Research article

Assessing the impacts of log extraction by typical small shovel logging system on soil physical and hydrological properties in the Republic of Korea

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ABSTRACT

Typical small shovel logging system, using manual felling and extraction by small crawler excavator with grapple and crawler carriers, is the predominant logging method in the Republic of Korea, due to the associated high productivity. The trails with ground pressure and one more passes of the shovel and carriers may lead to soil compaction. However, impacts of these bunching-extraction technologies on physical and hydrological properties of soils are not well known. The main objectives of this study were to: (1) determine the bulk density, porosity, and saturated hydraulic conductivity of soils in logging operation areas with three different disturbance types (i.e., undisturbed areas [UAs], bladed trails [BTs], and skid trails [STs]), and (2) compare soil compaction between these disturbance types. The most intense compaction occurred within BTs and STs, with increased bulk density and reduced porosity and hydraulic conductivity. Soil bulk density increased by 27–53% at all depths in BTs and STs compared to UAs, while porosity decreased by 23–49%. On average, saturated hydraulic conductivity at depths of 0–20 cm decreased from 337.5 mm h^{-1} to 30.5 mm h^{-1} in the most compacted sections of BTs and STs. Skid trails, which are characterized by trail construction and frequent vehicle movement, also caused greater impacts on soil compaction than BTs. This study provides useful insights to aid forest consultants and field managers in planning more environmentally sound mechanized logging operations.

1. Introduction

Mechanized logging operations are the most prevalent techniques for timber harvesting and have been used to enhance productivity, profitably, and reduce total operational costs (Passicot and Murphy, 2013; Melemez et al., 2014; Norizah et al., 2016; Enache et al., 2016). However, intense vehicular transits (especially for log extraction) can lead to soil disturbance and subsequent alterations in physical (Han et al., 2009; Cambi et al., 2016a, b; Marchi et al., 2016; Cambi et al., 2017) and hydraulic properties of soils (Ziegler et al., 2006; Rejšek et al., 2011; Abdi et al., 2017).

The extent and severity of soil disturbance caused by a logging operation depend on various factors: harvesting equipment (Miller and Sirois, 1986; Laffan et al., 2001; Marchi et al., 2014; Naghdi et al., 2015; Cambi et al., 2016a; Lee et al., 2017; Picchio et al., 2018a), harvesting system (Han et al., 2009; Korb et al., 2007; Labelle and Jaeger, 2011), machine track (Bygdén et al., 2004; Naghdi et al., 2015; Cambi et al.,

2016a), number of machine passes (McNabb et al., 2001; Naghdi and Solgi, 2014; Cambi et al., 2016a, b), and soil texture and structure (Håkansson and Lipiec, 2000; Sakai et al., 2008). Thus, a well-planned logging operation can limit detrimental soil disturbance (Sakai et al., 2008; Naghdi and Solgi, 2014; Cambi et al., 2015; Enache et al., 2015; Laschi et al., 2016; Picchio et al., 2018b, 2019).

On ground-based logging operations, skid trail construction, and trail passes for timber extraction can negatively impact physical and hydrological properties of soils, causing increases in bulk density and decreases in aerial porosity, surface infiltration rates, and saturated hydraulic conductivity (Ziegler et al., 2006; Demir et al., 2007; Shi et al., 2008; Han et al., 2009; Cambi et al., 2015; Poltorak et al., 2018). During logging operations, the weight (including the payload) of machines, vibration, tire pressure, and crawler/wheel slip directly exert compression to soil layers, causing compaction of both topsoil and subsoils (Cambi et al., 2016a; Solgi and Najafi, 2017).

In the Republic of Korea (hereafter Korea), forestlands have a total area of six million hectares, and more than 80% of forests exist on steep terrain (i.e., >40% slope). Typical small shovel logging system with a semi-mechanized logging method has been commonly employed since the early 1990s (Korea Forest Service, 2017; Korean Statistical Information Service, 2018). These operations are conducted in compliance with the Korea Forest Service regulation (revised on September 18, 2015; National Law Information Center, 2018). This technology commonly consists of a chainsaw for felling, delimbing, and bucking of trees into logs (typically 2–4 m in length), a small crawler excavator with log grapple (a.k.a. wood-grab; Supplementary Figure S1a), and a MST800VDL crawler carrier with rubber tracks (Morooka Co., Ltd., Ryuugasaki, Ibaraki, Japan; Supplementary Figure S1b) to bunching, extract and transport logs from the felling site to a skid trail side or main landing.

