Grazing impacts on bulk density and soil strength in the foothills fescue grasslands of Alberta, Canada

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Chanasyk, D. S. and Naeth, M. A. 1995. **Grazing impacts on bulk density and soil strength in the foothills fescue grasslands of Alberta, Canada**. Can. J. Soil Sci. **75**: 551–557. Alberta foothills fescue grasslands are very productive ecosystems but there is concern that the traditional season-long (continuous) grazing regimes may be leading to soil deterioration due to compaction and increased soil strength. The objectives of this study were to quantify grazing effects on soil bulk density and soil strength of sloped areas in the Alberta foothills fescue grasslands at the Agriculture Canada Stavely Range Substation. The effects of two grazing intensities (heavy and very heavy) for two treatments (short duration and continuous) on these two parameters were compared to an ungrazed control. Soil bulk density and soil water to a depth of 7.5 cm were measured with a surface water/density gauge. Soil strength was measured with a hand-pushed cone penetrometer to a depth of 45 cm. Cone index, the maximum penetration resistance in a given depth interval, was used as a measurement parameter for soil strength.

Grazing affected both soil bulk density and penetration resistance. Even short-duration treatments affected these soil properties, although their effects were similar for both heavy and very heavy grazing intensities. Distinction between heavy and very heavy continuous grazing treatments was clear for both bulk density and penetration resistance, with the very heavy treatment having the greatest detrimental effect on these two soil parameters for all treatments. Bulk density and soil strength values were always lowest in the spring after snowmelt and highest late in the growing season, reflecting the water status of these ecosystems. Identical treatment rankings were obtained using bulk density and penetration resistance, but cone index was a more sensitive indicator of the effects of grazing than bulk density.

Key words: Grazing, fescue grasslands, bulk density, soil strength

Chanasyk, D. S. et Naeth, M. A. 1995. **Incidences du pâturage sur la densité apparente et sur le dureté du sol dans les parcours à fétuque des avant-monts de l'Alberta au Canada.** Can J. Soil Sci. **75**: 551–557. Les parcours à fétuque des avant-monts de l'Alberta forment des écosystèmes très productifs mais on commence à craindre que les systèmes de paissance continue, couramment pratiqués puissent causer la détérioration du sol par la compaction et par l'accroissement de la dureté du sol. L'objet de nos recherches réalisées à la sous-station de recherches sur les parcours de Stavely (Agriculture Canada), était de quantifier les effets de la paissance sur la densité apparente et sur la compacité du sol dans les parcours à fétuque des avant-monts de l'Alberta. Nous comparions à un témoin non pâturé les effets sur ces deux paramètres de deux intensités de paissance (forte de très forte), sous deux traitements de durée (courte durée et continu. La densité apparente et la teneur en eau du sol dans les 7,5 premiers centimètres étaient mesurées au moyen d'une sonde électronique combinée MCI. La dureté du sol était mesurée par un pénétromètre à cône manuel jusqu'à une profondeur de 45 cm. L'index au cône, c.-à-d. la résistance maximale à la pénétration pour une tranche de profoundeur donnée, était utilisé comme paramètre de mesure de la compacité. La paissance influait à la fois sur la densité apparente et sur la résistance à la pénétration du sol. Même des épisodes de paissance de courte durée avaient un effet, bien qu'un degré semblable aux deux intensités de paissance. Il y avait une nette démarcation des effets des intensités de paissance sur les deux paramètres, le taux de chargement le plus élevé étant, de tous les traitements comparés, celui qui provoquait les effets négatifs les plus graves. Les valeurs de densité apparente et de dureté du sol marquaient toujours un creux au printemps après la fonte des neiges et un pic en fin de saison de végétation, reflétant ainsi l'état hydrique des deux écosystèmes. Des classements identiques des traitements étaient obtenus d'après la densité apparente et d'après la résistance à la pénétration, cette dernière se révélant toutefois un indicateur plus sensible des effets de la paissance que le premier paramètre.

