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Assessing Rut Depth Formation in a Skidding Operation Using UAV Photogrammetry*

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Abstract

Mechanical harvesting equipment used in forestry operations increases productivity; however, they may cause significant physical impacts on the soil. Among the most noticeable of these effects are wheel ruts caused by logging vehicles. Such effects can disrupt the physical structure of the soil, increase the risk of erosion, and damage forest ecosystems. In this study, wheel rut depths formed during ground-based skidding operations were analyzed comparatively using both a manual measurement method and a 3D image-based method implemented via Unmanned Aerial Vehicles (UAVs). The fieldwork was conducted during a skidding operation in the Dağtekke Forest Enterprise Chief in the city of İzmir. Manual measurements were performed using a ruler and a lath along skidding trails. For image-based method, aerial images of the study area were captured using UAV, and then used to generate Digital Surface Model (DSM). The results obtained from both methods were compared using correlation analysis and paired sample t-tests. The findings showed a high correlation between manual method and UAV-assisted method, indicating that UAV photogrammetry offers a fast and reliable alternative for rut depth monitoring. The UAV-derived measurements of rut depth showed a high level of accuracy, achieving a Mean Absolute Percentage Error (MAPE) of 16.86%. This study presents a novel application of UAV-based method for high-resolution, remote measurement of rut depth. It offers a cost-effective alternative to traditional methods while providing valuable insights into assessing the environmental impacts of mechanical equipment in forestry operations.

Keywords: Environmental impact, Soil disturbance, Rut depth, Remote sensing, UAV photogrammetry.

1. Introduction

The sustainability of forest ecosystems is fundamentally linked to preserving soil integrity. During timber harvesting operations, mechanized equipment such as skidders and forwarders can result in significant physical disturbances, with the formation of wheel rut being the most visible indicator of soil deformation. Rut depth serves as a critical metric for evaluating environmental impacts, as it reflects both surface-level changes and underlying deterioration of soil's physical and biological properties (Akay and Erdaş, 2007). Multiple operational factors influence rut formation, including vehicle specifications (i.e., weight, tire width, and inflation pressure) and site-specific conditions, such as soil bearing capacity (Nipkow, 1983).

Ground-based forestry equipment transfers axle loads to the soil through ground pressure exerted by the tire contact surfaces. When soil strength exceeds the applied pressure, tires expand their contact area, which reduces ground pressure per unit area (Abeels, 1983). This effect is amplified by low tire inflation pressures, which further increase the contact surface and distribute loads more evenly (Koger et al., 1985). Conversely, when applied pressures exceed soil bearing capacity, wheel sinking occurs, leading to rut formation. Over repeated loading cycles, this results in soil compaction, diminished hydraulic conductivity, and impaired root development (Ampoorter et al., 2007; Labelle and Jaeger, 2011).

Rut formation alters soil structure by decreasing porosity, accelerating erosion susceptibility, and restricting seedling establishment (Ampoorter et al., 2007; Labelle and Jaeger, 2011). These cumulative effects compromise forest regeneration capacity and long-term ecosystem resilience. Therefore, there is a need for precise monitoring of rut depth in sustainable forest management. Conventional manual measurement methods are commonly used to assess rut deformations. However, manual rut measurements face limitations in steep, dense, or inaccessible terrain. Remote Sensing (RS), particularly Unmanned Aerial Vehicles (UAVs),

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have emerged as transformative tools, enabling high-resolution photogrammetry and digital terrain modeling for spatially explicit deformation analysis (Puliti et al., 2019).

Compared to conventional manual measurement methods, the UAV-based photogrammetry approach offers a significant advantage by enabling rapid, non-invasive collection of soil deformation data in challenging terrain, with improved spatial coverage (Bilici et al., 2024). Astor et al. (2023) conducted a study in which orthophoto from low-altitude UAV was used to evaluate the accuracy of road condition assessment using UAV based 3D surface model. The statistical analysis conducted to compare the performance of the manual survey method and UAV-based photogrammetry in road deformation assessment revealed a close and unidirectional relationship between two methods. The most recent technologies, such as LiDAR technology, also offer high accuracy; however, the substantial cost associated with the equipment is a notable limitation (Hruza et al., 2025). On the other hand, UAV-based photogrammetry presents a more cost-effective alternative that still delivers reliable and sufficiently precise 3D data.