In general, productivity of shovels in clearcutting operation is high, whereas there is low soil impacts due to the wide crawler tracks with low ground pressure, one pass traffic treatment, and trafficking on residues (Sessions and Boston, 2006). However, the operation of shovel in Korea, unlike a pattern used in the western United State, makes no use of serpentine and vertical patterns on gentle terrain. The Korea's shovel logging system have been extensively used in steep terrain (greater than 40%) and 2–4 m logs is to travel on random trails to skid trails/landing areas (Figure 1). The extraction process with small shovel loaders was three steps: (1) starts to move from the skid trail to stump, (2) during climbing the stump, sorting into logs and residues by small shovel loader, and (3) descends when the small shovel return by pushing and throwing only logs to the skid trail (Figure 1). In addition, decision-making for the selection of shovel loader and rubber carrier pattern and skid trail construction are mostly subjective and are based on personal experience. For example, after applied this technology, the deep disturbances (topsoil removed, 15%; erosion feature, 2%; and rutted 26%) and compacted (5%) were observed 48% of the harvest area (Lee et al., 2017). During extraction operation, improperly planned, construction, or passing of shovel loader and rubber carrier can have a significant impact on soil environment (Boston, 2016).

Therefore, some researchers have noted that this extraction process potentially damages forest soils by accelerating compaction and soil loss, and obstructing soil regeneration (Kim and Park, 2013; Kim et al., 2017; Lee et al., 2017), however no studies have been done on effects of on-site traffic and skid trail construction under operational conditions. Furthermore, trends and severity of soil compaction are extremely challenging to anticipate due to soil heterogeneity (Craig, 2004; Boivin et al., 2006; Ampoorter et al., 2007).

The objective of this study was to determine post-harvest effects of small shovel loader and rubber carrier traffic on physical and hydrological properties (i.e., bulk density, porosity, and hydraulic conductivity) of near surface soils immediately after the extraction and transport of logs to landing areas.

2. Material and methods

2.1. Study sites and harvesting method

Three study areas (SAs), from which logs were extracted using small excavator with grapple and crawler carriers, were chosen to compare the impacts of typical small shovel logging system and steep slope harvesting methods on physical and hydrological properties of soils.

A 7.2 ha forest in Icheon, Gyeonggi-do (37°11′46″ N, 127°23′21″ E; hereafter study area 1 [SA1]; Supplementary Figure S2) was used in this study. Measurements of soil properties were conducted after logging operations had been carried out from September 2 to 5, 2015. Dominant species' in this study area were Korean red pine (*Pinus densiflora*), Mongolian oak (*Quercus mongolica*), and cork oak (*Quercus variabilis*). The average diameter, height, and stand volume were 20 cm, 15 m, and 131 m^3 ha^{-1}, respectively, and the ground slope of the study area ranged from 27–54%. The soil texture of SA1 was classified as loamy sand (88% sand, 6% silt, and 6% clay) to sandy loam (58% sand, silt 27%, and clay 15%) based on particle size distribution (USDA-NRCS, 1999; Supplementary Figure S3). The organic matter content of soil samples from this area ranged from 5–23% and was hence classified as 'low to medium' according to the International Organization for Standardization (ISO) standard 14688-1 (2017).

Soil texture and organic matter content was classified and analyzed in the soil laboratory of the National Instrumentation Center for Environmental Management (NICEM; College of Agriculture and Life Sciences, Seoul National University) in all study sites. Soil texture analysis completed by hydrometer method (American Society for Testing and Materials: ASTM D422-63, 2008). Soil organic matter determined by Walkley-Black dichromate method.

A subsequent assessment was carried out between February 20 and 28, 2017 in a 7.0 ha forest of Wanju, Jeollabuk-do (35°44′07″ N, 127°12′08″ E; hereafter study area 2 [SA2]; Supplementary Figure S2). This study area encompassed a mixed-conifer stand dominated by Hinoki

Small shovel loader operation

Starting when the small shovel leaves the skid trail

Sorting logs during climbing the steep slopes

Descending when the small shovel return by pushing and throwing logs to the skid trail