Mots clés: Paissance, parcours à fétuque, densité apparente, compacité du sol

The deleterious effects of grazing over the entire growing season (season-long) on soil physical properties depend on stocking density, soil texture, soil water and vegetation type. The most commonly quantified parameter is soil compaction measured by soil bulk density (usually with cores) and less frequently by penetration resistance measured by penetrometers (Roundy et al. 1990; Weigel et al. 1990). Gifford et al. (1977) reviewed five techniques for quantifying rangeland compaction. Readings from all instruments were affected by soil water and plant roots and were significantly correlated with soil core bulk density, with correlations highest for the air permeameter and proving ring penetrometer.

The role of soil texture in mitigating compaction due to grazing undoubtedly involves soil water. Fine-textured soils hold more water than coarse-textured soils and are thus more susceptible to compaction, especially if grazed when wet. This might explain Laycock and Conrad's (1967) observation that in humid regions bulk density was consistently higher in grazed than ungrazed areas, but in arid regions results were conflicting. However, Warren et al. (1986) found bulk densities of paddocks in Texas trampled dry (5% soil water) were actually higher than those trampled wet (25% soil water), but bulk density on both moist and dry paddocks followed the same long-term trend.

Increase in bulk density due to grazing is in the range of 10–15% and surprisingly independent of initial bulk density. Van Haveren (1983) found average bulk density on fine-textured soils in heavily grazed areas was 13 and 12% higher than in lightly and moderately grazed areas, respectively. The difference in bulk density between ungrazed and grazed areas measured by Orr (1960) was 12%. Scholl (1989) measured increases in bulk density of 2% for sand, 8% for loamy sand, 11% for sandy loam, 13% for loam and 11% for clay soils under moist conditions. McCarthy and Mazurak (1976) measured increases of 12 and 20% in bulk density for deferred and rotational grazing and continuous grazing over protected areas, respectively. Dormaar et al. (1989) measured an average 14% difference in soil bulk density in the uppermost 6 cm comparing ungrazed exclosures with short-duration grazing.

The zone of influence of grazing on soil compaction as measured by bulk density is shallow. Orr (1960) found bulk density of the 0–5 cm depth interval was significantly higher on grazed range than inside exclosures at three of four sites (average 0.87 Mg m^{-3} in exclosures and 0.97 Mg m^{-3} outside exclosures). Statistically significant differences in bulk density were found on only two sites in the 5–10 cm depth interval and not at all below 10 cm.

Only a few researchers have used penetrometers to quantify grazing effects on soil strength and have tended to concentrate on hoof prints versus non-printed areas at very shallow depths. Scholl (1989), in New Mexico, measured an average 123% increase in soil strength due to trampling, with values varying from 0.2 to 0.5 MPa in the control and from 0.3 to 1.2 MPa in trampled areas. Readings were taken when the cone base reached the soil surface (point depth was 3.8 cm). Weigel et al. (1990) measured an average increase of 28% in post-grazing soil strength on seven dates over 2 yr in Oklahoma. Soil strength ranged from 0.2 to 0.7 MPa in ungrazed areas and from 0.2 to 1.1 MPa in grazed areas and showed signs of reduction between years.

Recently, more intensive rotational and short-duration grazing systems have been proposed as alternatives to grazing continuously over the entire growing season. It has been speculated that these systems will help reduce, or perhaps eliminate, the deleterious effects of grazing on soil properties. Warren et al. (1986) concluded that on a silty clay soil, repeated high intensity trampling at levels typical of intensive rotational systems was detrimental to soil properties which are normally well correlated to infiltration rate and sediment production. Abdul-Magid et al. (1987), in evaluating continuous, rotationally deferred and short-duration rotational grazing systems, found that grazing systems did not consistently influence bulk density or water infiltration.

Alberta foothills fescue grasslands are very productive but there is some concern that traditional continuous grazing over the growing season may be leading to soil deterioration due to compaction and increased soil strength. Naeth et al. (1990a,b, 1991) studied non-sloped areas of these grasslands that had been continuously grazed (May through October) since 1949. They found that under heavy and very heavy grazing live vegetation, litter cover, litter biomass and below-ground organic matter all decreased, while bare ground, penetration resistance and bulk density generally increased, particularly at the soil surface. In 1988, a study was initiated to evaluate the impacts of grazing on sloped areas of these grasslands since slopes comprise over 70% of the area. The study compared 4-yr-old short-duration grazing treatments to those of the continuous long-term treatments. The objectives were to quantify the effects of season-long continuous grazing and short-duration grazing systems at both heavy and very heavy grazing intensities on bulk density and penetration resistance. The hypothesis was that grazing would increase both bulk density and penetration resistance and that these impacts would be related to grazing systems and grazing intensity.

