Soil Compaction by Grazing Livestock

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Soil compaction is a well-known concern on agricultural and forest land where heavy equipment traffic can form dense soil layers that retard soil water movement, root penetration, and reduce plant growth. It has also become apparent that human foot traffic can crush plants and compact soil where travel is concentrated along recognized trails and other frequently traveled rights-of-way. Although over half of all land in the U.S. is rangeland (Holechek et al. 2004), most of which is grazed by livestock or similar big game animals, surprisingly little is known about the impacts of this more diffuse animal impact on soil physical properties.

It is important to recognize that soil compaction is a natural and dynamic process. Gravity is the major cause of soil compaction. The weight of a layer of soil compacts the soil beneath it. The downward force of gravity applied to the soil surface by any object in contact with it compacts the soil. For instance, the weight of a tree is transferred down to the soil, which is compacted by the load. Interestingly, trees and other woody vegetation also compact soil through root expansion. It is not unusual to see trees that have formed a pronounced mound under their trunk by simple expansion of roots over many years pushing the soil up and away from the trunk. This lateral compression compacts nearby soils. The current compactness of soil is a dynamic equilibrium between these compactive factors and restorative processes that decompact soils. Restorative processes are very poorly understood and documented. Shrinking and cracking of vertic clay soils; freezing and thawing; activities of ants, worms, and other soil animals; and the formation of fine root channels by plants are frequently cited restorative forces. Livestock grazing may potentially influence these forces through impacts upon the litter layer that both insulates the soil surface and serves as food and habitat for soil surface organisms. The ability of these restorative forces to reform soil pore space and to increase water infiltration rates during periods of non-grazing is largely unknown.

I conducted a study in western Oregon during 2002-2004 to document the effects of 11 years of sheep grazing on soil water infiltration, soil bulk density, and soil porosity and to observe the rate of their change following cessation of grazing. These 3 characteristics, along with soil strength, are often used to measure soil compaction.

Methods

The study was conducted on the western edge of the Coastal Mountain Range near Corvallis, Oregon latitude (44.4°North, longitude 123°West). Elevation is approximately 120 m above sea level. Soil is a Philomath silty clay (*Vertic Haploxerol*), which is a shallow (<35mm deep), cracking clay developing above a basalt lava flow (Knezevich 1975). Prior to research, the entire 20 ha site was managed as a single pasture. The research area was plowed and harrowed in summer 1988. Agroforest plots were planted with 20 kg/ha of rhizobium innoculated subclover (*Trifolium subterraneum*) seed in September 1988. Three replications (plots) of forest and agroforest (Fig. 1) were established in 1989. Both forests and agroforests were planted with 568 low-elevation Douglas-fir (*Pseudotsuga menziesii*) bare root seedlings (2-0 stock) per hectare in February 1989. Forest trees were planted 4 m apart in a rectangular grid pattern. Agroforest trees were planted in rows with 2.5 m between trees within rows and 4 m between rows, as suggested by Sharrow (1992) to optimize tree and pasture production. Each plot was individually fenced with portable electric fencing and grazed as a single unit. Grazing occurred in early April and again in June each year from 1990-2001. Agroforests were grazed with sufficient sheep to consume approximately half of the forage standing within 4 days on each entry. This generally resulted in a stocking density of 200-400 ewes/ha. Forests were not grazed. Following planting to subclover, all plots went through a successional process as local grasses and other forbs reestablished. Within two years, forests were almost entirely tall oatgrass (*Arrhenatherum elatus*) and annual grasses (*Bromus mollis* and *Vulpia myurous*), while agroforests and pastures were approximately half subclover and half a mixture of perennial ryegrass (*Lolium perenne*), meadow foxtail (*Alopercurus pratensis*), and annual grasses.

