Croatia are strongly influenced by geomorphological and hydrological processes, which affect the formation and development of soil. Hydrological processes manifest in occasional flooding of habitats, water stagnation in winter and spring, and a high groundwater level during the growing season [35]. All the mentioned processes result in a microrelief with characteristic ridges and depressions.

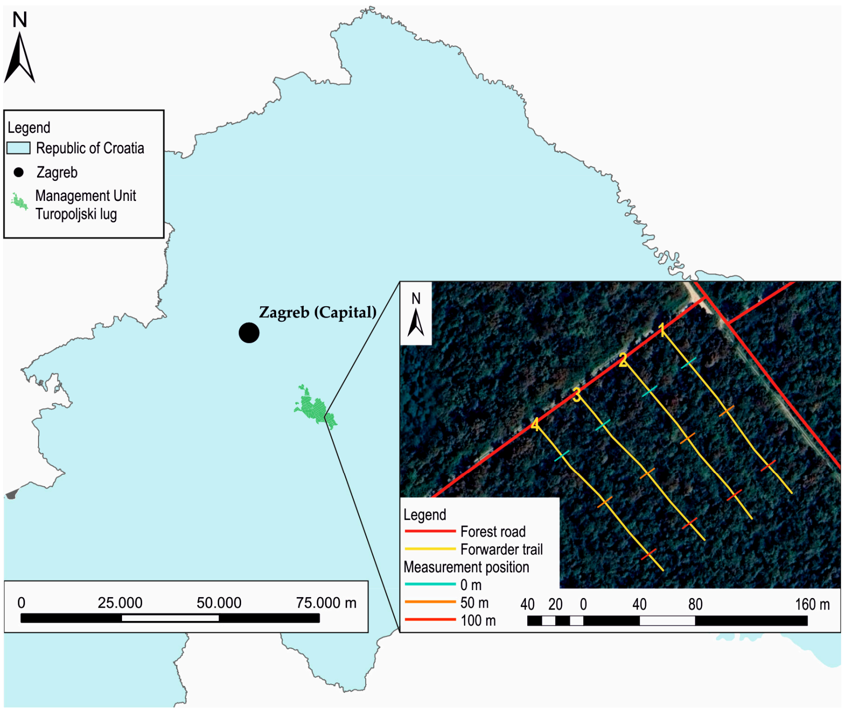

Figure 1. Research area in MU Turopoljski lug, subcompartment 137a, FO Velika Gorica.

The daily temperature during the research ranged from −11 °C to +8 °C, while the soil temperature at a depth of 10 cm was from 0 °C to +2 °C and only the humus layer was frozen. The current moisture of the surface soil layer ranged from 55% to 70%. A digital penetrometer Eijkelkamp Penetrologger (Giesbeek, The Netherlands) was used to measure penetration with a cone surface range of 2 cm^2 and the angle of cone at 30°. The soil cone index (CI) at a soil depth of 15 cm (CI_{15}) was 515 ± 160 kPa, with a range of 200 to 900 kPa, while at a depth of 5 to 25 cm ($CI_{5–25}$) it was 516 ± 179 kPa, with a range from 100 to 1100 kPa. The shear strength of the soil was measured with the Eijkelkamp—Field Inspection Vane Tester with 20 × 40 mm wing dimension, a measuring range of 0 to 130 kP, and a reading accuracy of 2 kPa. On the surface the shear strength was 9 ± 6 kPa, and 19 ± 8 kPa at a soil depth of 15 cm. The measurements of the soil's bearing capacity confirmed that it is an amphigley soil—soft soil with limited bearing capacity.

2.2. Rut Formation

The rut formation occurred as a result of the consecutive passage of a Komatsu 875 eight-wheeled forwarder along the same track. As mentioned, the research was carried out in January, as medium–heavy and heavy forwarders, like Komatsu 875, in the Republic of Croatia are mostly used for forwarding timber in the winter time [38].

