PART IV

APPENDICES

Appendix I

Description of the Experimental Area

Experimental Area

The experimental area, known as Big Ridge 1 (lat. 30°38'S, long. 151°34'E, altitude 1065 m), is a long-term stocking rate trial established on CSIRO's Pastoral Research Laboratory near Armidale, New South Wales, Australia. The experimental area is fenced into sixteen 0.40 ha plots in a 4x4 Latin square design to enable the effects of slope and variation in soil type across the contour to be removed in statistical analyses. Two replicate plots of each treatment were subdivided by fencing in 1973, and fertiliser use was discontinued on half of each plot. In 1993, two small areas in each grazed plot were excluded from grazing by fencing. The layout of the experimental area is shown in Figure 1.

Soil Types

Three soil types were identified in the experimental area by Schafer (1980): gleyed podzolic, prairie and wiesenboden (lateritic). Using the Australian soil classification (Isbell 1996), these soils correspond to brown chromosol, red ferrosol and brown ferrosol, respectively. Using Northcote's (1979) key, the soils were classified as Db4.22, Gn4.12 and Gn4.82. A lateritic variant of the gleyed podzolic was also identified by this research, and at the experimental area, the soil type mapped by Schafer as gleyed podzolic is probably better described as a grey-brown podzolic (Stace *et al.* 1968). The approximate boundaries between soil types are shown in Figure 2. The location of these boundaries is based on Schafer's published 1:10,000 scale map, profile descriptions of relatively undisturbed soil cores taken within each plot and observations made during field work. The experimental area was surveyed using a theodolite and the contour heights, relative to an arbitrary datum, are also indicated on Figure 2. Profile descriptions for the gleyed podzolic, lateritic podzolic, prairie and wiesenboden soils are included in Tables 1-4. These profile descriptions were made using the nomenclature of McDonald *et al.* (1990).

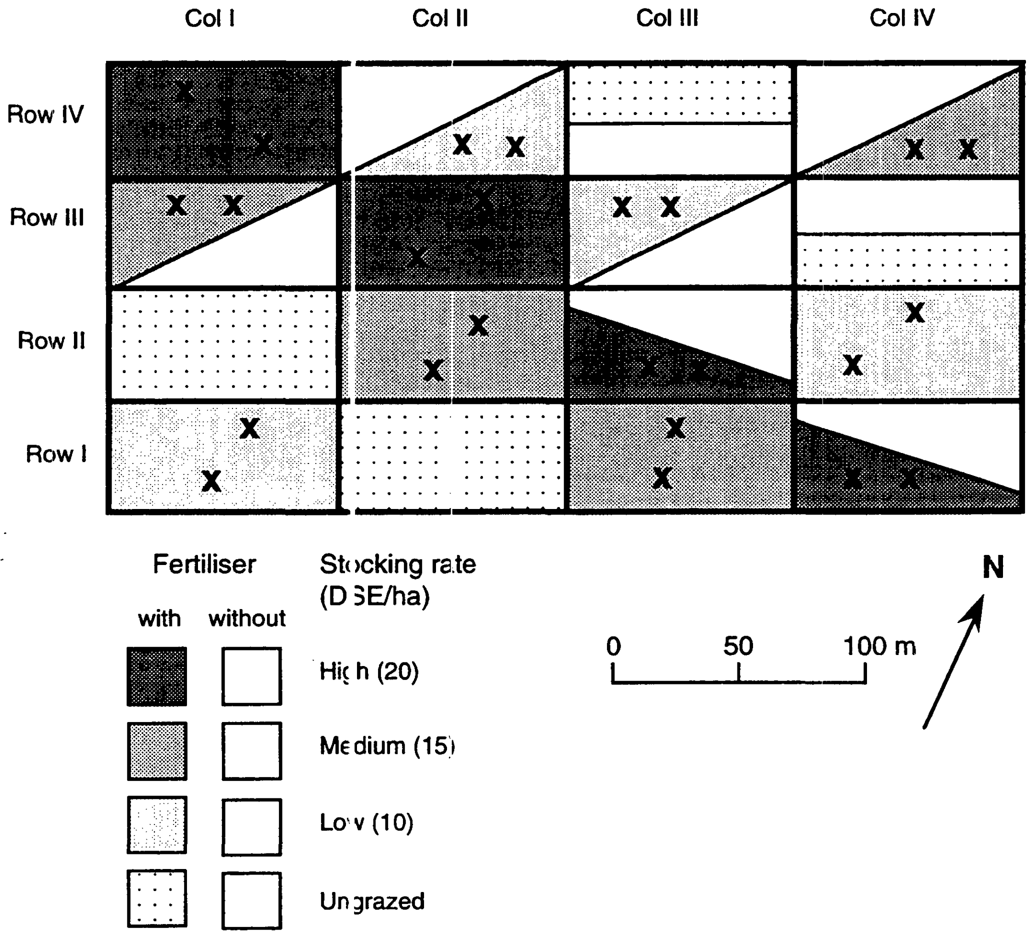

Figure 1. Layout of the experimental area, showing the four stocking rate treatments and two fertiliser treatments. The grazed fertiliser treatment plots were fenced diagonally to 'split' the sheep camps. The approximate location of each grazing exclusion area is indicated by an 'X'. The row and column numbers of the Latin square design are indicated

