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Impact of logging practices on second-generation stand growth of *Pinus patula* at Sao Hill forest plantation in Tanzania

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ABSTRACT

Logging is a fundamental component of forest management, facilitating the establishment of new stands through the removal of mature trees. However, logging operations often induce substantial soil disturbances, which may adversely affect the growth of second-generation stands. This study aimed to assess the impact of logging on the growth of second-generation *Pinus patula* stands at Sao Hill Plantation, Tanzania (SHFP), specifically focusing on the impacts of logging on stand growth and forest soil. Six compartments, three from each generation, representing stand ages of 1, 3, and 6 years, totaling 180 systematically sampled plots, each measuring 20 x 20 meters. First- and second-generation stands were treated as experimental groups. An independent t-test was used to analyze the impact of logging on stand growth across generations. Stand growth parameters including the number of stems, tree height, and diameter at breast height (DBH) decreased by 6.5% to 12.3% in second-generation stands compared to first-generation stands. Soil bulk density in second-generation stand increased by 25.7% and 26.2% in the top 10 cm and 20 cm of soil, respectively, compared to the first-generation stand. The findings emphasize the critical role of adopting reduced-impact logging techniques to minimize soil compaction, thereby supporting the long-term productivity.

Key Words: Logging practices-stand growth- soil compaction- second generation.

INTRODUCTION

Logging involves the transportation of felled timber from harvesting sites to processing facilities, such as sawmills and lumber yards (Sessions 2007). These operations can be conducted using fully manual, semi-mechanized, or fully mechanized systems (Masumian *et al*. 2017, Silayo *et al.* 2010). Globally, logging practices have increasingly shifted toward mechanized ground-based systems to enhance worker safety and operational efficiency (Mauya 2022). Mechanized logging typically involves the use of heavy machinery, including forwarders, skidders, and harvesters (Latterini *et al*. 2023). These machines are characterized by high engine power as well as engine-induced vibrations and substantial vehicle mass, which generate significant traction forces between the wheels and the ground surface (Nazari *et al.* 2023).

As a vital medium for tree growth, soil is highly susceptible to degradation from the operation of logging machinery, which can reduce stand productivity in subsequent rotations (Cambi *et al.* 2015, Dominati *et al*. 2010). Assessing the physical properties of soil before and after the passage of logging equipment provides valuable insight into the extent of soil disturbance (Ampoorter *et al*. 2007). Ground-based mechanized logging commonly results in adverse impacts such as soil compaction, rut formation, and the displacement or removal of topsoil layers (Agherkakli *et al.* 2010). The severity and nature of these disturbances are largely governed by a range of factors, including slope gradient (Picchio *et al.* 2020), soil moisture content (Naghdi *et al*. 2016, Naghdi *et al* 2020), vehicle mass (Langmaack *et al*. 2002), site-specific characteristics (Makineci *et al*. 2007), soil organic matter content, the type of skidding equipment used (Sadeghi *et al*. 2022), the frequency of machine passes, and engine-induced vibrations (Dembure *et al*. 2019).

The reduction in stand growth in second-generation stands is often linked to the effects of soil compaction caused by logging practices, which alter physical soil properties (Solgi *et al*. 2020). Eisenbies *et al.* (2005) reported that stand growth in later generations can decline by an average of 5% to 13% compared to the first generation. In this context, Mariotti *et al*. (2020) found that larger trees are less impacted than younger trees because only a small portion of the root system of larger trees lies within the compacted area, making them less vulnerable. Furthermore, Nash *et al.* (2021) and Crawford *et al.* (2021) stated that while compaction initially slows tree development, after several years, it may catch up to or even match the growth of similarly sized trees growing in uncompacted soil.

Baseline information on best logging practices is crucial for sustaining productivity in second-generations. Several studies have documented the impact of logging on soil quality in the southern part of Tanzania, specifically in the Sao Hill Forest Plantation (Kweka *et al.* 2014, Migunga 1996). However, there is limited information on the impact of logging on subsequent stand growth in forest plantations in Tanzania. This study aimed to address this knowledge gap. The findings will raise awareness of the impact of logging on subsequent stand growth in Tanzania and suggest ways to mitigate these impacts by adopting best logging practices. The study explored: 1) the impact of logging on subsequent stand growth, and 2) the impact of logging on forest soils in subsequent generations.