The net weight of the forwarder is 21,385 kg and it has a declared load capacity of 16,000 kg. The width of the forwarder used in the research was 2.98 m. Based on the width of the forwarder and the average width of the forwarder trail in the Republic of Croatia (3.5–4 m) [39], the width of the measuring position was defined, which is explained in detail in Section 2.3. *Route measurement*. During the passage on forwarder trails (FTs), the forwarder exported 34 logs of narrow-leaved ash with a total volume of 14,079 m^3 (gross), or 11,628 kg. The wheels of the front and rear axles were equipped with tires of the same dimensions, 710/45-26.5 20 PR (Ply Rating) (Nokian Forest King TRS 2), which, depending on the forwarder trail on which they were moving, were fitted with additional traction aid: (FT1) tracks on the front and rear axle; (FT2) tracks on the rear axle and chains on the front axle; (FT3) without mounted tracks or chains; and (FT4) tracks on the rear axle. Depending on the equipment used, the total weight of the forwarder with the load was between 33,013 kg and 36,503 kg (Figure 2). The measurement of the mass characteristics of the forwarder was performed under the ISO 13860 (2016) standard [40].

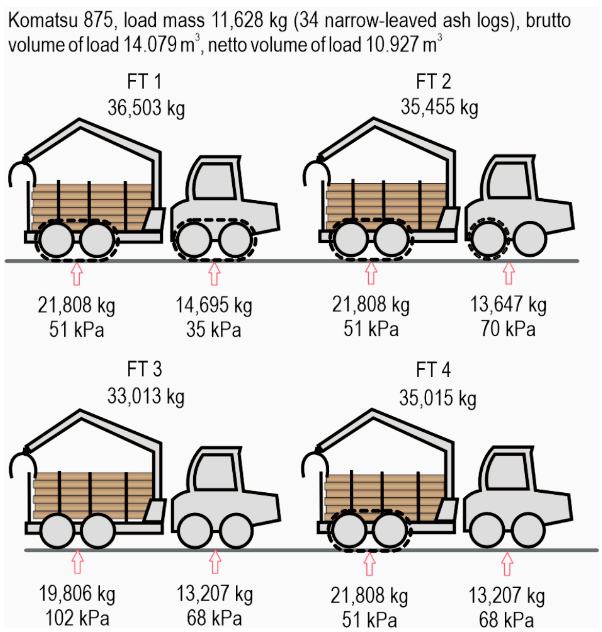

Figure 2. Mass characteristics of Komatsu 875 forwarder with different traction aid.

On FT1, FT2, and FT4, the forwarder made 10 passes as planned, while on FT3, due to 100% slipping, the forwarder could not make more than 6 passes. The total length of each of the forwarder trails was longer than 115 m.

2.3. Rut Measurement

Permanent measuring positions (MPs) where the rut depth was measured were located at the beginning (0 m) (MP 1), at the fiftieth meter (MP 2), and at the hundredth meter of the FT (MP 3). Before the initial (0 m) and final MPs, a certain length of the FT was left for the forwarder to reach operational speed and prevent soil damage due to movement from the MPs. The layout of the measurement site used in this research was based on the measurement method used by Meek [37] and Poršinsky [8]. The measuring positions were placed perpendicular to the direction of the forwarder movement, had a total width of 4.5 m, and consisted of two vertical posts on which there was a horizontal bar with marked measurement points. In contrast to the characteristic measurement points used by Meek [37], fixed measurement points were used during this research. The distance between the fixed measurement points was 20 cm (a total of 21 measurement points per MP) (Figure 3). The ruts were measured using three devices: measuring (geodetic) rod; total station STONEX TS R35WINCE (StoneX Group, New York, NY, USA); and RTK GNSS STONEX S900A terrestrial receiver with correction base CROPOS, whose characteristics are shown in Table 1. This research used the measuring rod as a reference measurement method. On each trail, two points necessary for georeferencing the total station were recorded; one point represented the position of the total station, while the other point represented back sight reading. The coordinates of the points were measured by the arithmetic mean of three 10 s independent measurements using the GNSS RTK method [41]. The recording on each measuring position started with the recording of the point with the total station, then the GNSS RTK device was placed on the same position, and then the measuring rod (leveling, geodetic rod) was also placed in the same position. To enable the recording of the same positions in the field, the recording was performed by 5 people (the total station operator, the person who carried the prism, the operator of the GNSS RTK device, the person who took the readings with the leveling bar, and the person who entered the results from the leveling bar in the prepared form). Later data processing was performed only for the measuring rod method in the manner described in Figure 3.

