Timber Harvest Trafficking and Soil Compaction in Western Montana

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ABSTRACT

Little evidence is documented regarding the effects of timber-harvest traffic on volcanic-ash-mantled glacial till soils and clay-rich Tertiary volcanic-derived soils of northwestern Montana. We identified and characterized differences in the soil physical properties between trafficked and nontrafficked areas. Soil-clod bulk density, infiltration, and soil-clod water retention were measured on 54 pedons from nontrafficked and moderately and severely trafficked sites. Soil mechanical properties were characterized using 18 nontrafficked pedons. Compared with nontrafficked areas, bulk densities in severely trafficked areas at the 15-cm depth were 76, 21, and 21% greater in ash over limestone till, ash over quartzite till, and Tertiary volcanic soils, respectively. Water retention at 0.002, 0.010, and 0.033 MPa was significantly lower at the 15-cm depth in trafficked than in nontrafficked areas of ash over limestone till. Similar differences were observed in ash over quartzite till. Compared with nontrafficked areas, cumulative 1-h infiltration in severely trafficked areas was 81% less in ash over limestone till, 79% less in ash over quartzite till, and 87% less in Tertiary volcanic soils. Similar but smaller differences were detected in moderately trafficked areas. Three independent measurements demonstrated significant differences in surface horizon physical properties between trafficked and nontrafficked areas. We detected significant physical manifestations of traffic-induced soil compaction below 30 cm.

IN THE TIMBERLANDS of northwestern Montana, field personnel observed that trafficking by heavy machinery during timber harvesting often affected forest regeneration and productivity. Most trafficking occurs when rubber-tired skidders or crawler tractors drag logs to landings for loading, collect and pile slash and stumps, and scarify the soil in preparation for planting seedlings. These activities can compact soils and, as a result, reduce plant growth.

Soil factors such as texture, water content, structure, and organic matter that control, in part, the process of soil compaction have been previously described (Snider and Miller, 1985; Howard et al., 1981; Means and Parcher, 1963; Lull, 1959; Trask, 1959; Langston et al., 1958; Trask and Close, 1958).

Previous workers (Trimble and Weitzman, 1953; Steinbrenner and Gessel, 1955; Tackle, 1962; Hatchel et al., 1970) reported decreased infiltration and increased overland flow and erosion on skid trails and other highly trafficked areas.

Compaction can alter the water-holding capacity of soils. Compaction generally reduces the available water-holding capacity of fine-textured soils; in coarse-textured soils, compaction can reduce the size of very large pores and increase water retention (Hyder and Sneva, 1956; Rashid and Sheikh, 1977).

It is important to identify soil compaction because of its potential for reducing plant growth. Veihmeyer and Hendrickson (1948) concluded that several species of plants from various climatological settings were

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Published in Soil Sci. Soc. Am. J. 55:1416–1421 (1991).

unable to penetrate soils above a threshold soil bulk density that varied with soil type. They observed no root penetration at bulk densities ≥ 1.9 Mg m^{-3}. The relationship between high soil density and restricted root penetration has been confirmed (Minore et al., 1969; Forristall and Gessel, 1955) for a variety of tree species in the Pacific Northwest.

Compaction associated with timber trafficking has been identified in Oregon (Allbrook, 1986; Snider and Miller, 1985), Idaho (Froehlich et al., 1985; Lenhard, 1986), and the Upper Gulf Coastal Plain (Gent and Morris, 1986). Little information is available on volcanic-ash-mantled glacial tills and clay-rich Tertiary volcanic-derived soils found in northwestern Montana. This study was conducted to identify and characterize differences in the physical properties between trafficked and nontrafficked areas of several forest soils formed from these geologic materials.

MATERIALS AND METHODS

Three sites, consisting of the following northwest Montana forest soil parent materials, were investigated: (i) continental, limestone-dominated glacial till overlain by a dominantly volcanic ash surface layer; (ii) continental, quartzite-dominated glacial till overlain by a dominantly volcanic ash surface layer; and (iii) clay-rich, Tertiary volcanic sediments with an overlying more silty layer.