To investigate the influence of logging practices on second-generation stand growth, the following, hypotheses were tested: The null hypothesis (H0) posit that logging practices have no significant effect on second-generation stand growth. The alternative hypothesis (H1): suggest that logging practices significantly affect second-generation stand growth.

MATERIALS AND METHODS

Description of study area

The study on the impact of logging practices on the growth of second-generation stands of *Pinus patula* was conducted at the Sao Hill Forest Plantation (SHFP) in Tanzania, located in the Mufindi District of the Iringa Region (Figure 1). SHFP is the largest forest plantation in Tanzania, covering a total area of 135,903 hectares, of which 54,070 hectares are planted with pine, while 3,500 hectares are planted with cypress and Eucalyptus species. The plantation is divided into four divisions and is managed under the SHFP Headquarters. The study was conducted in Divisions I and IV to capture first- and second-generation compartments. In this context, these divisions are characterized by differing climatic conditions and edaphic factors. Such environmental variations introduce potential confounding effects, making it difficult to isolate logging as the sole factor influencing stand growth responses. The environmental characteristics of the study area are presented in Table 1.

Data collection

This study assessed stand growth and soil physical parameters across compartments aged 1, 3, and 6 years, representing critical periods during which soil structure has not fully recovered following mechanized logging operations, as noted by Nazari *et al*. (2023). A total of six compartments were purposively selected-three representing first-generation stands from Division IV and and three representing second-generation.

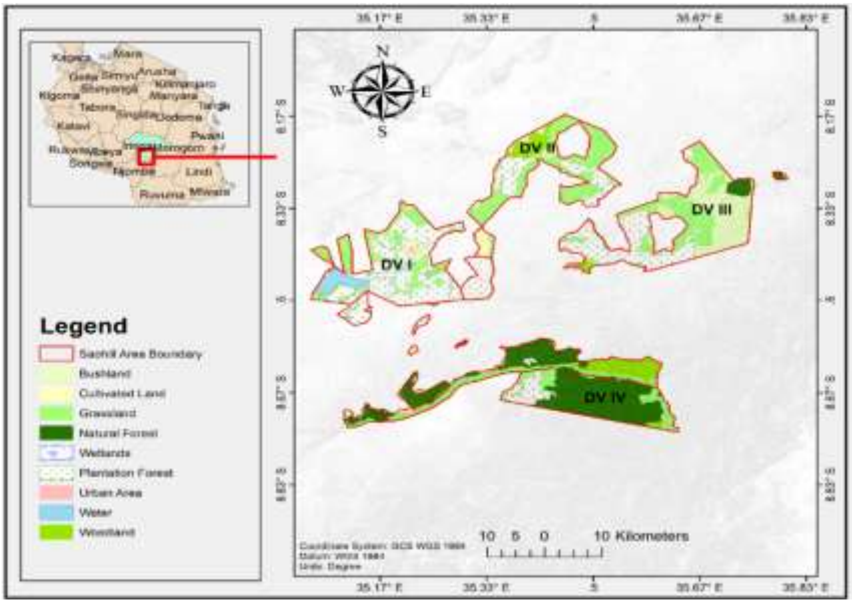

Figure 1. Location of the study area and sites. Source: Ntalikwa et al. (2024)

Table 1: Environmental conditions of Sao Hill Forest Plantation

Characteristics	**Condition**
Altitude (m, above sea level)	1400 to 2000
Precipitation (mm year^{-1})	725 to 1400
Temperature (^{o} C)	23 to 28
Soil (pH)	4.4 to 5.4
Soil type	Sandy to sandy loams

Source: Mauya (2022), Silayo et al. (2010), Beleko (2021)

Table 2: Compartments used to assess the impact of logging on subsequent stand growth in Sao Hill Forest Plantation

Generation status	**Compartment name**	**Age (years)**	**Area (ha)**	**Transect distance (m)**	**Sampling intensity (%)**	**Number of plots**
I	4/MP/1/39.5/PP	1	39.5	120	0.101	30
II	1/G3/27	1	27	120	0.148	30
I	4/KT2/19/30.5/PP	3	30.5	120	0.131	30
II	1/G1a/22.1	3	22.1	100	0.180	30
I	4/MP/1/18.3/PP	6	18.3	100	0.219	30
II	1/G3/30	6	30	120	0.133	30

