Geoderma 367 (2020) 114238

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Assessment of topsoil disturbance caused by different skidding machine types beyond the margins of the machine operating trail

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ARTICLE INFO

Handling editor: Yvan Capowiez

Keywords:
Bulk density
Crawler skidder
Skid trail edge
Traffic intensity
Trail slope

ABSTRACT

Forest soil disturbances are unavoidable in ground-based skidding operations and it is well-known that the extent, duration, and severity of disturbances increase with increasing trafficking from harvest equipment and slope gradient. It is unclear, however, how different types of harvest equipment affect the extent of disturbance along the margins of skid trails.

The aim of this study was to investigate changes in topsoil (0–10 cm depth) physical properties beyond the margins of skid trails in mountainous terrain in response to skidding with three different skidder types with varying tire ground pressure. Three skidder types (rubber tired "Timberjack 450C" skidder (site RT1), rubber tired "TAF E655" skidder (site RT2), "Onezhets 110" crawler skidder (site CS)), two levels of trail gradient (≤20% and > 20%), four levels of traffic frequency (4, 8, 15, and 40 passes), and four distances of buffer strip zones (0.5 m intervals from 0 to 2 m in distance) on both sides of the skid trail edges were analyzed. Results showed that topsoil bulk density increased with greater traffic intensity for all skidder types and on both slopes. With increasing traffic intensities topsoil physical properties gradually deteriorated in zones that were further from the skid trail margin. While this process occurred faster on steeper slopes (i.e., fewer passes were required), the pattern was consistent for all three machine types. Consequently, the area adversely affected by skidding machines increased with increasing harvest traffic, with soil conditions within the first 0.5 to 1 m along the skid trail margin more similar to the skid trail itself and the conditions > 1 m more similar to untrafficked areas. The significant effect of skid trail slope gradient on increased soil disturbance provides land managers with important information for designing skid trail systems that protect soil physical properties to maintain overall site productivity. The adverse effects of the extent and degree of soil disturbance can be controlled by operation constraints that include reducing tire pressure to the minimum allowable weight, installing larger diameter tires to increase the length of the machine footprint, increasing the number of axles or decreasing the number of equipment passes.

1. Introduction

Ground-based skidding systems in Iran consist primarily of crawler and wheel skidders. In addition to unavoidable damage to trees remaining along skid trails, these ground-based skidders may also cause serious damage to forest soil adjacent to the skid trail (Najafi et al., 2009; Naghdi et al., 2015; Naghdi et al., 2019). Some of the most common adverse impacts are related to the degradation of soil physical properties. Soil physical degradation such as compaction leads decreased total soil porosity (mainly of soil macroporosity, i.e. pores < 30 μm), reduced pore connectivity, increased soil density and shear strength (Picchio et al., 2012; Solgi et al., 2016a), decreased gas exchange between the soil and atmosphere, and decreased water infiltration resulting in increased runoff (Solgi et al., 2014). Reductions in air permeability and soil porosity reduce elongation and penetration of roots, and thus reduce root access to, and uptake of, water and nutrients (Greacen and Sands, 1980; Kozlowski, 1999; Naghdi et al., 2016a). Effects on root growth can have a significant influence on the performance of seedlings (Finzi and Canham, 2000; Kobe, 2006). Consequently, soil compaction can compromise seedling establishment and survival (Greacen and Sands, 1980; Arocena, 2000; Kim et al., 2010) and ultimately seedling growth and production (Zenner et al., 2007;

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https://doi.org/10.1016/j.geoderma.2020.114238
Received 16 July 2019; Received in revised form 30 January 2020; Accepted 2 February 2020
0016-7061/ © 2020 Published by Elsevier B.V.

Soto et al., 2015). The severity of seedling growth and production does, however, depend on the soil type and tree species among other factors (Kozlowski, 1999; Ampoorter et al., 2011).

The degree and extent to which a forest soil is compacted during ground-based harvest operations depends on several variables such as soil and site characteristics (soil texture, soil organic matter content, slope), season (soil water content, soil temperature) and the harvesting activity itself (machine type, machine mass, number of harvested trees, traffic intensity) (Greacen and Sands, 1980; Eliasson, 2005; Gerasimov and Katarov, 2010; Naghdi and Solgi, 2014; Naghdi et al., 2016b; Solgi et al., 2016b; Naghdi et al., 2017). Najafi et al. (2009) also reported that the extent of soil compaction depends not only on soil characteristics, but also on the pressure and vibration applied to the soil surface when rubber-tired skidders are used.

The impacts of different types of equipment on the extent and severity of soil compaction on skid trails have been well researched (Ares et al., 2005; Ampoorter et al., 2007; Jaafari et al., 2014), including some studies investigating machine trafficking impacts on soil physical properties at various distances from the skid trail edge (Solgi et al., 2015a; Solgi et al., 2016a). However, this knowledge is incomplete without the investigation of the effects of other important variables (e.g., number of passes, traffic intensity) on soil physical properties at various distance from the edge of skid trail. The aims of this study were: (i) to determine the effect of skidding operations on the degree and extent of soil compaction up to 10 cm depth of soil profile; (ii) to investigate how far from the margin of the skid trail into a 2 m buffer strip on both sides of the trail there is a significant effect of skidding on soil physical parameters; and (iii) to investigate these changes for different machine types on different slopes and traffic intensities.

2. Material and methods

2.1. Site description

This study was conducted during the period of August to September 2018 in compartment 41 of third district of the Shenrood forest in the Guilan Province of northern Iran (between 36° 31′ 56″ N and 36° 32′ 11″ N latitude and 51° 47′ 49″ E and 51° 47′ 56″ E longitude). Three study sites were selected in mature oriental beech (*Fagus orientalis* Lipsky) forests on a clay loamy soil (Table 1). The area is characterized by brown forest soils formed on unconsolidated limestone. Soils at all four sites are similar. They have a moderately deep profile and are classified as Eutric Cambisols (FAO/UNESCO 1990; Typic Eutrudepts in the USDA Soil Taxonomy, 1998). Soil textures in each trail was clay loam determined by particle size analysis using the Bouyoucos hydrometer method (Kalra and Maynard, 1991). The elevation of the study sites ranged between approximately 600–850 m above sea level with a northern aspect. The average annual rainfall is 1100 mm from the closest national weather station 25 km away from the research area. Maximum mean monthly rainfall is 153 mm in October and minimum monthly rainfall is 30 mm in August. The mean annual temperature is 16 °C, with the lowest temperatures in February. On each site, harvest and skidding operations were conducted when weather conditions were dry and warm, with a gravimetrically determined average soil moisture content of 21%. Each stand had never been harvested prior to this study and therefore had no legacy soil impacts.