Table 1. Precipitation (mm) for Stavely Range Research Substation

Month	1988	1989	1990	1991
May	17.0	28.7	85.9	73.4
June	58.4	45.7	46.2	124.0
July	15.2	36.6	99.1	4.1
August	108.5	54.9	90.4	24.6
September	20.6	40.1	7.9	16.0
October	10.2	26.9	15.2	44.7
May to October	229.9	232.9	344.7	286.8

STUDY SITE DESCRIPTION

The study site is located at the Agriculture and Agri-Food Canada Stavely Range Substation in Alberta (50°N and 114°W). Annual precipitation is approximately 550 mm with 40% occurring as snow. May to September precipitation is 230–370 mm (Strong and Leggat 1981). Mean annual air temperature is 5°C; the January mean is -10°C and the July mean is 18°C. There are approximately 230 growing days and the average frost free period is 25 days. Chinook winds moderate the climate during the winter.

Slopes range from 18 to 37%, with average slopes by position being 21, 25 and 32% for the upper-slope, mid-slope and lower-slope positions, respectively. Soils are generally fertile and well-drained Orthic Black Chernozems (Typic Cryoboroll) with a common horizon sequence of Ah (> 15 cm), Bm_1 (14–35 cm), Bm_2 (35–53 cm), BCk and Ck (60 cm) (Walker et al. 1991). Soil texture to 30 cm is generally clay loam and clay loam to loam below. With depth, sand content decreases, silt increases and clay decreases slightly. Organic matter averages 12.8% in the ungrazed control to a depth of 10 cm.

Festuca campestris Rydb. (rough fescue) dominates the ungrazed and lightly grazed areas; *Danthonia parryi* Scribn. (Parry's oatgrass) dominates the heavily grazed areas and exposed sites with thin soils. There are a variety of subdominant grasses, forbs and shrubs. Johnston et al. (1971) found lightly and heavily grazed fields were dominated by *Festuca campestris* and *Danthonia parryi*, respectively. Under very heavy grazing, *Festuca campestris* and litter were virtually eliminated. *Populus tremuloides* Michx. (trembling aspen) encroached upon lightly and moderately grazed grassland.

The area was moderately stocked with cattle for summer grazing from 1884 to 1908, with horses from 1908 to 1920, then again with cattle from 1920 to 1944 (Johnston 1961). It

Table 2. Date-averaged soil water, bulk density and cone index by slope position

	Grazing treatment				
		Short duration		Continuous	
Slope position	Control	Heavy	Very heavy	Heavy	Very heavy
	Surface (0–7.5 cm) soil water (cm^3 cm^{-3} × 100)				
Upper	15.2*c*	18.1*b*	20.3*a*	18.6*ab*	20.6*a*
Middle	16.6*b*	17.6*b*	20.1*a*	18.1*ab*	19.8*a*
Lower	16.1*c*	18.5*b*	20.3*ab*	21.2*a*	21.5*a*
	Surface (0–7.5 cm) bulk density (Mg m^{-3})				
Upper	0.74*c*	0.82*b*	0.84*b*	0.83*b*	0.91*a*
Middle	0.79*c*	0.85*b*	0.87*ab*	0.80*c*	0.88*a*
Lower	0.77*c*	0.83*b*	0.84*b*	0.88*a*	0.89*a*
	Cone index to 10.5 cm (MPa)				
Upper	1.38*d*	1.60*c*	1.93*b*	2.05*b*	2.59*a*
Middle	1.38*c*	1.58*b*	1.61*b*	1.73*b*	2.17*a*
Lower	1.02*c*	1.36*b*	1.45*b*	2.06*a*	2.10*a*
	Cone index to 30.0 cm (MPa)				
Upper	3.11*d*	3.39*c*	3.55*c*	3.76*b*	4.04*a*
Middle	2.40*c*	2.08*d*	2.35*c*	3.18*b*	3.96*a*
Lower	2.29*c*	2.68*bc*	2.90*b*	2.41*c*	3.46*a*

a-c Numbers followed by similar letters in a given row denote no significant difference at $P<0.05$.

was heavily grazed during the drought years of the thirties then lightly used as winter range from 1944 to 1949 when long-term continuous grazing treatments were established. The area where the short-duration treatments were established was ungrazed or lightly grazed since 1949.

