Soil compaction by grazing livestock in silvopastures as evidenced by changes in soil physical properties

Steven H. Sharrow

Abstract Livestock, pasture, and timber trees are intimately interrelated in silvopastures. Most silvopasture research to date has focused on forage/animal/tree interactions, with less attention paid to animal/soil interactions in silvopastures. While a considerable body of work has been devoted to understanding the effects of livestock trampling on plants and soils in pastures, less has been done for livestock grazing in forests, and even less is available for silvopastures. Three replications of Douglas-fir forest, Douglas-fir/subclover pasture/sheep silvopasture, and subclover/sheep pasture were established in 1989 near Corvallis, Oregon USA. Pastures and silvopastures were grazed each spring during 1990–2001. These plots were sampled in 2002, after 11 years of grazing, and again in 2004 following 2 years without grazing. Soil in the silvopastures had 13% higher bulk density and 7% lower total porosity than those in adjacent forests in 2002. Most of the difference in total porosity was air-filled pores. Average water infiltration rate was 38% less in silvopastures than in forests, however total water stored in the top 6 cm of soil at field capacity was similar. Soil bulk density, total porosity, and air-filled pore space was similar for forests, pastures, and silvopastures after 2 years without livestock grazing.

The infiltration rate of silvopasture soils in 2004 had increased to be similar to those of forests in 2002, however, forest soil infiltration rates also increased and continued to be higher than those of silvopastures. Plant production was not sensitive to changes in any of the soil parameters measured. Although livestock grazing did change soil infiltration rates, soil bulk density, and soil porosity, the effects were quickly reversed following cessation of grazing and had little detrimental effect on silvopasture forage or tree production.

Keywords Bulk density · Douglas-fir · Infiltration rate · Pasture · Soil porosity

Introduction

Livestock grazing in forests and woodlots is a common practice in both the United States and Canada. Clason and Sharrow (2000) estimate that 34% (70 million ha) of all forested land in the United States is grazed. This is substantially more than the approximately 53 million ha of improved pastures in the U.S. Not surprisingly, joint production of timber trees with managed pastures as silvopastures is the most common form of agroforestry in North America. Silvopasture research to date has focused primarily upon interactions between trees, livestock, and ground vegetation. Much less attention has been devoted to documenting and understanding livestock

S. H. Sharrow (✉)
Department of Rangeland Ecology and Management, Oregon State University, Corvallis, OR 97331, USA
e-mail: steven.h.sharrow@oregonstate.edu

grazing interactions with soil physical properties such as water infiltration, soil bulk density, and soil porosity in silvopastures.

Most forest managers are familiar with the issue of heavy equipment entry into forests impairing tree growth and increasing erosion by compacting soils (McNabb et al. 2001). The question of soil compaction by livestock grazing is frequently asked when forest grazing is considered. Since grazing animals can exert downward pressures on the soil surface similar to that of heavy equipment (Greenwood and McKenzie 2001), this concern is understandable. Willatt and Pullar (1983), for example, estimated force applied to the soil surface by cow, sheep, and goat hoofs to be 190, 80, and 60 kPa, respectively, which is similar to the 30–85 kPa referenced for various types of logging skidders in the review by Greacen and Sands (1980). Livestock hoof impact tends to directly compact the soil by collapsing the larger soil pores, thus forming more small pores, increasing soil bulk density (weight per unit volume), and reducing soil infiltration rates (Greenwood and McKenzie 2001). This process reduces soil aeration but increases soil water holding capacity by replacing large air filled pores with smaller water holding pores (Greacen and Sands 1980).