Table 1
Soil particle size distribution with corresponding soil textures for three research sites at a depth of 1–10 cm. The range of particle size was < 0.002, 0.002–0.05 and 0.05–2 mm for clay, silt, and sand, respectively.

Sample site	Soil particle size distributions (g 100 g − 1)			Soil texture
	Sand	Silt	Clay	
Site 1	27	34	39	Clay loam
Site 2	32	31	37	Clay loam
Site 3	31	33	36	Clay loam

Table 2
Pre-harvest characteristics of the study area and technical details of the skidding equipment used at Shenrood forest, Guilan Province, northern Iran.

Site and skidding equipment			
Specification	RT1	RT2	CS
Area (ha)	45	41	38
Canopy Cover (%)	79	85	82
Stand Density	168	184	179
Mean diameter (cm)	31	29	34
Mean height (m)	23.7	23.2	22.6
Equipment category	Rubber-tired skidder	Rubber-tired skidder	Crawler skidder
Weight (kg)	10,275	12,000	12,500
Ground pressure (kPa)	221	659	49
Engine power (hp)	177	65	120

RT1, rubber-tired skidder Timberjack 450C; RT2, rubber-tired skidder TAF E655; CS, crawler skidder

2.2. Harvest operations

At each of the three study sites, a combination of group selection and single tree selection were applied. Trees were felled by hand and tree processing was followed by transportation to the roadside by either a (i) rubber tired "Timberjack 450C" skidder (site RT1), (ii) rubber tired "TAF E655" skidder (site RT2), or (iii) "Onezhets 110" crawler skidder (site CS) (Table 2 and Fig. 1). The rubber-tired skidders and the crawler skidder were used to extract logs that were 3–4 m long on drivable terrain of up to 34% slope. Machine operators were trained and licensed for driving skidders and each driver had several years of experience. The specifications of the equipment used in this study are given in Table 2. During the study, the equipment operators were directed to maximize the amount of wood carried out in each load.

2.3. Study design and data collection

In this study, the impacts of different skidder types on skid trail mineral soil (0–10 cm depth) at the three sites were quantified using dry bulk density, total porosity, and macroporosity. Skid trails differed in slope and traffic intensity and were subsequently compared to the undisturbed area. Even though only one skidder type was used in each study site, thus confounding site with skidder type, similar site conditions with respect to soil texture and soil moisture content should permit comparisons of the effects of the different skidder types on soil physical properties across the sites in this study.

At each site, a skid trail was selected with a range of longitudinal slope steepness and without any lateral slope. On the identified skid trails a 4 × 2 factorial experimental design was applied for each piece of equipment (2 types of skidders, 1 crawler) with three replicates of each treatment combination: traffic frequency (4 classes) × slope (2 classes) × 3 replicates = 24 experimental units. The four traffic frequency classes consisted of four, eight, 15, and 40 round trips that included one empty and one loaded pass. The two slope classes consisted of trail segments that were located on gentle terrain (≤20% slope gradient, range: 3–15%) and steep terrain (> 20% slope gradient, range 23–28%).

At each trail, a total of 24 plots (10 m long by 4 m wide) were identified. The minimum distance between plots was at least 2 m and within each plot, a 2-m buffer zone was established between five sample lines delineated perpendicular to the trail to avoid interactions. Three of the five lines were randomly selected and used to measure soil physical properties.

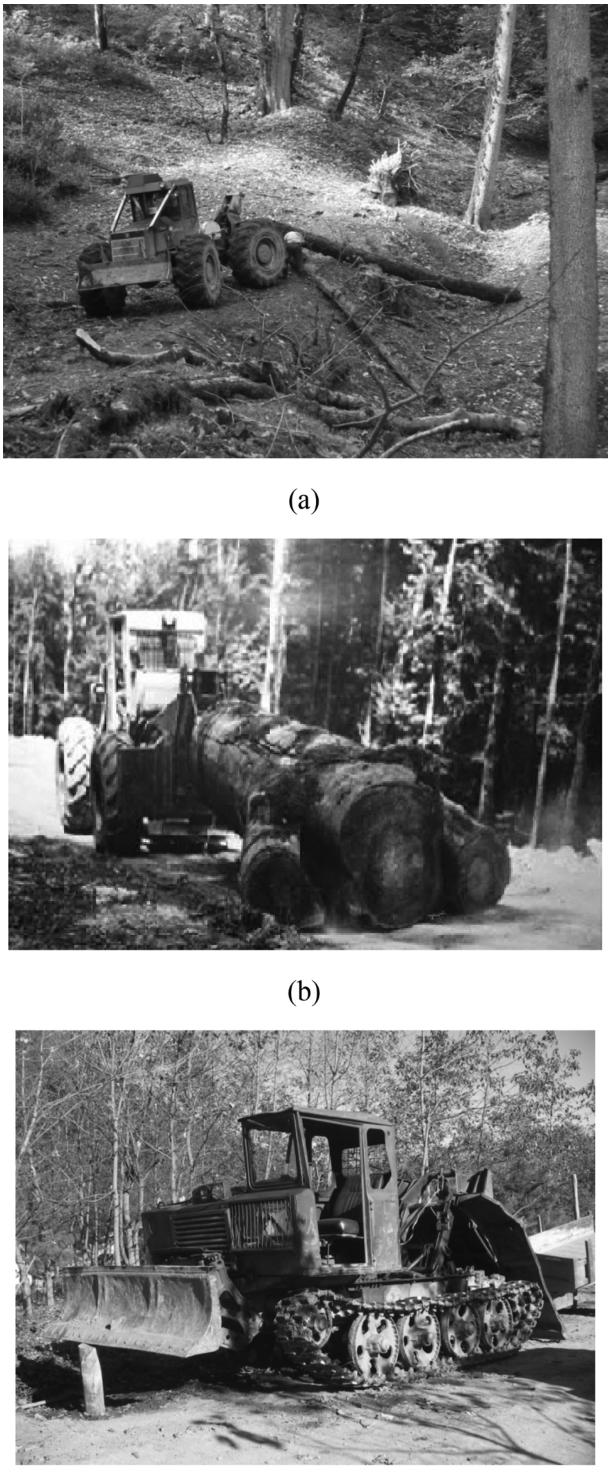

Fig 1. Pictures of skidding equipment used in this study of logging operations in a mountain forest in Iran. (a) rubber-tired skidder Timberjack 450C; (b) rubber-tired skidder TAF E655; (c) crawler skidder Onezhets 110.