The glacial till sites are in the Flathead and Kootenai National Forests between Kalispell and Libby, MT. The Tertiary volcanic site is in the Bitterroot National Forest near the west fork of the Bitterroot River south of Missoula.

Soil pedons were described and classified (Soil Survey Staff, 1975). The limestone-dominated glacial till soils (elevation 1356–1475 m) are classified as coarse or fine-loamy, mixed Boralfs (Typic or Cryic Paleboralfs, or Andeptic or Typic Cryoboralfs). The quartzite-dominated glacial till soils (elevation 1402 m) have the same classification and also include Typic, Andic, or Dystric Cryochrepts. Soils on Tertiary volcanic clay-rich sediments (elevation 1585–1780 m) are classified as fine or fine-loamy, montmorillonitic or kaolinitic, frigid Boralfs (Eutric Glossoboralfs, Typic Eutroboralfs, or Mollic Cryoboralfs).

Vegetation habitat type and timber-yield-capability rating were also determined on the study sites (Pfister et al., 1977). Vegetation on the volcanic ash over limestone-dominated glacial till site is subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.)–queenscup beadlilly (*Clintonia uniflora* [Schutt.] Kunth) habitat type, which has a high timber-yield-capability rating (6.5 m^3 ha^{-1} yr^{-1}). Vegetation on the volcanic ash over quartzite-dominated glacial till is subalpine fir/dwarf huckleberry (*Vaccinium caespitosum* Michx.) habitat type with moderate (5.5 m^3 ha^{-1} yr^{-1}) yield-capability rating. The Tertiary volcanic site is dominated by a Douglas fir (*Pseudotsuga mensiesii* [Mirbel] Franco)/twinflower (*Linnaea borealis* L.) habitat type having a moderate (4.55 m^3 ha^{-1} yr^{-1}) yield-capability rating.

Within each soil parent material, three replicate subsites in separate timber-harvest units were identified. During selection of subsites, an attempt was made to minimize effects due to the variability of the natural soil landscape. Study subsites were located within a particular geomorphic setting and profiles were selected with similar morphology, texture, horizon depth and sequence, drainage, reaction, color, slope, aspect, and vegetative cover. Duplicate soil pedons representing each of three degrees of trafficking were selected based on anthropogenic features considered indicative of the degree of trafficking:

1. Nontrafficked areas (no physical evidence or historical record of trafficking or timber-harvest activities).
2. Moderately trafficked areas (areas that have obviously experienced logging traffic but did not have the anthropogenic features associated with the severely trafficked areas).
3. Severely trafficked areas (areas characterized by anthropogenic features produced by repeated trafficking, such as skid trails, decks, and landings).

Access trenches were dug for sampling and physical testing of the 54 pedons investigated in the study. Eight nontrafficked pedons were characterized by particle-size analysis (Day, 1965) and Proctor analysis (ASTM, 1979a), and for Atterberg limits (ASTM, 1979b,c), particle density (Blake, 1965), and organic C content (Sims and Haby, 1971). Samples were collected from the surface E horizon and argillic horizons in the clay-rich Tertiary volcanic parent materials, and from a volcanic-ash-influenced horizon and 2E horizons in the glacial till parent materials.

Duplicate peds were collected from the 5-, 15-, 30-, and 45-cm depths to determine bulk density (saran-coated clod method [Soil Conservation Service, 1967]) and soil water-retention characteristics at 0.002, 0.010, and 0.033 MPa. Cumulative infiltration over a 1-h period was measured using a double-ring infiltrometer (0.0184 m^2). Three replications were run for each soil pedon.

An analysis of variance and covariance including repeated measures (Jennrich and Sampson, 1979) was used for the split-plot design (Snedecor and Cochran, 1980) and significance was determined using an F test at 0.05 and 0.01 levels of probability.