The longer-term effects of livestock grazing on soil physical properties are complex. They reflect the balance of restorative and compactive processes at work on grazed and ungrazed areas. Besides the direct effect of trampling, livestock can indirectly change soil properties by consuming vegetation that would otherwise contribute to soil organic matter available to support soil microfauna and by reducing the amount and extent of fine roots that open new soil channels and contribute nutrients that support the soil rhizosphere. Restorative effects of physical processes such as shrink/swell of vertic soils (Taddese et al. 2002) and freezing/thawing and biological processes such as microchannel formation by soil fauna may vary with change in soil surface microclimate and vegetation structure in forests vs. silvopastures. Increased forage production on silvopastures compared to forests (Sharrow et al. 1996; Clason and Sharrow 2000) increases soil organic matter (Sharrow and Ismail 2004) and potentially provides a cushion of stubble between hoof and soil during grazing (Greenwood and McKenzie 2001). However, compaction effects are cumulative over the first few

impacts (McNabb et al. 2001; Lei 2004), so higher producing sites, such as silvopastures, may be more subject to compaction because of the greater number of animal days of grazing they will support (Krzic et al. 1999, 2001).

Soil compactness of forests and silvopastures is complicated by the effects of tree growth. As trees grow, their aboveground weight is transferred to the soil through surface roots, which also exert compression forces on near-by soil as they increase in diameter during radial growth (Greacen and Sands 1980). A portion of the wind force exerted on trees must also be transferred to the soil if the tree is to remain upright. Increased tree growth often observed in prescription grazed forests (Sharrow 1994) and silvopastures (Clason and Sharrow 2000; Sharrow and Ismail (2004) should contribute to soil compactness compared to pastures or ungrazed forests. Therefore, it can be difficult to separate grazing effects from tree growth effects on soil physical properties in silvopastures. The relative importance of tree growth versus livestock trampling as contributors to soil compaction in silvopastures remains unexplored.

Given the complexity of process interactions in silvopastures, their net effect on soil compactness is difficult to predict. Wairiu et al. (1993) and Bezkorowajnyj et al. (1993) noted greater soil penetration resistance near trees in sheep-grazed and cattle-grazed silvopasture, respectively, suggesting soil compaction had occurred. Other than these data, little quantification of grazing effects on soil physical properties such as bulk density, porosity, or water infiltration rate has been done for silvopastures, so inferences must be drawn from what is reliably known about soil compaction in forests and pastures. In general, light to moderate livestock grazing on well drained pastures (Greenwood and McKenzie 2001) and rangelands (Gifford and Hawkins 1978; Trimble and Mendel 1995) contributes little to long-term overall soil compaction as measured by soil bulk density or water infiltration rate. Heavy grazing (Linnartz et al. 1966; Mapfumo et al. 1999) or grazing on wet soils (Proffitt et al. 1993; McNabb et al. 2001) often reduces water infiltration rates, reduces air-filled porosity, and increases bulk density. Unlike like logging equipment that can compact soil at depths exceeding 50 cm (Greacen and Sands 1980), most compaction by livestock hooves is

limited to the top 5–10 cm of soil (Orr 1960; Mapfumo et al. 1999; Greenwood and McKenzie 2001). This difference has practical implications because deeper soil layers are generally slower to recover (Rab 2004) from compaction. Presumably, soil physical action (freeze/thaw and wetting/drying) and biological activity decreases with soil depth, providing less opportunity for soil recovery.

The research reported here was conducted in western Oregon during 2002–2004 to ascertain the net effects of 11 years of sheep/timber silvopasture on soil physical properties and to observe the rate of their change following cessation of grazing. Silvopasture tree and pasture growth served as a biological assay to judge the practical significance of changes in soil properties on silvopasture aboveground productivity.