Soil samples were collected from the left wheel track (LWT), right wheel track (RWT), and at four distances up to 2 m on each side of the trail. Sample points in the buffer strips were located at (1) 0 to 0.5 m from the wheel track (SB1), (2) 0.5 to 1.0 m from the wheel track (SB2), (3) 1.0 to 1.5 m from the wheel track (SB3), and (4) 1.5 to 2.0 m from the wheel track (SB4). The paired values of LWT and RWT samples were averaged to determine an overall value for each skid trail (ST). In addition, soil samples were taken from an unharvested control area at least 50 m from the skid trail in locations where there were no direct skidding impacts. A schematic design of sample plot locations is shown in Fig. 2.

Soil samples were collected after each skidding cycle with a slide hammer (samples fitted with sleeves that were 5 cm wide × 10 cm long). Once collected, samples were placed in polyethylene bags, labeled, and transported to the laboratory where they were promptly weighed. Soil samples were oven dried at 105° C until constant mass was achieved to calculate the gravimetric moisture content (Kalra and Maynard, 1991).

2.4. Laboratory analysis

Total soil bulk density (D_b; g cm^{-3}) was calculated as Eq. (1):

$$D_b = W_d/VC \qquad (1)$$

where W_d is the weight of the dry soil (g), and VC is the volume of the soil cores (196.25 cm^3).

Total soil porosity (TP; %) was calculated as Eq. (2):

$$TP = 1 - (D_b/\ 2.65) \times 100 \qquad (2)$$

where 2.65 (g cm^{-3}) is the soil particle density.

Macroporosity (MP; %) was determined using the water description method (Danielson and Sutherland, 1986). Soil samples were placed in plastic tubes and saturated for 5 days. The water level was slowly raised to prevent air entrapment and weighed. The samples were then drained for 3 h and weighed again (Rivenshield and Bassuk, 2007; Ezzati et al., 2012). We calculated the macroporosity based on Eq. (3):

$$MP = [(Ws - Wdr)/V] \times 100 \qquad (3)$$

where Ws represents saturated weight (g), Wdr specifies the drained weight (g) and V refers to the volume (cm^3).

2.5. Statistical analysis

The SPSS 11.5 statistical package was used for statistical analyses after the application of the Kolmogorov–Smirnov test to check for normality and Levene's test to check for homogeneity of variance. Differences in soil physical properties (dry bulk density, total porosity, and macroporosity) were assessed through one-way and three-ways ANOVAs, considering different skidder traffic levels, trail gradients, machine types and related interactions. The comparison of soil physical properties among machine types was made by one-way ANOVA (p-level $\alpha \leq 0.05$) and Tukey's HSD test (Zar, 1999).

3. Results

The number of trafficking cycles, slope gradient, and machine type as well as their interactions significantly affected total bulk density, total porosity, and macroporosity (Table 3). Average total bulk density (range: 0.76–0.80 g cm^{-3}), total porosity (range: 71.7–73.8%), and macroporosity (range: 53.8–53.2%) did not differ between slope gradients in the unharvested control (untrafficked) areas (Table 4). Following trafficking, the average total bulk density increased to 0.93–1.57 g cm^{-3}, total porosity decreased to 38.6–63.7%, and macroporosity decreased to 39.8–9.7%. With each machine type, total bulk density increased and total porosity and macroporosity decreased with increasing traffic intensity on both slope gradients. At all traffic intensities, the CS machine type increased bulk density less and reduced total porosity and macroporosity less than the RT1 and RT2 machine types; similarly, the RT1 machine type resulted in less adverse soil physical conditions than the RT2 machine type. For each machine type and skidding cycle, the lowest compaction, and greatest total porosity and macroporosity, occurred in the lower slope gradient (< 20%) trails.

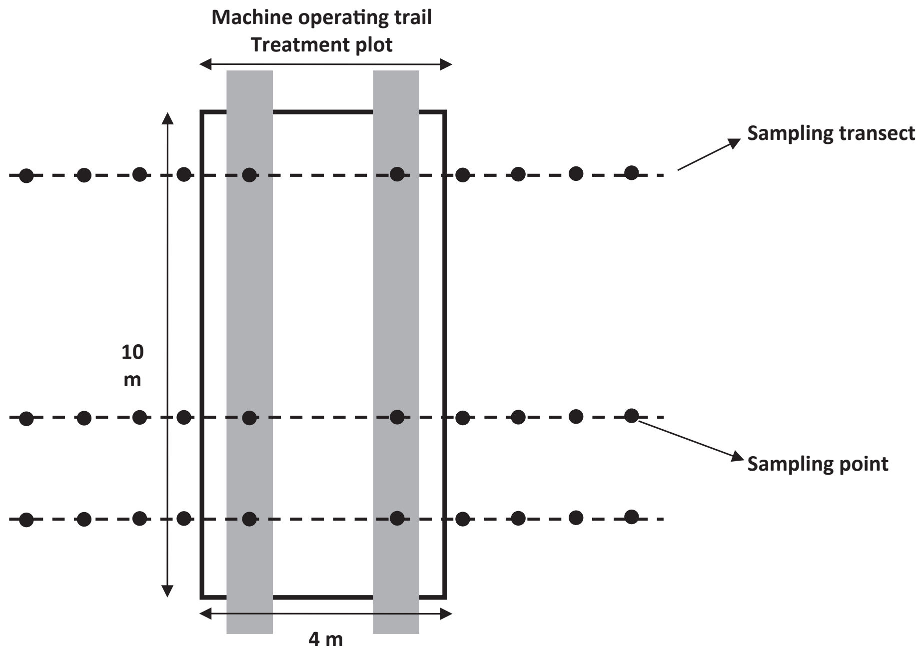

Fig 2. Layout of the sample areas.

Table 3
Analysis of variance (*p* values) of the effects of traffic intensity, trail slope and machine type on soil physical properties at Shenrood forest, Guilan Province, northern Iran.