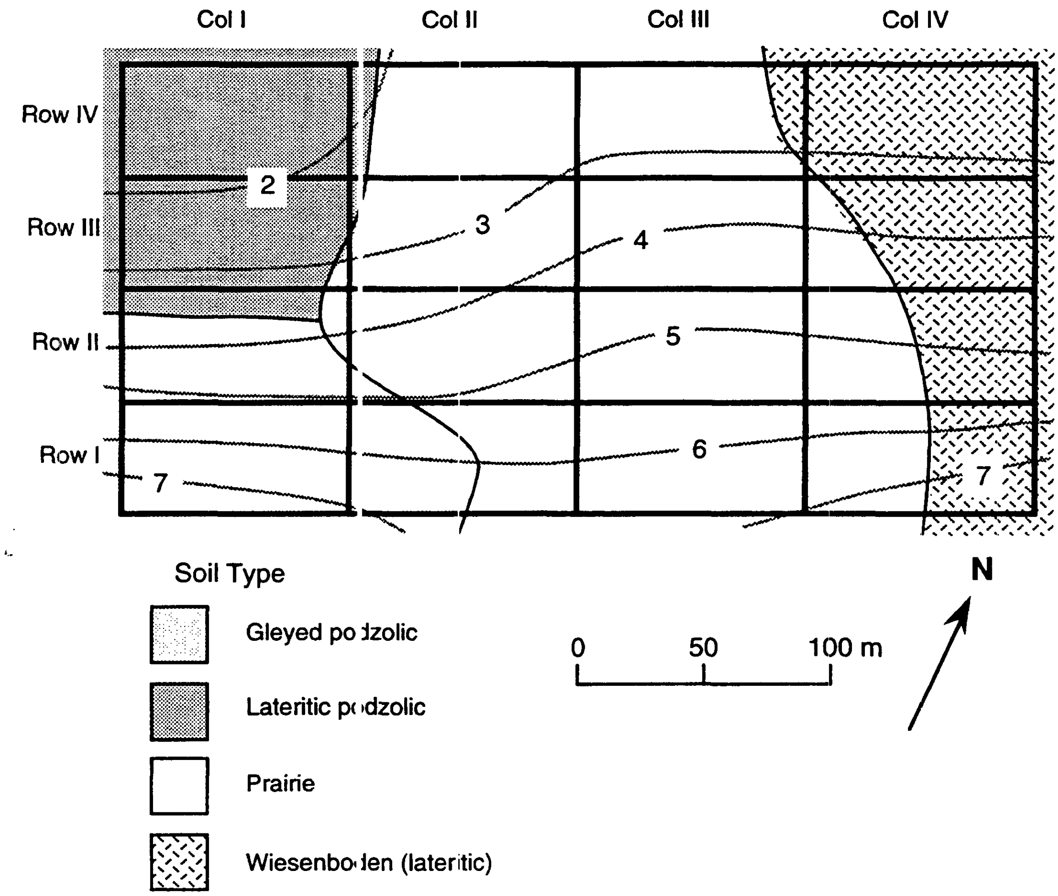

Figure 2. Distribution of soil types within the Big Ridge 1 experimental area. The contour interval is 1 m, relative to an arbitrary datum.

Table 1. Profile description for the gleyed podzolic soil type.

Location: Adjacent to the eastern side of Plot 1, Big Ridge 1
Type of soil observation: Soil pit
Described by: Kerry Greenwood
Date: 12/12/93

Classification:	Northcote Key: Db4.22
	Great Soil Group: Gleyed podzolic (Schafer 1980) or grey-brown podzolic
	Australian Soil Classification: Brown chromosol

Horizon	Depth (cm)	Morphology
A_1	0–24	Brownish black (7.5YR 3/2) clay loam, fine sandy; few, fine, distinct red mottles; weak, 20–50 mm subangular blocky peds parting to moderate, 2–5 mm polyhedral peds; rough ped fabric; fine cracks, few, very fine macropores; very weak consistence (moist); common, fine manganiferous nodules. Abundant, very fine roots. Field pH 5.5.
		Smooth and gradual to:
A_{21}	24–37	Brownish grey (7.5YR 4/1) loamy clay; few, fine, distinct red mottles; weak, 10–20 mm subangular blocky peds parting to moderate, 2–5 mm subangular blocky peds; rough ped fabric; fine cracks, few, very fine macropores; very weak consistence (moist); many, fine manganiferous nodules. Abundant, very fine roots. Field pH 6.0.
		Smooth and gradual to:
A_{22}	37–50	Brown (7.5YR 4/3) light medium clay; very few, medium, moderately strong, dispersed, subangular pebbles; weak, 10–20 mm subangular blocky peds parting to moderate, 2–5 mm subangular blocky peds; rough ped fabric; fine cracks, few, very fine macropores; weak consistence (moist); many, fine ferromanganiferous nodules. Many, very fine roots. Field pH 6.5.
		Wavy and abrupt to:
B_{21}	50–88	Brown (10 YR 4/4) medium heavy clay; common, fine, distinct red mottles; strong, 50–100 mm prismatic peds parting to strong, 20–50 mm angular blocky peds, smooth ped fabric; many, prominent stress cutans; fine cracks; very strong consistence (dry); many, medium ferromanganiferous nodules. Many, very fine roots. Field pH 6.0.
		Smooth and gradual to:
B_{22}	88–120+	Brown (7.5YR 4/4) medium heavy clay; many, fine faint orange mottles; strong, 50–100 mm prismatic peds parting to strong, 20–50 mm angular blocky peds, smooth ped fabric; many, prominent stress cutans; fine cracks; very strong consistence (dry); common, medium ferromanganiferous nodules. Common, very fine roots. Field pH 7.0.

Table 2. Profile description for the lateritic podzolic soil type.

Location: Lower end of Plot 4, Big Ridge 2
Type of soil observation: Soil pit
Described by: Kerry Greenwood and Janelle Douglas
Date: 25/3/94

Classification: Northcote Key: Dy5.42
Great Soil Group: Lateritic podzolic
Australian Soil Classification: Brown chromosol

Horizon	Depth (cm)	Morphology
A_1	0–16	Greyish brown (7.5YR 4/2) clay loam; moderate, 20–50 mm subangular blocky peds parting to 2–5 mm subangular blocky peds; rough ped fabric; many, very fine macropores; weak consistence (moderately moist); few, fine manganiferous nodules. Abundant, very fine roots. Field pH 5.5.
		Smooth and clear to:
A_{2e}	16–26	Light grey (7.5 YR 5/3—moist, 10YR 7/1—dry) clay loam, sandy; moderate, 10–20 mm subangular blocky peds parting to 2–5 mm subangular blocky peds; rough ped fabric; few, very fine macropores; very firm consistence (dry); many, medium ferromanganiferous nodules. Many, very fine roots. Field pH 6.0.
		Smooth and gradual to:
B_{21}	26–47	Greyish brown (5YR 5/2) light medium clay; common, fine, distinct, red mottles; moderate, 10–20 mm subangular blocky peds parting to 2–5 mm subangular blocky peds; rough ped fabric; few, very fine macropores; very firm consistence (dry); common, fine ferromanganiferous nodules. Many, very fine roots. Field pH 6.5.
		Smooth and gradual to:
B_{22}	47–105	Ironstone layer with many, fine, distinct, red mottles; moderate, 5–10 mm subangular blocky peds (?), rough ped fabric; few, very fine macropores; strong consistence (dry); very many, medium ferromanganiferous nodules. Few, very fine roots. Field pH 6.0.
		Wavy and gradual to:
B_{23}	105–180+	Yellowish brown (10YR 5/8) heavy clay; few, coarse, prominent, grey colour patterns due to biological mixing of soil material from other horizons; strong, 50–100 mm subangular blocky peds parting to 20–50 mm subangular blocky peds, smooth ped fabric; many, prominent slickensides; strong consistence (dry); few, medium ferromanganiferous nodules. Few, very fine roots. Field pH 7.0.

Table 3. Profile description for the prairie soil type.