This study aimed to analyze rut depth formation during a logging operation using manual measurements and a UAV-assisted method. Within this scope, wheel ruts formed by a skidding tractor were examined, and the measurements of both methods were compared to evaluate the potential of UAV technology in field applications. The findings may provide valuable insights into scientific understanding of soil disturbance, while demonstrating how UAV-assisted monitoring can enhance the efficiency and environmental sustainability of forestry practices through rapid and precise terrain assessment.

2. Materials and Methods

2.1. Study Area

The study was conducted in a Brutian pine (*Pinus brutia*) regeneration area within the Dağtekke Forest Enterprise Chief (FEC), administered by the İzmir Regional Forest Directorate (Figure 1). The spatial distribution of forest resources across FECs subordinate to the İzmir Forest Enterprise Directorate is presented in Table 1. In the study area, the soil was a loam-sandy loam with a soil moisture content of approximately 10%. The texture distribution was 56%, 17%, and 25% for sand, clay, and dust, respectively. Based on the meteorological data, a daytime temperature was 34°C and a nighttime temperature was 21°C. Humidity was recorded as 48%, wind speed was approximately 15 km/h, and atmospheric pressure was 990 hPa.

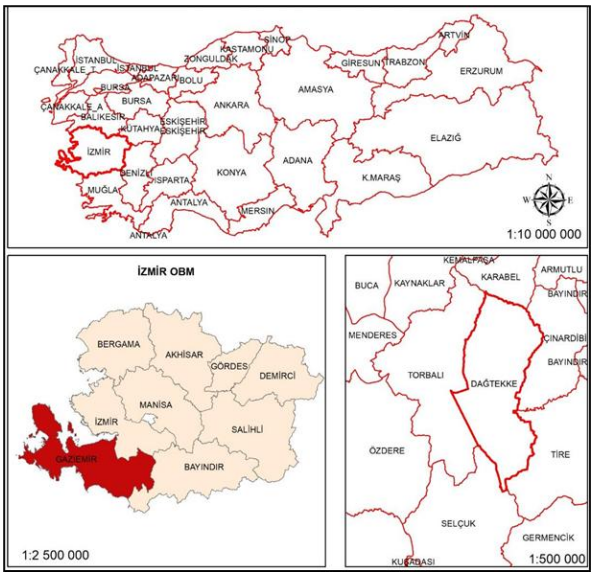


Figure 1. Dağtekke FEC Study within İzmir Forest Enterprise Directorate

Table 1. Forest resource distribution (ha) of FECs in the İzmir Forest Enterprise Directorate

FECs	High Forest (Ha)	Coppice Forest (Ha)	Total Forest Area (Ha)	Non-Forested Area (Ha)	Total Area (Ha)
Çeşme	5 417.00	19 243.00	24 660.00	24 258.50	48 918.50
Dağtekke	**6 114.50**	**1 860.00**	**7 974.50**	**19 017.00**	**26 991.50**
Gaziemir	5 217.00	2 165.00	7 382.00	9 984.50	17 366.50
Güzelbahçe	4 127.00	5 492.00	9 619.00	13 732.00	23 351.00
Karaburun	4 316.00	21 292.00	25 608.00	19 647.00	45 255.00
Menderes	6 663.50	5 810.50	12 474.00	12 481.50	24 955.50
Özdere	7 846.00	17 190.00	25 036.00	16 423.00	41 459.00
Seferihisar	6 692.50	9 024.00	15 716.50	17 374.00	33 090.50
Torbalı	3 127.00	5 287.00	8 414.00	21 553.00	29 967.00
Urla	9 598.50	17 641.00	27 239.50	13 068.00	40 307.50
Yeniköy	6 776.50	1 078.00	7 854.50	2 867.50	10 722.00
Total	65 895.50	106 082.50	171 978.00	170 406.00	342 384.00