Source of variable	d.f.	*P*-values		
		Bulk density	Total porosity	Macroporosity
Traffic intensity	3	**≤0.05**	**≤0.05**	**≤0.05**
Slope	1	**≤0.05**	**≤0.05**	**≤0.05**
Machine type	2	**≤0.05**	**≤0.05**	**≤0.05**
Traffic × Slope	3	**≤0.05**	**≤0.05**	0.419
Traffic × Machine type	6	**≤0.05**	0.621	**≤0.05**
Slope × Machine type	2	**≤0.05**	0.148	**≤0.05**
Traffic × Slope × Machine type	6	0.352	**≤0.05**	0.537

p-values < 0.05 are given in bold.

Heavy traffic on slopes > 20% resulted in the highest bulk densities, smallest total porosity and macroporosity, and the greatest difference to the unharvested control.

After four traffic cycles of all three machine types, bulk density, total porosity, and macroporosity in the top 10 cm of the soil differed significantly between the skid trail (wheel tracks) and all zones of the buffer strips on both slopes, but not between any portion of the buffer zone and the untrafficked area. With increased harvesting traffic, the zones that were significantly affected by skidding, and in which the soil physical properties differed significantly from untrafficked areas, expanded gradually. The speed of the expansion of significant skidding effects into the buffer zone depended on the machine type and was faster on steeper slopes. For example, on both slope gradients it generally took one additional traffic cycle class (e.g., from eight to 15 passes) to extend significant differences in soil physical conditions between distance zones and untrafficked areas when changing from the RT2 to the RT1 machine type and another traffic cycle class when changing from the RT1 to the CS machine type. In general, differences in soil physical conditions between different distance zones of the skid trail margin and untrafficked areas also occurred one traffic cycle class sooner on slope gradients > 20% compared to slope gradients ≤20%. For example, whereas significant differences between the 0.5 m distance zone and untrafficked areas were detected after 15 traffic cycles on the slope gradient ≤20%, this was the case after eight traffic cycles on the slope gradient > 20% (RT1 machine type). Further, it generally took also one more traffic cycle class to induce significant differences between the next further distance zone and the untrafficked areas, so that significant differences between the 1 m distance zone and untrafficked areas were detected after 40 traffic cycles on slope gradient ≤20% and 15 cycles on slope gradient > 20% compared 15 and eight cycles, respectively, in the 0.5 m zone (RT1 machine type). Overall, average bulk density increased and total porosity and macroporosity consistently decreased with increasing distance into the buffer zone along the skid trail margins as the number of traffic cycles increased. With the exception of the RT2 machine type on slope gradients > 20%, however, the 2-m distance class from the skid trail margin was not significantly different from the untrafficked areas. Supplemental Figs. 1–3 (a–f) show the proportional difference in average bulk density, total porosity, and macroporosity among the various distance zones compared to untrafficked areas.

4. Discussion

Ground-based skidding operations always transfer machine and log weights onto a small soil surface area, which results in unavoidable soil degradation such as increased soil compaction and reduced soil porosity (Greacen and Sands, 1980). At the Shenrood Forest, we also found that skidding operations have a large negative impact on the physical properties of the topsoil in the skid trail. However, this damage was not just restricted to the area of the designated skid trail but extended beyond the margins of the trail. Although not always statistically significant, there is a general trend for topsoil compaction increases up to 1.5 m on either side of the designated skid trail. Not surprisingly, most of the significant changes in topsoil compaction, porosity, and macroporosity occurred within the 0.5-m zone from the edge of the designated skid trail and it appears that topsoil physical properties were generally not compromised at a distance of 1.5–2 m from the skid trail.

Similar to work by Rhee et al. (2019) on gravel forest roads, there are several processes associated with vehicle trafficking on skid trails. Most common is compaction associated with direct compression of the

Table 4
Means (± std) of total bulk density (Mg m^{-3}) at each distance from the skid trail edges following different traffic intensities by three machine types (RT1, rubber-tired skidder Timberjack 450C; RT2, rubber-tired skidder TAF E655; CS, crawler skidder Onezhets 110) on two different trail slope gradients at Shenrood forest, Guilan Province, northern Iran. The ST location refers to the wheel tracks of the skid trails. Values of 0.5, 1, 1.5, and 2 refer to the distance class (in m) from the margin of the 4-m wide skid trail.

Type	RT1					RT2	
Zone	ST	0.5	1	1.5	2	ST	0.5
Passes	Slope Gradient < 20%						
4	$1.01^{aB} \pm 0.09$	$0.81^{aA} \pm 0.07$	$0.79^{aA} \pm 0.06$	$0.79^{aA} \pm 0.06$	$0.77^{aA} \pm 0.07$	$1.08^{aB} \pm 0.09$	$0.84^{aA} \pm 0.09$
8	$1.27^{bB} \pm 0.13$	$0.84^{aA} \pm 0.08$	$0.82^{aA} \pm 0.08$	$0.80^{aA} \pm 0.09$	$0.80^{aA} \pm 0.07$	$1.34^{bC} \pm 0.11$	$0.91^{bB} \pm 0.08$
15	$1.41^{cC} \pm 0.11$	$0.93^{bB} \pm 0.07$	$0.84^{aA} \pm 0.08$	$0.81^{aA} \pm 0.08$	$0.78^{aA} \pm 0.08$	$1.47^{cD} \pm 0.14$	$1.08^{cC} \pm 0.11$
40	$1.45^{cD} \pm 0.16$	$1.09^{cC} \pm 0.09$	$0.92^{bB} \pm 0.09$	$0.83^{aA} \pm 0.09$	$0.79^{aA} \pm 0.07$	$1.50^{cE} \pm 0.14$	$1.23^{dD} \pm 0.14$
Passes	Slope Gradient > 20%						
4	$1.14^{aB} \pm 0.12$	$0.84^{aA} \pm 0.09$	$0.81^{aA} \pm 0.09$	$0.82^{aA} \pm 0.09$	$0.79^{aA} \pm 0.08$	$1.21^{aC} \pm 0.11$	$0.95^{aB} \pm 0.11$
8	$1.38^{bB} \pm 0.14$	$0.94^{bA} \pm 0.10$	$0.85^{aA} \pm 0.09$	$0.82^{aA} \pm 0.10$	$0.81^{aA} \pm 0.08$	$1.48^{bD} \pm 0.13$	$1.14^{bC} \pm 0.13$
15	$1.50^{cD} \pm 0.16$	$1.11^{bC} \pm 0.12$	$0.96^{bB} \pm 0.10$	$0.84^{aA} \pm 0.08$	$0.82^{aA} \pm 0.09$	$1.53^{bE} \pm 0.16$	$1.31^{cD} \pm 0.15$
40	$1.54^{cE} \pm 0.16$	$1.26^{cD} \pm 0.12$	$1.13^{cC} \pm 0.11$	$0.97^{bB} \pm 0.11$	$0.85^{aA} \pm 0.07$	$1.57^{bE} \pm 0.15$	$1.42^{dD} \pm 0.14$