Location: Adjacent to the eastern side of Plot 3, Big Ridge 1
Type of soil observation: Soil pit
Described by: Kerry Greenwood
Date: 13/12/93

Classification: Northcote Key: Gn4.12
Great Soil Group: Prairie (Schafer 1980)
Australian Soil Classification: Red ferrosol

Horizon	Depth (cm)	Morphology
A_1	0–13	Dull reddish brown (5YR 4/4) clay loam; strong, 20–50 mm subangular blocky peds parting to moderate, 2–5 mm subangular blocky peds; rough ped fabric; fine cracks; few, very fine macropores; weak consistence (moderately moist); few, fine, manganiferous nodules. Abundant, very fine roots. Field pH 5.5.
		Smooth and gradual to:
A_{31}	13–31	Dark reddish brown (5YR 3/4) clay loam; moderate, 2–5 mm subangular blocky peds; rough ped fabric; fine cracks; few, very fine macropores; weak consistence (moderately moist); few, fine, manganiferous nodules. Many, very fine roots. Field pH 6.5.
		Smooth and gradual to:
A_{32}	31–53	Dark reddish brown (5YR 3/6) clay loam; moderate, 2–5 mm subangular blocky peds; rough ped fabric; fine cracks; few, very fine macropores; weak consistence (moderately moist); common, medium, manganiferous nodules. Many, very fine roots. Field pH 7.0.
		Smooth and gradual to:
B_{21}	53–85	Reddish brown (5 YR 4/6) light clay; very few, medium, moderately strong, dispersed, subangular pebbles; moderate, 10–20 mm subangular blocky peds parting to moderate, 2–5 mm subangular blocky peds, rough ped fabric; fine cracks; many, very fine macropores; very firm consistence (dry); many, medium, ferromanganiferous nodules. Many, very fine roots. Field pH 7.0.
		Smooth and gradual to:
B_{22}	85–110+	Dull reddish brown (5YR 4/4) light clay; moderate, 10–20 mm subangular blocky peds parting to moderate, 2–5 mm subangular blocky peds, rough ped fabric; fine cracks; many, very fine macropores; very firm consistence (dry); very many, medium, ferromanganiferous nodules. Common, very fine roots. Field pH 6.5.

Table 4. Profile description for the wiesenboden (lateritic).

Location: Adjacent to the northern side of Plot 8, Big Ridge 1
Type of soil observation: Soil pit
Described by: Kerry Greenwood and Janelle Douglas
Date: 25/3/94

Classification:	Northcote Key: Gn4.82
	Great Soil Group: Wiesenboden (lateritic) (Schafer 1980)
	Australian Soil Classification: Brown ferrosol

Horizon	Depth (cm)	Morphology
A_1	0–18	Brown (7.5YR 4/3) clay loam; few, fine, distinct, red mottles; moderate, 20–50 mm subangular blocky peds parting to 2–5 mm subangular blocky peds; rough ped fabric; common, very fine macropores; firm consistence (dry); few, fine manganiferous nodules. Abundant, very fine roots. Field pH 6.0.
		Wavy and gradual to:
B_{21}	18–32	Bright brown (7.5 YR 5/6) light clay; moderate, 10–20 mm subangular blocky peds parting to 2–5 mm subangular blocky peds; rough ped fabric; common, very fine macropores; firm consistence (dry); common, medium ferromanganiferous nodules. Many, very fine roots. Field pH 7.0.
		Smooth and clear to
B_{22}	32–43	Bright reddish brown (5YR 5/6) light clay; few, fine, faint, red and brown mottles; weak, 2–5 mm subangular blocky peds; rough ped fabric; few, very fine macropores; very firm consistence (dry); many, medium ferromanganiferous nodules. Many, very fine roots. Field pH 7.0.
		Smooth and clear to
B_{23m}	43+	Moderately cemented, continuous, nodular, ferricrete pan with very few, dispersed, moderately strong, subrounded, large basalt pebbles.

References

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Stace, H. C. T., Hubble, G. D., Brewer, R., Northcote, K. H., Sleeman, J. R., Mulcahy, M. J., and Hallsworth, E. G. (1968). 'A Handbook of Australian Soils'. (Rellim Technical Publications: Glenside, S. Aust.)

Appendix II

Neutron Probe Calibration Data

The neutron probe was calibrated at four locations adjacent to the experimental area. These locations were chosen to cover the range of soil types identified: gleyed podzolic, lateritic podzolic, prairie and lateritic wiesenboden soil types. At each location, three access tubes were installed and, after 32 second neutron probe counts were made, undisturbed cores were collected from a backhoe pit adjacent to one of the access tubes. Sampling was undertaken when the soil was dry, moist and intermediate. In two of the soil types, it was not possible to take core samples at lower depths to due to a hard ironstone layer. In these cases, volumetric water content was calculated from the gravimetric water content and bulk density, determined using the Saran resin method (Brasher *et al.* 1966; Blake and Hartge 1986). The calibrations for each depth were calculated according to Greacen *et al.* (1981) and are included in Tables 1–4. Data from adjacent depths were combined when the depths appeared to have the same calibration equations.

The calibrations for the lateritic wiesenboden at 60–80 cm depth were obviously in error and a new calibration was derived using a representative slope fitted through the average of the relevant data points.

The bulk density at each depth in each soil type is given in Table 5.

Table 1. Neutron probe calibration coefficients for the gleyed podzolic soil type. The general equation is $\theta = (RCR - a')/b'$ where θ is the volumetric moisture content (m^3/m^3) and *RCR* is the relative count ratio from the neutron probe. Calibrations were made for two neutron probes (NP1 and NP2) and corrected for bias as described by Greacen *et al.* (1981). The coefficients of determination (r^2) were determined before correcting the calibration equations for bias.

	NP1			NP2		
Depth (cm)	*a'*	*b'*	r^2	*a'*	*b'*	r^2
10	0.086	1.1	0.96	0.131	1.01	0.95
20	0.114	1.2	0.96	0.150	1.16	0.97
30	0.091	1.5	0.95	0.125	1.43	0.95
40	0.104	1.3	0.97	0.110	1.38	0.97
50	0.212	1.1	0.97	0.210	1.24	0.97
60	0.153	1.2	0.85	-0.035	1.76	0.92
70	0.173	1.2	0.44	0.245	1.06	0.64
80	0.101	1.3	0.71	0.132	1.32	0.76
90	-0.127	1.9	0.83	0.050	1.51	0.85
100	-0.081	1.8	0.87	-0.010	1.65	0.86
Combined Depths						
70–80	0.123	1.3	0.59	0.179	1.21	0.72
90–100	-0.106	1.8	0.84	0.010	1.60	0.85

Table 2. Neutron probe calibration coefficients for the lateritic podzolic soil type. The general equation is $\theta = (RCR - a')/b'$ where θ is the volumetric moisture content (m^3/m^3) and *RCR* is the relative count ratio from the neutron probe. Calibrations were made for two neutron probes (NP1 and NP2) and corrected for bias as described by Greacen *et al.* (1981). The coefficients of determination (r^2) were determined before correcting the calibration equations for bias.