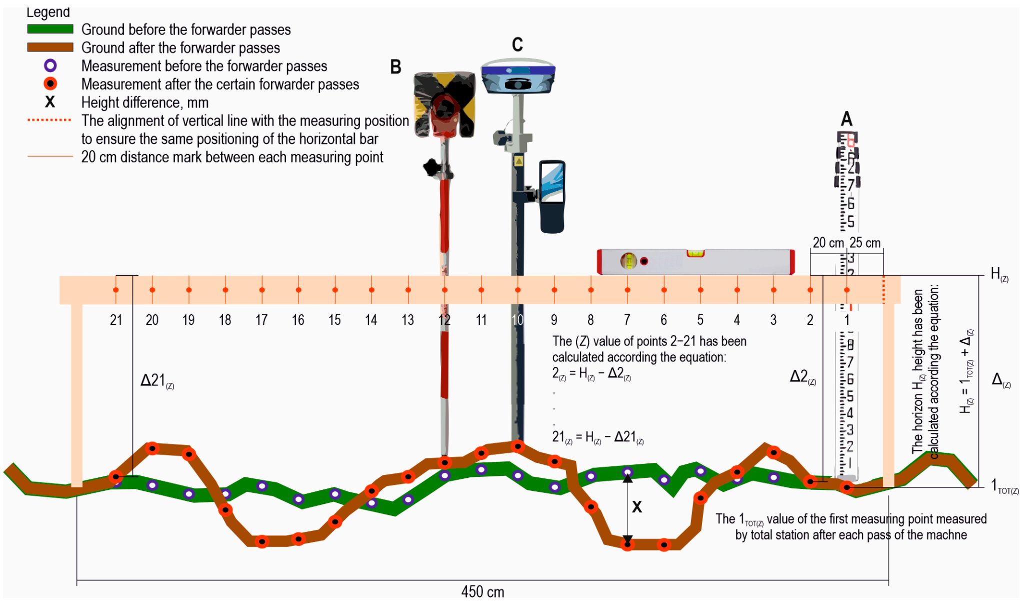

Figure 3. Graphic representation of measurement position and measuring equipment used: (**A**) measuring rod; (**B**) prism (part of the total station STONEX TS R35WINCE); (**C**) GNSS RTK.

Table 1. Technical specification of equipment used.

Total Station Stonex R35		RTK GNSS Receiver Stonex S900A	
ANGLE MEASUREMENT (angle units)	DEG 360°/GON 400/MIL 6.400	**RECEIVER (satellite tracked)**	GPS: L1 C/A, L1C, L1P, L2C, L2P, L5
			GLONASS: L1 C/A, L1P, L2C, L2P
			BEIDOU: B1, B2, B3
			GALILEO: E1, E5a, E5b
			QZSS: L1 C/A, L1C, L2C, L5
			SBAS: L1, L5
DISTANCE MEASUREMENT RANGE	Standard mode prism 3.000 m	**INTERNAL RADIO (range)**	3–4 Km in urban environment Up to 10 Km with optimal conditions
	Long mode prism 5.000 m		
DISTANCE MEASUREMENT ACCURACY	Standard mode prism 2 mm + 2 ppm	**POSITIONING (real time kinematic)**	Fixed RTK Horizontal (8 mm + 1 ppm RMS)
	Long mode prism 2 mm + 2.5 ppm		Fixed RTK Vertical (15 mm + 1 ppm RMS)
LASER PLUMMET (laser type)	635 nm semiconductor laser	**COMMUNICATION (Bluetooth)**	2.1 + EDR, V4.0
POWER SUPPLY (battery)	7.4 V/3.400 mAh Li-ion	**POWER SUPPLY (battery)**	2 rechargeable and replaceable 7.2 V—3400 mAh Intelligent lithium batteries
POWER SUPPLY (working time (angle + distance meas.))	Up to 5 h	**POWER SUPPLY (working time)**	Up to 12 h (2 batteries hot swap)
PHYSICAL SPECIFICATION (dimensions)	206 × 203 × 360 mm	**PHYSICAL SPECIFICATION (dimensions)**	Φ 157 mm × 76 mm
PHYSICAL SPECIFICATION (weight including battery and tribrach)	6.1 kg	**PHYSICAL SPECIFICATION (weight)**	1.19 kg (with one battery) 1.30 kg (with two batteries)