Type	RT2			CS				
Zone	1	1.5	2	ST	0.5	1	1.5	2
Passes	Slope Gradient < 20%							
4	$0.79^{aA} \pm 0.07$	$0.80^{aA} \pm 0.09$	$0.77^{aA} \pm 0.08$	$0.93^{aB} \pm 0.11$	$0.79^{aA} \pm 0.07$	$0.79^{aA} \pm 0.07$	$0.80^{aA} \pm 0.09$	$0.77^{aA} \pm 0.08$
8	$0.81^{aA} \pm 0.09$	$0.78^{aA} \pm 0.08$	$0.75^{aA} \pm 0.08$	$1.11^{bB} \pm 0.13$	$0.82^{aA} \pm 0.09$	$0.80^{aA} \pm 0.09$	$0.81^{aA} \pm 0.08$	$0.76^{aA} \pm 0.08$
15	$0.94^{bB} \pm 0.10$	$0.83^{aA} \pm 0.09$	$0.78^{aA} \pm 0.09$	$1.30^{cB} \pm 0.15$	$0.80^{aA} \pm 0.09$	$0.79^{aA} \pm 0.08$	$0.77^{aA} \pm 0.08$	$0.77^{aA} \pm 0.09$
40	$1.10^{cC} \pm 0.12$	$0.93^{bB} \pm 0.10$	$0.80^{aA} \pm 0.09$	$1.41^{dC} \pm 0.16$	$0.98^{bB} \pm 0.11$	$0.81^{aA} \pm 0.09$	$0.78^{aA} \pm 0.07$	$0.80^{aA} \pm 0.09$
Passes	Slope Gradient > 20%							
4	$0.83^{aA} \pm 0.08$	$0.84^{aA} \pm 0.08$	$0.81^{aA} \pm 0.09$	$1.03^{aB} \pm 0.11$	$0.84^{aA} \pm 0.08$	$0.83^{aA} \pm 0.09$	$0.81^{aA} \pm 0.09$	$0.81^{aA} \pm 0.07$
8	$0.98^{bB} \pm 0.12$	$0.87^{aA} \pm 0.09$	$0.83^{aA} \pm 0.09$	$1.32^{bB} \pm 0.14$	$0.87^{aA} \pm 0.09$	$0.84^{aA} \pm 0.09$	$0.82^{aA} \pm 0.10$	$0.80^{aA} \pm 0.10$
15	$1.18^{cC} \pm 0.13$	$0.97^{bB} \pm 0.11$	$0.85^{aA} \pm 0.10$	$1.46^{cB} \pm 0.16$	$0.87^{aA} \pm 0.10$	$0.84^{aA} \pm 0.10$	$0.80^{aA} \pm 0.09$	$0.82^{aA} \pm 0.09$
40	$1.29^{dC} \pm 0.15$	$1.09^{cB} \pm 0.12$	$0.95^{bA} \pm 0.11$	$1.50^{cD} \pm 0.15$	$1.17^{bC} \pm 0.13$	$0.95^{bB} \pm 0.11$	$0.81^{aA} \pm 0.10$	$0.79^{aA} \pm 0.09$

Different letters within each treatment show significant differences ($P < 0.05$). Different capital letters indicate significant differences among the four distances from the skid trail edge, separate for each slope class (column). Different lower-case letters indicate significant differences among the four skidding cycles for each slope category and distance from the skid trail (row). Gray cells indicate statistically significant differences from untrafficked control areas with a mean bulk density of 0.78 Mg m^{-3}.

Table 5

Means (± std) of total porosity (%) at each distance from the skid trail edge following different traffic intensities and by three machine types (RT1, rubber-tired skidder Timberjack 450C; RT2, rubber-tired skidder TAF E655; CS, crawler skidder Onezhets 110) on two different trail slope gradients at Shenrood forest, Guilan Province, northern Iran. The ST location refers to the wheel tracks of the skid trails. Values of 0.5, 1, 1.5, and 2 refer to the distance class (in m) from the margin of the 4-m wide skid trail.

Type	RT1					RT2	
Zone	ST	0.5	1	1.5	2	ST	0.5
Passes	Slope Gradient < 20%						
4	$62.9^{aB} \pm 3.74$	$71.5^{aA} \pm 4.52$	$71.8^{aA} \pm 4.35$	$71.8^{aA} \pm 4.26$	$72.1^{aA} \pm 4.28$	$57.3^{aB} \pm 3.29$	$71.5^{aA} \pm 4.62$
8	$52.4^{bB} \pm 3.45$	$70.9^{aA} \pm 4.47$	$71.6^{aA} \pm 4.82$	$72.2^{aA} \pm 4.32$	$71.8^{aA} \pm 4.36$	$50.5^{bC} \pm 3.05$	$63.2^{bB} \pm 4.15$
15	$46.9^{cC} \pm 4.18$	$63.6^{bB} \pm 3.61$	$70.8^{aA} \pm 4.39$	$71.4^{aA} \pm 4.29$	$72.3^{aA} \pm 4.45$	$44.6^{cD} \pm 2.55$	$56.8^{cC} \pm 3.93$
40	$45.7^{cD} \pm 26.9$	$57.1^{cC} \pm 3.05$	$63.9^{bB} \pm 3.95$	$71.7^{aA} \pm 4.41$	$72.5^{aA} \pm 4.63$	$43.7^{cE} \pm 2.74$	$51.6^{dD} \pm 3.51$
Passes	Slope Gradient > 20%						
4	$56.8^{aB} \pm 3.69$	$69.8^{aA} \pm 4.12$	$70.5^{aA} \pm 4.31$	$71.2^{aA} \pm 4.58$	$72.2^{aA} \pm 4.48$	$51.9^{aC} \pm 3.19$	$62.5^{aB} \pm 3.67$
8	$48.4^{bC} \pm 3.32$	$62.8^{bB} \pm 3.83$	$68.7^{aA} \pm 4.16$	$71.1^{aA} \pm 4.33$	$71.5^{aA} \pm 4.82$	$41.5^{bD} \pm 2.65$	$55.4^{bC} \pm 3.32$
15	$43.1^{cD} \pm 25.8$	$56.3^{cC} \pm 3.18$	$62.1^{bB} \pm 3.62$	$70.9^{aA} \pm 3.97$	$71.2^{aA} \pm 5.01$	$40.8^{bE} \pm 2.54$	$50.3^{cD} \pm 3.08$
40	$41.7^{cE} \pm 2.43$	$51.1^{dD} \pm 3.21$	$55.8^{cC} \pm 3.31$	$61.9^{bB} \pm 3.72$	$70.4^{aA} \pm 4.76$	$38.6^{bE} \pm 2.08$	$44.4^{dD} \pm 2.64$