Available historical information did not allow the age of harvest, exact number of vehicle passes, or moisture content at the time of compaction to be determined precisely. Variability attributed to time since trafficking between subsites was evaluated by grouping subsites into age-since-harvest categories of young (0–4 yr), medium (5–9 yr), and ole (10–17 yr). No significant differences were detected associated with time-since-trafficking categories in cumulative 1-h infiltrations, soil water retentions, or bulk densities. As a result, the data were grouped by degree of trafficking severity for analysis.

RESULTS AND DISCUSSION

Compaction Properties of Soils from Nontrafficked Areas

Proctor tests were used to determine the optimum water content for soil compaction and maximum compacted density of soil samples from the nontrafficked areas (Table 1). Of the soils investigated, the glacial till subsoils compacted to the greatest density (1.89–2.04 Mg m^{-3}), followed by the loamy E horizons in the Tertiary volcanic sediments (1.83 Mg m^{-3}), the Bt horizons of Tertiary volcanic sediments, and the volcanic-ash horizons (Bs) of the glacial till soils (1.36–1.50 Mg m^{-3}).

Atterberg limits indicated that the volcanic-ash surface horizons are nonplastic (Table 1). A soil is termed *nonplastic* when its plastic limit is equal to or greater than its liquid limit. The 2E, 2Ck, and 2C horizons in the glacial till have plastic indexes of 21 to 35 mg kg^{-1}. The 2Bt, 2E/B, and 2B/E glacial till horizons have plastic indexes of 36 to 75 mg kg^{-1}. This group of horizons is susceptible to vibrational compaction. In contrast, the clay-rich Bt horizons of the Tertiary volcanics have plastic indexes of 316 and 437 mg kg^{-1}. These soils should be more susceptible to compressional compaction. The plastic limit is about 200 mg water kg^{-1} for the glacial tills and from 240 to 300 mg

Table 1. Physical properties of soils derived from three parent materials on nontrafficked forest areas in northwestern Montana.

		Proctor analysis†		Atterberg limits‡			Water-holding characteristics			
Parent material	Horizon	Optimum water content	Maximum density	PL	LL	PI	0.033 MPa	1.5 MPa	WHC§	Organic C content
		g kg^{-1}	Mg m^{-3}	g kg^{-1}						
Volcanic ash over limestone till	Bs	256	1.36	NP	NP	NP	737	148	589	23
	2E	127	1.89	214	242	28	248	74	174	4
	2E/B or 2B/E	137	1.91	207	243	36	325	114	211	4
	2Bt	147	1.89	208	276	68	330	125	205	4
	2Ck	111	2.02	194	226	32	278	92	186	2
Volcanic ash over quartzite till	Bs	228	1.5	NP	NP	NP	478	156	322	12
	2E	117	1.97	203	224	21	249	73	176	4
	2E/B	120	2.00	199	274	75	290	76	214	4
	2C	106	2.04	194	229	35	257	77	180	2
Tertiary volcanics	E	155	1.83	236	266	30	255	102	153	11
	Bt1	216	1.70	297	613	316	388	235	153	5
	Bt2	235	1.60	258	695	437	541	242	299	4

† Does not include a correction for coarse-fragment content.
‡ PL = plastic limit, LL = liquid limit, PI = plastic index; NP = nonplastic.
§ WHC = water-holding capacity.

kg^{-1} for the Tertiary volcanic-soil horizons. These values exceed the Proctor-test optimum water-content values (by 11–15% for glacial till, and 15–23% for Tertiary volcanic soil horizons).

In general, the optimum water content required to achieve maximum density, as determined by the Proctor test, is considerably less than 0.033 but higher than 1.5 MPa (Table 1). The optimum water contents for compaction under field conditions could be somewhat higher when harvesting is conducted under high soil water-content conditions, such as can exist after spring snowmelt.

