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Land-use intensification in New Zealand: effects on soil properties and pasture production

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SUMMARY

Land-use intensification requires more farm inputs to sustain or increase farm product outputs. However, a common concern for land-use intensification is the potential deterioration of soil. The North Otago Rolling Downlands (NORD) region of New Zealand is drought prone, and although traditionally limited to extensive sheep farming, there are large-scale conversions to intensive cattle grazing operations such as dairy farming resulting from an irrigation scheme commissioned in 2006. Pallic soils (Aeric Fragiaqualf in US Soil Taxonomy) such as those in the NORD region are prone to soil compaction because of their 'high' structural vulnerability under intensive management. To address these concerns, a field trial was established on a common NORD Pallic soil (Timaru silt loam) to determine how land-use intensification affects indicators of soil quality (macroporosity, bulk density, structural condition score, total and mineralizable carbon and nitrogen and earthworms) and pasture production. The treatments compare irrigated *v.* dryland pasture and sheep *v.* cattle grazing on 16 plots. The findings show that soil physical quality responds more quickly to changes in land-use pressure than do biochemical and organic indicators. Both irrigation and cattle grazing, particularly in combination, increased soil compaction; macroporosity on irrigated plots grazed by cattle ranged from 9·1 to 13·3% v/v at a depth of 0–50 mm, compared to dryland plots with sheep grazing (18·9–23·0% v/v). Soil compaction/damage has implications for pasture production, soil hydrology and nutrient movement. Land management practices for intensive cattle grazing of irrigated soil prone to treading damage therefore need to implement high compaction risk strategies to avoid or ameliorate potential changes to soil quality.

INTRODUCTION

Agricultural intensification has been widespread in New Zealand over the past 15–20 years (MacLeod & Moller 2006) and is happening on soils more vulnerable to structural degradation or on farms with natural limitations requiring inputs such as irrigation water or artificial drainage systems (Anonymous 2007). One concern about intensification of agriculture is the potential deterioration of soil quality, particularly structural degradation and carbon sequestration. Soil quality or health is commonly perceived as a soil resource, which is 'fit for purpose' (Pierce & Larson 1993). An effectively functioning soil provides food and fibre for human consumption through key biological, chemical and physical activities, which produce a growing medium for plant production. Larson & Pierce (1991) defined soil quality as the capacity of a soil to function within the ecosystem boundaries and interact positively with the environment external to that ecosystem.

The North Otago Rolling Downlands (NORD) of New Zealand is one example of a region undergoing considerable land-use change and intensification as a result of a large community irrigation scheme (*c.* 10 000 ha) and related increases in pasture production, fertilizer inputs and animal carrying capacity (Houlbrooke *et al.* 2008). The NORD is dominated by Pallic soils (Hewitt 1998) (Aeric Fragiaqualf in US Soil Taxonomy) derived from fine-textured loessial material windblown from the Waitaki Valley (Morton *et al.* 1996). Pallic soil types are characterized by poorly structured subsoil with a pronounced fragipan

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(Cx horizon) below 500 mm, which limits water movement and root development (Hewitt 1998). Fragic Pallic soils (as found in the NORD) also have a high structural vulnerability (defined as a susceptibility to degradation) under intensive management, suggesting that land management practices should be monitored for long-term effects (Hewitt & Shepherd 1997). Under irrigation management, NORD pastoral land use has typically changed from traditional low-intensity dryland sheep farming (8–10 stock units/ha; su/ha, defined below) to a mix of intensive lamb or beef cattle finishing, dairy support grazing or dairy farming (>20 su/ha).

Most controlled studies into declining soil physical quality on Pallic soil types have considered single animal grazing types, not compared direct stock types (e.g. Drewry & Paton 2000). The effect of intensive cattle, sheep, and mixed sheep and cattle grazing systems on soil physical quality under Pallic soils has previously been examined in two separate studies using regional soil sampling under different land use (Drewry *et al.* 2000; Houlbrooke *et al.* 2008). In a survey of Pallic soils in the NORD region, Houlbrooke *et al.* (2008) reported greater bulk density under cattle-grazed farms compared to predominantly sheep-grazed farms, but no differences in macroporosity. This was explained by differences in winter grazing management and the common presence of cattle on predominantly sheep-grazed operations. Drewry *et al.* (2000) reported significant decreases in air permeability and saturated hydraulic conductivity on dairy farms in Southland compared with sheep farms across three soil orders (Pallic, Brown and Recent), but no significant differences in bulk density or macroporosity, as most dairy farms surveyed were on free draining and more resilient Brown and Recent soil orders. There was a significant soil order effect, with Fragic Pallic soils having the greatest bulk density and lowest macroporosity, independent of stock type. A survey of 500 New Zealand soils (Sparling & Schipper 2002) has collated soil quality data based on land use, and demonstrated a decrease in physical status (higher bulk density, lower macroporosity, lower water-holding capacity) of soils under intensive land uses such as dairy farming and arable cropping.

While soil physical status changes with differing animal grazing type and stocking intensity, there are few studies investigating the impacts of intensification as a direct result of adding irrigation water. As part of the NORD district survey of Pallic soils, Houlbrooke *et al.* (2008) reported a decrease in soil macroporosity between dryland and irrigated farms in the district, but no difference in soil bulk density. The length of time under irrigation had no effect on either soil macroporosity or bulk density under irrigated land use, suggesting that differences in soil quality occur shortly after intensification following the addition of irrigation water. Two further studies in Nigeria and Turkey that investigated land-use intensification following irrigation water inputs reported deterioration in soil physical quality when compared with areas that either received only rain-fed water (Urama 2005) or areas with only a short history of irrigation inputs (Yilmaz *et al.* 2003). A review by Greenwood *et al.* (2010) highlighted the potential impact of irrigation practice on nutrient leaching and soil compaction and advocated the use of improving soil monitoring equipment and data telemetry to make increasingly smarter decision-making part of the management process.