Legend
— Bladed trail
— Skid trail
▨ Landing
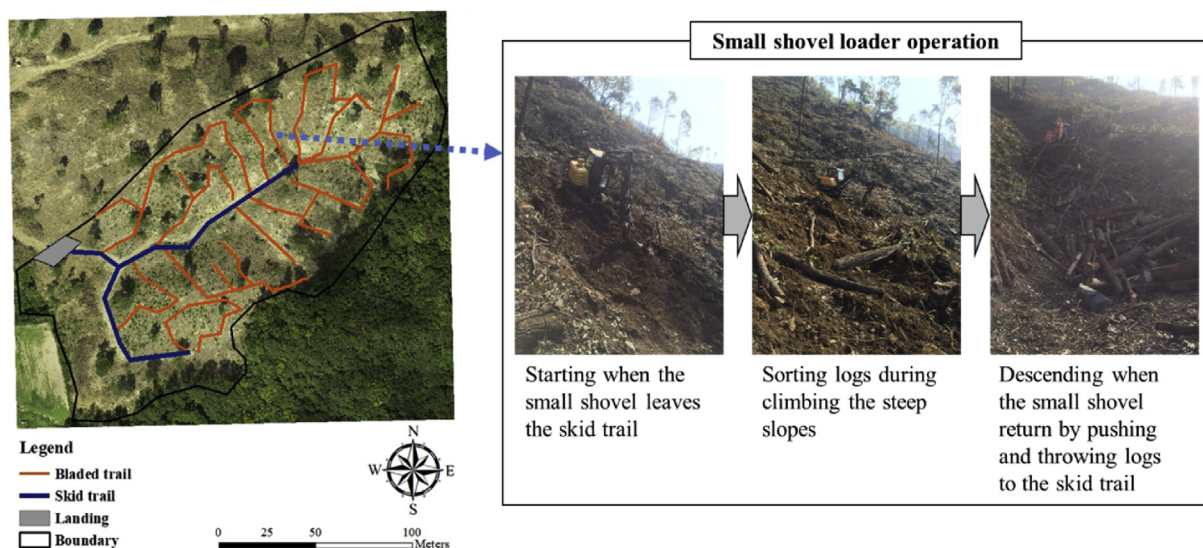▢ Boundary

0 25 50 100 Meters

Figure 1. Post-harvest image for the study area 1: map showing the bladed trail, skid trail, landing, timber-harvesting boundary. Trail patterns designated by logger's choice. The right indicates the small shovel loader operation stages.

cypress (*Chamaecyparis obtusa*), Japanese larch (*Larix leptolepis*), and Mongolian oak (*Q. mongolica*). The mean diameter, mean height, and stand volume were 20 cm, 23 m, and 241 m^3 ha^{-1}, respectively, and the terrain was uneven with ground slopes of up to 70%. Soil from SA2 were classified as sandy loam or silty loam, and the organic matter content of soil samples ranged between 4–10%, with an average of 6%.

A 15.1 ha mixed forest in Gimcheon, Gyeongsangbuk-do (36°00′00″ N, 128°06′48″ E; hereafter study area 3 [SA3]; Supplementary Figure S2) was selected as a third study area. Soil sampling and in situ measurements were conducted in May, 2017. This area was dominated by Korean red pine (*P. densiflora*), pitch pine (*Pinus rigida*), Mongolian oak (*Q. mongolica*), and cork oak (*Q. variabilis*). The topography was steeply sloping, ranging from 36–47% ground slope. The mean diameter, mean height, and stand volume were 23 cm, 17 m, and 142 m^3 ha^{-1}, respectively. The soils were characterized as loamy sand or sandy loam (72% sand, 17% silt, and 11% clay), and the organic matter content of undisturbed forest soils was classified as 'low to medium', ranging from 4–11% (ISO 14688-1, 2017).

A small shovel logging system, with a clear-cutting operation as a silvicultural treatment, was used in the three study areas. This involved manual felling, delimbing, and cutting of stems to 2–4 m in length at the stump by two fellers using a STIHL MS261 chainsaw with a 3-kW. Logs were extracted from felling sites and transported to a landing area by a crawler excavator equipped with a wood-grab. A small excavator was used for the downhill extraction of logs on drivable terrain (slopes up to 70%), and another excavator constructed a skid trail during the extraction process. The skid trails were temporarily constructed with slopes of 5–30% and a width of 3 m for timber transportation by a crawler carrier.

The small crawler excavator with grapple used in this study was equipped with a 52-kW diesel engine that was 2.5 m (length) by 0.3 m (width). The total weight of the excavator with the standard log grabber was approximately 6.0 tonnes with a ground contact pressure of 30–40 kPa. A crawler carrier equipped with an 86-kW diesel engine was used for log transportation following completion of the extraction operation. The empty weight of the carrier was 6.0 tonnes, and it was fitted to a 4.5 m (length) by 0.6 m (width) crawler. The rear section of the machine was capable of loading up to 6.0 tonnes of logs, and had a recommended ground contact pressure between 15-30 kPa.

2.2. Field data collection

Bulk density, porosity, and saturated hydraulic conductivity were measured in soil samples taken with different disturbance types: undisturbed areas (UAs), bladed trails (BTs; Supplementary Figure S4a), and skid trails (STs; Supplementary Figure S4b). Undisturbed areas were located nearly 2 m from BTs and STs and were considered 'control' sites, having no direct impacts from logging traffic (McMahon, 1995). Bladed trails were defined as the exposed soil surface that has one or two passes of small excavators, while STs were defined as temporary roads that allow transport of logs to landing sites. In this study, STs experienced more than 10 carrier passes during logging operations.