The field measurement was performed before the passage of the forwarder (undamaged ground), and after the 1st, 5th, and 10th passes for FT1, FT2, and FT4, and after the 1st and 5th passes for FT3 due to vehicle slippage.

In order to reduce potential human errors to a minimum, during the conducted research, the total station was positioned in a fixed place around the middle of each researched FT, the height of the prism was not changed, and care was taken to keep the prism upright, which was achieved by using a central spirit level installed on the prism.

The used correction base of the GNSS RTK device CROPOS represents a system of 57 permanent reference GNSS stations located at 70 km from each other. Reference stations collect satellite measurement data and calculate correction parameters available to field users via mobile Internet (GPRS (General Packet Radio Service)/GSM (Global Systems for Mobile)) [42].

2.4. Data Analysis

A database was formed in Microsoft Excel 2021 (Microsoft Corporation, Redmond, WA, USA) by transferring data collected by a total station and GNSS RTK device and by entering data collected by a measuring rod (Figure 4). For the purposes of this research, net rutting (N) and gross rutting (G) were analyzed. Net rutting represents the difference between the soil terrain's elevation before the vehicle passage and the compacted soil terrain's elevation (after vehicle pass) while gross rutting represents the sum of the bulge height (B) and value of net rutting. Bulge height describes the difference between the elevation of the soil ejected from each side of the rut and the elevation of the terrain before the vehicle passes. To calculate the gross rutting, bulge height value was calculated as the average height of the ejected soil on both sides of the rut.

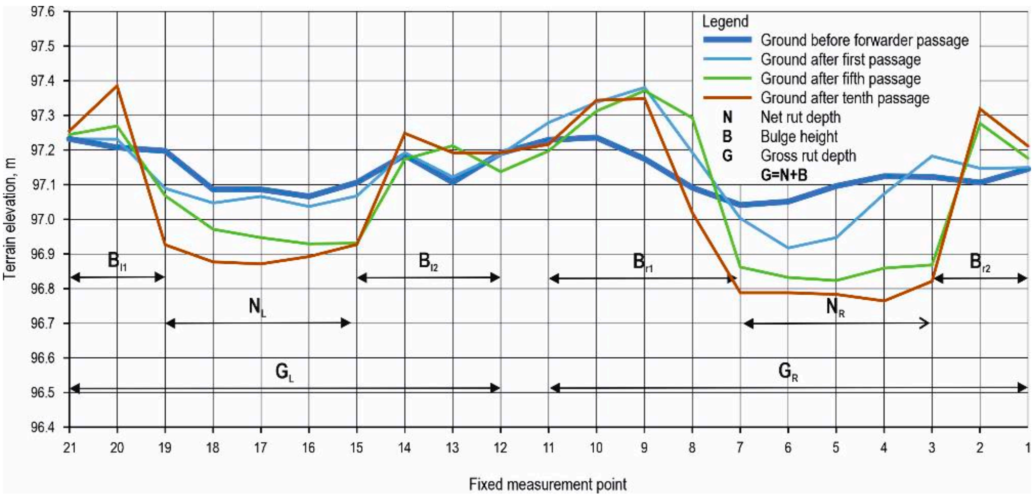

Figure 4. Example of a rut graphic display. Marked on the graphic display are the measurements used for calculating net rutting (**N**), bulge height (**B**), and gross rutting (**G**).