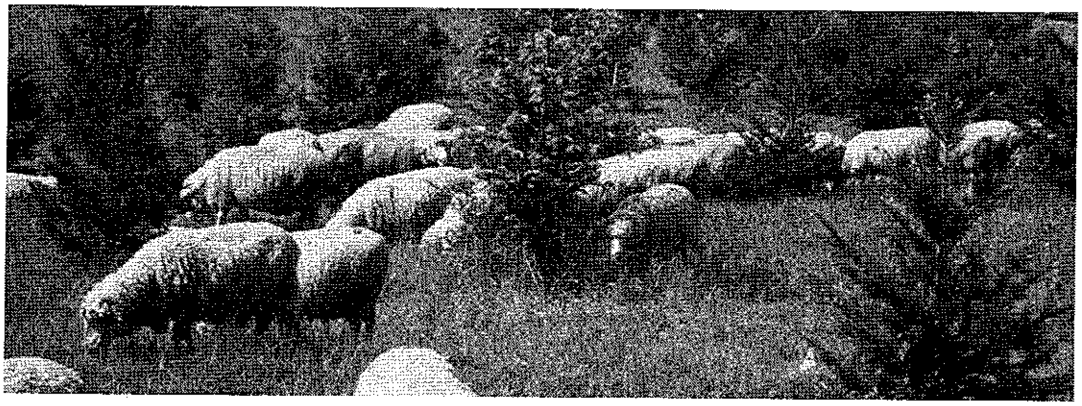

Figure 1. Agroforests were silvopastures, that combined conifer forest with improved grass/clover pasture.

Standard techniques were used to evaluate soil compaction. Soil samples and infiltrometer data were collected from forest and agroforest plots in June 2002. All forest, agroforest, and forest plots remained ungrazed during 2002-2004 and were then sampled in June 2004. Soil infiltration was assessed from a sample of 12 randomly placed 15 cm diameter single-ring infiltrometer (Bouwer 1986) runs per treatment plot. Infiltrometer rings were driven approximately 8 cm into the soil, filled to a depth of 8 cm with water, then allowed to drain for 1to 2 hours before measurements began. Infiltration was measured as the amount of water required to maintain 2 cm of head within the ring. Infiltration was recorded every 5 minutes for 30 minutes. Plots were then allowed to thoroughly drain. The entire infiltrometer and soil core was lifted and its top and bottom structure visually assessed. A wet (field capacity) soil sample was then obtained by excavating 8 cm diameter x 6 cm tall metal ring which was driven into the center of each infiltrometer plot. Wet soil samples were weighed to the nearest 0.1 g in the field, then dried in an oven at 105°C. The dry weight of these samples provided an estimate of soil bulk density. Soil moisture holding capacity was calculated from the difference between sample wet and dry weights. Total soil porosity was calculated from bulk density and soil particle density (2.65 g/cc) as described by Danielson and Sutherland (1986). Since water weighs 1 g/cc at room temperature, area occupied by water-filled pores can be calculated from weight of water stored at field capacity. Air-filled pore volume was then estimated as the difference between total pore volume and water-filled pore volume. The soil immediately under each infiltrometer was probed to a depth of approximately 20 cm to find any soil channels or other large voids. All low density areas were excavated to identify their cause.

Results and Discussion

Because the entire research location was a single large pasture at the beginning of the experiment, differences in soil properties between agroforest and forest plots in 2002 (Table 1) were logically the accumulated result of 11 years of livestock grazing. Soil in the agroforests was more dense (higher bulk density) and somewhat less porous than those in adjacent forests. Most of the difference in total porosity was air-filled pores, whose total volume was over 40% less in agroforest than in forest soils. Water-filled pore volume was similar among treatments in 2002.

Table 1. Physical characteristics of the top 7 cm of soil in Witham Hill forests and agroforests in spring 2002.

	Bulk Density* (g/cc)	% Porosity* (cc/cc)	% Water-filled Pores* (cc/cc)	% Air-filled Pores* (cc/cc)
Forest	0.93 [a]	64.8 [a]	37.4 [a]	37.3 [a]
Agroforest	1.05 [b]	60.4 [b]	39.6 [a]	20.8 [b]
MSE	***0.007***	***0.26***	***0.86***	***0.74***

*Means not sharing a letter differ, p<.05, Tukey's W Procedure

Differences in porosity were reflected in infiltration rates (Fig. 2). Average water infiltration rate was 35% less in agroforests, being 1104 vs. 714 liters/m^2/hour for forests and agroforests, respectively. However, total water stored in the top 6 cm of soil at field capacity was similar being approximately 18 and 17.7 liters/m^2 for forests and agroforests, respectively.