stands from Division I. A systematic sampling approach was applied to establish 180 square plots (20 × 20 m) across all compartments. All six compartments were used for stand growth assessments, while two were selected for soil sampling. Plot allocation was guided by plantation maps and a reconnaissance survey, with four transects established per compartment. The initial plot in each transect was randomly located, followed by systematically spaced plots determined by dividing transect length by the number of allocated plots as shown in Table 2. Skid trails and landing sites were included to capture spatial heterogeneity. Stand growth data included number of stem (for all age classes) and measurements of diameter at breast height (DBH) and total tree height (for 3- and 6-year-old stands), following standard inventory procedures outlined by Malimbwi *et al.* (2018). Soil samples were collected at depths of 10 cm and 20 cm using intact core extraction methods with metal rings (6.8 cm diameter, 4 cm height), as described by Kweka *et al.* (2011). A total of 30 samples were obtained per depth across the selected compartments.

Data analysis

The stand parameters used to describe growth were the number of stems, quadratic mean diameter, and tree height. The quadratic mean diameter (QMD = √((di^2)/n), where QMD = quadratic mean diameter, and di = diameter at nth) was used instead of the arithmetic mean diameter (DBH) because it gives greater weight to larger trees and is equal to or larger than the arithmetic mean diameter by an amount depending on the variance (Curtis and Marshall 2000). Soil samples from both generations were transferred into containers and oven-dried at 105°C until a constant weight was achieved and confirmed. The oven-dried mass of the sample was divided by the sample volume to determine the soil bulk density, as described by Hao *et al.* (2008).

An independent t-test was conducted to assess whether the mean values of stand growth parameters (i.e., number of stems, quadratic mean diameter, and tree height), and soil bulk density differed significantly between the first- and second-generation compartments ($p < 0.05$). All statistical analyses were carried out using Microsoft Excel software.

RESULTS

Stand growth

Number of stems

In the second-generation compartments aged 1, 3, and 6 years, the results showed that the number of stems was reduced by an average of 8.6%, 10.3%, and 6.5%, respectively, compared to the first-generation compartments (Table 3). However, the statistical results of an independent t-test indicated that the mean number of stems between first- and second-generation compartments was statistically significant at the 0.05 level ($P < 0.05$).

Table 3: Impact of logging practices on the number of stems in second-generation stands

Compartment	Age (years)	GS	Number of stems (N/ha)			n	SD	t-statistic	df	P-value	Change in Number of stems (%)
			Min	Max	Mean						
4/MP/1/39.5/PP	1	I	850	1050	976	30	65.661	-4.144	58	0.000*	8.6
1/G3/27	1	II	725	1025	898	30	85.332				
4/KT2/19/30.5/PP	3	I	850	1050	962	30	48.572	-6.225	58	0.000*	10.3
1/G1a/22.1	3	II	675	975	872	30	62.537				
4/MP/1/18.3/PP	6	I	475	1000	916	30	86.971	-2.836	58	0.006*	6.5
1/G3/30	6	II	700	1000	860	30	66.463				

Note: = Significant Difference at P<0.05, n = number of samples, GS = Generation status, SD = standard deviation, df = degree of freedom*

Table 4: Impact of logging practices on tree height second-generation stands

Compartment	Age (years)	GS	Tree height (m)			N	SD	t-statistic	df	P-value	Change in tree height (%)
			Min	Max	Mean						
4/KT2/19/30.5/PP	3	I	2.7	6.2	4.2	30	0.960	-7.440	58	0.255n.s	7.7
1/G1A/22.1	3	II	2.3	6.0	3.9	30	0.965				
4/MP/1/18.3/PP	6	I	8.3	10.1	9.1	30	0.447	-1.148	58	0.000*	10.9
1/G3/30	6	II	7.5	9.3	8.2	30	0.484				

Note: = Significant Difference at P<0.05, n.s = Implies no significant difference, GS = Generation status, SD = Standard deviation, df = Degree of freedom, n = Number of samples.*

Tree height

Results on tree height indicated that the 3-year-old and 6-year-old compartments in the second generation decreased by an average of 7.7% and 10.9%, respectively, compared to the first-generation compartments (Table 4). Statistical analysis revealed that the 3-year-old compartment was insignificant at the 0.05 level (P > 0.05). However, the 6-year-old compartments were significant at the 0.05 level (P < 0.05).

Quadratic mean diameter

The findings showed that, compared to first-generation compartments, the quadratic mean diameter in the second generation's 3- and 6-year-old compartments decreased by an average of 12.3% and 9%, respectively (Table 5). Statistical analysis indicated that the 3-year-old and 6-year-old compartments were statistically significant at the 0.05 level (P < 0.05).