2.2. Rut depth measurements

Field measurements were conducted along a 120-meter skid road at Dağteke FEC to quantify rut depths generated by a Fiat 60-56 farm tractor (Figure 2). The technical specifications of the farm tractor are given in Table 2. To analyze potential slope effects, the skid road was divided into two topographic classes: flat terrain (0-10% slope, 70 m length comprising cross-sections 1-7) and gentle slopes (10-20% slope, 50 m length comprising cross-sections 8-12). Rut depth assessment was performed at 12 systematically distributed cross-sections using complementary methods: (1) direct physical measurements using calibrated rulers (Figure 3), and (2) UAV-assisted 3D modeling of wheel tracks from high-resolution imagery. These two approaches enabled comparative validation of measurement techniques while controlling for topographic variation across the study transect.



Figure 2. Fiat 60-56 farm tractor

Table 2. Technical Specifications of the Fiat 60-56 Tractor

Specifications	Values
Length	3200 mm
Front Track Width	1435 mm
Rear Track Width	1435-1935 mm
Ground Clearance	380 mm
Weight	2490 kg
Engine	60 hp
Engine Displacement	2931 cc
Towing Material	Rope
Drive Type	2WD (Two-Wheel Drive)



Figure 3. Sample measurement made with ruler and lath

Rut depth quantification was performed through a multi-temporal UAV photogrammetric approach using a DJI Mavic Pro platform. DJI Mavic Pro UAV was selected for its high-resolution imaging capabilities (4000×3000 pixels for still images; 4K/1080p video) and integrated 3-axis gimbal stabilization system, which effectively mitigates vibration artifacts caused by wind during data acquisition (Figure 4). The UAV images were obtained at three operational stages: pre-operation baseline (control), after 10 trips, and after 20 trips of the skidding tractor. Flight missions were planned using Pix4D software with single grid mode (Grid Mission), maintaining a constant altitude of 70 m with 80% forward and lateral overlap (Figure 5). The acquired imagery was processed in Agisoft Metashape 2.2.1 through a standardized workflow: (1) image alignment and optimization using six ground control points distributed throughout the study area, (2) dense point cloud generation, (3) digital surface model (DSM) derivation, and (4) orthophoto production (Figure 6). This processing sequence was independently executed for each monitoring stage (pre-operation, post-10 trips, post-20 trips) to enable temporal comparison of terrain deformation.



Figure 4. UAV used in the study

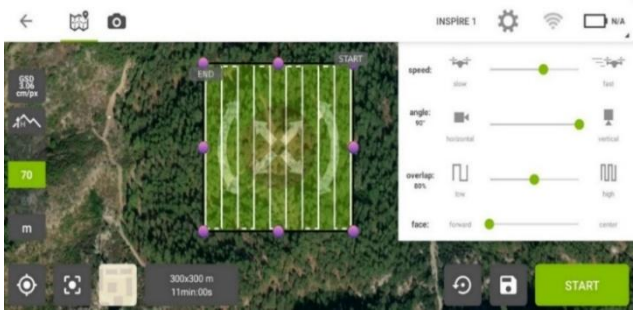


Figure 5. Pix4d flight settings screen

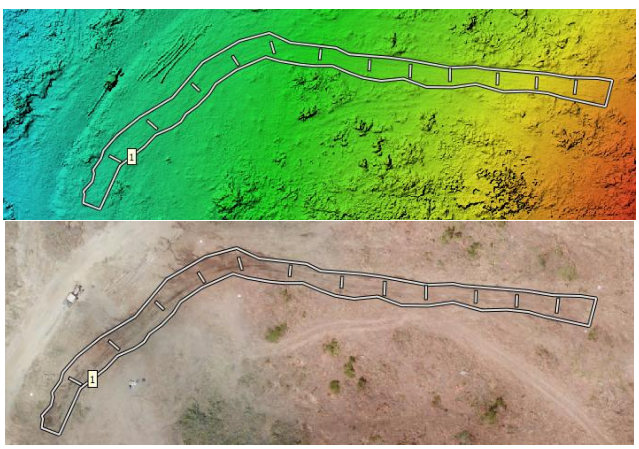


Figure 6. DEM (top) and orthophoto (bottom)