Materials and 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 (<35 mm 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. Three replications (plots) of forest, silvopasture (Fig. 1) and pasture were established in fall 1988. The research area was plowed and harrowed, then silvopasture and pasture plots were

Fig. 1 A 10-year-old silvopasture, a combination of conifer forest with improved grass/clover sheep pasture near Corvallis Oregon

planted with 20 kg/ha of *rhizobium* innoculated subclover (*Trifolium subterraneum* L.) seed. Both forests and silvopastures were planted with 568 low-elevation Douglas-fir (*Pseudotsuga menziesii* (*Mirbel Franco*) bare root seedlings (2–0 stock) ha^{-1} in February 1989. Forest trees were planted 4 m apart in a square grid pattern. Silvopasture 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 pasture and silvopasture plot was individually fenced with portable electric fencing in March 1990 and grazed as a single unit thereafter. Grazing occurred in early April and again in June each year from 1990 to 2001. Grazed plots were stocked 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 and pasture residue stubble heights of approximately 5 cm. Forests were not grazed. Following plowing, 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* L., *Presel.*) and annual grasses (*Bromus mollis* L. and *Vulpia myurous* (L.) *K.C. Gmel.*), while silvopastures and pastures were approximately half subclover and half a mixture of perennial ryegrass (*Lolium perenne* L.) meadow foxtail (*Alopercurus pratensis* L.), and annual grasses.

Pasture and silvopasture species composition in 2000 (Sharrow and Ismail 2004) was predominately subclover (30–40% of total cover), perennial ryegrass (15–16%), and annual grasses (18–21%) while forests were predominately tall oatgrass (48%) and lacked any subclover. Understory production of ground vegetation was assessed at peak standing crop by hand harvesting all vegetation within fifteen randomly located 0.1 m^2 round quadrats in each forest, pasture, and silvopasture plot in August 2002 and 2003. Harvested samples were dried in a 60°C oven until they ceased to lose weight and their dry weights recorded. Forest and silvopasture Douglas-fir tree heights and diameters were recorded in September 2004. Height of each tree was measured to the nearest cm using a calibrated tree pole. Basal diameter (at 16 cm above the soil surface) and DBH (diameter at breast height—measured at 137 cm above the soil surface) were measured to the nearest mm with a

caliper. Stem volume was calculated from basal diameter and height using the formula for a cone: volume = $1/3\pi*(1/2 \text{ diameter})^2*\text{height}$.

Soil water infiltration rate, bulk density, and porosity were used to investigate soil compaction. Soil samples and infiltrometer data were collected from forest and silvopasture plots in June 2002 and from forest, silvopasture and pasture plots in June 2004. All forest, silvopasture, and forest plots remained ungrazed during 2002–2004. 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 16 cm with water, then allowed to drain for 2 h 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 min for 30 min. 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 a 8 cm diameter × 6 cm tall metal ring which was pushed into the center of each infiltrometer plot. Wet soil samples were weighed to the nearest 0.1 g in the field, then dried in a oven at 105°C. The oven 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). Volume occupied by soil water was calculated from weight of water stored at field capacity divided by the specific gravity of water. Air-filled pore volume was then estimated as the difference between total pore volume and water-filled volume. The soil immediately under each infiltrometer ring 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.

Data for 2002 and 2004 were statistically examined separately using plots as replications in a randomized complete block ANOVA (Steel and Torrie 1980). Soil water infiltration data were analyzed with management system as main plots and sample period (time) as subplots in a split-plot (repeated measures) design (Steel and Torrie 1980).

Means of significant factors ($P < 0.05$) were separated using Scheffe's Test at $P < 0.05$.