After calculating ruts according to each method, further statistical data processing was carried out in the program Statistica v. 14.0.0.15. (TIBCO software Inc. Palo Alto, CA, USA): data normality testing (Kolmogorov–Smirnov and Lilliefors tests); descriptive statistical analysis; *t*-test for determining differences between data and calculating the statistical significance of differences in mean values. One-way analysis of variance (ANOVA) followed by the Tukey post hoc test was used to determine differences between all 3 used measuring methods and the relationship between calculated rut depths and other independent variables, while factorial ANOVA was used to determine the relation between measuring methods and forwarder trails for rut depth (net rutting) and rut depth increase between passages.

3. Results

A total of 945 field measurements were recorded for each method, a total of 2835. Regardless of the calculation method, the data were normally distributed. Due to the specific microrelief on which the rut measurements were carried out, the rut values, measured with a measuring rod as a reference method, ranged between 0 and 59.13 cm.

3.1. Net Rutting

A total of 288 measurements per method were used to calculate the net rutting. The total station measured the deepest average net rut depth (12.12 cm), while the measurement using the GNSS RTK device gave the lowest average depth (8.77 cm). The average value of the ruts measured by the reference method (measuring rod) was 11.63 cm. The largest calculated rut depth was 49.8 cm and was measured using a GNSS RTK device. It was observed that the depth of the ruts between different vehicle passages (for example, between the 5th and 10th passages) decreased, and in some readings, the depth showed a positive sign, which would mean that there was an uplift of the ground after the passage compared to the zero state. This phenomenon occurred in the same places and passages regardless of the measurement method, and an error during measurement can be ruled out as the reason for this phenomenon.

ANOVA followed by post hoc Tukey HSD (honestly significant difference) test indicated statistically significant differences for net rutting between measuring methods. No statistically significant difference was found between the reference method and the total station, while they were found when comparing GNSS RTK measurements with the ones from the other methods (Figure 5).

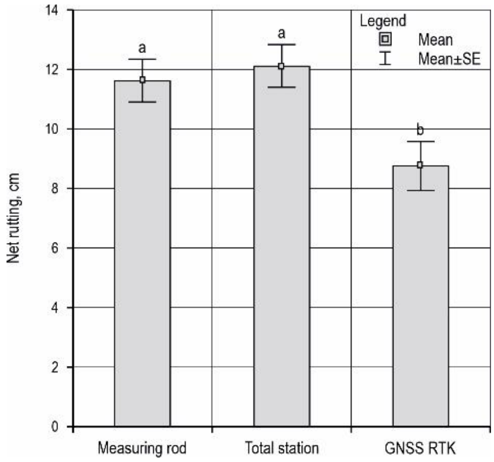

Figure 5. Difference in net rutting by measuring methods. Data are presented as mean ± SE (standard error). Letters denote statistical difference between measuring methods (Tukey HSD), respectively, at $p < 0.05$.

Although the factorial ANOVA showed no statistical significance between interaction of measuring method and FT for rut depth, the biggest deviation of the GNSS RTK device can be clearly seen on the FT1 (Figure 6). The FT1 (tracks on front and rear tires) had the smallest rut depth with an average depth of 5.90 cm measured by the reference method. The average rut depth measured by the GNSS RTK device was 1.30 cm on FT1. The GNSS RTK device underestimated the rut depth values on all forwarder trails except FT2 (tracks on the rear axle and chains on the front axle).

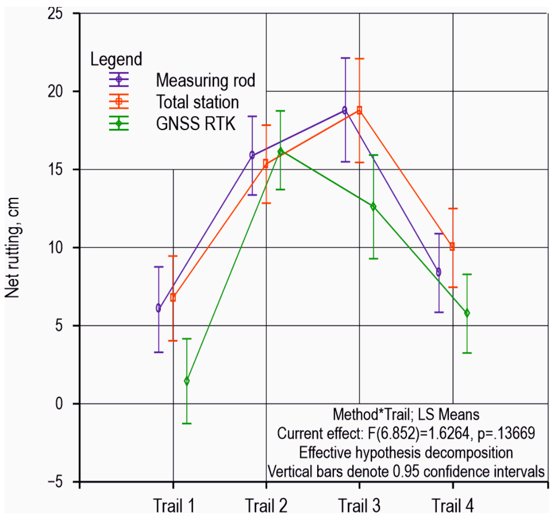

Figure 6. Difference in net rutting depth by measuring methods (method), forwarder trails, and combination of both (method * trail).