Type	RT2			CS				
Zone	1	1.5	2	ST	0.5	1	1.5	2
Passes	Slope Gradient < 20%							
4	$72.8^{aA} \pm 5.01$	$72.4^{aA} \pm 4.51$	$72.1^{aA} \pm 4.21$	$63.7^{aB} \pm 4.05$	$72.5^{aA} \pm 4.80$	$72.4^{aA} \pm 5.05$	$71.9^{aA} \pm 4.82$	$73.0^{aA} \pm 7.86$
8	$72.7^{aA} \pm 4.82$	$71.5^{aA} \pm 4.27$	$73.1^{aA} \pm 4.11$	$57.3^{bB} \pm 3.86$	$71.5^{aA} \pm 4.77$	$71.4^{aA} \pm 4.86$	$72.1^{aA} \pm 4.97$	$73.2^{aA} \pm 5.23$
15	$62.9^{bB} \pm 4.35$	$71.6^{aA} \pm 4.41$	$71.8^{aA} \pm 3.98$	$51.8^{cB} \pm 3.42$	$71.0^{aA} \pm 4.52$	$72.7^{aA} \pm 4.46$	$72.9^{aA} \pm 5.12$	$73.0^{aA} \pm 5.18$
40	$57.7^{cC} \pm 3.61$	$63.2^{bB} \pm 3.65$	$71.5^{aA} \pm 4.34$	$47.1^{dC} \pm 3.25$	$63.2^{bB} \pm 3.29$	$70.8^{aA} \pm 4.27$	$71.6^{aA} \pm 5.06$	$70.9^{aA} \pm 4.69$
Passes	Slope Gradient > 20%							
4	$70.5^{aA} \pm 4.85$	$70.3^{aA} \pm 4.18$	$71.1^{aA} \pm 4.15$	$61.4^{aB} \pm 4.01$	$69.8^{aA} \pm 4.13$	$70.3^{aA} \pm 4.15$	$72.4^{aA} \pm 4.93$	$72.1^{aA} \pm 4.34$
8	$61.6^{bB} \pm 4.20$	$69.2^{aA} \pm 4.02$	$70.1^{aA} \pm 3.99$	$51.2^{bB} \pm 3.27$	$69.3^{aA} \pm 3.95$	$69.8^{aA} \pm 3.78$	$70.1^{aA} \pm 4.32$	$71.8^{aA} \pm 4.72$
15	$55.1^{cC} \pm 3.55$	$61.8^{bB} \pm 3.63$	$69.7^{aA} \pm 3.65$	$45.2^{cB} \pm 2.74$	$68.5^{aA} \pm 4.16$	$70.1^{aA} \pm 4.08$	$72.3^{aA} \pm 4.04$	$71.8^{aA} \pm 4.83$
40	$50.13^{dC} \pm 3.03$	$56.4^{cB} \pm 3.05$	$62.9^{bA} \pm 3.49$	$43.9^{cD} \pm 2.58$	$55.6^{bC} \pm 3.31$	$64.5^{bB} \pm 3.69$	$70.3^{aA} \pm 4.17$	$72.4^{aA} \pm 5.03$

Different letters within each treatment show significant differences ($P < 0.05$). Different capital letters indicate significant differences among the four distances from the skid trail edge, separate for each slope class (column). Different lower-case letters indicate significant differences among the four skidding cycles for each slope category and distance from the skid trail (row). Gray cells indicate statistically significant differences from untrafficked control areas with a mean total porosity of 72.6%.

Table 6
Means (± std) of Macroporosity (%) at each distance from the skid trail edge following different traffic intensities by three machine types (RT1, rubber-tired skidder Timberjack 450C; RT2, rubber-tired skidder TAF E655; CS, crawler skidder Onezhets 110) on two different trail slope gradients at Shenrood forest, Guilan Province, northern Iran. The ST location refers to the wheel tracks of the skid trails. Values of 0.5, 1, 1.5, and 2 refer to the distance class (in m) from the margin of the 4-m wide skid trail.