	NP1			NP2		
Depth (cm)	*a'*	*b'*	r^2	*a'*	*b'*	r^2
10	0.093	1.0	0.99	0.118	1.11	0.99
20	0.093	1.4	0.96	0.107	1.44	0.96
30	0.160	1.1	0.99	0.182	1.13	0.98
40	0.228	0.9	0.84	0.258	0.87	0.76
50	-0.044	1.8	0.53	-0.094	2.09	0.51
60	-0.003	1.5	0.31	0.010	1.59	0.22
70	0.151	1.2	0.46	0.092	1.51	0.69
80	0.256	0.9	0.58	0.267	0.95	0.59
90*	0.487	0.1	0.70	0.471	0.27	0.70
100*	0.193	1.1	0.61	0.126	1.34	0.61

* Two calibration points only (compared with three for other depths).

Table 3. Neutron probe calibration coefficients for the prairie soil type. The general equation is $\theta = (RCR - a')/b'$ where θ is the volumetric moisture content (m^3/m^3) and *RCR* is the relative count ratio from the neutron probe. Calibrations were made for two neutron probes (NP1 and NP2) and corrected for bias as described by Greacen *et al* (1981). The coefficients of determination (r^2) were determined before correcting the calibration equations for bias.

	NP1			NP2		
Depth (cm)	*a'*	*b*	r^2	*a'*	*b'*	r^2
10	0.027	1.25	0.91	0.095	1.14	0.94
20	0.119	1.14	0.96	0.142	1.13	0.95
30	0.096	1.27	0.96	0.142	1.18	0.97
40	0.041	1.49	0.90	0.100	1.34	0.89
50	0.004	1.65	0.85	0.024	1.69	0.80
60	-0.002	1.71	0.95	0.023	1.77	0.89
70(*NP1)	-0.397	3.02	0.48	0.078	1.56	0.90
80	0.084	1.34	0.92	0.099	1.45	0.91
90	0.043	1.50	0.85	-0.010	1.91	0.76
100*	0.107	1.35	0.96	0.032	1.90	0.96
Combined Depths						
70–80	0.000	1.69	0.90	0.024	1.73	0.84
90–100	0.064	1.44	0.91	0.086	1.51	0.90

* Two calibration points only (compared with three for other depths).

Table 4. Neutron probe calibration coefficients for the lateritic wiesenboden soil type. The general equation is $\theta = (RCR - a')/b'$ where θ is the volumetric moisture content (m^3/m^3) and *RCR* is the relative count ratio from the neutron probe. Calibrations were made for two neutron probes (NP1 and NP2) and corrected for bias as described by Greacen *et al.* (1981). The coefficients of determination (r^2) were determined before correcting the calibration equations for bias.

	NP1			NP2		
Depth (cm)	*a'*	*b'*	r^2	*a'*	*b'*	r^2
10	0.060	1.22	0.67	0.039	1.42	0.81
20	0.344	0.63	0.92	0.372	0.58	0.91
30	0.338	0.72	0.77	0.393	0.60	0.77
40	0.145	1.24	0.82	0.201	1.12	0.82
50	0.134	1.25	0.90	0.187	1.12	0.89
60*	1.255	-2.53	0.17	1.082	-1.90	0.17
70*	0.699	-0.48	0.76	0.644	-0.35	0.76
80*	1.981	-4.43	0.60	1.718	-3.58	0.60
Combined Depths						
40–50	0.129	1.28	0.87	0.178	1.17	0.86

* Two calibration points only (compared with three for other depths). The calibration actually used for 60, 70 and 80 cm depth was calculated from a line of slope $b'=1.40$ passing through an "average" point for the data. The value for the slope was chosen after looking at data for the ironstone layers in the lateritic podzolic soil type.

Table 5. Bulk density (Mg/m^3) at 10 cm depth intervals for each soil type.

Depth (cm)	Gleyed podzolic	Lateritic podzolic	Prairie	Lateritic wiesenboden
10	1.40	1.52	1.46	1.34
20	1.52	1.70	1.54	1.36
30	1.57	1.63	1.53	1.38
40	1.46	1.97	1.61	1.53
50	1.40	1.99	1.67	1.79
60	1.38	2.18	1.66	2.07
70	1.35	2.21	1.75	2.04
80	1.41	2.17	1.79	1.98
90	1.44	1.87	1.77	—
100	1.55	1.63	1.80	—

References

Blake, G. R., and Hartge, K. H. (1986). Bulk density. In 'Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods'. (Ed. A. Klute.) pp. 363-75 (ASA/SSSA: Madison, Wisconsin.)

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Greacen, E. L., Correll, R. L., Cunningham, R. B., Johns, G. G., and Nicolls, K. D. (1981). Calibration. In 'Soil Water Assessment by the Neutron Method'. (Ed. E. L. Greacen.) pp. 50-81 (CSIRO: Australia.)

Appendix III

Conference Papers

The following abstracts have been presented at conferences during the course of this research project and are reproduced in this appendix.

Greenwood, K. L. (1994). Soils: downtrodden or compacted? In 'Dollars or Dirt? ...The Answer Lies in the Soil'. Glen Innes Natural Resources Advisory Committee Seminar on Soils.

Greenwood, K. L., Hutchinson, K. J., MacLeod, D. A., and Scott, J. M. (1995). Stocking rate affects soil moisture under pasture. Proceedings of the Tenth Annual Conference of the Grassland Society of New South Wales, Armidale, NSW. p. 114.

Greenwood, K. L. (1996). Colour images enhance interpretation of soil water content data. Proceedings of the Australian and New Zealand National Soils Conference, Melbourne. Vol. 3 pp. 89-90.

Greenwood, K. L., MacLeod, D. A., and Hutchinson, K. J. (1996). Long term grazing effects on soil physical properties. Proceedings of the Australian and New Zealand National Soils Conference, Melbourne. Vol. 2 pp. 101-2.

Soils: Downtrodden or Compacted?

Kerry Greenwood
Postgraduate Student
CSIRO Div. of Animal Production/University of New England

Paper presented to Glen Innes Natural
Resources Advisory Committee
seminar on soils:

"Dollars or Dirt?
...the answer lies in the soil"

Friday, 15th April, 1994

Introduction

There has been a lot of research and farmer interest in compaction on agricultural land. The compaction is caused by heavy farm machinery and tillage equipment. But compaction can also occur on grazing lands due to the impact of the hooves of the grazing animal and, over time, pasture production can be affected. There has been relatively little research on the effects of grazing on compaction and other aspects of soil structure. There is even less research on management to alleviate or minimise the problem.

Grazing can be divided into three separate actions: treading, defoliation and return of excreta. This paper focuses on the treading effect of grazing and its influence on soil physical properties, especially compaction.

What is Compaction?