3.2. Gross Rutting

The calculated gross rutting gave statistically insignificant differences between the methods used in relation to the calculated net rutting. The average gross rutting measured by the GNSS RTK device was 21.82 cm and, as with the net ruts, it was smaller compared to the total depth of the ruts measured by the measuring bar and the total station, 22.33 cm and 22.21 cm, respectively (Table 2). The GNSS RTK device underestimated the rut depth values on all forwarder trails except for FT2, where the highest depth values were calculated compared to other methods. Positive values of the gross rutting (the height after the passage is higher than the height of the ground before the first passage) were observed again, but they were smaller compared to the net ruts. The reason for the lower values is the method of calculation where the height of the ejected soil is added to the net depth of the rut.

Table 2. Gross and net rutting by methods.

Rutting Values	Measuring Rod	Total Station	GNSS RTK
Max. net rutting	38.76 cm	42.82 cm	37.19 cm
St. Dev. net rutting	12.24 cm	12.21 cm	13.97 cm
Mean net rutting	11.63 cm	12.12 cm	8.77 cm
Max. gross rutting	57.79 cm	59.13 cm	55.23 cm
St. Dev. gross rutting	13.80 cm	14.07 cm	14.39 cm
Mean gross rutting	22.33 cm	22.21 cm	21.82 cm

ANOVA followed by post hoc Tukey HSD test did not show statistically significant differences for gross rutting between measuring methods.

3.3. Bulge Height

The absence of a statistically significant difference between the gross rutting measured by the GNSS RTK device and other methods, while it was determined in the case of net rutting, indicates that the bulge height influenced the reduction in the difference between the methods used. For this reason, the measured bulge heights were further analyzed. As expected, the heights measured by the GNSS RTK device were the highest, on average higher by 2.89 cm, compared to the reference method. The heights measured by the total station were the smallest on average. The average height of the ejected soil was 10.43 cm. ANOVA followed by a post hoc Tukey HSD test showed a statistically significant difference in the measured heights of the ejected soil between GNSS RTK devices and other measurement methods (Figure 7).

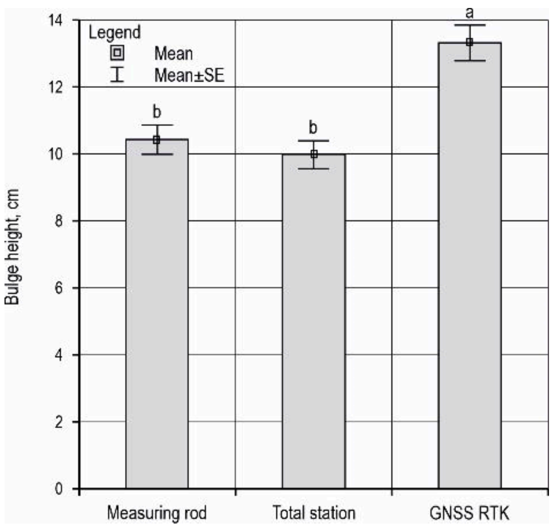

Figure 7. Difference in bulge height by measuring methods. Data are presented as mean ± SE. Letters denote statistical differences between measuring methods (Tukey HSD), respectively, at $p < 0.05$.

The most significant differences in the bulge height between the GNSS RTK device and other measurement methods were recorded on the FT1 and FT3, i.e., forwarder trails, where the GNSS RTK device most underestimated the rut depths when calculating the net rutting. The smallest differences between measurements were recorded on FT2.

3.4. Rut Depth Increase

Finally, the influence of the number of vehicle passes on net and gross rutting was analyzed based on the calculated values. The obtained results point to the fact that, regardless of the measurement method, the greatest increase in the value of the net rut depth occurred between the first and fifth passes of the forwarder and amounted to field measurement: with a measuring bar (85.19% of the gross rut value); total station (86.28% of the gross rut value); or GNSS RTK device (86.42% of the gross rut value). Similar results, but with a slightly lower percentage, were also observed in the analysis of the gross value of ruts. The largest increase in the value of the gross rutting occurred between the first and fifth passes of the forwarder and amounted to field measurement: with a measuring bar (83.66% of the gross rut value); total station (82.99% of the gross value of the rut depth); or GNSS RTK device (81.48% of the gross value of the rut depth) (Figure 8).