Soil data (bulk density)

In the second-generation compartment, soil bulk density increased by an average of 25.7% and 26.2% in the 10 cm and 20 cm upper soil layers, respectively, in plots harvested during the dry season compared to the control plots in the first-generation compartments (Table 6). Based on soil depths of 10 cm and 20 cm, soil bulk density within the compartments changed by an average of 0.9% and 1.3%, respectively, between the first- and second-generation compartments.

Table 5: Impact of logging practices on quadratic mean diameter in second-generation stands

Compartment	Age (years)	GS	Quadratic mean diameter (cm)			n	SD	t-statistic	Df	P-value	Change of quadratic mean diameter (%)
			Min	Max	Mean						
4/KT2/19/30.5/PP	3	I	4.16	7.19	5.84	30	0.882	-2.83	58	0.006*	12.3
1/G1A/22.1	3	II	3.56	6.59	5.20	30	0.891				
4/MP/1/18.3/PP	6	I	11.81	13.26	12.70	30	0.309	-13.76	58	0.000*	9.0
1/G3/30	6	II	10.61	12.07	11.65	30	0.298				

Note: = Significant Difference at P<0.05, SD = Standard deviation, GS = Generation status, df = Degree of freedom, n = Number of samples*

Table 6: Impact of logging practices on bulk density in second-generation stand

Compartment	GS	Depth (cm)	Bulk density (g/m^3)			n	SD	t-statistic	df	P-value	Change of bulk density (%)
			Min	Max	Mean						
4/MP/1/39.5/PP	I	0 – 10	0.977	1.023	0.996	30	0.014	30	58	0.000*	25.7
1/G3/27	II	0 – 10	0.990	1.287	1.252	30	0.031	30			
4/MP/1/39.5/PP	I	10 – 20	0.743	1.040	1.005	30	0.007	30	58	0.010*	26.2
1/G3/27	II	10 – 20	1.249	1.295	1.268	30	0.009	30			

Note: = Significant Difference at P<0.05, n.s = implies no significant difference, n = number of samples, SD = standard deviation, df = degree of freedom, SG = generation status*

DISCUSSION

A reduction in stand growth parameters (number of stems, tree height, and quadratic mean diameter) was observed in the second-generation compartments compared to the first-generation compartments (Tables 3, 4, 5). These effects were attributed to the passage of logging machines over forest soils, which led to changes in physical soil properties, such as increased soil bulk density as reported by Allman *et al.* (2015). This, in turn, led to localized declines in site productivity, manifesting as reduced above-ground tree growth, as documented in previous studies (Luckow and Guldin 2007, Gebauer and Martinková 2005).

As the compartment age increased, the percentage reduction in stand growth parameters in the second generation decreased was observed. This finding is consistent with the studies by Mariotti *et al.* (2020), and Picchio *et al.* (2020) which indicated that soil compaction primarily occurs in the top 30 cm of soil, increasing the risk of compaction for young trees compared to older ones. Additionally, the study by Hwang *et al.* (2020) reported that the root growth of small trees tends to grow horizontally rather than vertically, which increases the effects for young trees.

Increased soil bulk density in second rotation, driven by logging activities, contributes to reduced soil productivity by compacting soil particles, decreasing pore space, and increasing soil mass per unit volume (Naghdi *et al.* 2016). Our results are consistent with findings that the passage of logging machinery on forest soils can increase soil bulk desnity (Naghdi *et al.* 2009, Jourgholami *et al.* 2014, Sirén *et al.* 2019). Additionally, soil bulk density was found to increase with soil depth, likely due to declining organic matter content, further affecting soil structure as reported by Sirén *et al.* (2019).

The study is constrained by several factors. Data was restricted to Division 1 and Division 4, which are characterized by distinct climatic conditions and edaphic factors. These environmental variations introduce potential confounding effects, making it challenges to isolate logging as the sole determinant of stand growth responses. Consequently, the observed growth pattern may reflect an interaction between logging intensity and site-specific climatic influences. For more comprehensive inference, future studies should employ stratified sampling across a wider range of ecological gradient.

CONCLUSION AND RECOMMENDATIONS

The study found that logging practices affect stand growth in second-generation at Sao Hill Forest Plantation, Tanzania. However, the sustainability of stand growth in subsequent rotations in Tanzania is not guaranteed due to the observed changes of physical soil property (bulk density) that limit root growth as result of the passage of logging machinery.