A total of 180 soil samples were collected from the three study areas (i.e., SA1, SA2, and SA3) according to the category of soil disturbances (UA, BT, and ST). Half the samples were collected from depths of 0–10 cm, and half were taken from depths of 10–20 cm, using an established core sampling method (Page-Dumroese et al., 1999). A slide soil corer (Eijkelkamp Soil & Water, Giesbeek, Netherlands) with a 98 cm^3 volume (5 cm inner diameter, 5 cm length) was used to collect soil samples from specific depths. Samples were sealed in plastic bags and transported to the laboratory where they were oven-dried at 105 °C in paper bags until a constant weight was reached. Bulk density and porosity were determined according to the ASTM D6683-19 (2019) and D854-00 (2000) methods, respectively.

Saturated hydraulic conductivity (i.e., providing K_{sat} values) was measured to assess effects of logging trails on hydrological property of soils. A Guelph Permeameter 2800K1 (Eijkelkamp Soil & Water,

Giesbeek, Netherland; Kanwar et al., 1989, Figure 2) was used to measure in-situ hydraulic conductivity (i.e., the GP test). This is a portable instrument capable of accurately measuring water infiltration rate at the point when a steady-state infiltration velocity condition is reached (Elrick and Reynolds, 1992). Infiltration experiments were separately conducted using two pressure heads (5 cm and 10 cm) and an air-inlet tip. After borehole tests, K_{sat} was estimated from each measurement by applying the following equation from Reynolds and Elrick (1986):

$$K_{sat} = 35.22 \times (-0.0054 \times R_1 + 0.0041 \times R_2), \qquad (1)$$

where R_1 and R_2 are the steady-state water infiltration velocity (cm^{-1} sec^{-1}) in 5 cm and 10 cm head of well tube, respectively.

Hydraulic conductivity was measured at 20 sites for each disturbance type (i.e., UA, BT, and ST) in SA3 only, due to restrictions imposed by a current regeneration and restoration scheme to assess the actual soil loss after harvesting. To conduct GP tests, a sharpened soil auger with a 6 cm diameter was used to create a 20 cm deep hole. A Guelph Permeameter was then placed over the hole, and the water head in the well tube was set to 5 cm or 10 cm. Water infiltration rate was recorded every 1–2 min until the steady-state flow conditions at each of well heights were achieved. Finally, K_{sat} values were calculated from Eq. (1) (Reynolds and Elrick, 1986).

2.3. Statistical analysis

Prior to analysis of variance (ANOVA), data normality was assessed using the Kolmogorov-Smirnov test. ANOVA was performed to analyze response variables by study areas (SA1 vs. SA2 vs. SA3) and soil disturbance types (UA vs. BT vs. ST). Additionally, soil physical properties were separately analyzed within different soil layers (0–10 cm and 10–20 cm depths). Post-hoc tests were conducted using Scheffe's test and Dunnett's
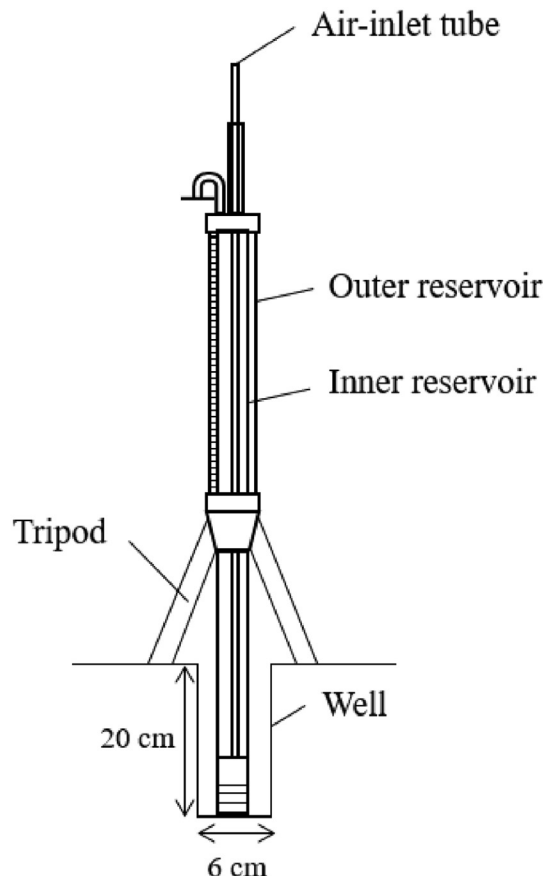

Figure 2. Schematic diagram of the Guelph Permeameter 2800K1.