RESEARCH DESIGN AND METHODS

Site Establishment

Research sites were established in 1988 to contrast among long-term continuous grazing, 4-yr-old short-duration grazing and an ungrazed control. Continuous treatments were grazed from May through October; short-duration treatments were grazed for 1 wk in mid-June. Heavy [2.4 **animal unit months (AUM)** ha^{-1}] and very heavy (4.8 AUM ha^{-1}) stocking densities, commonly encountered in the area, were imposed upon both the continuous and short-duration grazing experiments. The short-duration treatments consisted of two 30 by 120 m grazed strips [**short-duration heavy (SDH) and short duration very heavy (SDVH)**] and a 10 by 120 m ungrazed control each replicated three times, running down slope in a randomized split block design. The continuous treatments [**continuous heavy (CH) and continuous very heavy (CVH)**] with the same experimental design were located approximately 0.5 km from the short-duration sites. The control treatment for the short-duration treatments and exclosures in the continuous treatments were not significantly different (as determined from *t*-tests for soil bulk density, soil strength and plant species composition) thereby obviating a second control for this study. All treatments faced east.

Meteorological Conditions

Daily air temperature and precipitation were measured at the study site generally from mid-April to mid-November, depending upon the time of snowmelt and freeze-up. Daily values for these two parameters were obtained for 1988 to 1991, inclusive, and compared with the long-term normal and study years for the nearest long-term monitoring station at Claresholm, 50 km away.

Soil Physical Parameters

Penetration resistance (PR) was measured to a depth of 45 cm four times per year at five locations at each slope position with a hand-pushed, manually read 30°, 21-mm diameter cone penetrometer in 1988 and a 13-mm-diameter cone penetrometer during the remainder of the study. Penetration resistance was recorded at 30 depths with the former probe (every 1.5 cm to a depth of 45 cm) and at nine depths (0, 2.5, 5, 7.5, 10, 15, 22.5, 30 and 45 cm) with the latter probe. The maximum penetration resistances between 0–10.5 and 0–30 cm were reported as cone index in both cases. Surface (0–7.5 cm) soil water and bulk density were measured at the time of PR measurement adjacent to each PR measurement spot using a Campbell Pacific Nuclear MC1 surface moisture/density gauge. Soil water to a depth of 50 cm was measured with a Campbell Pacific Nuclear neutron probe in access tubes located within a meter from each PR measurement site.

Statistical Analyses

For each parameter, significant differences of the means were detected using Analysis of Variance techniques with design following the convention outlined in the SPSS-X User Manual (SPSS 1988) for split blocks. Significant effects were further evaluated using Duncan's Multiple Range Test at the 5% level of significance (Steel and Torrie 1980).

RESULTS AND DISCUSSION

Meteorological Conditions

Considering the 4 yr of data at the study site, precipitation was notably high in August 1988; May, July and August 1990; and May and June 1991 (Table 1). It was very low in

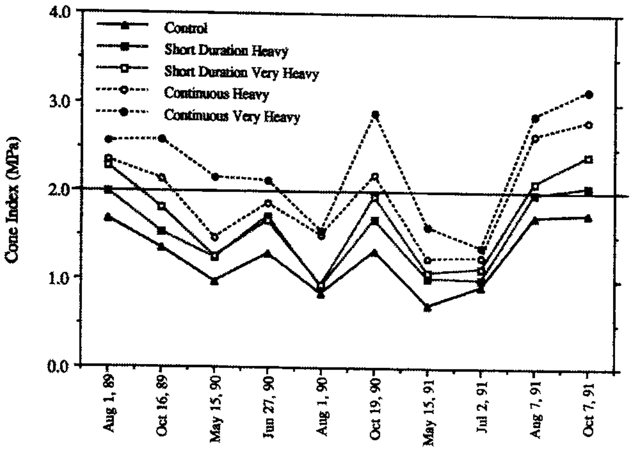


Fig. 1. Slope-averaged cone index to 10.5 cm.