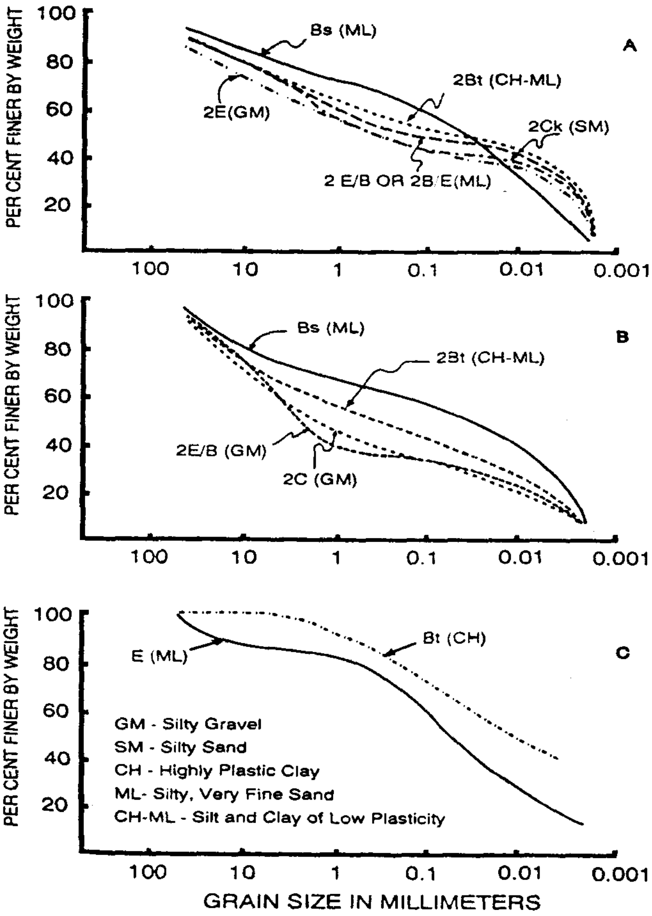

Fig. 1. Particle-size distribution and Unified Soil Classification for major horizons of soils formed from (A) volcanic ash over limestone-dominated glacial till, (B) volcanic ash over quartzite-dominated glacial till, and (C) Tertiary volcanic parent materials.

Organic C is highest in the surface horizons, with much lower amounts in subsurface horizons (Table 1). The higher organic-C levels of the limestone till Bs horizons probably contribute to the lower Proctor maximum density and higher calculated available water-holding capacity, compared with the quartzite till or Tertiary volcanic surface horizons.

All surface horizons are well-graded and, hence, prone to compaction (Fig. 1). The high coarse-fragment content of the glacial till soils may make them generally less prone to compaction than the Tertiary volcanic soil materials.

Effects of Trafficking on Soil Bulk Density and Soil Water Relationships

Bulk density in the moderate and severely trafficked areas was significantly greater than in the nontrafficked areas at both 5 and 15 cm in the limestone till (Table 2). In the quartzite till, bulk density was significantly higher in severely trafficked areas at the 5-cm depth, although no differences in bulk density were measured at the 15-cm depth.

Although the E horizons of all three soils had a similar plastic index, they were located at 3 cm in the tills and at 15 cm in the Tertiary volcanic soil. This variability in depth to the E horizon probably contributes to the difference in compaction of this horizon in the three soils. In all three soils, bulk density at the 30-cm depth was significantly higher than at the upper depths. No differences in bulk density between degrees of trafficking was detected at or below 30 cm. The applied pressure of trafficking was apparently dissipated and insufficient to impact physical properties of the underlying higher density materials.

In the limestone till and the Tertiary volcanic soils, no difference in bulk density was detected between

Table 2. Trafficked clod bulk densities of three major horizons in soils formed from volcanic ash over limestone- and quartzite-dominated glacial tills, and Tertiary volcanics in western Montana.