(T3) test, and Pearson's correlation coefficients were used to determine relationships between K_{sat} and bulk density. Statistical analyses were conducted using the Statistical Package for the Social Sciences (SPSS) v. 22.0 (International Business Machines (IBM) Corp., 2013).

3. Results

3.1. Soil physical properties

In UAs, bulk densities of soil samples from depths of 0–10 cm were 1.26 g cm^{-3} ($\pm$0.03 standard error [SE]) at SA1, 1.21 g cm^{-3} ($\pm$0.03 SE) at SA2, and 1.15 g cm^{-3} ($\pm$0.04 SE) at SA3. At depths of 10–20 cm, the bulk density of soils from UAs were 1.35 g cm^{-3} ($\pm$0.05 SE) at SA1, 1.31 g cm^{-3} ($\pm$0.04 SE) at SA2, and 1.20 g cm^{-3} ($\pm$0.03 SE) at SA3 (Figure 3). Comparison of soil porosity between study areas is shown in Figure 4; at depths of 0–10 cm, soil porosity was 52% ($\pm$1.28 SE) for SA1, 54% ($\pm$1.23 SE) for SA2, and 56% ($\pm$1.38 SE) for SA3, whereas the porosity at depths of 10–20 cm were 49% ($\pm$1.92 SE) at SA1, 50% ($\pm$1.50 SE) at SA2, and 54% ($\pm$1.36 SE) at SA3. There were no statistically significant differences among the sites ($p > 0.05$) with respect to soil bulk densities or porosities within either depth range. Soil textures varied between loamy sand and silt loam, however no significant differences were found in physical properties of soils among study areas ($p > 0.05$).

Post-trafficking physical properties of soils (i.e., bulk density and porosity) are presented in Figures 5 and 6, according to the disturbance type. Bulk density was significantly higher and the porosity was significantly lower in BTs and STs, compared to UAs ($p < 0.05$; Figures 5 and 6). Compacted soils in STs clearly showed the highest rates of change. The bulk density was higher in both BTs and STs compared to UAs, ranging from 27–53% at all soil depths, whereas porosity was reduced and varied from 23–49%. Additionally, bulk density and porosity of soils from depths of 10–20 cm differed considerably among sites (SA1 and SA3 vs. SA2), even though soil physical properties were statistically similar ($p > 0.001$). In the STs of the three sites, bulk density and porosity did not different significantly with depth ($p > 0.05$).

Among study sites and trail types, STs had higher bulk density and lower porosity than BTs at all analyzed soil depths. Soil bulk density was increased by 24% (ranging from 13–41%) and porosity was reduced by 13–42% in STs compared to BTs; significant differences between trail types were detected ($p < 0.001$).

3.2. Soil saturated hydraulic conductivity

After the GP test, K_{sat} values in the UAs of SA3 ranged from 14.6–1080.0 mm h^{-1} (mean 337.5 mm h^{-1}) at soil depths of 10–20 cm

(Figure 7). The mean K_{sat} values of the two trail types (BTs and STs) were 56.4 mm h^{-1} ($\pm$21.5 SE) and 4.7 mm h^{-1} ($\pm$1.9 SE), respectively, and K_{sat} was reduced from 78~98% in BTs and STs compared to UAs. Additionally, soils from BTs and STs had significantly altered hydrological properties compared to UAs ($p < 0.001$). Thus, the results demonstrated that soil compaction was caused by mechanized logging traffic along STs and BTs.

There was a significant difference in saturated hydraulic conductivity between UAs and BTs, and between UAs and STs (Figure 7). Our data revealed that K_{sat} values of STs were approximately 90% lower than those of BTs in this case study, yet they were not statistically different ($p > 0.05$) (Figure 7). The K_{sat} values were considerably lower in STs compared to BTs at SA3, however our data were limited to only this site because of artificial regeneration procedure such as time interval at SA1 and SA2. The general trend shows that logging traffic and skid trail construction had detrimental impacts on saturated hydraulic conductivity of soils in SA3.

The relationships between K_{sat}, bulk density and disturbance level were investigated (Figure 8), and showed that K_{sat} values were significantly (and adversely) correlated with bulk density, i.e., bulk density increased when K_{sat} decreased under all disturbance conditions. We found that when K_{sat} values were reduced by 25%, bulk density increased by 10% due to soil compaction. Additionally, bulk density was significantly different between trail types (BT vs. ST; $p < 0.001$), whereas K_{sat} was not ($p > 0.05$). Hence, our results indicate that bulk density is a considerable driver in changes in K_{sat} values of soils.