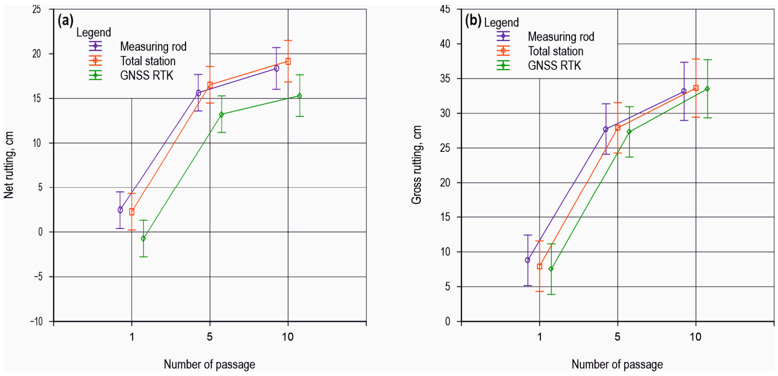

Figure 8. Rut depth increase between passages: (**a**) net rutting; (**b**) gross rutting.

The correlation coefficient (r) between the net rut depth and the error in relation to the reference measurement method was 0.45 with $p = 0.00021$, indicating a weak connection between the tested variables. The data equalization curve is GNSS RTK measuring error = $-5.062 + 0.21955 \times$ GNSS RTK rutting, with a determination coefficient (r^2) of 0.20 (Figure 9). The described curve has an upward trend.

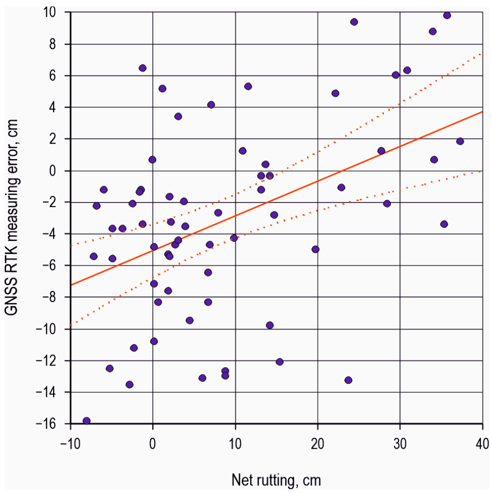

Figure 9. Impact of net rut depth on measuring error.