Despite efforts to reduce logging's impact on Tanzania forest soil, this study urges policymakers to adopt sustainable logging practices including use of designed skid trails, harvesting during dry seasons, use of slash mats, reduced traffic frequency, and soil restoration post-logging. This supports long-term forest health development. However, the study is constrained by site-specific variability such as terrain conditions and microclimates, across the Sao Hill Forest Plantation. To enhance future studies, it is recommended to broaden sampling across multiple divisions and control for environmental variability to better isolate logging effect and enhance reliability.

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REFERENCES

Agherkakli, B., Najafi, A. & Sadeghi, S. 2010. Ground based operation effects on soil disturbance by steel tracked skidder in a steep slope of forest. *Journal of Forest Science* 56(6): 278–284.

Allman, M., Ferenčík, M., Jankovský, M., Stanovský, M. & Messingerová, V. 2015. Damage caused by wheeled skidders on cambisols of Central Europe. Croatian Journal of Forest Engineering: *Journal for Theory and Application of Forestry Engineering* 36(2): 205–215.

Ampoorter, E., Van Nevel, L., De Vos, B., Hermy, M. & Verheyen, K. 2010. Assessing the effects of initial soil characteristics, machine mass and traffic intensity on forest soil compaction. *Forest Ecology and Management* 260(10): 1664–1676.

Beleko, S. 2020. Pine resin productivity at Sao Hill forest plantation, Southern Tanzania. *Tanzania Journal of Forestry and Nature Conservation* 90(1): 82–95.

Cambi, M., Certini, G., Neri, F. & Marchi, E. 2015. The impact of heavy traffic on forest soils: *A review. Forest Ecology and Management* 338: 124–138.

Crawford, L. J., Heinse, R., Kimsey, M. J. & Page-Dumroese, D. S. 2021. Soil sustainability and harvest operations: A review. Gen. Tech. Rep. RMRS-GTR-421. Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station. 39pp.

Curtis, R. O. & Marshall, D. D. 2000. Why quadratic mean diameter? *Western Journal of Applied Forestry* 15(3): 137–139.

Dembure, T. P., McEwan, A., Spinelli, R., Magagnotti, N. & Ramantswana, M. 2019. A comparison between two alternative harvesting systems in the thinning of fast-growing pine plantations under the conditions of low labour cost. *European Journal of Forest Research* 138: 43–52.

Dominati, E., Patterson, M. & Mackay, A. 2010. A framework for classifying and quantifying the natural capital and ecosystem services of soils. *Ecological Economics* 69(9): 1858–1868.

Eisenbies, M. H., Burger, J. A., Aust, W. M. & Patterson, S. C. 2005. Soil physical disturbance and logging residue effects on changes in soil productivity in five-year-old pine plantations. *Soil Science Society of America Journal* 69(6): 1833–1843.

Gebauer, R. & Martinková, M. 2005. Effects of Pressure on the Root Systems of Norway Spruce Plants (*Picea Abies* [L.] Karst.). *Journal of Forest Science* 51(6): 268–75.

Hao, X., Ball, B. C., Culley, J. L. B., Carter, M. R., Parkin, G. W. & Gregorich, E. G. 2008. Soil density and porosity. In: Soil Sampling and Methods of Analysis (pp. 743–759). Canadian Society of Soil Science.

Hwang, K., Han, H.S., Marshall, S. E. & Page-Dumroese, D. S. 2020. Soil compaction from cut-to-length thinning operations in young redwood forests in northern California. *Canadian Journal of Forest Research* 50(2): 185–192.

Jourgholami, M., Majnounain, B. & Abari, M. E. 2014. Effects of tree-length timber skidding on soil compaction in the skid trail in Hyrcanian forests. *Forest Systems* 23(2): 288–293.

Kweka, A. E., Mauya, E. & Mallya, H. 2011. Impact of mechanized logging operations on wet and dry soils of sao hill forest plantations, Tanzania. *Tanzania Journal of Forestry and Nature Conservation* 81(1): 1–9.

Langmaack, M., Schrader, S., Rapp-Bernhardt, U. & Kotzke, K. (2002). Soil structure rehabilitation of arable soil degraded by compaction. *Geoderma* 105(1–2): 141–152.

Latterini, F., Dyderski, M. K., Horodecki, P., Rawlik, M., Stefanoni, W., Högbom, L., Venanzi, R., Picchio, R. & Jagodziński, A. M. 2024. A Meta-analysis of the effects of ground-based extraction technologies on fine roots in forest soils. *Land Degradation & Development* 35(1): 9–21.