In the next stage, the twelve cross-sections were generated along with the skidding road in the Agisoft Metashape. Diagrams were generated for these cross-sections using DEM obtained from UAV images. This step ensures a high-resolution, 3D representation of the terrain, enabling the precise extraction of rut depth. Then, rut depths were determined for both wheel tracks on each cross-section with the Agisoft Metashape. This method provides automated, repeatable measurements, reducing human error compared to manual techniques. Finally, it was tested whether there was a statistically significant difference between the rut depth measurements from the UAV and ruler based manual method using the Paired Sample T-Test in SPSS 20.0. R^2 value was calculated to evaluate the accuracy relationships between rut depth values measured using the manual method and the UAV-based method.

$$MSE = \frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_{i)})^2 \quad (1)$$

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|y_i - \hat{y}_i| \quad (2)$$

$$MAPE = \frac{1}{N}\sum_{t=1}^{n}\left|\frac{y_i - \hat{y}_{i)}}{y_i}\right| \quad (3)$$

In order to analyze the accuracy of the UAV-derived rut depth measurements, the measurement error between the rut depths obtained with two methods was determined using the Mean Squared Error (MSE), Mean Absolute Error (MAE) and Mean Absolute Error Percentage (MAPE) methods. Measurement errors were calculated using the following equations, where N is the total number of rut depth measurements (N = 48), yi is the ruler-based manual measurement, and ŷi is the UAV-based measurement.

3. Results and Discussion

Wheel rut depths were assessed using two methods: UAV-derived DEMs and manual ruler measurements. In the flights conducted with the UAV, the mean positional error from the camera was 1.858-3.989 m. After positional verification with six ground control points, these values were reduced to 0.058 m-0.062 m, respectively. Thus the positional errors were reduced to the centimeter level. Across 12 sections, 24 rut depths were recorded for both the 10th and 20th trips, totalling 48 measurements for statistical analysis (Table 3). On flat terrain, the maximum rut depth in the 10th trip was 3.6 cm for UAV-derived measurement and 3.1 cm for ruler-based measurement. In comparison, the minimum depths were 1.6 cm and 1.5 cm for UAV-derived measurement and ruler-based measurement, respectively. Similar trends were observed in the 20th trip, with UAV measurements peaking at 4.2 cm compared to the ruler's 4.4 cm. These results indicated close agreement between methods for minimum depths, while slight discrepancies in maximum depths suggest potential smoothing effects in UAV data or minor manual measurement variability.

In the gentle slope area, the maximum rut depth during the 10th trip was 4.3 cm (UAV) versus 4.2 cm (ruler), while the minimum depths for UAV and ruler based methods were at 1.8 cm and 1.5 cm, respectively. By the 20th trip, depths increased to 5.1 cm (UAV) and 6.1 cm (ruler) for maximum values and 3 cm (UAV) and 3.2 cm (ruler) for minimum values. These findings highlighted progressive rut formation with repeated passes, which is a trend consistent with Öztürk's (2014) observations of soil deformation during tractor skidding operation. Additionally, the deeper ruts observed in low-slope areas supported findings of Gülci and Şireli (2019), who reported increased wheel-track deformation on gentle skid trails compared to steeper terrain. This difference likely arises from prolonged wheel-soil interaction on low-slope areas.

Table 3. Rut depths (cm) obtained by two methods for the 10th and 20th trips

Trips	10th Trip				20th Trip			
	Left Tire		Right Tire		Left Tire		Right Tire	
	UAV	Ruler	UAV	Ruler	UAV	Ruler	UAV	Ruler
1	2.8	2.2	2.3	2.1	2.8	2.4	2.4	2.3
2	2.2	1.7	1.8	1.6	2.6	3.2	2.6	2.2
3	2.5	3.1	2.1	1.5	3.2	4.1	2.4	2.5
4	2.3	2.6	3.6	2.5	2.8	3.2	3.8	4.4
5	2.6	2.3	1.6	1.8	3.8	3.6	3.2	2.6
6	2.8	2.5	2.8	2.5	3.1	3.5	3.3	3.8
7	1.8	2.3	3.2	2.6	2.4	2.6	4.2	4.1
8	2.9	3.8	4.3	3.5	4.8	6.1	4.8	5.5
9	3.6	4.2	3.6	3.5	4.6	5.2	5.1	5.2
10	3.8	2.2	1.8	2.5	4.0	4.2	3.0	3.2
11	1.9	2.4	2.2	1.5	3.8	3.2	3.4	3.6
12	3.3	2.8	3.8	3.6	4.8	4.6	4.8	4.5