4. Discussion and conclusions

Ground-based extraction activities and skid trail construction result in structural changes to and compaction of soils, which is immediately evident in measurements of parameters such as bulk density, porosity (Ares et al., 2005; Curran et al., 2007; Han et al., 2009; Arthur et al., 2013; Solgi and Najafi, 2014; Cambi et al., 2016a, b; Marchi et al., 2016; Cambi et al., 2017) and K_{sat} (Ziegler et al., 2006; Curran et al., 2007; Rejšek et al., 2011; Arthur et al., 2013; Abdi et al., 2017). Generally, steel-tracked small shovel loaders and rubber-tracked carriers are the most frequently used machinery in logging operations in Korea. Therefore, this study assessed impacts of these extraction operations on measurable physical and hydrological characteristics of soils at different levels of soil disturbance. The results showed compaction, increased bulk density, and decreased porosity and hydraulic conductivity in soils from disturbed areas (i.e., BTs and STs).

Log extraction activities, such as vehicular (small crawler excavator with grapple and crawler carrier) movement and trail construction, may
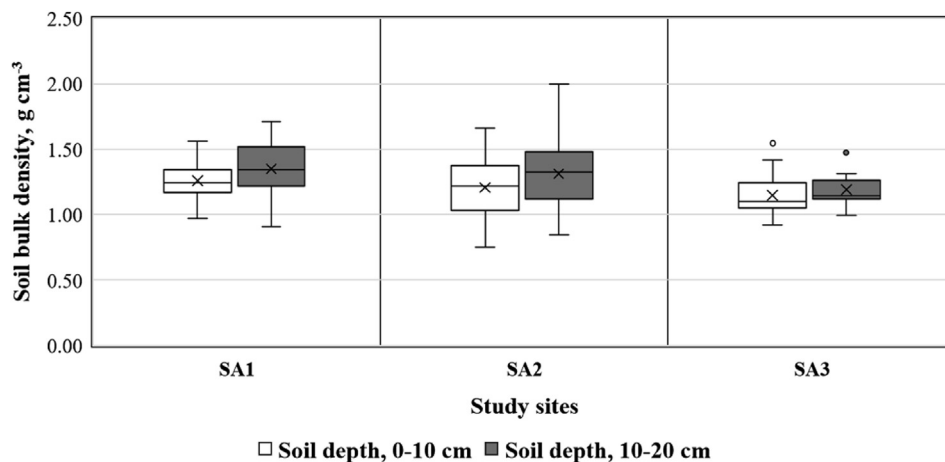

Figure 3. Bulk density of soils in undisturbed areas (UAs) among the study sites: Hobeop-myen, Icheon-si, Gyeonggi-do (study area 1; SA1), Sanggwan-myeon, Wanju-gun, Jeollabuk-do (study area 2; SA2), and Joma-myeon, Gimcheon-si, Gyeongsangbuk-do (study area 3; SA3). The circles show outliers, and the line and X are mean values. The bars display full range of variation, and the box is first and third quartiles.
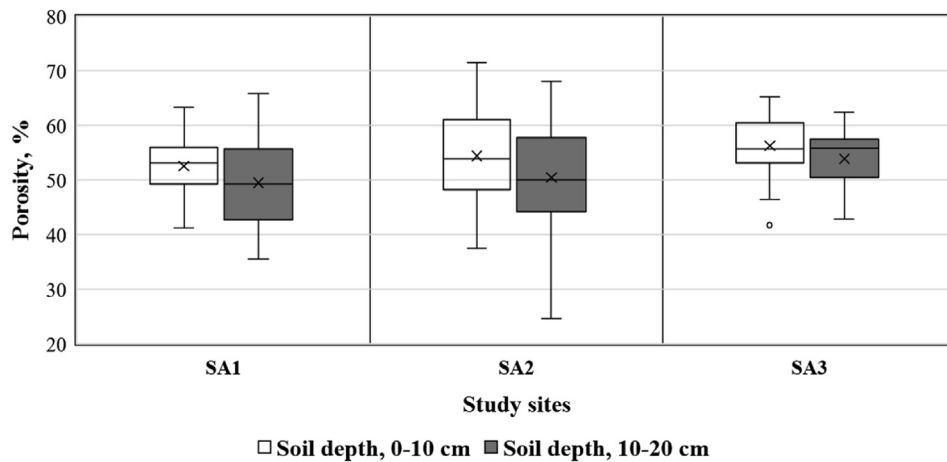
Figure 4. Porosity of soils in undisturbed areas (UAs) in the study sites: Hobeop-myen, Icheon-si, Gyeonggi-do (study area 1; SA1), Sanggwan-myeon, Wanju-gun, Jeollabuk-do (study area 2; SA2), and Joma-myeon, Gimcheon-si, Gyeongsangbuk-do (study area 3; SA3). The circles show outliers and the line and X are mean values. The bars display full range of variation, and the box is first and third quartiles.
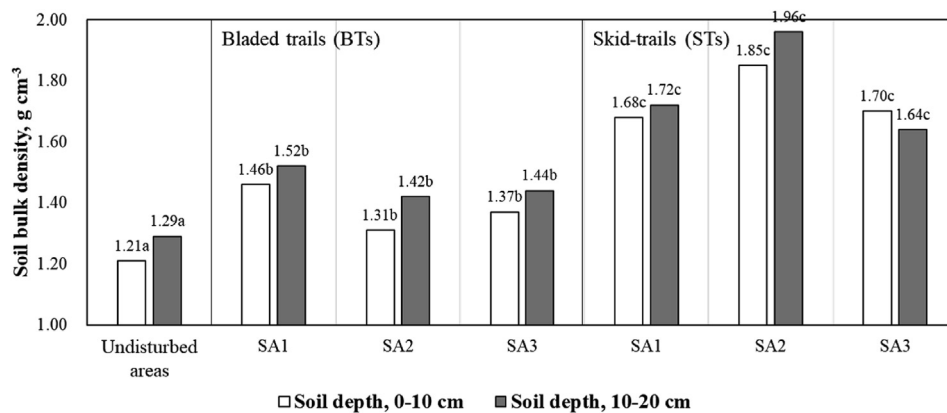