Latterini, F., Venanzi, R., Picchio, R. & Jagodziński, A. M. 2023. Short-term physicochemical and biological impacts on soil after forest logging in Mediterranean broadleaf forests: 15 years of field studies summarized by a data synthesis under the meta-analytic framework. *Forestry* 96(4): 547–560.

Makineci, E., Demir, M. & Yilmaz, E. 2007. Long-term harvesting effects on skid road in a fir (*Abies bornmulleriana* Mattf.) plantation forest. *Building and Environment* 42(3): 1538–1543.

Malimbwi, R., Eid, T. & Chamshama, S. 2018. Allometric tree biomass and volume models in Tanzania. *Morogoro: E & D publishing on behalf of Department of Forest Resources Assessment and Management, Sokoine University of Agriculture* 129pp.

Mariotti, B., Hoshika, Y., Cambi, M., Marra, E., Feng, Z., Paoletti, E. & Marchi, E. 2020. Vehicle-induced compaction of forest soil affects plant morphological and physiological attributes: A meta-analysis. *Forest Ecology and Management* 462: 118004.

Masumian, A., Naghdi, R., Zenner, E. K., Nikooy, M. & Lotfalian, M. 2017. Comparison of different erosion control techniques in the Hyrcanian forest in northern Iran. *Journal of Forest Science* 63(12): 549-554.

Mauya, E. W. 2022. Production Rates of Mechanized Tree Felling Operations at Sao-Hill Forest Plantation, Tanzania. *Tanzania Journal of Forestry and Nature Conservation* 91(1): 45–57.

Migunga, G. A. (1996). *Tropical forest soil compaction: Effects of multiple log skidding tractor passes on surface soil bulk density at Sao Hill, Tanzania*. Proceedings of a Symposium organised by IUFRO Subject Group S3.0500 ‘Forest Operations for Sustainable Forestry in the Tropics’. 1–3pp.

Naghdi, R., Solgi, A., Labelle, E. R. & Nikooy, M. 2020. Combined effects of soil texture and machine operating trail gradient on changes in forest soil physical properties during ground-based skidding. *Pedosphere* 30(4): 508–516.

Naghdi, R., Solgi, A., Zenner, E. K., Tsioras, P. A. & Nikooy, M. 2016. Soil disturbance caused by ground-based skidding at different soil moisture conditions in Northern Iran. *International Journal of Forest Engineering* 27(3): 169–178.

Nash, M., Foltz, M., Page-Dumroese, D. & Napper, C. 2021. Soil disturbance rehabilitation: A desk guide to techniques and monitoring. 2025-1804-NTDP. San Dimas, CA: US Department of Agriculture, Forest Service, National Technology and Development Program. 56pp.

Nazari, M., Arthur, E., Lamandé, M., Keller, T., Bilyera, N. & Bickel, S.

2023. A meta-analysis of soil susceptibility to machinery-induced compaction in Forest ecosystems across global climatic zones. *Current Forestry Reports* 9(5): 370–381.

Picchio, R., Mederski, P. S. & Tavankar, F. 2020. How and how much, do harvesting activities affect forest soil, regeneration and stands? *Current Forestry Reports* 6(2): 115–128.

Sadeghi, S., Solgi, A. & Tsioras, P. A. 2022. Effects of traffic intensity and travel speed on forest soil disturbance at different soil moisture conditions. *International Journal of Forest Engineering* 33(2): 146–154.

Silayo, D. S. A., Kiparu, S. S., Mauya, E. W. & Shemwetta, D. T. 2010. Working conditions and productivity under private and public logging companies in Tanzania. Croatian Journal of Forest Engineering: *Journal for Theory and Application of Forestry Engineering* 31(1): 65–74.

Sirén, M., Ala-Ilomäki, J., Lindeman, H., Uusitalo, J., Kiilo, K. E., Salmivaara, A. & Ryynänen, A. 2019. Soil disturbance by cut-to-length machinery on mid-grained soils. *Silva Fennica 53*(2): 2019.

Solgi, A., Naghdi, R., Tsioras, P. A. & Nikooy, M. (2015). Soil compaction and porosity changes caused during the operation of Timberjack 450C skidder in northern Iran. Croatian Journal of Forest Engineering: *Journal for Theory and Application of Forestry Engineering* 36(2): 217–225.