Results and discussion

The entire research location was a single large pasture at the beginning of the experiment. Therefore, differences in soil properties between silvopasture and forest plots in 2002 were logically the accumulated result of 11 years of forest vs. silvopasture management. Soil in the silvopastures had 13% higher bulk density and 7% lower total porosity than those in adjacent forests (Table 1). 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 soil volume at field capacity was similar among treatments in 2002. These data are consistent with bulk densities for these same areas in 2000 reported by Sharrow and Ismail (2004). At that time, forests had numerically lower soil bulk density in the upper 0–15 cm depth than silvopastures and pastures, being 0.93, 0.98, and 0.97, respectively. The increase in surface soil bulk density over the 11 years of this study is similar to the 7–17% increase reported following 26 years of cattle grazing in California oak woodland (Tate et al. 2004), the 6% increase reported following 7–8 years of cattle grazing pine plantations in British Columbia, Canada (Krzic et al. 1999), and Chanasyk and Naeth's (1995) general observation that grazing increases soil bulk density by 10–15% regardless of its initial bulk density. The relatively low impact of grazing on smaller, water retaining pores compared to larger air filled pores is also typical (Greacen and Sands 1980). Linnartz et al. (1966), for example, report that 10 years of cattle grazing in a southern pine forest had little discernable effect on small pore volume of grazed vs. ungrazed soils. Soil bulk density and large pore volume, however, were reduced by 5 and 18%, respectively, by light grazing and by 7 and 47% by heavy grazing in their study.

Differences in soil bulk density and porosity were strongly reflected in infiltration rates (Fig. 2). Average water infiltration rate during the 30-min measurement period was 38% less ($P < .05$) in silvopastures, being 1.0 versus 1.6 mm min^{-1} for forests and silvopastures, respectively. However, total water stored in the top 6 cm of soil at field capacity was similar ($P > 0.05$)

Table 1 Physical characteristics of the top 6 cm of soil in forests and silvopastures near Corvallis, Oregon USA in June 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]
Silvopasture	1.05[b]	60.4[b]	39.6[a]	20.8[b]
MSE	0.007	0.26	0.86	0.74

* Means in a column not sharing a letter differ, $P < .05$, Scheffe's Test
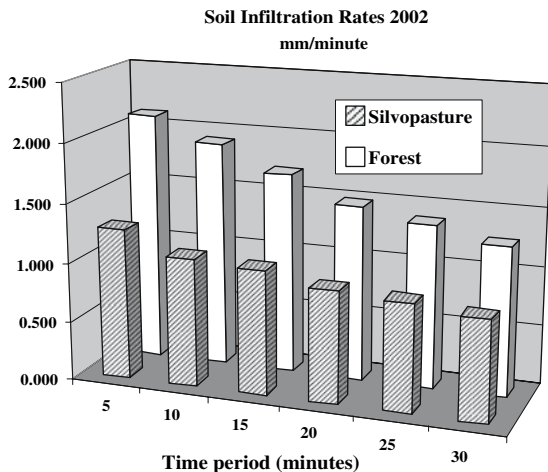
Fig. 2 Mean water infiltration rates for silvopastures and forests near Corvallis, Oregon USA, in June 2002

being approximately 17.7 and 18 liters m^{-2}, for forests and silvopastures, respectively. Water infiltration rate is strongly influenced by both the amount of large pore space and its arrangement into coherent channels for water to flow along. The relatively similar magnitude of differences in air-filled pore space (44%) and water infiltration rate (38%) between forest and silvopasture soils suggest that the volume of large pore space rather than pore connectivity was the major limiting factor for soil infiltration rate in silvopasture soils in 2002. The Corvallis area has a climate in which most precipitation falls as low intensity rain storms. It is unusual to receive more than 50 mm of precipitation in a 24-h period. The 100-year record sustained rainfall intensity for Corvallis is 0.6 mm min^{-1}. The average rates observed for both silvopastures and forests appear to be adequate to infiltrate rainfall from all but the most severe and unusual rainfall events. This conclusion is supported by lack of any visual evidence of either soil erosion or overland water flow occurring in either silvopasture or forest plots.