Soil physical damage (in particular the loss of macroporosity) has been shown to have a negative effect on pasture production because of decreased air and water transmission and root growth development (Drewry *et al.* 2008). Soil compaction and treading damage also increases surface runoff or overland flow from either rainfall or irrigation-applied water (McDowell *et al.* 2003; McDowell & Houlbrooke 2009). Drewry *et al.* (2004) found that macroporosity (at depths of 0–50 and 5–100 mm) strongly correlated with spring pasture yield when studying dairy pasture response to soil physical properties; they determined that a 1% increase in macroporosity at 0–50 and 50–100 mm depth would increase relative spring pasture yield by 1·8 and 2·5%, respectively. The relationship was considered linear between 5 and 22% v/v. However, a precautionary value of >10 % v/v is often advised to minimize the impact of soil physical quality on plant health and pasture production (Drewry *et al.* 2008).

Soil organic resources and biochemical properties provide important ecosystem services for sustainable production systems, but can be sensitive to the impacts of land-use change and intensification. Soil carbon (C) is an important measure of soil quality because of its effects on the chemical, biological and physical processes of functioning soil (Sparling *et al.* 2003). Sequestration of C in soils could also affect global climate change (Entry *et al.* 2002). However, Tate *et al.* (1997) reported that New Zealand soils in pastoral land use may already be at steady state or equilibrium levels of C. Therefore, more information is required on the response of soil C and other organic and biochemical resources to land-use change in New Zealand. Sparling & Schipper (2002) reported that arable, pastoral and forestry land use affected organic matter properties (total C and N, carbon-to-nitrogen (C:N) ratio, mineralizable N). However, these properties were too variable to demonstrate a significant difference between pastoral land uses such as dairy and drystock (sheep and beef) farming. It is commonly perceived that a highly productive irrigated pasture will increase C levels from greater organic matter inputs and returns. However, there are few studies on soil C status or other organic resources under land-use intensification following irrigation (Conant *et al.* 2001).

Table 1. *Summary of grazing events' stocking rates and SMC at the time of grazing*

	2004/05		2005/06		2006/07		2007/08	
	Dry	Irrigated	Dry	Irrigated	Dry	Irrigated	Dry	Irrigated
Total grazing events	5	5	8	10	7	9	10	11
Stocking rate (no. of units)	16·7	19·3	15·6	28·2	13·4	33·1	14·6	44·4
Events at SMC >30% θv	0*	1*	1	8	0	5	0	7
Events at SMC% θv ⩾FC	0*	0*	0	3	0	1	0	1
Mean SMC% θv at grazing	20·7*	30·2*	20·4	33·0	14·7	29·1	14·0	30·0

Stocking rates are presented as stock units as defined by Coop (1965).
* Data collected from Feb onwards only (three grazing events).

The objective of this research was to assess the impacts of land-use intensification on soil quality by determining how irrigation and livestock type affected measured physical, chemical and biological soil properties under pastoral land use in the NORD region of New Zealand. The research hypothesis is that increasing land-use intensification will deteriorate soil quality on the Pallic soil type as a result of its high structural vulnerability.

MATERIALS AND METHODS

Site details and treatments

A research site was established in a paddock with a north facing slope of *c*. 7–15° on a Timaru silt loam near Windsor, North Otago (45°01′S 170°45′E, *c*. 200 m asl). North Otago has a relatively evenly distributed mean annual rainfall of 550 mm/year, a mean January temperature of 15 °C and a mean July temperature of 5 °C. The soil is characterized by a fragipan or Cx horizon with restricted drainage, and classified as a Mottled Fragic Pallic soil by the New Zealand soil classification (Hewitt 1998) or an Aeric Fragiaquept by USDA taxonomy (Soil Survey Staff 1998). Soil tests at establishment, expressed in 'Quick test' units (Cornforth & Sinclair 1984), were pH 5·9, Olsen P 28 mg/g, sulphate S 9·3 mg/g, K 19·6 mg/g and Ca 6·2 mg/g. The site has historically been used for dryland sheep and dairy support grazing, with a recent history (2 years) of short rotation feed crops (kale and barley silage) preceded by long-term permanent pasture. The research trial contained 16 fully fenced plots (*c*. 10 × 25 m), running down the slope. In April (autumn) 2004, the site was established by direct drill into a bare fallow with a mix of perennial ryegrass (*Lolium perenne*) of cultivar Quartet AR1 and white clover (*Trifolium repens*) pasture. The experimental design at the plot level consisted of the factorial combination of irrigation (irrigated *v*. dryland) and stock grazing (sheep *v*. cattle) treatments in four randomized complete blocks. The dryland sheep treatment represents the steady-state or traditional long-term land use of the NORD region.

Management

Each plot was grazed by either sheep or cattle, with the stocking rate determined by available feed. Grazing sheep were usually mature lambs or hoggets and sometimes ewes, while cattle ranged from yearlings to mature dairy cows. The average live weight of cattle ranged from 270 to 530 kg/beast, and the average lamb or hogget from 32 to 55 kg. Grazing rotations were 27 days long on average during the growing season (defined as 15 August–15 May). Stocking rates were determined using the live weight loading 'stock unit system' devised by Coop (1965), based on livestock grazing equivalents of a 55 kg ewe with lamb at foot. The mean livestock loading was 22·3, 43·0, 7·9 and 19·4 su/ha/year for the dryland cattle, irrigated cattle, dryland sheep and irrigated sheep treatments, respectively. A summary of annual variability of stocking rate under irrigation and dryland treatments is presented in Table 1. All treatments were grazed at the same time when pasture cover on the irrigated treatment reached 3500 kg dry matter (DM)/ha, grazing down to *c*. 1500 kg DM/ha. As such, soil water content was not a driver for scheduling grazing events and therefore varied between treatments and between grazing events for the same treatment (Table 1, Fig. 1). Grazing treatments did not begin until late spring of 2004/05 (Year 1), with a total of five grazing events on both irrigated and dryland plots (Table 1). The number of grazing events on irrigated plots totalled 10, 8 and 10 for 2005/06 (Year 2), 2006/07 (Year 3) and 2007/08 (Year 4), respectively, with two fewer events on dryland plots for Years 2 and 3, and one less in Year 4 (Table 1).