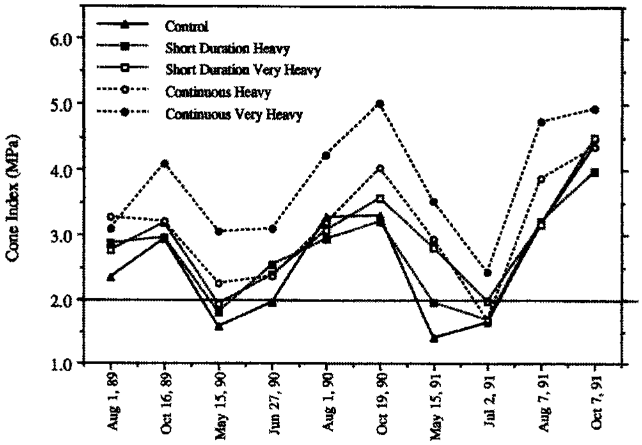


Fig. 2. Slope-averaged cone index to 30.5 cm.

May and July 1988, September 1990 and July 1991. Overwinter precipitation (1 November to 31 March, inclusive) at the Claresholm monitoring station was 127, 105 and 170 mm for 1988–1989, 1989–1990 and 1990–1991, respectively. Mean annual air temperature was close to the long-term normal in 1989 and above it in the other three years of the study (+1.7, +0.6 and +1.2°C in 1988, 1990 and 1991, respectively). Mean monthly air temperature was generally above normal throughout the study period (data not shown).

Soil Water

Surface soil water (0–7.5 cm) across slope positions was consistently lowest in the control, highest in the SDVH, CH and CVH and intermediate in SDH treatments (Table 2). These results are due to large vegetation and litter biomasses (Naeth et al. 1991) in the control which intercepted precipitation; their absence under heavier grazing would increase surface soil water (Naeth and Chanasyk 1995b). This differs from data of Dormaar et al. (1989), who measured soil water only during the spring and fall of two study years.

Bulk Density

Surface bulk density (0–7.5 cm) ranged from 0.74 to 0.91 Mg m^{-3} (Table 2) with values in the control < SDH and SDVH < CH < CVH. Several low bulk densities for the CH treatment in the mid-slope position (possibly due to the large and deep rooted woody vegetation) reduced the average bulk density to near that of the control. Increases in bulk density attributed to grazing over that in the control, averaged across slope positions and ignoring the mid-slope value for the CH treatment, were 8.7, 10.9, 13.2 and 16.7% for the SDH, SDVH, CH and CVH treatments, respectively. These results are similar in magnitude to those in the literature and clearly demonstrate the effects of grazing on bulk density.

Bulk density increased with grazing by a maximum of 0.24 Mg m^{-3} (data not shown), notably under CVH grazing. Surface bulk densities under CH and SDH grazing were similar, but values were clearly higher under CVH than SDVH grazing. Time between grazing treatments (51 wk) likely allowed amelioration by plant growth and the retention of deeper rooted species in the short-duration than the continuous treatments. Overall, the detrimental effects of very heavy grazing on soil bulk density have been demonstrated.

Bulk density of the short-duration treatments increased due to annual grazing, but it also increased slightly in the control over the same period (data not shown). Average changes in bulk density across slope positions for a distinct drying period in 1991 (2 July to 7 August; 4.6 mm of precipitation) were +0.05, +0.04, +0.10, +0.01 and +0.07 Mg m^{-3} for the control, SDH, SDVH, CH and CVH, respectively. In contrast, the average changes for the next 2-mo period (7 August to 7 October; 34.5 mm of precipitation) were practically negligible: -0.01, +0.00, -0.01, +0.02 and +0.01 Mg m^{-3} for the control, SDH, SDVH, CH and CVH, respectively. Laycock and Conrad (1967) noted that bulk density should not be used to compare the effects of grazing on soil compaction unless comparative data are taken on both ungrazed and grazed areas because bulk density varies with soil water. Increases in bulk density could be erroneously attributed to grazing, when in fact soil drying increased bulk density. However, such a trend was not evident in either 1989 or 1991 with not enough data in 1990 for a similar comparison. Thus the effects of short-duration grazing on soil bulk density are negligible or perhaps hard to quantify with bulk density as the measurement parameter.