Compaction is the reduction in volume of a given mass of soil - that is, an increase in the bulk density of the soil. Soil physical problems may involve other problems besides compaction - for example, rearrangement of the soil aggregates may occur which increases the soil strength. Treading in very wet conditions can produce pugging (or poaching) where the soil is remoulded but not compacted.

How Downtrodden?

The average hoof pressure of sheep, cattle and other grazing animals when standing is shown in Table 1. The actual pressure exerted on the ground when the animal is moving however is much greater due to the body weight being supported by only 2-3 feet and additional pressures from movement. For example a 530 kg cow exerted a pressure underfoot when walking of 300 kPa (Scholefield *et al.*, 1985).

Table 1. Average foot pressures of grazing animals when standing.

Animal	Liveweight (kg)	Foot Area (cm^2)	Static Pressure (kPa)
Camel	450-650	4x411	27-39
Kangaroo	30-66	2x36	41-90
Sheep	40-55	4x21	47-64
Cattle	500-600	4x115	76-92
Horse	400-700	4x184	53-93

Source: Noble and Tongway (1986)

It has been calculated that sheep take approximately 8000 to 10000 steps per day. Multiply this by the hoof area and, on average, an estimated 0.6-0.8 ha of pasture is trodden by one sheep each year. For a paddock stocked at 10 sheep/ha for 10 years, each area of ground would be trodden 60-80 times, on average.

Effects of Treading

Compaction is the main effect of animal treading but there are also other related effects of treading. These are discussed in the following paragraphs:

Loss of Pore Space

Where compaction has occurred, there is an increase in the bulk density of the soil. The soil particles themselves do not compact but rather there is a loss of pore space between the particles. This pore space may have contained either air or water. Figure 1 shows that is mainly the larger pores which are "lost" due to compaction. The loss of pore space reduces the habitat for soil organisms, especially those which cannot excavate soil. Loss of pore space also makes it more difficult for roots to grow through the soil and percolation of water through the soil is slowed.

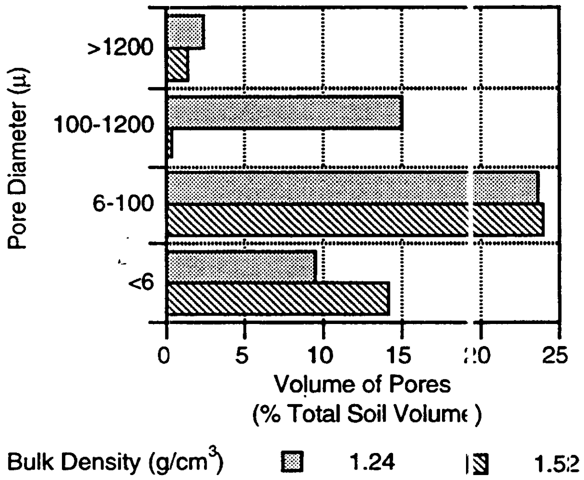

Figure 1. Bulk density increases at the expense of loss of large pores.

Source: Schuurman (1965).

Decreased Infiltration and Increased Runoff

One the major deleterious effects of compaction on soil is a reduction of the infiltration rate of water into and through the soil. Figure 2 shows the results of some infiltration measurements taken on 30 y.o. pasture grazed at four stocking rates. The highest infiltration rates were obtained on the ungrazed pasture and the lowest infiltration rates on the heavily grazed pasture. The infiltration rates on the low and medium stocking rates were intermediate.

When the rainfall intensity is greater than the soil's infiltration rate, runoff occurs. For the pastures studied in Figure 2, runoff is most likely to occur on the highest stocking rate. For intense falls of rain, such as occur during storms, a large proportion of the rainfall may run off an overgrazed pasture while all the rain infiltrates into the soil of a lightly grazed pasture.

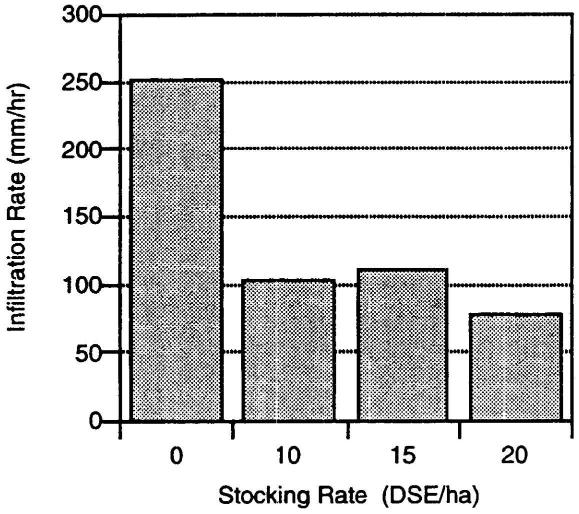

Figure 2. Infiltration of water into soil under pasture grazed at four stocking rates for 30 years. (Measured using a disc permeameter at 10 mm tension).

Less Water Available for Plants

Loss of water from the pasture via runoff results in less water being available for plant growth. Usually, the higher the stocking rate, the lower the available moisture content of the soil. A lightly grazed pasture will have more water available for growth and the additonal standing pasture and litter will act as a mulch to reduce evaporation from the surface of the soil.

Increased Soil Strength

Soil strength can increase under grazing due to compaction of the soil or due to rearrangement of the soil particles. As soil dries, strength increases. High soil strengths restrict root growth and can often inhibit root growth even when water is not limiting growth. The availability of moisture under degraded and ideal soil conditions, as affected by soil strength, is compared in Figure 3.

Pasture Yield and Botanical Composition

Some early work by Edmond (1958, 1963) in New Zealand examined the effect of treading alone on pasture. He studied treading by walking sheep up and down a wide race a predetermined number of times which he had calculated to simulate various stocking rates. Not only did higher rates of treading

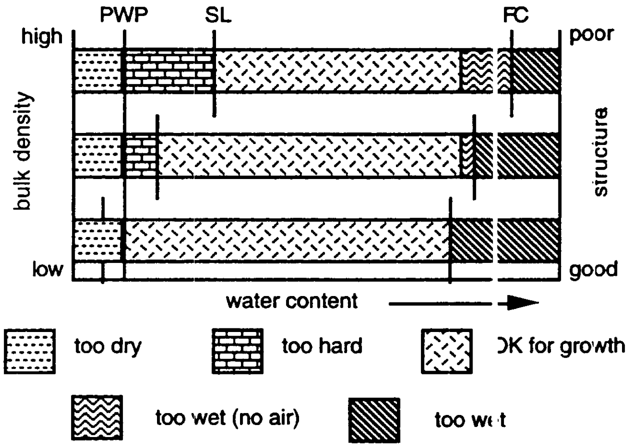

Figure 3. Effect of soil structure and soil strength on plant available water. Poorly structured soils usually have poor aeration when wet, and high soil strength when dry limits root growth. PWP - permanent wilting point (too dry for plant growth); SL - strength limit (roots are unable to grow when soil is drier than this limit due to high soil strength); FC - field capacity (water above this limit is not available because it readily drains).