Irrigation water was applied using fixed low application rate (*c*. 2 mm/h) sprinklers (K-Line pods) between September and April each year. In Year 1, 200 mm of irrigation water was applied over three

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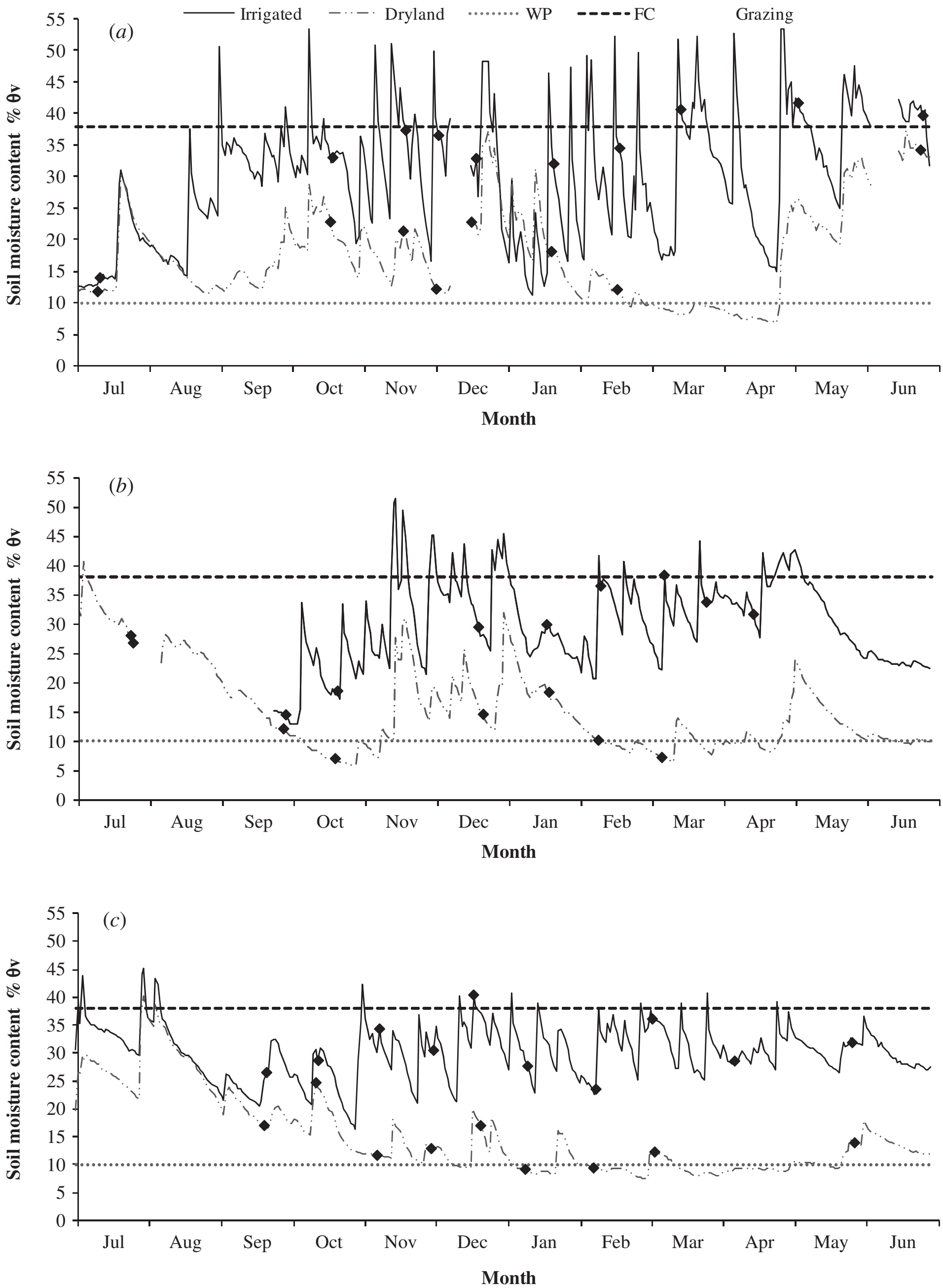

Fig. 1. SMCs for (*a*) 2005/06, (*b*) 2006/07 and (*c*) 2007/08. Grazing events (diamonds) are shown in relation to SMC, and compared with moisture contents for FC (field capacity, –10 kPa at 0–200 mm) and WP (wilting point, – 1500 kPa, 0–200 mm).

events. Irrigation was applied as part of the farm irrigation schedule, taking into account local weather conditions. In Years 2, 3 and 4, irrigation water was applied in response to measured soil water content at the research site; the trigger point was defined as 0·50 of available water capacity (as determined by an *in-situ* Aquaflex™ SI.60 soil moisture tape; Streat Instruments Ltd, Christchurch). Total irrigation for

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Years 2, 3 and 4 were 478, 351 and 456 mm of water applied over 11, 11 and 12 irrigation events, respectively. Mean application depth was 38 mm per event applied over an 18-h period. In Year 1, only one of the three grazing events that took place when soil moisture content (SMC) was >0·30 θv (*c.* one-third of available soil water), and no events were greater than field capacity (Table 1). For the irrigated plots, Year 2 (Fig. 1*a*) had the most grazing events on wet soils with 0·8 of events at SMC >0·30 θv, with 0·3 of events at SMC ⩾ field capacity. Year 2 had the highest average irrigated SMC of all years. Years 3 and 4 had *c.* 0·63 of grazing events at SMC >0·30 θv, but only 0·12 and 0·09 of events, respectively, at SMC ⩾ field capacity (Table 1). In contrast, the dryland plots were usually well below 25% θv (*c.* 0·50 of available soil water) for most of the growing season, and there were no grazing events at SMC ⩾ field capacity (Fig. 1).