Infiltration data often has high spatial variability. This study area was certainly no exception to this rule. Silvopasture soil infiltration rates in 2002, for example, varied from approximately 0.3–4.2 mm min^{-1} for individual infiltrometer runs during the final 5-min period within a replication. Visual examination of infiltrometer cores 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 pores <1 mm in size and a generally more granular soil structure, presumably formed by small soil fauna. One of the striking differences between forests and silvopasture or pastures was the relatively well established layer of both standing and soil surface grass litter present on forests. Pastures and silvopastures largely lacked this layer. Sharrow and Ismail (2004), working in these same research plots, estimated that forests had over 800 kg ha^{-1} of herbaceous litter, while pastures and silvopastures had less than 100 kg ha^{-1} of litter, some of which was shed conifer needles. This led to 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 (Taddese et al. 2002). The food source and physical habitat within the litter layer and underlying surface soil could greatly favor pore formation by surface feeding soil organisms. If soil organisms or energetic physical processes are responsible for establishing and maintaining soil pore structure, changes with different management could be rapid. Wheeler et al. (2002) reported that while cattle grazing reduced water infiltration rates and increased soil bulk density of montane riparian pastures, soil properties returned to pre-grazed levels

within a year after grazing ceased. Drewry et al. (2004) studying seasonal changes in soil bulk density and macropore space of dairy pastures, noted that soil structural damage accompanying spring grazing had largely been reversed by fall. This prompted me to see if 2 years of non-grazing could measurably ameliorate soil compaction in silvopastures. Unfortunately, tree growth can also compact soils, and trees in the silvopastures grew faster than in forests (Sharrow and Ismail 2004). It was unclear how much of the greater soil compactness in silvopastures was due to the larger trees there. Pastures (no trees) were sampled in 2004 in order to sort out this "tree growth effect".

Average soil water infiltration rates in June 2004 were 1.7, 1.9, and 3.6 mm min^{-1} for pastures, silvopastures, and forests, respectively. Similar to 2002, average soil water infiltration rates of silvopastures in 2004 were substantially less ($P < .05$) than those of forests (Fig. 3). However, average silvopasture infiltration rate in 2004 (1.9 mm min^{-1}) was 90% greater than their 2002 rate (1.0 mm min^{-1}) and exceeded those measured for forests in 2002 (1.6 mm min^{-1}). Infiltration rates on forest plots during these two years doubled to be 3.6 mm min^{-1} in 2004. Clearly things had improved on both the forest and agroforest plots. Average pasture infiltration rate in 2004 was similar to that of silvopasture, suggesting that there was no significant "tree effect".

Soil physical characteristics of pastures, silvopasture, and forests were generally similar in 2004 (Table 2). The single exception was slightly lower

Fig. 3 Mean water infiltration rates for pastures, silvopastures, and forests near Corvallis, Oregon USA, June 2004

water-filled pore volume in forest soils compared to pasture or silvopasture soils. Total water holding capacity of the top 6 cm of soil was also similar among treatments ($P > 0.05$), being approximately 16.4, 15.4, and 16.2 l m^{-2} for pastures, forests, and silvopastures, 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. Average pasture bulk density, and porosity in 2004 was similar ($P < .05$) to that of silvopasture, further suggesting that there was no meaningful "tree effect" on soil compaction.

Lower soil water infiltration rate, higher soil bulk density, and lower soil air-filled volume of silvopastures compared to forests, seen in 2002, did not appear to interfere with pasture or tree growth. Douglas-fir trees in 2000 (Sharrow and Ismail 2004), averaged 10.5 cm DBH and 516 cm height in silvopastures compared to 8.4 cm DBH and 460 cm height in forests. Pasture production in 2000 (Sharrow and Ismail 2004) was 4,900, 4,100, and 2,800 kg ha^{-1} for pastures, silvopastures, and forests respectively. Likewise, improvement in soil bulk density, water infiltration rate, and air-filled pore space (seen between 2002 and 2004) did not improve silvopasture or forest forage productivity. Pasture forage growth during 2002 and 2003 (Table 3) was over twice that of forests and silvopastures, despite soil properties that were similar to those of silvopastures. This probably reflected tree competition with ground vegetation for water and light. Forest and silvopasture forage production was similar both years. Although not statistically significant for inferential purposes, trees in silvopastures were physically larger than those in forests. Total tree stem volume of silvopastures in 2004 was approximately 13 m^3 ha^{-1} more than forests and 49 m^3 ha^{-1} more than pastures (that lacked trees). Assuming a typical 1:3 root:shoot ratio for Douglas-fir of this size (Gholz et al. 1979; Sharrow and Ismail 2004), silvopasture roots should occupy only approximately 17 m^3 of the 3,500 m^3 ha^{-1} (0.5%) of soil present on the site. Even allowing for concentration of roots near individual trees, root expansion effects are unlikely to have been a significant factor impacting soil physical properties in a timber stand of this age.