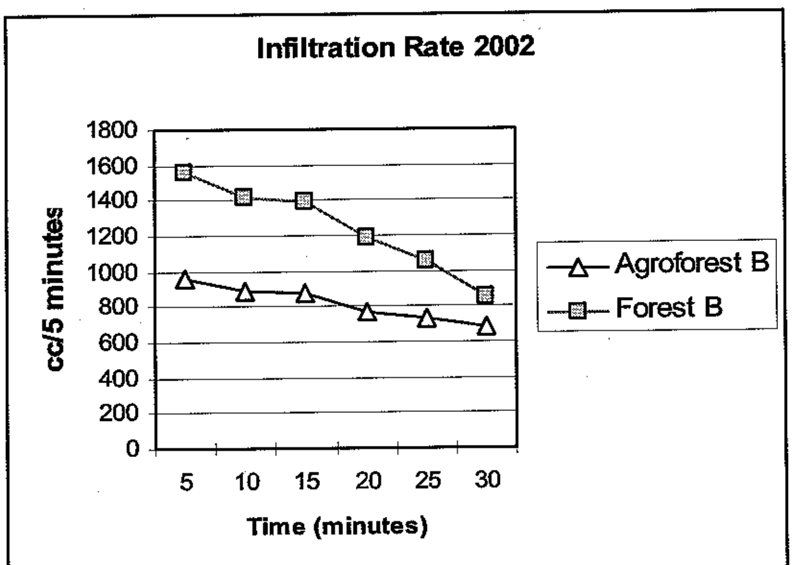

Figure 2. Witham Hill plot water infiltration rate, June 2002.

These observations are most easily understood by considering the nature of soil physical structure. Soil is similar in construction to a piece of bread. It is mostly a series of holes (pores) joined by a matrix of mineral soil and organic matter. The holes are squeezed together as soil is compressed by gravity, animal foot pressure, or equipment wheels or tracks. The largest, air-filled pores are the first to crush and be lost; while smaller, water-filled pores are much more stable under pressure. Only very severe compaction will crush the small pores where water is stored and actually squeeze water out of the soil. Movement of water and air into the soil is immediately reduced by loss of the large interconnected pores during initial compaction. This reduces water infiltration and soil aeration even under moderate levels of compaction. The loss of pore connectivity may be more important than the reduction of total large pore space in reducing water and air movement through the soil. Generally, once these large pores are crushed, they do not spring back after the pressure is removed. As air is squeezed out of soil, what remains is the heavier mineral soil and soil organic matter. So, the weight of soil per cubic inch of volume (soil bulk density) increases. It is unusual to compact soils to the point that even the smaller pores are crushed. So compaction usually does not reduce soil water-holding capacity. To the extent that larger, air-filled pores are squeezed down to become smaller water-holding pores, water-holding capacity of soil may even increase with moderate compaction. Because roots must now try to grow through denser soil with fewer interconnected pathways to follow, soil resistance to penetration (soil strength) increases with compaction.

It is logical to assume that the sheep grazing agroforest plots were responsible for the evidence of compaction seen in Table 1. Livestock can exert considerable downward force through their feet. The issue of how much pressure is placed on the soil by animal hooves is surprisingly complicated. The simplest approach is to just divide the weight of an animal by the area of its foot-print. A more refined calculation takes into account that moving animals may have one or more feet off the ground as well as having a downward and forward motion of their body weight as they travel. The general result of such calculations is that cattle, sheep, and humans can easily exert as much downward pressure on soil as do agricultural tractors, and unloaded forestry harvest equipment. However, the total amount of pressure exerted is not the whole story. The area over which the pressure is applied is also important. When the pressure is exerted over a very small area, such as a cattle or sheep hoof, some of the soil can respond by moving to the side as well as downward. This helps to dissipate the load near to the soil surface. Larger pressure sources, such as a broad agricultural tire or a caterpillar track, predominately transfer their loads downward and can compact soil to a much greater depth. Therefore, soil compaction by livestock is generally concentrated in the top few cm of soil, while heavy equipment compacts soils to a depth of well over a half meter. I limited the study to the top 6 cm of soil, which is the zone in which soil compaction by livestock should be most evident.