Source: adapted from Letey (1985).

decrease pasture production but there was also an effect on the pasture species. White clover was sensitive to treading while ryegrass appeared to be more tolerant (Figure 4).

Factors Affecting Compaction

Moisture Content

Compaction of soil occurs when the soil is wetter than a critical limit. When the soil is wet, it is often not strong enough to withstand the load of a grazing animal and the soil structure collapses resulting in an increase in the bulk density of the soil. When the soil is very wet, pugging or remoulding of the soil occurs. Dry soil is unlikely to be compacted unless it is very loosely structured.

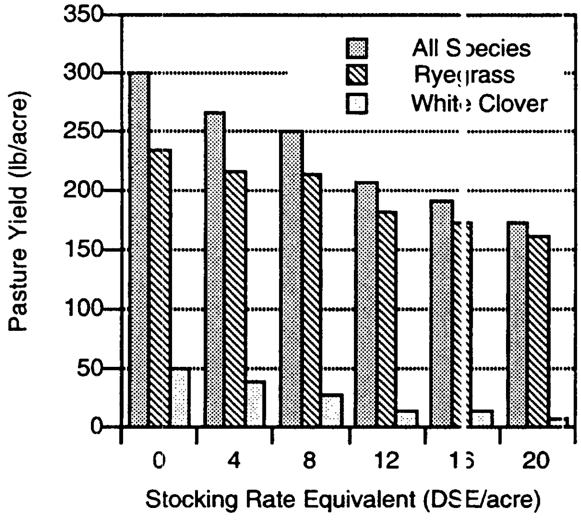

Figure 4. Effect of treading on yield of pasture species.

Source: Edmond (1958).

Initial Bulk Density

There is very little "elasticity" in soil so that once soil is compacted, it does not "bounce back". If an area is compacted twice by the same force, most of the effect will occur with the first compaction. In a grazing situation, the effect of heavier stocking is probably to affect a greater proportion of the paddock rather than to increase the degree of compaction.

Pasture Condition

Soil under pasture is probably less likely to compact than a bare soil. The pasture would absorb some of the impact of treading and the roots would act as reinforcement giving the soil more strength to resist deformation. Organic matter from faeces and decomposing plant material may also help the soil resist compaction.

Soil Type

Coarse textured soils such as granite soils are well drained with large soil particles. These soils are probably least susceptible to compaction by grazing. Loamy and fine textured soils are both readily compacted given the right conditions. However, the shrink-swell properties of clay soils, which cause cracking, gives them a natural regenerative capacity. Thus, it is the loamy textured soils, such as trap soils, which exhibit the most compaction.

Management

Do You Have a Compaction Problem?

It is likely that most soils under grazed pasture will be compacted to some extent.

Compaction is not really a problem unless it is limiting the productivity of the pasture.

A spade full of soil can be visually assessed to determine whether there are structural problems. A soil with good structure will be mostly aggregates of 1-10 mm diameter. Massive soil structures or soils consisting of very fine material only are not as desirable.

If runoff occurs frequently then water essential to pasture growth is being wasted. If soil strength is too high, even when water is not limiting root growth, then productivity is limited. Evidence of runoff can be seen during the storm itself or from the swales of seeds and litter fragments deposited by the runoff. High soil strength can be measured using a cone penetrometer or may be evident from stunted root growth or roots growing at odd angles.

Getting Rid of Compaction

As I mentioned at the start of this paper, there is very little information on managing soil physical problems under grazing situations. The following notes are some of my ideas which have not been tested.

Research in the United States has shown that an area would need to be excluded from grazing for at least two years for soil structure to regenerate naturally by the action of roots and soil organisms. Trials are currently underway at CSIRO's Pastoral Research Laboratory at "Chiswick" to determine whether a similar length of time is required under local conditions.

Clay soils, such as basalt soils, are able to regenerate soil structure by shrinking and swelling with changes in moisture content. The structure of these soils is most likely to improve after a period of no-grazing.

In severe cases, it may be worth ploughing or chiselling a pasture to a depth of about 20 cm to break up the compacted surface soil. This would be costly and there would be no guarantee that problems would not recur very quickly. It may be worth trialing using a test strip, similar to fertiliser test strips, to determine to what extent productivity is increased by chiselling. An adjacent area should be left untreated but under the same grazing management as a control to provide a valid comparison. Grazing may need to be excluded for a while to allow the soil to settle naturally. Besides alleviating compaction, cultivation may result in a release of nutrients from the soil (mineralisation) and nutrients would also be more available as roots are better able to exploit the soil.

Avoiding Compaction

It may be possible to manage grazing to minimise compaction, at least on the most productive pastures of the property. As most compaction occurs when the soil is wet, grazing at these times could be limited to the better drained paddocks, for example, those on higher ground or granite soils. Pastures in low-lying areas which are likely to be wet for longer periods would be better grazed when they are dry. Areas of pasture which are not as productive could be grazed when wet with the productivity of the best pastures being maintained by avoiding grazing during wet periods.

Summary

The major cause and effect pathways relating compaction to plant growth are summarised in Figure 5. The relationships are quite complex, and, if decreased plant growth makes pasture soils more susceptible to compaction, a vicious cycle is created. However, with current awareness of pasture degradation and the desire for sustainable grazing systems, soil compaction under grazing situations should be able to be minimised.

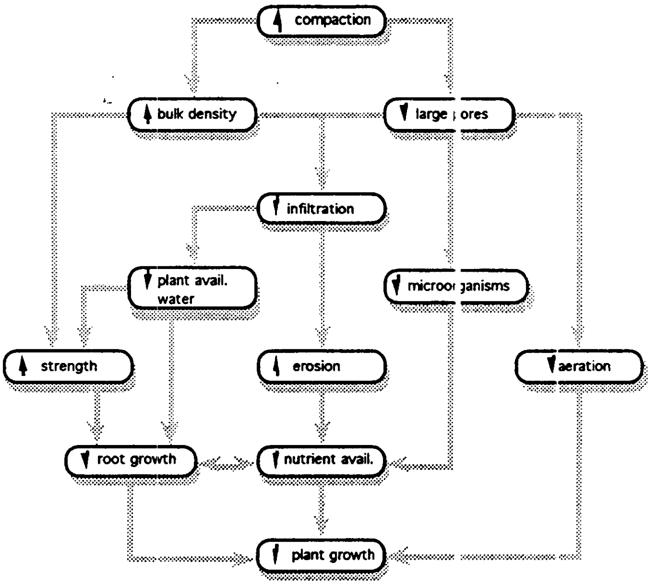

Figure 5. A summary of cause and effect pathways between compaction and plant growth. The small arrows in the "boxes" indicate the direction of the effect e.g. decreased infiltration leads to decreased plant available water.