Parent material	Horizon	Depth	Degree of Traffic		
			None	Moderate	Severe
		cm	Mg m^{-3}		
Volcanic ash over limestone till	Bs	5	0.61 (0.24)†	0.84** (0.24)	0.97** (0.28)
	Bs	15	0.53 (0.15)	0.97** (0.32)	0.93** (0.09)
	2E	30	1.55 (0.20)	1.53 (0.12)	1.39 (0.25)
Volcanic ash over quartzite till	Bs	5	0.64 (0.27)	0.66 (0.25)	1.01** (0.38)
	Bs	15	0.76 (0.25)	0.88 (0.32)	0.92 (0.22)
	2E	30	1.71 (0.13)	1.52 (0.51)	1.75 (0.18)
Tertiary volcanics	E	15	1.30 (0.07)	1.53* (0.21)	1.58** (0.18)
	Bt1	30	1.67 (0.11)	1.63 (0.11)	1.81 (0.21)
	Bt2	45	1.66 (0.25)	1.58 (0.18)	1.72 (0.18)

*,** Significantly different from nontrafficked area at 0.05 and 0.01 levels of probability, respectively.

† Standard deviation shown in parentheses.

moderate and severely trafficked areas. This result lends support to the general observation that most compaction occurs during the first and second passage of equipment. In the quartzite till material, significant differences in bulk density were observed only in the severely trafficked areas.

The differences observed in bulk density between degrees of trafficking severity agreed with the cumulative 1-h infiltration data (Table 3). Infiltration was significantly lower in both the moderate and severely trafficked areas on all three parent materials, with one exception. While infiltration was lower in the moderately trafficked areas than the nontrafficked areas of the Tertiary volcanic parent material, it was not statistically different.

Table 3. Cumulative 1-h infiltration, by double-ring infiltrometer, for three degrees of harvesting traffic.

Parent material	Cumulative 1-h infiltration		
	No traffic	Moderate	Severe
	cm		
Volcanic ash over limestone till	38.5	8.3**	7.3**
Volcanic ash over quartzite till	36.1	8.9**	7.4**
Tertiary volcanics	29.0	16.8	3.7*

*,** Significantly different from the nontrafficked area at 0.05 and 0.01 levels of probability, respectively.

Water retention in samples from the 15-cm depth in trafficked areas of the limestone till soils was significantly less than that observed in nontrafficked areas at all three matric potentials (Table 4). This agrees with the increase in bulk density. Also, no significant differences in water retention between degrees of trafficking were observed at depths below 15 cm in the limestone till soils. This is in agreement with the lack of differences found in bulk density. A similar tendency, though not statistically significant, was observed at all three matric potentials in the 15-cm depth of the quartzite till. A coincident, nonsignificant higher bulk density was also measured at this depth (Table 2).

Bulk density at the 15-cm depth is the Tertiary volcanic soils was significantly higher in both moderately and severely trafficked areas. While clods from both levels of traffic consistently retained less water than those from nontrafficked areas at all three potentials, these differences were not significant. The analysis suggests that the water-retention properties of the Tertiary volcanic surface horizon are variable and that a larger number and size of samples would be required to adequately characterize and detect differences between trafficked and nontrafficked areas.

While water retention (Table 4) of the Tertiary volcanic subsites was lower in the moderately and severely trafficked areas than in the nontrafficked areas

Table 4. Water content at 0.002, 0.01, and 0.033 MPa for three degrees of timber-harvest trafficking for major horizons of soils formed in three parent materials in western Montana.