The research site received 200 kg/ha of diammonium phosphate at the time of pasture establishment. In subsequent years, P fertilizer was applied in spring at 22 kg/ha/year. Nitrogen fertilizer was applied throughout the growing season based on farm practice at the hosted research site (37, 74 and 111 kg N/ha/year in years 2, 3 and 4, respectively). Dryland plots were fertilized according to irrigated plot maintenance nutrient requirements, to eliminate short-term nutrient supply differences between treatments on plant productivity. This fertilizer strategy created no immediate differences in soil fertility levels between the irrigated and dryland treatments over the 4-year experimental period.

Measurements

Within-plot soil sampling in late autumn each year measured percentage macroporosity (v/v), soil bulk density (t/m^3), structural condition score (SCS), total carbon (TC), total nitrogen (TN) and C:N ratio, while mineralizable carbon (MC) and mineralizable nitrogen (MN) were measured in the autumn of Years 1 and 3 and population of earthworms in the autumn of Year 2. Pore size distribution and bulk density was determined at depths of 0–50 and 50–100 mm from three different randomly chosen paired samples per plot, providing a total of six samples per depth per variable, and measured in a manner previously described in detail by Drewry & Paton (2000); cores were trimmed and the surface peeled off to provide a natural soil surface. Earthworms were removed using formaldehyde, then all cores equilibrated on a tension table to −1 and −10 kPa to determine the percentage of soil pores >300 μm diameter and the percentage of soil pores >30 μm diameter (macroporosity). Macropores are a measure of air-filled pores at field capacity. In comparison, micropores (pores <30 μm diameter) are water filled when the soil water content is at field capacity. Dry bulk density was calculated from the oven-dry weights and volume of the macroporosity sample cores. The structural condition score was semi-quantitatively assessed on three square sub-samples per site (200 × 200 mm by 100 mm deep) of intact soil, dug with a spade. The score was judged on visual assessment of the size, shape and porosity of aggregates, and their cohesion and root development. The SCS ranged from 1 to 5 in half-unit increments, where a high value related to a well-structured soil characterized by friable loose aggregates with abundant root distribution throughout. In comparison, a low value corresponded to a poorly structured soil where aggregates were coarse or absent with evidence of poor and restricted root growth activity. Scores were determined after breaking up and spreading each sample onto a rectangular tray, following the method from Peerlkamp (1967). The soil plastic limit (the point where soil behaviour changes from being friable to being plastic under pressure), determined on a volumetric basis for the 0–200 mm depth, was 37% θv (Standards Association of New Zealand 1986).

Total C and N concentrations were determined on soil (bulked samples to 150 mm depth at three sites per plot) using a LECO CNS200 furnace/gas analyser (McGill & Figueirdo 1993) after oven-drying <2 mm sieved soil at 60 °C overnight. The C:N ratio was determined as the ratio of TC to TN for each analysed sample. C and N mineralization was determined by aerobic incubation, adapted from Hopkins (2008); 50 g moist soil was incubated for 35 days at 22 °C. Carbon dioxide concentration was measured by an infrared gas analyser (LICOR LI-7000) after 1, 3, 7, 10, 14, 21, 28 and 35 days of incubation. Nitrogen mineralization was determined as the difference between pre- and post-incubation mineral N contents. Worm population was determined by separating out all worms from soil contained in 100 mm diameter soil cores, 12 per plot, taken to a depth of 250 mm. Data are presented as number per unit surface area.

Pre- and post-grazing pasture mass was assessed using a locally calibrated rising plate meter (L'Huiller & Thompson 1988) to provide pasture yields before and after each grazing event throughout the four growing seasons.

Data treatment and statistical methods

Soil physical data (bulk density and macroporosity) at each depth, and compared between years, were assessed by analysis of variance, with the block structure given by subsample within sample, within plot and within block, and the treatment structure (which was randomized within the plot stratum) given by irrigation and stock treatments and their interaction. Soil condition score, TC, TN, C:N ratio, MC, MC and worm numbers were analysed similarly, except that there was no sample stratum. Patterns of change for these variables over the 4 years of the trial were

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Table 2. *Soil physical properties for stock type and irrigation treatments*

		Irrigated		Dryland		S.E.D.		*P*	
Year	Depth (mm)	Cattle	Sheep	Cattle	Sheep	(9 D.F.)	Stock (S)	Water (W)	S × W
Macroporosity % (v/v)									
2004/05	0–50	10·5	13·9	13·1	18·9	0·76	<0·001	<0·001	ns
	50–100	12·2	12·4	13·4	17·3	1·45	<0·01	<0·05	ns
2005/06	0–50	9·1	16·7	17·2	21·6	1·48	<0·001	<0·001	ns
	50–100	7·8	12·9	15·1	16·3	0·93	<0·001	<0·001	<0·05
2006/07	0–50	13·3	16·5	17·6	23·9	1·66	<0·01	<0·001	ns
	50–100	11·5	13·0	17·0	18·2	0·77	<0·05	<0·001	ns
2007/08	0–50	11·0	15·9	18·6	22·2	1·20	<0·001	<0·001	ns
	50–100	10·1	12·8	14·0	16·8	1·47	<0·05	<0·01	ns
Bulk density (t/m^3)									
2004/05	0–50	1·27	1·19	1·27	1·18	0·016	<0·01	ns	ns
	50–100	1·30	1·29	1·30	1·25	0·019	<0·05	ns	ns
2005/06	0–50	1·29	1·14	1·26	1·19	0·048	<0·01	ns	ns
	50–100	1·38	1·28	1·31	1·28	0·022	<0·01	<0·05	ns
2006/07	0–50	1·27	1·17	1·24	1·13	0·038	<0·01	ns	ns
	50–100	1·36	1·30	1·28	1·24	0·011	<0·001	<0·001	ns
2007/08	0–50	1·25	1·17	1·22	1·13	0·029	<0·01	ns	ns
	50–100	1·36	1·30	1·32	1·25	0·028	<0·01	<0·05	ns
Structural condition score (1–5)									
2004/05	0–100	2·3	2·09	2·8	3·7	0·43	<0·05	<0·05	ns
2005/06	0–100	1·8	3·3	3·0	4·1	0·54	<0·01	<0·05	ns
2006/07	0–100	1·7	2·6	2·9	3·8	0·59	<0·05	ns	ns
2007/08	0–100	2·5	3·5	2·8	3·9	0·64	<0·05	<0·05	ns