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Stocking rate affects soil moisture under pasture

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The competing effects of lower evapotranspiration and lower infiltration rates with higher stocking rate (SR) on soil moisture found by Langlands and Bennett (1973), are likely to be complicated further after long term grazing where botanical composition is also changed (Hutchinson 1992). This research examines the relationship between soil moisture tension and SR after long term grazing by sheep.

Methods

The experimental site is a 30 year grazing trial at CSIRO's "Chiswick" Pastoral Research Laboratory, Armidale, NSW. Soil moisture tension was measured using puncture-type tensiometers (Marthaler *et al.* 1983) when the soil was moist and filter papers (Greacen *et al.* 1989) during dry periods at depths of 10 and 20 cm. Fortnightly measurements were taken between September 1993 and January 1995 – a period which included a severe drought – at four random sites in two replicate plots grazed at 0, 10, 15 and 20 sheep/ha.

Results and Discussion

At most measurement times, the upper 20 cm of soil under the lower SRs was wetter. However, after long, dry periods in winter and spring, there was still plant available moisture at the high SR (Table 1). During summer and autumn, the high SR was much drier possibly due to the dominance of summer growing plants in this pasture. Evaporation from the ungrazed pasture would be much lower due to the mulching effect of approximately 5 cm litter. In contrast, at the high SR, litter was minimal and this may also contribute to the drier soil moisture conditions at some times of the year.

Table 1. Soil moisture tension (kPa) for a range of SRs. The drier the soil, the higher the soil moisture tension: 10 kPa is field capacity,1500 kPa is permanent wilting point. At the highest SR, the soil was driest after rain in summer, and yet soil moisture was still available after two weeks without rain in spring.

Date	17 Feb., 1994		27 Sept., 1994	
Prev. 7 day rainfall (mm)	43		0	
Prev. 14 day rainfall (mm)	57		0	
Depth (cm)	10	20	10	20
Stocking Rate (DSE/ha)				
0	398	162	1500	1500
10	591	302	1500	1360
15	420	212	800	900
20	1000	446	720	728

Conclusion

The relationship between soil moisture and SR after long term grazing by sheep may depend not only on evapotranspiration and water infiltration rates, but also changes in the botanical composition of the pasture.

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Colour Images Enhance Interpretation of Soil Water Content Data

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Introduction

Large amounts of data are often collected in soil water studies using neutron probes. Traditionally, the data have been presented as either changes in total profile water content over time or by comparing the profile distribution of soil water content for selected dates or treatments. This form of data presentation is often limited by the number of points which can be shown clearly on each graph.

Colour contour plots offer the advantage of being able to display large amounts of data in one image. In fact, larger data sets are preferable to smaller ones. This paper describes some applications of colour contour plots to soil water studies.

Materials and methods

Colour contour plots can be produced from soil profile data of water content collected over time. Time is represented on the x-axis of the plot and depth on the y-axis. Appropriate colours are used to indicate the range of water contents. Separate images can be generated from data for each neutron probe access tube, or data may be averaged to generate images for each treatment.

Examples of the use of colour contour plots in this paper used a data set collected from a long term stocking rate trial at CSIRO's Pastoral Research Laboratory near Armidale, NSW (Hutchinson *et al.* 1995). Data were collected from 64 access tubes, at 10 cm intervals to 80 cm, every 2–3 weeks from April 1993 to June 1995.

Data for each access tube were arranged into a matrix with rows for each depth and columns for each measurement date. Simple, scaled images and interpolated (smoothed) images were generated from this text data using Spyglass® Transform on an Apple Macintosh computer. A number of pre-defined colour tables are available but, in this case, a user-defined colour table, to reflect soil water conditions, was used. Once a suitable template had been made with the desired output format, the software's macro facility enabled new plots to be generated or updated easily. Spyglass® Format was used to annotate the images for presentation.

Results and discussion

Colour images enabled a number of features to be easily identified in the sample data set to be presented in the poster. The frequent changes in soil water content near the soil surface, characterised by large variations of colour along the top of the image, contrasted with the slow drying of the soil at depth, where colour changes were small. The average rainfall during winter 1993 and good rain in January 1995 were associated with "wet" colours in contrast to the other periods of below average rainfall. After significant rainfall, there was a time lag of 3–6 weeks before the soil water content at 80 cm depth started to increase.

Differences between the soil water distribution for the ungrazed and high stocking rate treatments could be qualitatively assessed by comparing images for each treatment. The ungrazed pasture tended to have a higher soil water content than grazed pasture most of the time. This was particularly evident near the soil surface. Differences between treatments can be highlighted by "subtracting" one image from another.

Spurious data points, caused in this data set by a malfunctioning neutron probe cable and incorrect identification of access tubes, were detected by producing simple, scaled colour plots for each access tube where each data point remains as a separate pixel i.e. the data were not interpolated. If plots are updated after each data collection, errors can be found and remedied quickly.

Colour contour plots allow interesting parts of the data set to be identified for more intensive analysis. They have also been useful for poster and seminar presentations, to illustrate the effect of stocking rate on soil water distribution under pasture, to farmer groups and scientific colleagues. Colour contouring may also be useful for presentation other soil data which change with depth and time.

Desirable features in a contouring package for producing colour images of soil water data include an ability to accept irregularly spaced data, facility to automate the task of producing the colour contour images and the flexibility to generate user-defined colour tables.

Conclusions

Colour contour images of soil water content changes with time are a powerful tool for exploratory data analysis in soil water studies, especially for large data sets. The colour contour plots can be used for qualitative assessment of treatment differences, detection of spurious data points and for group presentations.

Acknowledgments

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Long Term Grazing Effects on Soil Physical Properties

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Introduction

Grazing animals exert a pressure on the ground which is comparable to that of agricultural machinery and, as a result, soil under pasture can be compacted. Under continuous grazing at 10 sheep/ha, each area of pasture will be trodden an average of about 25 times per year. In grazing systems based on permanent pastures, there is little opportunity to ameliorate poor soil physical conditions through tillage.

Previous papers have reported that detrimental effects of grazing on soil physical properties are not as great at lower stocking rates (Langlands and Bennett 1973; Curll and Wilkins 1983), but these studies were undertaken on pastures less than five years old. This study was undertaken to determine the effects of long term grazing at a range of stocking rates on selected soil physical properties.

Methods

Field measurements of unsaturated hydraulic conductivity, soil strength and profile water content were taken at a 30 year old stocking rate trial at CSIRO's Pastoral Research Laboratory at Armidale, NSW. At the time of sampling, the stocking rates were 0,10,15 and 20 sheep/ha. Each paddock was 45 by 90 m. Treatments were replicated four times, forming a Latin square design.