Penetration Resistance

Cone indices to 105 and 300 mm for 1989–1991 were generally significantly different among continuous and short-duration grazing treatments, with the lowest values in the control and the highest in the CVH treatment (Table 2). Treatment ranking was identical to that for bulk density. Cone index increased with grazing intensity under continuous grazing but not always under short-duration grazing. The lack of a grazing intensity trend for the short-duration treatments may again reflect the greater rooting depths of

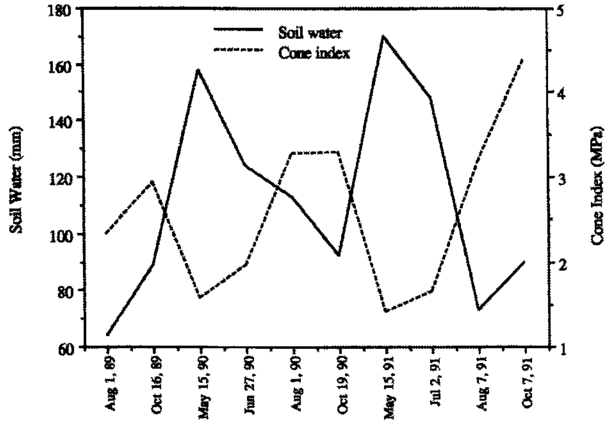


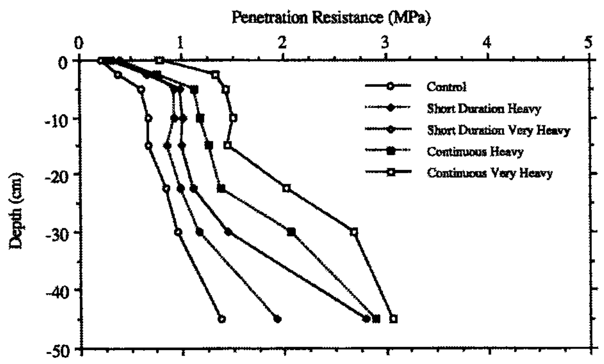
Fig. 3. Trends in soil water to 50 cm and cone index to 30 cm over time in the ungrazed control.

plant species under short-duration versus continuous grazing (Naeth et al. 1991). There were no trends in cone index with slope, for either 105 or 300 mm depth intervals.

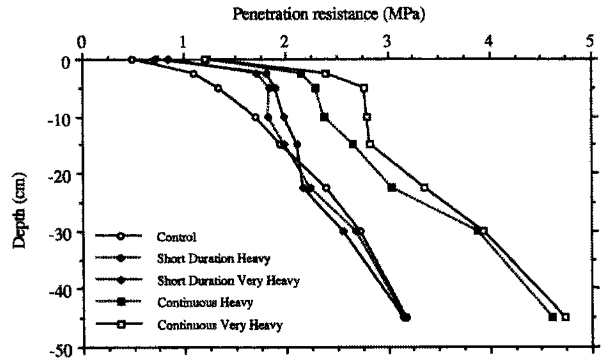
Trends in cone index over time were generally similar across grazing treatments (Figs. 1 and 2), peaking in the fall and being lowest in the spring of each year (with the exception of 1989 to a depth of 10.5 cm). To depths of both 10.5 and 30.0 cm, cone index was lowest in the control and highest in the CVH treatment. Values in cone index to 30.0 cm were grouped closer to each other for all treatments except the CVH compared with cone index to 10.5 cm where there were wider treatment differences. In all 3 yr of the study, cone index to both depths was highest in October, corresponding to times of low soil water (Naeth and Chanasyk 1995b).

A value of 2.0 MPa is often accepted as a threshold value potentially limiting to root growth (Graecen 1986). To a depth of 10.5 cm, this value was exceeded on most measurements dates in the CVH treatment (Fig. 1), but only in the other grazing treatments on the last two measurement dates in 1991. In contrast, on only four dates, and only for select treatments was this value not exceeded to a depth of 30.0 cm (Fig. 2). Penetration resistance is thus potentially root growth limiting at a depth between 10.5 and 30.0 cm. At this site, this is a surprising result given the high organic matter content of the soil.