Figure 5. Soil bulk density in study areas within undisturbed areas (UAs), bladed trails (BTs) and skid trails (STs): Hobeop-myen, Icheon-si, Gyeonggi-do (study area 1; SA1), Sanggwan-myeon, Wanju-gun, Jeollabuk-do (study area 2; SA2), and Joma-myeon, Gimcheon-si, Gyeongsangbuk-do (study area 3; SA3). The same letter shows there were no significant differences (p value >0.05).
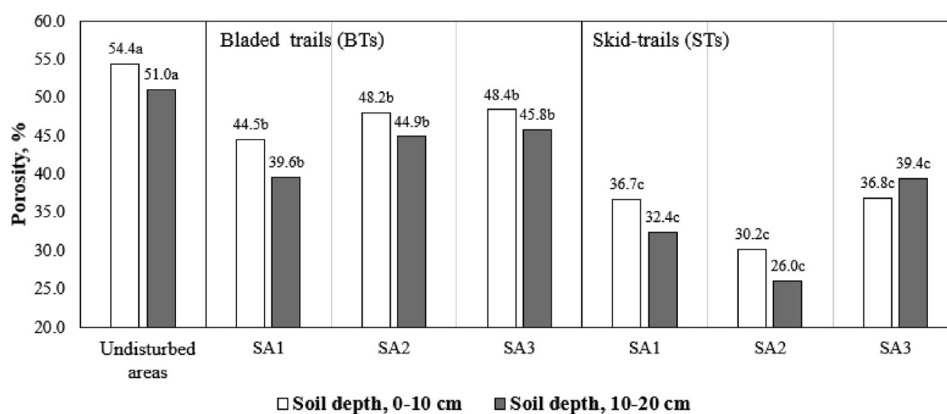

Figure 6. Soil porosity in study areas within undisturbed areas (UAs), bladed trails (BTs) and skid trails (STs): Hobeop-myen, Icheon-si, Gyeonggi-do (study area 1; SA1), Sanggwan-myeon, Wanju-gun, Jeollabuk-do (study area 2; SA2), and Joma-myeon, Gimcheon-si, Gyeongsangbuk-do (study area 3; SA3). Means with the same letter were not statistically different (p value >0.05).

cause severe soil compaction and detrimental impacts on soil permeability. Numerous studies have shown that machine trafficking can cause changes to soil properties (e.g., Solgi and Najafi, 2014; Cambi et al., 2015; Cambi et al., 2016a, b; Marchi et al., 2016; Poltorak et al., 2018).

According to Bygdén et al. (2004), Battiato et al. (2013), and Cambi et al. (2015), the primary result of such activities is soil compaction, with the severity being influenced by factors including vertical accelerating/braking of vibration tracks or tires, static pressure, and machine
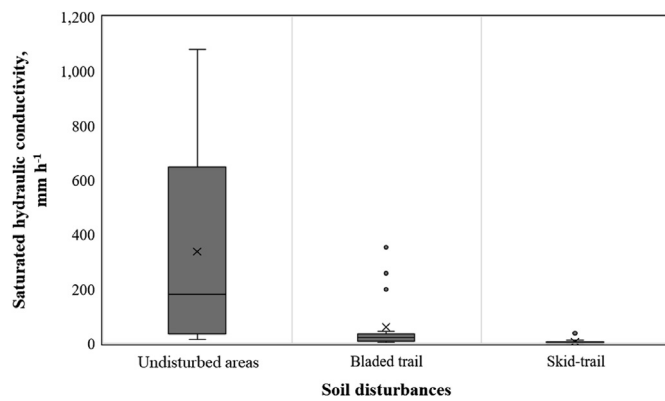
Figure 7. Saturated hydraulic conductivity (K_{max} values) of soils in areas with different disturbance types; undisturbed areas (UAs), bladed trail (BTs), and skid-trail (STs). The circles show outliers and the line and X are mean values. Error bars show the standard error.

payload. The surface contact pressure of logging machines can also cause soil particles to become compacted (Craig, 2004). Thus, vehicle trails may cause both soil sealing and pore clogging.