4. Discussion

This research analyzed the accuracy of the different rut measurements using a total station and a GNSS RTK device with a CROPOS correction base in relation to the measuring rod that represented the reference method. A total of 2835 measurements were performed. The analysis of net rutting (ground elevation before vehicle passage–ground elevation after each measured passage) indicated that the total station underestimated the depth of ruts by 0.49 cm on average, which represents a satisfactory accuracy and a statistically insignificant error. During the research, minor deflections were noticed in the central spirit level due to the passage of the forwarder near the total station. We believe that moving the total station to a place further away from the passage of a forest vehicle would give more accurate results. However, in that case, it would be necessary to have higher visibility from the total station to the prism in a wider area, which could not be recommended because of further reduction in the productive area of the forest stand. In addition, it was determined that the width of the measuring area along the forwarder trail of 4.5 m may be insufficient. It was observed that because of the successive passage of the forwarder and the widening of the ruts, the poles that marked the first and the last place of measurement slightly moved. The widening of the ruts and the ejection of a large amount of soil was caused by the high current moisture of the surface layer of the soil, which ranged from 55% to 70%, and the soil had a limited bearing capacity. Košir [43] stated that as a result of the repeated passage of vehicles, the tread width of the ground expands by 0.5 m in each direction. The forwarder used during this research was 2980 mm wide, so the gate width of 4.5 m is the limiting value. For future research, it is recommended to use a measuring site width of 5 m, as already applied in some research [8,44], if this width would not significantly affect the stand. The GNSS RTK device made an average error of 2.86 cm when measuring net depths. Similar results were found in the study by Ring et al. [15], who reported an error of 4 cm, although it is unclear what rut depth they measured. Considering that rut depths of up to 10 cm are environmentally acceptable, as recommended by the EcoWood protocol and Bavarian State Institute of Forestry for effective wood harvesting on sensitive forest soils [45], measurement errors in the amount of 2.86 cm can be the reason for stopping timber harvesting operation if they are not necessary. The GNSS RTK device underestimated the rut depth values on all forwarder trails except FT2. Weather and other conditions did not change during the research, and the settings of the device itself were the same on all investigated forwarder trails; unfortunately, the reason for the smallest errors of the GNSS RTK device on FT2 cannot be concluded. The calculated gross rutting did not differ statistically significantly between the depth measurement methods used. Based on this result, a statistical analysis of the bulge height was performed, which showed a statistically significant difference between the GNSS RTK device and other methods. The GNSS RTK device gave an average of 2.89 cm higher values of the height of the ejected soil. From this, we can conclude that the GNSS RTK device constantly measured the higher altitude of all recorded points. Due to the method of calculating the net rutting and bulge height, the sum of which constitutes the gross rut value, no statistically significant difference was observed between the gross rut depths of the analyzed methods. For this reason, we believe that the use of GNSS RTK devices is possible in operational forestry for measuring gross rutting. This way of measuring gross ruts would enable the forestry profession to measure gross rutting daily, quickly, and accurately enough. The smallest differences between measurement methods, during the calculation of all components of the analysis of this research, were observed on FT2. The reason for this could not be determined from the collected data. The weak correlation between the measured net rutting of the GNSS RTK device and the error concerning the depth measured by the measuring rod indicates that the error does not depend, or depends only slightly, on the rut depth; that is, the greater the depth of the rut, the greater the error. Influence of the number of vehicle passes on net and gross rutting was also analyzed and it indicated that the greatest increase in the value of rutting was between the first and fifth passes, which is in accordance with the research of other authors [46–48]. The obtained smaller rut values between two passes and the positive value of the rut depth, as in Ring et al. [15], can be explained by the pressing of the soil under the wheels due to the pronounced microrelief full of depressions and humps. Also, it should be noted that the research was conducted in winter, when the canopies of the trees in the research area were without leaves, and for this reason, the visibility of the GNSS RTK device to a sufficient number of satellites was not questionable. According to [22,23], the canopy structure would affect the accuracy and time effect during data collection, and in our opinion, the vegetation period measurements with the RTK device would not be possible, that is, this should be determined by further research. Measuring with a measuring rod, although accurate, is time-consuming, both in the field and during field data entry into a personal computer with a higher probability of a human error. Regardless of the method of measurement and calculation of net and gross rut depth, it was determined that the change in rut depth is the greatest during the first five passes of a forwarder along the same track.

5. Conclusions

Finally, we can conclude that the total station as a measuring instrument is reliable and accurate for measuring ruts, be it net or gross rutting. Time consumption during fieldwork with this instrument is identical to that with a measuring rod, with less possibility of an error when reading measurements and much faster and easier data transfer to a personal computer. Moving the instrument away from where the forest vehicle is passing and ensuring a stable base is a critical phase of the measurements. The GNSS RTK device, if used for measuring gross rutting, represents a sufficiently accurate method that is as time-consuming as the other methods used. However, the use of the GNSS RTK device requires one operator, while the other methods require at least two people. The observed constant overestimation of the altitude of the measured points makes it impossible to accurately measure net rutting. In addition to the impossibility of accurate measurement of net rutting, the use of GNSS RTK devices is limited to the winter period when the canopy is without leaves [21–24]. On the other hand, the canopy does not represent a limitation in the operation of the total station. However, an accurate method, such as a tape measure, measuring rod, or manual measurement, is subject to human error. As stated in the introduction, water inside the ruts is challenging when measuring with photogrammetry or LiDAR sensors. Based on all the above, the analysis of the obtained data, and the review of the available literature, we believe that the total station represents the optimal field measurement method for determining gross or net ruts in lowland flooded forests.

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