Lack of a vegetation response to treatment differences observed in soil properties probably reflects a
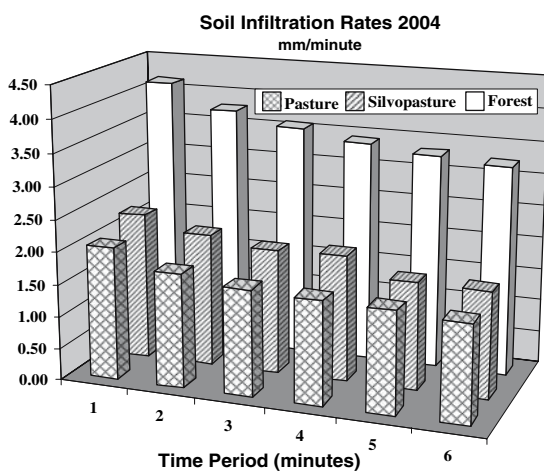
Table 2 Physical characteristics of the top 7 cm of soil in forests, silvopasture and pastures near Corvallis, Oregon USA in spring 2004

	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]
Silvopasture	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 in a column not sharing a letter differ, $P < .05$, Scheffe's Test

Table 3 Average total forage production measured in August 2002 and 2003 and Douglas-fir tree diameter at breast height (DBH) and total stem volume measured in August 2004 for pastures, forests and silvopastures near Corvallis, Oregon USA

	Forage 2002* kg ha^{-1}	Forage 2003* kg ha^{-1}	Height 2004* cm	DBH 2004* cm	Volume 2004* m^3 ha^{-1}
Pasture	3,224[a]	2,398[a]	–	–	–
Forest	1,122[b]	752[b]	716[a]	13.2[a]	36.7[a]
Silvopasture	1,354[b]	1,280[b]	795[a]	14.8[a]	49.6[a]
MSE	205	248	87	1.6	13.5

* Means in a column not sharing a letter differ, $P < .05$, Scheffe's Test

general adequacy of soil structure to support vegetation, regardless of management system. Soil compaction most commonly reduces plant growth by increasing resistance of soil to root penetration (increasing soil strength), reducing available water by lowering soil water infiltration rates, and by reducing soil aeration by loss of air-filled macropore space (Greacen and Sands 1980). Soil bulk densities observed in this study were all well below those reported to reduce root growth in forests (Monire et al. 1969; Heilman 1981). Soil strength was not measured, however the relatively low soil bulk density values observed (Table 1) suggest that resistance to root penetration would not be limiting during the main spring growing season when soils were damp. Likewise, all treatments had average soil air-filled pore volume over the 10% value often cited (Rab 2004) as the point where soil anoxia becomes a problem. While soil infiltration rates of pastures and silvopastures were consistently lower than forests, all rates were adequate to completely accept rainfall at the intensities prevalent on the site. Stored soil water at field capacity tended to be numerically higher on pastures and silvopastures than in forests.

Differences in forage production observed between pastures and forests or silvopastures in 2002 and 2004 most logically reflect competition with trees for soil water and nutrients and shading effects of overstory trees on pasture plants, rather than differences in soil physical properties. For early to mid-rotation tree stands, such as these 12 to 14-year-old forests and agroforests, competition for soil water and nutrients is probably more important than competition for light (Sharrow 1999). In this case, soil ability to accept and store water appeared to be much less important to pasture production that water use by trees.