The extent and severity of soil compaction was significantly higher in STs compared to BTs. Similarly, Startsev and McNabb (2000), Jourgholami et al. (2014), Cambi et al. (2016a, b), Marchi et al. (2016), and Cambi et al. (2017) reported numerous changes in physical properties (e.g., bulk density and porosity) of loam-textured soils occurring after 5–10 vehicle passes. Other studies have shown that the degree of soil compaction is affected by road construction activities, such as earth movement (Weindorf et al., 2013; Caliskan, 2013) and scraping (Laurance et al., 2009). In the present study, higher soil compaction in STs than in BTs is evidence of impacts of different logging operation activities. Furthermore, the intensity of machine traffic (i.e., the number of vehicle passes) and trail construction appear to be primary factors controlling soil compaction in the study areas.

Soil compaction may also indicate a considerable reduction in soil permeability. For example, Rejšek et al. (2011) and Abdi et al. (2017) reported that wheel contact areas contributed to lower rates of soil infiltration (which can reduce soil saturation) than in other zones, such as undisturbed regions and the center of trails (because the rutted zones of skid trails are regularly compacted by vehicle movement). During the GP test, the K_{sat} values in BTs and STs were significantly lower than in UAs. However, there were no statistical differences between BTs and STs, which may be due to the small sample size and the local heterogeneity in

macropore flow within soils (Pirastru et al., 2013; Bastianelli et al., 2017). Overall, the results suggest that the main impacts on hydraulic conductivity likely occurred within the first few passes or during additional passes (>10) of logging vehicles, and subsequent construction of skid trails.

In conclusion, this study describes alterations of physical and hydrological properties of soils according to three different soil disturbance types, and contributes to improved understanding of effects of traditional logging extraction operations on soils in Korea. Our data clearly show that areas with different levels of disturbance exhibited significantly different severities and permanence of soil compaction and sealing. Furthermore, increased areas of impervious surfaces (due to vehicular traffic and trail constructions) negatively impacted hydrological properties of soils. Thus, small shovel logging operation may significantly alter soil structure and hydraulic processes of near-surface soils. Subsequent studies of traditional logging in Korea are needed to determine if soil compaction results in reduced soil CO_2, soil biota, diffusion tree's root, or inhibits tree growth and natural regeneration.

Declarations

Author contribution statement

Eunjai Lee: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Qiwen Li, Song Eu: Performed the experiments.

Sang-Kyun Han: Conceived and designed the experiments.

Sangjun Im: Conceived and designed the experiments; Wrote the paper.

Competing interest statement

The authors declare no conflict of interest.

Additional information

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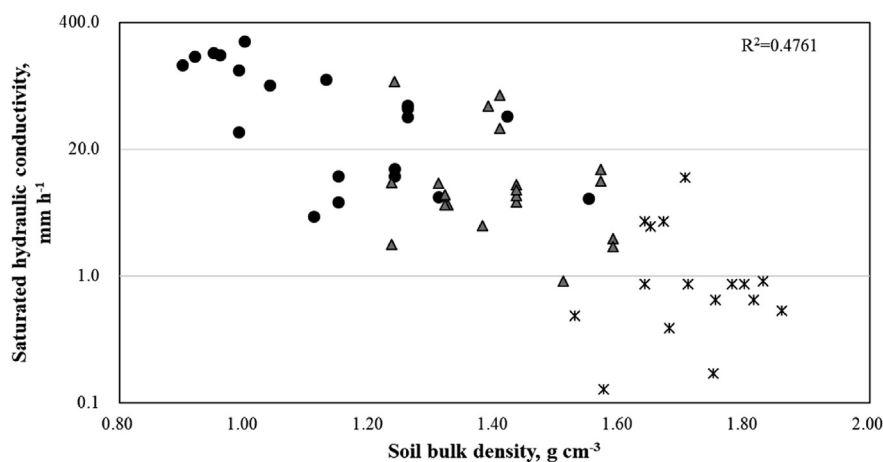

Figure 8. Relationship between saturated hydraulic conductivity and bulk density in soil samples at 20 cm depth in undisturbed areas (UAs), bladed trail (BTs), and skid-trail (STs) within study area 3 (SA3).

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