Infiltration data generally have very high spatial variability. My study area was certainly no exception to this rule. Agroforest soil infiltration rates in 2002, for example, varied from approximately 19 $cc/cm^2/hr$ to 632 $cc/cm^2/hr$ for individual infiltrometer runs. Visual examination of infiltrometer cores during 2002 suggested that high infiltration rate was not generally the result of large channels, such as gopher tunnels or worm holes, either in or under the core. It resulted from a large number of small pores <1 mm in size, presumably formed by small soil fauna. One of the striking differences between forests and agroforests or pastures was the relatively well established layer of both standing and soil surface grass litter present on forests. Pastures and agroforests largely lacked this layer. Sharrow and Ismail (2004), working in these same research plots, estimated that forests had over 800 kg/ha of herbaceous litter, while pastures and agroforests had less than 100 kg/ha of litter, some of which was shed conifer needles. This led me to consider the hypothesis that grazing management effects on soil physical properties may be as much from their impact upon the development of a persistent litter layer as they are from direct hoof impact upon the soil. The presence of a litter layer could change soil surface dynamics by insulating the soil surface and reducing opportunities for frost heaving and shrink/swell during wetting/drying cycles. On the other hand, the food source and physical habitat within the litter layer and underlying surface soil could greatly favor pore formation by soil organisms. If soil organisms were responsible for establishing and maintaining soil pore structure, changes with different management could be much more rapid than if physical mechanisms (frost heaving or shrinking/swelling) must be relied on. This prompted me to see if 2 years of non-grazing could impact soil infiltration. Unfortunately, tree growth can also compact soils, and trees in agroforests grow faster than in forests. It was unclear how much of the greater soil compactness in agroforests was due to the larger trees there. Pastures (no trees) were sampled in 2004 in order to sort out this "tree growth effect."

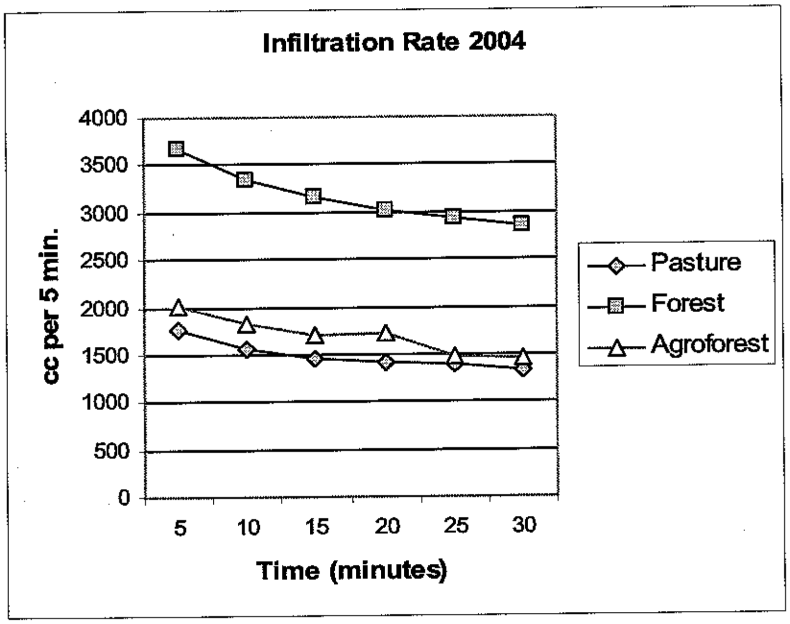

Figure 3. Witham Hill plot water infiltration rate, June 2002.

Similar to 2002, average soil water infiltration rates of agroforests in 2004 were substantially less than those of forests (Fig. 3). However, agroforest infiltration rate in 2004 (1080 liter/m^2/hr) was over 60% greater than the 2002 rate (710 liter/m^2/hr) and was very similar to those measured for forests in 2002 (1100 liter/m^2/hr). Infiltration rates on forest plots during these two years almost doubled to 2010 liter/m^2/hr in 2004. Clearly things had improved on both the forest and agroforest plots. Average pasture infiltration in 2004 (950 liter/m^2/hr) was similar to that of agroforests, suggesting that there was no significant "tree effect".

Table 2. Physical characteristics of the top 7 cm of soil in Witham Hill forests, agroforests and pastures in spring 2004.