For all treatments, in a given growing season, cone indices to 30.0 cm were highest in October (Fig. 2). However, these high fall values were ameliorated by soil water recharge due to snowmelt (consider cone index and soil water for these periods in Fig. 3). Averaged across slope positions and two winters (1989/1990 and 1990/1991), the reduction in cone index to 30.0 cm was 52, 40, 29, 30 and 28% for the control, SDH, SDVH, CH and CVH, respectively, with little difference between years (data not shown). The higher reduction in the control is likely due to greater snow trapping and higher snowmelt infiltration in that treatment (Naeth and Chanasyk 1995a). The decrease in cone index over-winter may also have occurred due a reduction in bulk density due to freezing/thawing. Data collected could not be used to test this hypothesis, but given that the standard deviations for bulk density for both the control and the continuous very heavy treatments over the 4-yr study ($n = 12$) were only 0.03 Mg m^{-3}, one might surmise that this hypothesis should not be accepted.



(a) May 1991



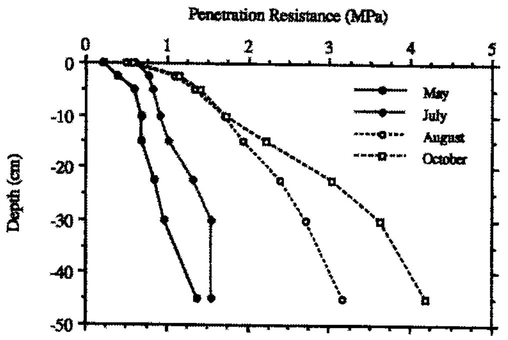
(b) August 1991

Fig. 4. Slope-averaged penetration resistance with depth in (a) May 1991 and (b) August 1991.

Slope-averaged PR with depth was considered for two dates in 1991: 15 May when soil water was highest and 7 August 1991 when soil water was very low (Fig. 4). PR on 15 May generally increased with depth for all treatments and there was a clear treatment trend of increasing PR magnitude at all depths: control < SDH < SDVH < CH < CVH (Fig. 4a). PR on this date was less than 2.0 MPa for the control and SDH treatments at all depths. Moving from the SDVH to CH to CVH treatments, PR exceeded 2.0 MPa at depths of 45, 30 and 22.5 cm, respectively, indicating the influence of grazing on PR and the presence of potentially root-limiting PRs nearer to the surface as grazing intensity increased and as the grazing system changed from short-duration to continuous.

PR on 7 August 1991 also increased with depth (Fig. 4b), but more steeply than on 15 May. Under dry soil water conditions on this date, PR was similar for the control, SDH and SDVH treatments below 10 cm, exceeding 2.0 MPa for all depths > 15 cm. Trends in the two continuous grazing treatments were distinct from the other three treatments and from each other, with PR for CVH exceeding that for CH at all depths. In both treatments, PR was > 2.0 MPa at all depths

(a) Control



(b) Continuous Very Heavy Grazing

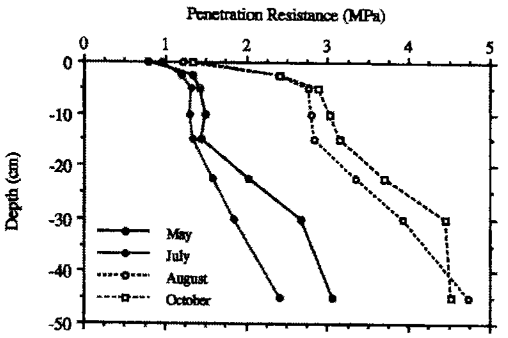


Fig. 5. Changes in slope-averaged penetration resistance during the 1991 growing season in (a) the control and (b) under continuous very heavy grazing.

greater than 5 cm and > 3.0 MPa at depths greater than 22.5 cm. PR increased between May and August at all depths for all treatments, likely due to a decrease in soil water, as bulk density did not change appreciably over this period.