P values are presented for comparison between treatments.
ns, not significant.

analysed by random coefficient regression, with random effects given by plot and year within plot, with an unrestricted covariance between these terms. Fixed effects were given by irrigation and stock treatments, depth (soil physical data), year and all significant interactions involving these terms. All analyses were carried out using the statistical package GenStat 11 (2008) with error described by the standard error of the difference (S.E.D.). Unless stated otherwise, all reported changes in time or differences between treatments are significant at $P<0·05$.

RESULTS

Soil physical measures

The effect of treatments on soil physical properties (Table 2) shows more compaction and treading damage under cattle grazing than under sheep grazing, and greater compaction and treading damage under irrigation practice than for dryland, and little evidence for interaction between these treatments. Over the 4 years, macroporosity was always lowest in the irrigated treatment with cattle (range 9·1–13·3% v/v at 0–50 mm) and greatest in the dryland plots grazed by sheep (18·9–23·0% v/v at 0–50 mm). Similarly, bulk density was always greatest for the irrigated treatment with cattle (1·25–1·29 t/m^3 at 0–50 mm) and lowest for the dryland sheep (1·13–1·19 t/m^3 at 0–50 mm). The stock type effect was shown in average differences between sheep and cattle over the trial of 4·80 (S.E.D. 0·54; $P<0·001$) and 2·29 (S.E.D. 0·51; $P<0·01$) for macroporosity at 0–50 and 50–100 mm, respectively, and of −0·097 (S.E.D. 0·014; $P<0·001$) and −0·053 (S.E.D. 0·010; $P<0·001$) for bulk density at 0–50 and 50–100 mm, respectively, with a corresponding difference of 0·90 (S.E.D. 0·31; $P<0·05$) for SCS at 0–100 mm. An irrigation treatment effect showed an overall mean difference between dryland and irrigated treatments for macroporosity of 5·64 (S.E.D. 0·54; $P<0·001$) at 0–50 mm and of 4·47 (S.E.D. 0·51; $P<0·001$) at 50–100 mm ($P<0·05$); for bulk density of −0·016 (S.E.D. 0·014; $P<0·05$) at 0–50 mm and of −0·045 (S.E.D. 0·010; $P<0·001$) at 50–100 mm; and of 0·74 (S.E.D. 0·31; $P<0·05$) for SCS at 0–100 mm.

Bulk density decreased on average by 0·17 (S.E. 0·004) per year for the dryland treatment at 0–50 mm depth, and increased by 0·11 (S.E. 0·004) per year for

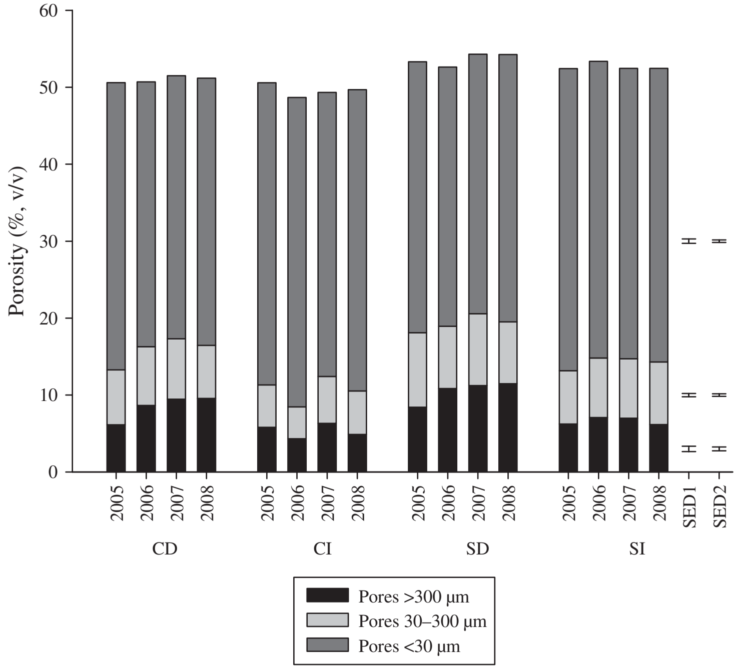

Fig. 2. Pore size distribution (v/v) across years and over treatments for 0–100 mm depth. CD = cattle, dryland, CI = cattle, irrigated, SD = sheep, dryland, SI = sheep, irrigated. SED1 error bar represents S.E.D. across treatments. SED2 error bar represents S.E.D. within treatments over time.

the irrigation treatment at 50–100 mm, but otherwise showed no significant trend over time ($P<0{\cdot}05$ for treatment × year interaction; $P<0{\cdot}001$ for depth × year interaction). Mean macroporosity increased by 0·99 (S.E. 0·198) per year at the 0–50 mm depth ($P<0{\cdot}001$ for depth × year interaction), but showed no trend with time at 50–100 mm depth and no significant trend over time for either treatment ($P<0{\cdot}05$).