Type	RT1					RT2	
Zone	ST	0.5	1	1.5	2	ST	0.5
Passes	Slope Gradient < 20%						
4	$33.2^{aB} \pm 2.18$	$52.6^{aA} \pm 3.12$	$53.1^{aA} \pm 3.18$	$53.1^{aA} \pm 3.65$	$53.7^{aA} \pm 4.15$	$28.7^{aB} \pm 1.23$	$52.8^{aA} \pm 3.18$
8	$24.1^{bB} \pm 2.65$	$51.9^{aA} \pm 3.07$	$52.7^{aA} \pm 3.12$	$53.1^{aA} \pm 3.48$	$52.9^{aA} \pm 4.09$	$14.5^{bC} \pm 0.85$	$32.7^{bB} \pm 2.45$
15	$10.5^{cC} \pm 0.83$	$33.8^{bB} \pm 2.15$	$51.8^{aA} \pm 3.64$	$52.7^{aA} \pm 3.19$	$53.5^{aA} \pm 3.87$	$9.6^{cD} \pm 0.71$	$29.5^{cC} \pm 1.82$
40	$10.2^{cD} \pm 0.74$	$29.8^{cC} \pm 1.79$	$32.7^{bB} \pm 2.25$	$52.5^{aA} \pm 3.12$	$53.7^{aA} \pm 4.01$	$9.3^{cE} \pm 0.68$	$21.4^{dD} \pm 1.39$
Passes	Slope Gradient > 20%						
4	$28.1^{aB} \pm 1.53$	$51.3^{aA} \pm 3.10$	$52.5^{aA} \pm 3.64$	$52.4^{aA} \pm 3.55$	$53.9^{aA} \pm 4.25$	$23.2^{aC} \pm 1.53$	$33.4^{aB} \pm 2.36$
8	$13.9^{bC} \pm 1.08$	$33.4^{bB} \pm 2.24$	$51.4^{aA} \pm 3.57$	$52.4^{aA} \pm 3.27$	$52.8^{aA} \pm 4.19$	$9.2^{bD} \pm 0.91$	$27.6^{bC} \pm 1.62$
15	$9.2^{cD} \pm 0.75$	$27.6^{cC} \pm 1.67$	$32.9^{bB} \pm 1.94$	$51.9^{aA} \pm 3.04$	$52.5^{aA} \pm 3.97$	$9.1^{bE} \pm 0.62$	$14.2^{cD} \pm 1.10$
40	$9.0^{cE} \pm 0.68$	$22.7^{dD} \pm 1.44$	$27.3^{cC} \pm 1.64$	$32.6^{bB} \pm 1.94$	$51.7^{aA} \pm 4.11$	$8.9^{bD} \pm 0.59$	$9.4^{cD} \pm 0.83$

Type	RT2			CS				
Zone	1	1.5	2	ST	0.5	1	1.5	2
Passes	Slope Gradient < 20%							
4	$53.3^{aA} \pm 4.21$	$53.7^{aA} \pm 3.71$	$53.8^{aA} \pm 3.72$	$32.7^{aB} \pm 2.24$	$53.5^{aA} \pm 3.81$	$53.5^{aA} \pm 4.27$	$53.3^{aA} \pm 4.21$	$53.9^{aA} \pm 3.88$
8	$53.4^{aA} \pm 3.74$	$53.1^{aA} \pm 3.64$	$53.9^{aA} \pm 3.61$	$27.6^{bB} \pm 1.69$	$52.6^{aA} \pm 3.94$	$53.4^{aA} \pm 4.16$	$53.1^{aA} \pm 3.94$	$54.1^{aA} \pm 4.32$
15	$33.2^{bB} \pm 2.04$	$53.2^{aA} \pm 3.29$	$53.3^{aA} \pm 3.28$	$21.6^{cB} \pm 1.43$	$53.5^{aA} \pm 3.65$	$52.9^{aA} \pm 4.10$	$53.8^{aA} \pm 4.08$	$53.8^{aA} \pm 4.16$
40	$28.2^{cC} \pm 1.75$	$40.2^{bB} \pm 2.77$	$53.1^{aA} \pm 4.08$	$11.1^{dC} \pm 1.03$	$33.7^{bB} \pm 2.26$	$52.9^{aA} \pm 3.89$	$53.5^{aA} \pm 4.22$	$53.7^{aA} \pm 4.17$
Passes	Slope Gradient > 20%							
4	$53.4^{aA} \pm 3.67$	$53.1^{aA} \pm 4.05$	$53.6^{aA} \pm 3.28$	$31.4^{aB} \pm 2.14$	$51.2^{aA} \pm 3.54$	$52.5^{aA} \pm 4.11$	$54.0^{aA} \pm 4.38$	$53.0^{aA} \pm 3.76$
8	$32.5^{bB} \pm 2.26$	$52.6^{aA} \pm 3.96$	$53.2^{aA} \pm 3.17$	$15.1^{bB} \pm 1.15$	$52.1^{bA} \pm 3.72$	$52.3^{aA} \pm 4.36$	$52.8^{aA} \pm 3.99$	$53.8^{aA} \pm 4.12$
15	$26.3^{cC} \pm 1.82$	$32.5^{bB} \pm 2.36$	$52.4^{aA} \pm 3.51$	$9.7^{cB} \pm 0.87$	$52.1^{bA} \pm 3.84$	$52.4^{aA} \pm 4.18$	$53.9^{aA} \pm 4.06$	$53.1^{aA} \pm 4.03$
40	$20.2^{cC} \pm 1.40$	$28.3^{cB} \pm 1.94$	$33.7^{bA} \pm 2.15$	$9.3^{cD} \pm 0.63$	$26.8^{cC} \pm 1.83$	$34.6^{bB} \pm 2.95$	$53.1^{aA} \pm 4.21$	$54.0^{aA} \pm 4.35$

Different letters within each treatment show significant differences ($P < 0.05$). Different capital letters indicate significant differences among the four distances from the skid trail edge, separate for each slope class (column). Different lower-case letters indicate significant differences among the four skidding cycles for each slope category and distance from the skid trail (row). Gray cells indicate statistically significant differences from untrafficked control areas with a macroporosity of 53.5%.

soil particles in the wheel tracks. During trafficking, soil particles can be pushed directly into the mineral soil, but they can also be swept and compressed at the side of the trail. Soil churned into the trail edge from tire action is the likely reason the trail edges are compacted and why the effect dissipates with distance from the wheel track (Rhee et al. 2018). Soil moisture, organic matter content, texture, and particle size distribution will all determine the degree of soil compaction during trafficking and the compression of particles away from the main trail. Furthermore, the vibration of equipment can cause compaction under and next to the equipment (Johnson et al. 2007) and can be detected to depths up to 30 cm (Page-Dumroese 1993).

Each skidder type had a significant negative impact on the three topsoil physical properties (bulk density, total porosity and macroporosity) and, despite some differences in among machine types in the specific pattern of adverse effects that occurred with increasing traffic intensity on both slope gradients, the general response pattern was nearly identical. Regardless of machine type, increased soil bulk density and reduced pore space observed after the first few equipment passes is consistent with findings in other studies that show a bulk density increase of up to 50% after the first three passes and much lower rates of increase thereafter (Solgi and Najafi, 2014; Solgi et al., 2015b). The degree of compaction in the wheel tracks and areas adjacent to the tracks is large when compared to the areas where no trafficking took place. The strong adverse effect of increasing slope of the skid trail on bulk density and porosity is likely a consequence of the difficulties in skidding on steep terrain where machine wheels can slip, pushing soil particles closer together (Frey et al., 2009), and increased topsoil vibration due to lower speed on steeper slope results in more severely disturbed soils compared to flat terrain (Solgi et al., 2016b; Naghdi and Solgi, 2014; Williamson and Neilsen, 2000) through enhanced soil puddling, churning or displacement (Gayoso and Iroume, 1991). Further, changes in machine weight distributions toward the rear axle when driving uphill in steeper terrain means that the rear axle carries a greater load, resulting in greater ground pressure for the same load compared to flat terrain.