For the statistical analyses, the normality of the data was first checked (Table 4 and Table 5). The skewness and kurtosis values fell within the acceptable range of -3 to +3, indicating normal distribution (Ross and Willson, 2018). While the normality test showed significance values below 0.05, the parametric assumptions were still met, justifying the use of the Paired Sample T-Test. Table 6 presents the correlation between the 48 paired measurements obtained from UAV and ruler methods. Subsequently, a Paired T-Test was performed to determine whether a statistically significant difference existed between the two measurement techniques (Table 7).

Table 4. Descriptive statistics of measurements made with ruler and UAV

			Values	Std. Error
Ruler	Mean		3.148	0.1579
	95% Confidence Interval	Lower Bound	2.830	
		Upper Bound	3.466	
	5% Trimmed Mean		3.097	
	Median		2.950	
	Variance		1.197	
	Standard Deviation		1.0943	
	Minimum		1.5	
	Maximum		6.1	
	Distribution		4.6	
	Interquartile Range		1.5	
	Skewness		0.711	0.343
	Kurtosis		0.038	0.674
UAV	Mean		3.152	0.1336
	95% Confidence Interval	Lower Bound	2.883	
		Upper Bound	3.421	
	5% Trimmed Mean		3.133	
	Median		3.050	
	Variance		0.857	
	Standard Deviation		0.9258	
	Minimum		1.6	
	Maximum		5.1	
	Distribution		3.5	
	Interquartile Range		1.4	
	Skewness		0.384	0.343
	Kurtosis		-0.685	0.674

Table 5. Normal distribution compliance test for measurements made with ruler and UAV

	KolmogorovSmirnov[a]			ShapiroWilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Ruler	0.171	48	0.001	0.947	48	0.029
UAV	0.106	48	0.200*	0.960	48	0.104

*. This is a lower bound of the true significance. a. Lilliefors Significance Correction

Table 6. Correlation analysis results for ruler and UAV measurements

		Ruler	UAV
Ruler	Pearson Correlation	1	0.850**
	Sig. (2-tailed)		0.000
	N	48	48
UAV	Pearson Correlation	0.850**	1
	Sig. (2-tailed)	0.000	
	N	48	48

Table 7. Paired sample T-Test results for ruler and UAV measurements

		95% Confidence Interval of the Difference							
		Mean	Std. Deviation	Std. Error Mean	Low	Up	t	df	Sig. (2tailed)
Pair 1	RULER - UAV	-0.0042	0.5757	0.0831	-0.1713	0.1630	-0.050	47	0.960

Statistical analysis revealed a robust correlation coefficient of 0.850 between UAV and ruler measurements, demonstrating near-perfect agreement between the two methods. The subsequent paired t-test yielded a non-significant p-value ($p = 0.960$), which far exceeded the $\alpha = 0.05$ threshold, confirming that there was no statistically detectable difference between the measurement methods. These results confirm that UAV photogrammetry provides measurement accuracy comparable to conventional manual methods for multiple loading cycles (10th and 20th trips). The strong concordance between methods, coupled with the UAV's inherent advantages in data density and collection efficiency, positions aerial photogrammetry as a reliable alternative for quantifying rut depth in terrain deformation studies.