Pore size distributions for all treatments over 4 years of the trial are presented in Fig. 2. The contrast between Years 1 and 4 of the trial shows the dryland treatment with cattle increased pore size fractions >300 μm and pores 30–300 μm and decreased pores <30 μm (micropores) with no significant increase in total porosity. All pore fractions in irrigated plots grazed by cattle fluctuated between years, with no significant difference in total porosity between years or over the duration of the trial. The dryland sheep treatment increased pore size fractions >300 μm and pores 30–300 μm between Years 1 and 4 of the trial, with no significant change in micropores or total porosity. There were no significant changes in pore size distribution over time for irrigated plots grazed by sheep. The irrigated plots with cattle had fewer pores >300 μm than either dryland cattle or dryland sheep treatments for all 4 years, and for two out of the 4 years compared to sheep irrigated treatments. The fraction of pores 30–300 μm was smaller under the irrigated treatment with cattle than for all other treatments, while microporosity was greater than for both dryland treatments.

Soil chemical and biological quality

A significant stock-type effect ($P<0{\cdot}05$) was evident for TC and TN for three out of the 4 years of the trial, with lower C and N levels on sheep plots than on cattle plots (Table 3). No irrigation treatment effects were evident on TC for any of the 4 years ($P<0{\cdot}05$), or on TN for three out of the 4 years. However, TN was significantly greater ($P<0{\cdot}001$) on irrigated rather than on dryland plots in Year 4. Generally, the highest levels of TC and TN were found on the irrigated plots with cattle and lowest on the sheep dryland plots (Table 3). There was an overall increase in TC of 0·61 (S.E. 0·27; $P<0{\cdot}05$) mg/m^3/year with no significant treatment effects, while TN increased by an average of 0·13 mg/m^3/year for the irrigation treatment, compared to 0·03 (S.E.D. 0·055; $P<0{\cdot}05$) for dryland. Dryland plots grazed by sheep had returned to Year 1 levels by Year 4. In contrast, the C:N ratio decreased by 0·096 (S.E. 0·043; $P<0{\cdot}05$) per year, with no significant differences between treatments. No stock-type treatment differences in C:N ratio were apparent

Table 3. *Chemical and biological soil properties (0–150 mm) for stock type and irrigation treatments*

Year	Irrigated		Dryland		S.E.D.	P		
	Cattle	Sheep	Cattle	Sheep	(9 D.F.)	Stock (S)	Water (W)	S×W
Total C (mg/ml)								
2004/05	37·8	35·3	38·0	36·5	1·00	<0·05	ns	ns
2005/06	41·2	35·9	39·1	38·6	1·60	<0·05	ns	ns
2006/07	40·7	40·9	38·4	38·0	2·95	ns	ns	ns
2007/08	40·1	38·3	40·1	36·4	1·18	<0·01	ns	ns
Total N (mg/ml)								
2004/05	3·60	3·38	3·67	3·51	0·115	<0·05	ns	ns
2005/06	4·04	3·55	3·72	3·62	0·151	<0·05	ns	ns
2006/07	4·01	4·03	3·68	3·68	0·306	ns	ns	ns
2007/08	4·06	3·83	3·86	3·52	0·078	<0·001	<0·001	ns
C:N ratio								
2004/05	10·52	10·45	10·34	10·40	0·192	ns	ns	ns
2005/06	10·21	10·13	10·50	10·65	0·088	ns	<0·001	ns
2006/07	10·16	10·17	10·43	10·36	0·097	ns	<0·01	ns
2007/08	9·88	9·98	10·35	10·35	0·221	ns	<0·05	ns
Mineralizable C (mg/kg)								
2004/05	600	620	630	710	39	ns	ns	ns
2006/07	870	840	810	790	29	ns	<0·05	ns
Mineralizable N (μg/g)								
2004/05	82	93	79	89	7·5	ns	ns	ns
2006/07	87	80	54	62	21·6	ns	ns	ns
Earthworms (number/m^2)								
2005/06	259	859	12	4	111	<0·01	<0·001	<0·01

P values are presented for comparison between treatments.
ns, not significant.

($P<0·05$). No treatment effects of stock type or irrigation were evident in Year 1 for MC ($P<0·05$). A significant irrigation effect ($P<0·05$) was evident in Year 3, with greater MC under irrigated plots than dryland plots. However, there was only a significant difference between irrigated plots grazed by cattle (866 mg/kg) and dryland plots grazed by sheep (794 mg/kg). Temporal trends showed an increase in MC between Years 1 and 3 under all treatments, but particularly under irrigated treatments. No significant treatment differences were evident for MN for either Year 1 or 3.

The number of earthworms present (measured in Year 2 only) showed a significant stock × water interaction ($P<0·01$) with numbers greater in irrigated plots with sheep but conversely greater in dryland plots with cattle. Irrigated plots with cattle and with sheep had a greater worm population than dryland plots grazed by cattle and sheep, respectively ($P<0·001$).

Pasture production

The effect of treatments on pasture yield (Table 4) shows greater DM production under irrigation (13·4–21·5 t DM/ha/year) than on dryland plots (5·2–11·0 t DM/ha/year) for each of the four growing seasons ($P<0·01$) and on a total cumulative basis ($P<0·001$). However, there was no significant effect of stock type on DM production.

DISCUSSION

Changes in soil physical measures

There were decreases in soil macroporosity and SCS in response to adding irrigation water, and to the conversion from sheep to cattle grazing (Table 2). However, at 0–50 mm, differences in bulk density were only apparent between grazing animals, suggesting that bulk density is a less sensitive measure than macroporosity when assessing the effects of soil compaction and treading damage because of decreasing structural rather than textural (micro) pore space. Figure 2 suggests a compensatory micropore response to treading pressure, where decreased macroporosity under irrigated plots grazed by cattle is compensated by increased micropore space, hence little difference in total porosity or bulk density. The large effect of stock

Table 4. *Annual and cumulative pasture yield for stock type and irrigation treatments*

Pasture yield (t/ha)	Irrigated		Dryland		S.E.D.		*P*	
	Cattle	Sheep	Cattle	Sheep	(9 D.F.)	Stock (S)	Water (W)	S × W
2004/05	14·4	13·4	11·0	9·9	1·13	ns	<0·01	ns
2005/06	18·2	21·5	9·4	7·5	1·63	ns	<0·001	ns
2006/07	17·8	21·5	8·8	8·6	1·32	ns	<0·001	ns
2007/08	20·0	18·4	5·5	5·2	0·99	ns	<0·001	ns
Cumulative total	70·4	74·8	34·6	31·2	3·93	ns	<0·001	ns

P values are presented for comparison between treatments.
ns, not significant.

type on all soil physical measures over all years of the trial is not surprising, considering that cattle are considerably heavier than sheep and hoof contact imposes more downward pressure on the soil per unit area. Greenwood & McKenzie (2001) reported greater static loading pressure under cattle grazing (*c*. 138 kPa) compared to sheep (*c*. 66 kPa).