Parent material	Horizon	Depth	0.002-MPa water content			0.01-MPa water content			0.033-MPa water content		
			N.T.†	Moderate	Severe	N.T.	Moderate	Severe	N.T.	Moderate	Severe
		cm	g kg^{-1}								
Volcanic ash over limestone till	Bs	15	829 (295)‡	653* (187)	597** (152)	783 (268)	620* (168)	553** (182)	739 (267)	586** (184)	539** (175)
	2E	30	297 (30)	271 (64)	266 (49)	272 (33)	254 (65)	246 (45)	254 (33)	244 (63)	232 (44)
	2E	30	282 (36)	261 (0)	307 (0)	262 (42)	241 (0)	294 (0)	238 (39)	229 (0)	282 (0)
Volcanic ash over quartzite till	Bs	15	576 (176)	431 (238)	430 (219)	509 (183)	386 (256)	386 (231)	478 (174)	334 (236)	309* (236)
	2E	30	249 (40)	314 (58)	236 (29)	241 (38)	304 (56)	222 (27)	229 (40)	288 (58)	202 (33)
	2E	45	306 (154)	296 (84)	300 (98)	291 (142)	287 (83)	282 (88)	269 (127)	268 (0.08)	259 (73)
Tertiary volcanics	E	15	331 (59)	282 (46)	278 (43)	308 (58)	263 (44)	256 (46)	255 (92)	207 (66)	207 (59)
	Bt	30	418 (97)	335 (170)	390 (132)	407 (94)	318 (162)	375 (127)	388 (85)	288 (182)	341 (136)
	Bt	45	590 (157)	420* (104)	441 (258)	577 (157)	405** (104)	430 (250)	541 (117)	381** (117)	265** (87)

*,** Significantly different from the nontrafficked area at the 0.05 and 0.01 levels of probability respectively.

† N.T. = Nontrafficked.

‡ Standard deviation shown in parenthesis.

Table 5. Water-holding capacity (0.033–1.5 MPa) of a volcanic-ash surface layer on quartzite and limestone glacial till under three degrees of trafficking.

Soil	No traffic	Moderate	Severe
		$\mathrm{g\ kg^{-1}}$	
Bs horizon 15 cm Volcanic ash over quartzite till	322	178* (55%)†	153** (47%)
Bs horizon, 15 cm Volcanic ash over limestone till	592	438 (74%)	391* (66%)

*,** Significantly different from nontrafficked area at 0.05 and 0.01 levels of probability, respectively.

† Percent of nontrafficked area.

at the 30- and 45-cm depths (significantly at 45 cm), there was no significant difference in bulk density (Table 2), and thus total porosity. Lower water retention in the trafficked areas indicates fewer pores of the size that retain water at 0.002, 0.010, and 0.033 MPa soil water matric potential. A conversion of macropores to an equal volume of micropores would explain the reduction in macropores without a corresponding reduction in porosity. Variability in the data is relatively high, however, and further investigation is needed to verify this interpretation.

The volcanic-ash surface horizons of the limestone and quartzite till sites had greater bulk density and reduced water retention in the trafficked than in the nontrafficked areas. This suggests that, not only was total porosity reduced, but a lower volume of the large pores was available to hold water at the higher water potentials.

The water-holding capacity of many coarse- and medium-textured soils is determined primarily by water held in large pores. Reduction in the amount of water held in the large pores of a soil at field capacity results in a reduction in the water-holding capacity of the soil. Using the 0.033 and 1.5 MPa water contents as respective estimates of field capacity and wilting point, calculated water-holding capacity was significantly lower in the moderately and severely trafficked areas than in the nontrafficked areas of the ash over quartzite till and in the severely trafficked areas of the ash over limestone till (Table 5).

CONCLUSIONS

Timber-harvest traffic affects the physical properties of productive forest soils formed in three parent materials in western Montana. The volcanic-ash surface horizon overlying the glacial till soils is well-graded, cohesionless, and prone to vibrational compaction. The Tertiary volcanic soil, which has a higher clay content and is somewhat plastic in the surface horizon, is more vulnerable to compressional compaction.

Three independent physical measurements demonstrate significant differences in the surface-horizon physical properties between trafficked and nontrafficked areas of the study soils. Cumulative 1-hr infiltration was significantly less and clod bulk density was greater in the trafficked areas of all three parent material sites. Macropore soil water retention and calculated water-holding capacity was lower in the volcanic-ash surface layers of the limestone and quartzite till sites. No significant physical manifestations of traffic-induced soil compaction were detected below 30 cm.

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