	Bulk Density* (g/cc)	% Porosity* (cc/cc)	% Water-filled Pores* (cc/cc)	% Air-filled Pores* (cc/cc)
Forest	0.97 [a]	63.5 [a]	34.4 [a]	29.1 [a]
Agroforest	0.97 [a]	63.5 [a]	36.3 [b]	27.2 [a]
Pasture	0.94 [a]	64.7 [a]	36.8 [b]	27.9 [a]
MSE	***0.035***	***1.33***	***0.78***	***1.64***

*Means not sharing a letter differ, p<.05, Tukey's W Procedure

Soil physical characteristics of pastures, agroforests, and forests were similar in 2004 (Table 2). The single exception was slightly lower water filled pore volume in forest soils compared to pasture or agroforest soils. Total water holding capacity of the top 6 cm of soil was similar among treatments, being approximately 16.4, 15.4, and 16.2 liters/m^2 for pastures, forests, and agroforests, respectively. The higher infiltration rates of forest soils in 2004 coupled with their lower total air-filled pore space that year compared to 2002 suggests that pore connectivity must have improved, increasing the effectiveness of the available pore space to conduct water.

Conclusions

Eleven years after establishment, soils in agroforests were denser, had lower water infiltration rates, and less air filled pore volume than those in forests. These all suggest soil compaction. Since pasture and agroforest soil properties were similar, soil compaction in agroforests was from either the direct (hoof impact) or indirect (litter reduction) effects of livestock grazing rather than from increased tree growth compared to forest plantations. Of these two, the indirect effects of grazing on litter appear to be more important. Grazing had little impact on soil water holding capacity. Soil infiltration rates and pore space rapidly improved when grazing ceased.

Practical Implications

Results of this study are consistent with the extensive review of published literature reported by Greenwood and McKenzie (2001), grazing does indeed compact soil. However, moderate livestock grazing on rangelands often has little real impact on water infiltration (Gifford and Hawkins 1978), and it is unusual for livestock treading on drained soils to sufficiently compact soils to hinder plant growth. Indeed, many of the studies that showed increased soil strength and increased bulk density after grazing failed to show any associated reduction in plant growth. Unless soils are very compact to start with, it takes considerable compaction to make them dense enough or poorly aerated enough to hinder plant growth. In my case, pastures and agroforests consistently produced more herbage than forests, and agroforest trees grew faster than forest trees. Clearly, "soil compaction" had not hindered plant growth, even though grazing occurred at high densities, on clay soils, during wet weather.

It is important to point out here that I avoided grazing when soils were saturated with water. The water filled pores of saturated soils are less easily compressed than the air-filled pores of drained soils, so pressure is more fully transferred from the hoof to the soil matrix. When soil is saturated, even moderate pressure expels water from the larger flooded pores. The lower structural strength of wet soils, particularly those with considerable clay content, along with the expelled water that serves as a lubricant, allows even relatively small pores to collapse and the soil to flow around the hoof. The resulting creation of deep hoof prints in wet pastures has been called poaching or pugging. Pugging is generally very undesirable because it reduces soil water infiltration, soil aeration, soil water storage capacity, and increases soil strength, all of which depress plant growth. The many small holes punched into pasture soils during pugging tend to collect water making the soil surface wetter and more susceptible to continued pugging.

The large increase in soil water infiltration rate of forest soils during the two years of this study demonstrates the potential for rapid change in infiltration rates. It also points out the importance of continuous channels through water may quickly move (pore connectivity) rather than just total porosity or soil bulk density when trying to describe and understand effects of management practices on soils. The reason for such a large change in infiltration or pore connectivity is unclear. Research often generates as many new questions as it answers old questions. It is possible that the soil fauna are going through a successional process of orderly change and have reached a stage at which their members are producing more connected pores. This may continue or may change with time. We will revisit the plots again in 2006 and see what the situation is at that time.

The relatively rapid "recovery" of soil porosity and infiltration rates with non-use in pastures and agroforests is most likely related to the rapidity with which a litter layer and its micro-fauna can be established. It offers considerable opportunities to use rotational grazing or hay cutting strategies to manipulate soil structure and water infiltration, especially on high producing sites.

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