Unsaturated hydraulic conductivity was measured using disc permeameters (Perroux and White 1988) at tensions of 5, 15, 25 and 35 mm water (Reynolds 1993). Calculation of the conductivity from measurements of steady state flow followed the method of Ankeny *et al.* (1991). Eight measurements were made in each paddock and log transformed data were used to compare treatment effects using analysis of variance (AOV). Data for each infiltration tension were analysed separately.

Gravimetric water content was determined from samples collected at two sites in each paddock on 16 January 1995. Samples were taken at 5 cm depth intervals from 2.5 to 27.5 cm using a 3.9 cm diameter corer. Data for each depth were compared using AOV.

Soil strength was measured using a cone penetrometer at two sites in each paddock. The 30° cone had a 1.0 cm base diameter. Ten probes were made at each site, recording soil strength at 0.5 cm depth increments to 32.5 cm but these data were then averaged over 5.0 cm depth intervals from 2.5 to 22.5 cm. The gravimetric soil water content was determined from samples taken at the same depth intervals. Measurements of soil strength were repeated at a range of soil water contents. Exponential relationships between strength and gravimetric water content were fitted with the predicted strength, at water contents of 0.10, 0.15 and 0.20 kg/kg, for each depth analysed (AOV) separately.

Results

The ungrazed treatment had a significantly ($P<0.05$) higher unsaturated hydraulic conductivity at 5 and 15 mm tension (Table 1). There were no significant differences in conductivity at tensions of 25 and 35 mm water.

Table 1. Stocking rate effects on unsaturated hydraulic conductivity (mm/hr) at four tensions. The means and standard errors of the log transformed data are shown in brackets.

	Tension (mm water)			
Sheep/ha	35	25	15	5
0	3.6 (1.3)	6.6 (1.9)	31.0 (3.4)	190 (5.3)
10	4.4 (1.5)	6.7 (1.9)	15.7 (2.8)	61 (4.1)
15	4.9 (1.6)	7.2 (2.0)	15.2 (2.7)	49 (3.9)
20	4.3 (1.5)	6.3 (1.8)	13.2 (2.6)	46 (3.8)
s.e.	(0.25)	(0.25)	(0.21)	(0.19)

Soil water content on 16 January 1995 was significantly higher at all depths to 25 cm under the ungrazed pasture (Fig. 1a). Water contents were lower at higher stocking rates.

There were no significant differences between soil strengths at different stocking rates when compared at the same water content. However, there was a trend ($P<0.15$) for soil strength to be lower in the ungrazed treatment at 2.5–7.5 cm depth at a water content of 0.15 kg/kg (Fig. 1b). Soil strength increased with depth and decreased with water content. Differences in soil strength between the three grazed treatments at all depths were small.

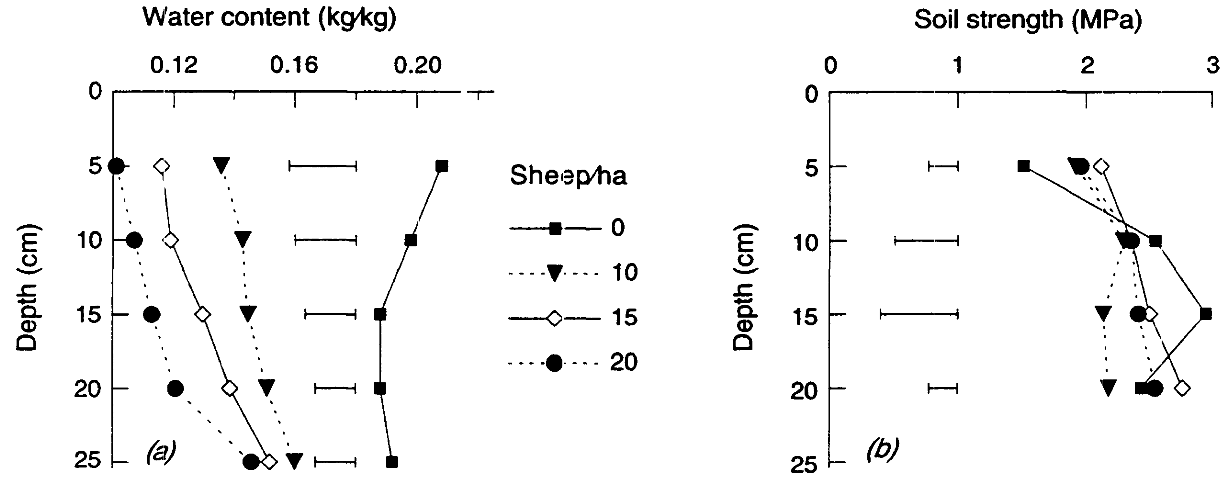

Fig. 1. Stocking rates effects on a) gravimetric water content measured on 16 January, 1995 and b) predicted soil strength at a water content of 0.15 kg/kg. The bars indicate one standard error.

Discussion

Surface soil hydraulic properties indicate that the decline in unsaturated hydraulic conductivity with grazing is due mainly to loss of larger pores (>1.2 mm diameter). This loss of larger pores is consistent with other studies which have found that compaction reduces macroporosity. The low unsaturated hydraulic conductivities at high stocking rates indicate that, at high rainfall intensities, runoff may occur. This would result in less water being available for pasture growth under the higher stocking rates.

The lack of significant differences in soil strength between treatments is due to high spatial variability and the presence of iron and manganese nodules throughout the profile. However, the trends between stocking rates suggest that high soil strength would limit root growth in the surface soil of the grazed treatments more frequently than under the ungrazed treatment due to higher soil strength at equivalent water contents and also greater frequency of drier soil under the grazed treatments. These high strengths at the soil surface may reduce the success of pasture establishment where the soil remains undisturbed. High soil strengths under perennial pasture, however, may not be as great a problem as under annual crops, as root growth can occur during favourable wet periods.

The significantly higher soil water content under the ungrazed treatment, as measured on 16 January 1995, has often been noted during routine neutron probe measurements at the site. During the drought periods of 1993–95, the higher soil water contents under the lower stocking rate treatments were probably due to low evapotranspiration rates. Evaporation from the ungrazed pasture would have been lower than on the grazed pasture due to the mulching effect of approximately 5 cm of litter.

Conclusions

The greatest differences in soil physical properties after long term grazing by sheep were between grazed and ungrazed treatments. Soil physical properties may reach a common equilibria when grazed at different stocking rates (cf. ungrazed) for a long time, which is not shown by short term experiments. Soil water content and unsaturated hydraulic conductivity were more sensitive to stocking rate effects than soil strength, at this site. The effects of grazing on soil physical properties under permanent pastures are probably limited to the surface 5–10 cm of the soil.

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