Despite the lack of irrigation treatment effect on soil bulk density, degraded soil structure is apparent after irrigation by the large decrease in soil macroporosity (mean of 4·3% v/v) over all years at both 0–50 and 50–100 mm depth from wetter soils and associated increases in livestock loading (Table 2). This effect was evident under both sheep and cattle grazing, but more pronounced under cattle-grazed plots because of the above-mentioned differences in static loading pressure. Increased livestock loading pressure on irrigated plots compared to dryland plots would have contributed to the irrigation effect (Table 1). However, it appears that the irrigation treatment response reflects a greater likelihood for animal grazing to occur under considerably greater SMC than that from associated dryland plots.

The variability of SMC and stock loading rates between seasons (presented in Table 1) demonstrates that the greatest influence on soil compaction and treading damage was the mean SMC, not the stocking rate. Livestock grazing on wet soil has been reported to have an unfavourable effect on soil physical quality (Willat & Pullar 1984; Proffitt *et al*. 1995). Climo & Richardson (1984) investigated the susceptibility to stock treading of three different soil types and reported that all soils exhibited a strong relationship between SMC and penetration resistance, demonstrating that when all soils are wet (i.e. close to field capacity) they are all susceptible to soil damage. However, it was noted that differences in drainage characteristics influenced the time that soils remained near field capacity, and were therefore prone to damage following livestock grazing. Soil compaction following grazing during wet periods will recover to pre-existing levels once conditions are less conducive to soil damage, allowing soil processes such as freeze–thaw, shrink–swell, and natural plant root and earthworm exploration (Drewry 2006). However, under an irrigated pasture system, SMC is regularly returned to field capacity, meaning treading damage can occur at any time during the year that grazing coincides with high SMC, which lessens natural compaction recovery processes during summer and autumn.

Soil damage following animal grazing will result in either pugging or compaction. Soil pugging involves the deformation and remoulding of soil when animal loads exceed a soil's bearing capacity. Pugging typically takes place when SMC is greater than the plastic limit. Soil compaction reduces or compresses soil pore space and can occur when soil is in both a friable or plastic state (Bilotta *et al*. 2007). At the research site used in the present study, no grazing events caused considerable visual pugging damage. The critical SMC for greatest compaction potential depends on soil texture and soil organic carbon (Dahwood *et al*. 1999). As a guide, the critical SMC for greatest compaction is close to, but slightly drier than, either field capacity or plastic limit, whichever is less (Mapfumo & Chanasyk 1998). Curves presented by Betteridge *et al*. (1999) and Dahwood *et al*. (1999) suggest that SMC within 5–10% θv of the drier side of the critical SMC would also have a compaction risk. In summary, the potential for soil compaction decreases, as the risk of soil pugging increases with greater SMC (Betteridge *et al*. 1999; Drewry *et al*. 2008).

The Timaru silt loam has a plastic limit *c*. 1% lower than the soil's field capacity of 38% θv, although such a small difference is likely to be within the margin of error for determining a field property with a laboratory analysis. However, it would be expected that any grazing events in at least the upper one-third of soil water-holding capacity (*c*. 30% θv) would have some soil compaction/treading damage effect. Figure 1 and Table 1 demonstrate that at least half of the animal grazing events from Years 2 to 4 (Year 1 was not instrumented for SMC) were at an SMC level likely to increase soil compaction risk. The year of the most measured soil degradation contained the highest number of at-risk grazing events, including three that took place at or above field capacity. It can be seen in Fig. 2 that the fraction of pores <30, >30 and >300 µm on the most compacted cattle-irrigated treatment fluctuate considerably between years. The decreased macroporosity was largely driven by the loss of large structural pores (>300 µm) following animal treading, with a subsequent (but smaller) increase in textural pore space (<30 µm). This may also be influenced by changes in animal carrying capacity between years, as determined by stock units (Table 1). However, the greatest stock unit capacity of 44 for a single year (determined by the method described in Coop 1965) was associated with Year 4, compared to 28 stock units in Year 2. It would seem that SMC at the time of animal grazing dominated subsequent changes in soil structure.

Some related research on the same experimental site by McDowell & Houlbrooke (2009) identified that increasing soil compaction (as measured by macroporosity and bulk density) was responsible for increases in the generation of overland flow following irrigation and rainfall events and a subsequent increase in phosphorus and sediment losses. This potential deleterious impact of decreased soil physical quality as a result of land-use intensification requires further research and land management guidance in order to identify farm system practices that can mitigate and prevent the effects of soil compaction.