Conclusions

About 11 years after establishment, soils in silvopastures were denser, had lower water infiltration rates, and less air filled pore volume than those in forests. These are all consistent with increased soil compaction having occurred in silvopastures. Since pasture and silvopasture soil properties were similar in 2004, additional soil compaction in silvopastures compared to forests was most likely due to either the direct (hoof impact) or indirect (litter reduction) effects of livestock grazing rather than from increased tree growth. There is no evidence for any "tree effect" on soil compactness in this study. This may be due to the size of the trees at the time of sampling. Presumably, larger trees would have larger, more influential root systems and a tree effect may materialize with

additional time. Soil infiltration rates and air-filled pore space rapidly improved when grazing ceased, suggesting that soil physical structure in the experimental area is maintained by dynamic processes and can quickly change with changing conditions. This provides opportunities to manipulate soil structure through pasture and forest management. On areas, such as those in this study, where soil physical structure provides adequate infiltration rates to accept rainfall and sufficient macropore space to aerate soils, changes in soil physical structure from grazing livestock should not be expected to influence plant growth unless soils are severely trampled. While soil surface infiltration rates were very responsive to differences in soil structure, particularly macro-pore space, neither soil water holding capacity nor plant production was particularly responsive. This points out the need to measure more than one soil parameter in order to understand the implications of soil compaction on silvopasture productivity. Increased soil compaction does not necessarily imply reduced pasture or tree growth in silvopastures.

References

Bezkorowajnyj PG, Gordon AM, McBride RA (1993) The effect of cattle foot traffic on soil compaction in a silvo-pastoral system. Agroforest Syst 21:1–10

Bouwer H (1986) Intake rate: cylinder infiltrometer. In: Klute A (ed) Methods of soil analysis, Part 1. American Society of Agronomy. Madison, Wisconsin, USA, pp 825–844

Chanasyk DS, Naeth MA (1995) Grazing impacts on bulk density and soil strength in the foothills fescue grassland of Alberta, Canada. Can J Soil Sci 75:551–557

Clason TR, Sharrow SH (2000) Silvopastoral practices. In: Garrett HE, Rietveld WJ, Fisher RF (eds) North American agroforestry: an integrated science and practice. American Society of Agronomy, Madison, Wisconsin, USA, pp 119–147

Danielson RE, Sutherland PL (1986) Chapter 8—Porosity. In: Klute A (ed) Methods of soil analysis—Part 1—Physical and mineralogical methods. American Society of Agronomy, Madison, Wisconsin, USA

Drewry JJ, Paton RJ, Monaghan RM (2004) Soil compaction and recovery cycle on a Southland dairy farm: implications for soil monitoring. Aust J Soil Res 42:851–856

Greacen EL, Sands R (1980) Compaction of forest soils—a review. Aust J Soil Res 18:163–189

Greenwood KL, McKenzie BM (2001) Grazing effects on soil physical properties and consequences for pastures: a review. Aust J Exp Agric 41:1231–1250

Gifford GF, Hawkins RH (1978) Hydrologic impact of grazing on infiltration; a critical review. Water Resour Res 14:305–313

Gholz HL, Grier CC, Campbell AG, Brown AT (1979) Equations for estimating biomass and leaf area of plants in the Pacific Northwest. Forest Research Lab Research Paper 41. Oregon State University, Corvallis, Oregon, USA, 40 pp

Heilman P (1981) Root penetration of Douglas-fir seedlings into compacted soil. For Sci 27:660–666

Knezevich CA (1975) Soil survey of Benton County Area, Oregon. USDA, Soil Conservation Service, Washington DC, USA

Krzic M, Newman RF, Broersma K, Bomke AA (1999) Soil compaction of forest plantations in interior British Columbia. J Range Manage 52:671–677