It was also found that there is a linear relationship (R^2=0.72) between the rut depth values determined by manual measurements and those derived from UAV measurements (Figure 7). The study conducted by Marra et al. (2021) measured where rut depth caused by forestry machine traffic moving over forest terrain using both manual method and UAV-based methods, and found a similar linear relationship (R^2=0.77) between manual measurements and UAV-derived measurements. At the final stage, the Mean Square Error (MSE), Mean Absolute Error (MAE), and Mean Absolute Percentage Error (MAPE) methods were used to determine the measurement error between the rut depths obtained from the ruler method and UAV method. According to the comparison of the rut depth data, the MSE was 0.325, while the MAE and MAPE were 0.475 and 16.86%, respectively. The results show that the rut depths obtained with the UAV-based method had acceptable accuracy (Lindroos et al., 2018; Krause et al., 2019, Pierzchała et al., 2025). The MAPE value of 16.86% indicated that the rut depths measured by UAV provided a highly accurate estimation (Karaatlı et al., 2014). These findings were consistent with studies in the literature, which have shown that UAV-based methods provide reliable results with low error in field measurements (Salmivaara et al., 2018). Therefore, the calculated low error values suggest that UAV methods can be a strong alternative to traditional methods in terms of measurement reliability and validity.

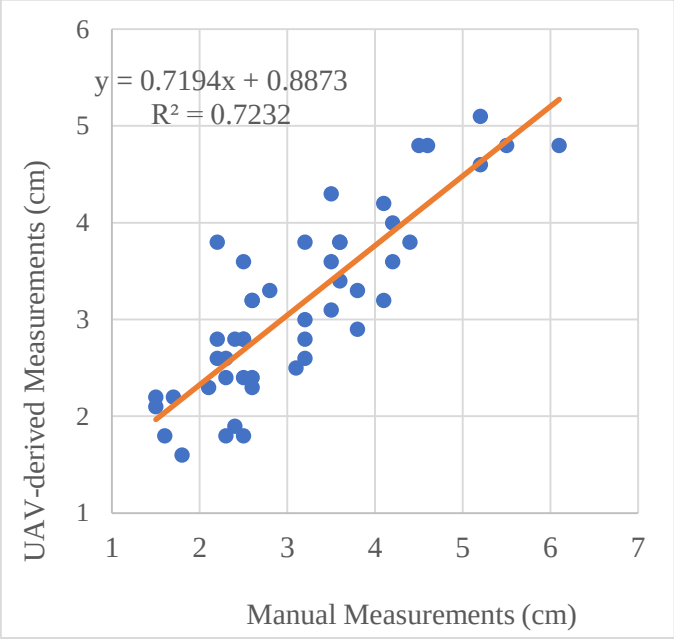


Figure 7. Linear relationship between rut depths obtained by two methods in the first area

3. Conclusion

This study was conducted to evaluate the physical impacts of tractors used in timber extraction operations, focusing on rut depth formation, by comparing two different measurement methodologies. The findings demonstrate that both the number of extraction passes and terrain slope significantly affect the formation rut depth. Furthermore, a direct correlation was observed between the number of trips and rut depth. A key contribution of this research lies in the comparative evaluation of measurement techniques. The study revealed a strong positive correlation ($r = 0.850$) between UAV-based photogrammetric measurements and the traditional ruler method. Paired-sample t-test analysis

confirmed no statistically significant difference between these methods (p = 0.960). These results indicate that UAV technology can serve as a reliable and efficient tool for post-harvest environmental monitoring. Considering the substantial advantages of UAV-based measurements in terms of time efficiency, labor requirements, and accessibility, we recommend broader adoption of this technology as either a complementary or alternative approach to conventional methods. In conclusion, this study provides a comparison between traditional measurement techniques and UAV-assisted remote sensing, confirming the validity of both approaches for assessing ground deformation. The findings underscore the importance of adopting technological solutions for monitoring the environmental impacts of forestry operations. Such advancements will facilitate the development of more precise, efficient, and environmentally sustainable monitoring systems, ultimately contributing to more effective sustainable forest management practices. In addition to demonstrating the accuracy and reliability of UAV photogrammetry for assessing rut depth, this study highlights its practical value in operational forestry. The method can support informed decision-making in logging operation planning by identifying areas at high risk of soil disturbance, optimizing machine routing, and enabling timely interventions to minimize long-term site degradation. Moreover, the approach provides a scalable and repeatable tool for post-harvest impact assessment, contributing to more sustainable forest management practices.

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