Changes in soil organic resources

Stock-type treatment effects on TC and TN were evident for three out of 4 years, with greater topsoil TC and TN levels under plots grazed by cattle than by sheep (Table 3). However, these differences are largely attributed to differences in soil bulk density between cattle- and sheep-grazed treatments (similar C and N content in a smaller volume of soil), as TC and TN contents expressed as a weight/weight basis (data not presented) showed no animal grazing effect over the trial. TC and TN data are typically presented on a volumetric basis, which allows accurate comparisons of C and N within a given soil depth for inventory purposes. Despite trends suggesting a small increase in TC under irrigation treatment, the large variability within treatments meant that no significant difference between dryland and irrigated treatments was measured. Similar results were evident for TN for Years 1–3. However, a significant difference in Year 4, when variability within treatments was lower, showed greater TN under irrigated plots than dryland. It would be expected that this difference in TN reflected greater pasture growth under irrigation treatment (Table 4). The NORD district survey on similar Pallic soil types (Houlbrooke *et al.* 2008) found no difference in TC or TN contents between dryland and irrigated properties, and a tendency for reduced C reserves under long-term irrigation. These results differ from two other studies that reported an increase in C storage following the addition of irrigation water (Rixon 1966; Entry *et al.* 2002). However, both of those studies started from a very low base of C prior to land-use change. In comparison, many New Zealand soils under long-term pastoral land use may already be at a state of equilibrium (Tate *et al.* 1997), where larger inputs of organic matter under irrigation are balanced by higher turnover of previously stable C (Sparling *et al.* 2003). Metherell (2003) associated a slower accumulation of C storage under high-frequency long-term irrigation, compared with dryland C storage with increased C decomposition rates from soil that has high soil moisture status.

The C:N ratio was strongly influenced by irrigation treatment; this ratio narrowed in irrigated plots *v.* dryland plots over time. The C:N ratios were very similar in Year 1 for all treatments, but by Year 4 that of irrigated plots had fallen below 10. Decreases in C:N ratios are a feature of a developing pastoral system, as organic N storage increases but C storage reaches a steady state (Jackman 1964). However, it should be noted that the differences in ratios between treatments were relatively small, and while statistically significant, they are not likely to be biologically significant. All treatments had relatively narrow C:N ratios typical of New Zealand pastoral systems of ryegrass-white clover with high levels of both C and organic N (Ledgard & Steele 1992). The lower C:N ratio under irrigation treatment reflected an increase in TN rather than a decrease in TC. It has been suggested by Schipper *et al.* (2004) that a narrowing of C:N ratio effectively decreases the capacity of a soil to store N, therefore increasing the risk of N leaching and gaseous loss.

Changes in soil biological measures

In this study, trends between Years 1 and 3 suggest increasing MC for all treatments over time (Table 3). As with TC, there was a high degree of variability. However, by Year 3 a significant irrigation effect was apparent, with greater MC from irrigated plots not reflected in TC (as described above). Mineralizable C is largely a function of soil microbial activity and the available pool of organic C (Sparling *et al.* 2000). The addition of regular irrigation water may therefore have stimulated microbial activity in a soil that was otherwise suffering from regular soil water deficits throughout the growing season. Mineralizable N reflects the supply and release of mineral N readily available for plant uptake from organic pools. Soil compaction reportedly decreases the rate of MN (Rhoades & Coleman 1999). However, in the present study, there were large variations in MN and no changes were evident between the more compacted cattle-grazed and irrigated plots compared with the less compacted sheep-grazed and dryland plots.

The assessment of earthworms in Year 2 identified greater activity under irrigated management, and more earthworms under irrigated plots grazed by sheep than by cattle (Table 3). This effect is likely to be related to long-term differences in SMC between dryland and irrigated treatments, and the influence of animal treading. Under dryland conditions, earthworm populations are known to be deeper and less active than populations closer to the surface of irrigated land (Fraser *et al*. 1994). Therefore, it is likely that most of the population under dryland management would be found deeper than the 25 mm sampling depth when SMC was at or below the wilting point. The difference in earthworm numbers between irrigated sheep and cattle plots probably reflects greater soil compaction on the dryland plots grazed by cattle. The population of earthworms under irrigated plots grazed by cattle is considered low compared to a desired population of $>500/m^2$ required to maintain productive capacity and soil function, and is at the lower end of typical population sizes of 200–1000 worms/m^2 under most land-use scenarios (Lee 1985).

Impacts on pasture production

Unlike cropping studies, there is little research that has investigated the effect of soil compaction (often measured as bulk density or macroporosity) on pasture yield (Drewry *et al*. 2008). Much of the research on the effects of animal treading conducted under pastoral farming systems have identified plant yield penalties as a result of considerable sward damage caused by one-off wet soil pugging/poaching damage under stock hooves rather than from the cumulative effects of soil compaction (Greenwood & McKenzie 2001; Drewry *et al*. 2008). Some previous research has suggested that pasture yield is depressed with increasing soil physical damage independent of pasture sward damage with a value of 10% v/v macroporosity, often suggested as a threshold where a decline in yield should be expected (Houlbrooke *et al*. 1997; Drewry *et al*. 2004; Drewry *et al*. 2008). In this study, there was no evidence of decreased pasture growth attributable to soil physical condition as the more damaged cattle-grazed plots did not produce more pasture DM than the equivalent sheep-grazed plots. Furthermore, the more irrigated plots (particularly irrigated cattle-grazed plots) with lower soil macroporosity produced more DM than the equivalent dryland plots. However, macroporosity was only measured as <10% v/v for cattle-grazed irrigated plots during the 2005/06 season. With water-limiting potential pasture production in this environment, pasture yields from irrigated plots were at least twice that of dryland plots under equivalent stock types (104% increase under cattle grazing and 139% increase under sheep grazing). This suggests that the highly significant effect of water irrigation has masked any potential soil physical effects on pasture production.

The main conclusions from this work are that under pastoral land use, soil physical quality responds quickly to changes in land-use pressure as both irrigation practice and cattle grazing, particularly in combination, have increased the soil physical damage as measured by the decreased macroporosity and increased bulk density (50–100 mm). The change in soil physical quality was evident within 1 year of land-use intensification and sustained over the 4 years of research, suggesting a new equilibrium of soil condition is quickly reached. However, soil organic and biochemical indicators of soil quality are less responsive to land-use change in the short term compared to soil physical properties. As such, long-term trends are difficult to predict following only a 4-year study. In dryland environments subject to regular and large soil water deficits, the addition of irrigation water will prove the most beneficial management practice to increase pasture yield.

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