Krzic M, Broersma K, Newman RF, Ballard TM, Bomke AA (2001) Soil quality of harvested and grazed forest cutblocks in Southern British Columbia. J Soil Water Conserv 56:192–197

Lei SA (2004) Soil compaction from human trampling, biking, and off-road motor vehicle activity in a blackbrush (Coleogynr ramosissima) shrubland. West N Am Nat 64:125–130

Linnartz NE, Hse C-Y, Duvall VL (1966) Grazing impairs physical properties of a forest soil in central Louisiana. J For 64:239–243

Mapfumo E, Chanasyk DS, Neath MA, Baron VS (1999) Soil compaction under grazing of annual and perennial forages. Can J Soil Sci 79:191–199

McNabb DH, Startsev AD, Nguyen H (2001) Soil wetness and traffic level effects on bulk density and air-filled porosity of compacted boreal forest soils. Soil Sci Soc Am J 65:1238–1247

Minore D, Smith CE, Woolard RF (1969) Effects of high soil density on seedling root growth of eleven northwestern tree species. USDA forest service, Pacific Northwest forest and range experiment station, Research note PNW-112, 6 pp

Orr HK (1960) Soil porosity and bulk density on grazed and protected Kentucky bluegrass range in the Black Hills. J Range Manage 13:80–86

Proffitt APB, Bendotti S, Howell MR, Eastham J (1993) The effect of sheep trampling and grazing on soil physical properties and pasture growth for a red-brown earth. Aust J Agric Res 44:317–313

Rab MA (2004) Recovery of soil physical properties from compaction and soil profile disturbance caused by logging of native forest in Victorian Central Highlands, Australia. For Ecol Manage 191:329–340

Sharrow SH (1999) Silvopastoralism: competition and facilitation between trees, livestock, and improved grass-clover pastures on temperate rainfed lands. In: Buck LE, Lassoie JP, Frenandes ECM (eds) Agroforestry in sustainable agricultural systems. Lewis Publishers, Boca Raton, Florida, USA, pp 111–130

Sharrow SH (1992) Tree planting pattern effects on forage production in a Douglas-fir agroforest. Agroforest Syst 16:167–175

Sharrow SH (1994) Sheep as a silvicultural management tool in temperate conifer forest. Sheep Res J 97–104 Special issue (1994)

Sharrow SH, Ismail S (2004) Carbon and nitrogen storage in agroforests, forests, and pastures in western Oregon, USA. Agroforest Syst 60:123–130

Sharrow SH, Carlson DH, Emmingham WH, Lavender D (1996) Productivity of two Douglas fir/subclover/sheep agroforests compared to pasture and forest monocultures. Agroforest Syst 34:305–313

Steel RGD, Torrie JH (1980) Principles and procedures of statistics. McGraw-Hill Book Company, New York, New York, USA, 633 pp

Taddese G, Mohamed Saleem MA, Ayalneh W (2002) Effect of livestock grazing on physical properties of a cracking and self-mulching vertisol. Aust J Exp Agric 42:129–133

Tate KW, Dudley DM, McDougald NK, George MR (2004) Effect of canopy and grazing on soil bulk density. J Range Manage 57:411–417

Trimble SW, Mendel AC (1995) The cow as a geomorphic agent—a critical review. Geomorphology 13:233–253

Wairiu M, Mullins CE, Campbell CD (1993) Soil physical factors affecting the growth of sycamore (*Acer pseudoplatanus* L.) in a silvopastoral system on a stony upland soil in North-East Scotland. Agroforest Syst 24:295–306

Wheeler MA, Trlica MJ, Frazier GW, Reeder JD (2002) Seasonal grazing affects soil physical properties of a montane riparian community. J Range Manage 55:49–56

Willatt ST, Pullar DM (1983) Changes in soil properties under grazed pastures. Aust J Soil Res 22:343–348