Changes in PR with depth over the growing season in 1991 were considered for the control and CVH treatments (Fig. 5) which had the extreme PR values shown in Fig. 4. There were four measurement dates and precipitation during the three interim periods was 162.1, 9.9 and 39.6 mm. PR with depth increased slightly in the control between May and July but declined in the CVH treatment, perhaps reflecting better profile soil water recharge in the latter treatment. The greatest changes in PR in both treatments occurred between July and August: a rather dry period with high evapotranspiration. Little further increase in PR with depth occurred under CVH grazing between August and October (Fig. 5b), while PR with depth in the control increased at an increasing rate for this period, likely reflecting soil water withdrawal by deeper rooted plants. The greater hospitability of the soil in the control from a PR perspective is clear from Fig. 5: PR in the control was greater than 3.0 MPa only at 45 cm in August and below 22.5 cm in October, while PR in the CVH treatment was greater than 3.0 MPa at approximately 20 cm in August and 10 cm in October. In addition, PR exceeded 4.0 MPa below 30 cm in both August and October in the CVH treatment. However, the harsh soil environment late in the growing season is evident even in the control.

Interrelationships among Soil Water, Bulk Density and Penetration Resistance

Several authors, most notably Laycock and Conrad (1967), have indicated the importance of considering soil water when assessing treatment effects on bulk density. The two study years, 1988 and 1991, offered a range of soil water values. Surface soil water and bulk density (both to 7.5 cm) and cone index to 10.5 cm were compared to assess the interrelationships among these three variables. All data were slope-averaged before further analyses. Data for 1988 were kept separate from those for 1991 since a larger diameter cone was used in 1988 than in 1991.

There was no trend in either 1988 or 1991 relating bulk density to soil water, with R^2 less than 0.032 on linear relationships (data not shown), indicating changes in bulk density among treatments over time could not be simply attributed to changes in soil water. Soil water and bulk density were compared for the control, considering slope position, across study years, but this relationship was only marginally better than for all treatments. This result justifies greater confidence in using bulk density to monitor effects of grazing on soil compaction at this site. However, because these results differ from those of Laycock and Conrad (1967), further research of bulk density-soil water relationships are required, with careful consideration being given to amount and type of clay present in the study soils.

Cone index was negatively correlated with soil water in both years, with R^2 values of 0.383 and 0.185 for the 1988 and 1991 data, respectively, but positively correlated with bulk density both years, with values of 0.181 and 0.600 in 1988 and 1991, respectively (data not shown). Thus results differ between cone sizes and years, suggesting that further research is required before definitive relationships among soil water, bulk density and cone index can be derived. Direct comparisons with results from other studies reported in the literature must be made with caution to allow for differences in cone size and in depth of penetration (note several studies reported penetration resistance as that at the time the cone has just penetrated the soil surface, in contrast to the greater depths of this study).

To investigate the link between cone index to 30 cm and soil water to 50 cm, data for all the treatments were slope-averaged, pooled and regressed (data not shown). Using the resulting regression equation (R^2 = 0.444), values of 171, 112 and 53 mm of water to a depth of 50 cm would correspond to cone indices of 2.0, 3.0 and 4.0 MPa, respectively. Given that the permanent wilting point is 95 mm for this depth interval, then cone indices of slightly greater than 3.0 MPa could be expected near wilting point. This also means that the potentially limiting cone index of 2.0 MPa would be experienced at relatively high soil water levels (field capacity is 155 mm). Further field testing is required to verify these results.

CONCLUSIONS

Negative impacts of grazing on soil were evidenced in both bulk density and penetration resistance. Even short-duration treatments affected these soil properties, with similar effects for both heavy and very heavy intensities. Distinction between heavy and very heavy continuous grazing treatments was clear for both bulk density and penetration resistance, with the very heavy treatment having the greatest effect on these two soil parameters. Parameter values were always lowest in the spring after snowmelt and highest late in the growing season, reflecting the water regime of these ecosystems. Treatment rankings were identical for both bulk density and cone index, but cone index was a more sensitive indicator of the effects of grazing than bulk density.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge funding from Farming for the Future. Use of the Stavely Research Station facilities provided by Agriculture and Agri-Food Canada made this research possible and is gratefully acknowledged. The interest and cooperation of Drs. John Dormaar and Walter Willms were greatly appreciated. The technical assistance of Ms. Kelly Ostermann, Ms. Robin Lagroix-McLean, Mr. Hank Coulter, Mr. Dan Murray and Mr. Bart Kessler was much appreciated. Numerous summer students are also thanked for their help. Mr. Barry Irving and Ms. Chung Nguyen are acknowledged for their statistical analyses.

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