Greater bulk density and reduced topsoil porosity on permanent skid trails pose a challenge for maintaining site productivity, particularly on steeper and more compacted skid trails (Najafi et al., 2009, 2010; Naghdi et al., 2016c). The increase in bulk density and the reduction of total porosity after trafficking typically occurs at the expense of the large air-filled pores in the soil surface layers due to a conversion of soil macropores to micropores (Williamson and Neilsen, 2000). Macroporosity of at least 10% is a prerequisite to allow for sufficient air diffusion, microbial activity, and root proliferation (Brady and Weil, 2002). However, even values under this critical level can severely limit site productivity (Ampoorter et al., 2007) due to impaired soil aeration and microbial function (Horn et al., 2004). Even though skid trails are designated for permanent use and are thus not used for timber production, trees that regenerate at the edge of skid trails have an important role in stabilizing topsoil structure and reinforcing the skid trail against further soil damage (Fernández et al., 2019).

The increase in bulk density and decrease in total porosity and macroporosity observed in the designated skid trail with increasing traffic intensity was also observed in the skid trail margins in this study, which has also been reported in other studies following changes after ground-based harvest operations (Helms and Hipkin, 1986; Williamson and Neilsen, 2000; Defossez and Richard, 2002; Solgi et al., 2016a). In general, adverse effects were less pronounced with increasing distance from the skid trail margins, but the distance beyond the skid trail margin that was adversely affected increased with increasing traffic intensity on both slope gradients and with all three machine types. It is readily apparent from Tables 4–6 that each increase in traffic intensity widens the distance from the edge of the skid trail that exhibits bulk densities and soil porosities less similar to the control areas and in-between those observed in control areas and the designated skid trail. In practical terms, the effect of increasing the slope gradient of the skid trail hastens this process such that fewer passes are required on steeper slopes to reach the same degree of topsoil deterioration as on more gentle slopes.

Nonetheless, there were some subtle differences among machine types. The use of the CS resulted in less topsoil disturbance compared to the two RTS, but the rubber-tired "TAF E655" skidder resulted in greater soil disturbances than the rubber-tired "Timberjack 450C" skidder and the "Onezhets 110." These differences are presumably due differences in static ground pressures among the machines (Table 2) and the results are consistent with previous findings where machinery with greater ground pressure (such as the Clark 66 rubber-tired skidder) caused greater soil damage than machines with lower ground pressure (such as an FMC 100 soft-track skidder; Murphy, 1984). This attests to the strong positive relationship between equipment ground pressure and compaction (Botta et al., 2008). Similarly, Solgi et al. (2016c) reported that the equipment with the lowest ground pressure caused the smallest increases in topsoil bulk density in the 0–10 cm depth.

Soil root-limiting bulk density is also a critical component for determining the impact of harvest operations on subsequent stand productivity. There is little data on root-limiting bulk density in forest soils, but Veihmeyer and Hendrickson (1948) reported that sunflower root growth in fine-textured soils was stopped when the soil bulk density ranged from 1.46 to 1.63 Mg m^{-3}. In agricultural trials, the root-limiting bulk density of clay loam soils was 1.45 Mg m^{-3} (Daddow and Warrington, 1983). In a northern Wisconsin, USA forest with a coarse-loamy soil the root-limiting bulk density was estimated to be 1.30 Mg m^{-3}, but even after 12 passes with harvest equipment the soil bulk density did not reach this level (Shetron et al. 1988). In a greenhouse experiment with several pine species it was noted that trees growing in lower density soils grow better across a wide-range of moisture contents than those growing in higher density soils, but this trend did not fit all species tested (Siegel-Issam et al. 2005). Site-specific data will be required to determine how productivity is affected. If 1.45 Mg m^{-3} is used as the root-limiting bulk density for our forest sites, then the trend was that this was exceeded in the skid trails tracks after 15 passes for all equipment and both slope angles (Table 4). It seems reasonable to allow 10–15 passes on a skid trail to reduce soil impacts, but care must be taken to account for local conditions that may limit soil recovery. Fine-textured soils are particularly slow to recover after compaction unless there is an active freeze–thaw cycle, fluctuating water table, or have clays with a shrink-swell potential (Page-Dumroese et al. 2006).

5. Conclusion

We used measurements of soil bulk density, total porosity, and macroporosity to assess the effects of increasing traffic intensities of different skidder types on gentle (≤20%) and steep (> 20%) slopes on surface soils along the margin of a skid trails. This study demonstrates that different skidding machines can produce different amounts of topsoil disturbance, extending results reported from other studies to the mountainous beech forests of Iran. We find that topsoil impacts are not limited to designated skid trail and can extend up to 2 m on each side of the skid trail into the harvest unit, effectively doubling the areal extent of soil impacts caused by ground-based operations. Within the limits of our experimental conditions, there are several recommendations that can reduce the degree and extent of soil impacts during forest operations:

- The type of equipment used in ground-based skidding operation is a significant factor in determining the extent of soil disturbance. Select the lowest weight equipment to safely skid timber to the landing. For example, the CS has a much lower ground pressure than the RTS1 and RTS2. Further, use modern equipment that avoids dragging logs over the soil.
- Soil compaction is significantly affected by the number of machine passes. Limit the number of passes to < 15 or designate skid trails as

high-traffic areas to limit the areal extent of disturbance. This includes planning ahead to build skid trails in the optimum locations.
- Ground-based skidding should be limited to slopes ≤20%. On steep ground, other methods of timber extraction should be used.
- Limit the length of logs that is transported on skid trails. Longer logs are more likely to extent outside of the skid trail, causing soil compaction when dragged over the soil.
- Directional tree felling to position harvested trees such that skidder drivers do not leave the designated skid trail or move the skidder to the side at an angle that facilitates the winching of logs to the machine.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2020.114238.

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