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SOIL RESEARCH

Effect of irrigation on soil physical properties on temperate pastoral farms: a regional New Zealand study

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ABSTRACT

Context. Many regions in the world have undergone rapid land use change and intensification of agricultural land, such as through irrigation expansion, upgrading irrigation systems, and changing grassland, stock, and nutrient management practices. With more intensive land use, changes to soil properties can occur, such as soil compaction and changes in soil water storage. The effects of modern sprinkler-irrigated pastoral farming on soil physical properties are not well quantified internationally, particularly for temperate climates. **Aims.** This regional study evaluates the effect of irrigation on soil physical properties in topsoil and subsoil, under modern pastoral grazing and sprinkler irrigation, across Canterbury, New Zealand. **Methods.** Paired sites were sampled, consisting of a spray-irrigated paddock (field) and an adjoined part of the same paddock that was dryland (unirrigated), with other management the same for each pair. **Key results.** Under irrigation there was a shift towards a greater abundance of smaller pores. This was reflected in macroporosity and readily available water capacity being significantly lower under irrigation, while semi-available water capacity and unavailable water held below permanent wilting point both increased. **Conclusions.** These differences reflect increased compaction under irrigated grazed pasture, particularly under dairy grazing, consistent with findings in similar studies. This study quantified changes in both the topsoil and subsoil but showed that most differences were confined to the topsoil (30 cm depth). **Implications.** For irrigation management, our study indicates the lower readily available water capacity on irrigated pasture is significant, with farmers potentially having to irrigate more frequently. Adopting deficit irrigation could minimise impacts of compaction.

Keywords: available water capacity, compaction, crop lower limit, land use change, macroporosity, readily available water capacity, soil health, soil quality.

Introduction

Global population growth is increasing the demand for food and agricultural products. Land use change is occurring to support this demand on agricultural food production, with expansion and intensification of dairy, sugarcane, cropping, and other agriculture in many countries, for example, in Brazil (Cherubin *et al.* 2016; Koppe *et al.* 2021), China (Bai *et al.* 2018; Zuo *et al.* 2018), and Argentina (Viglizzo *et al.* 2011).

In New Zealand, agriculture has also undergone land use change and intensification, as reflected in a 53.6% decrease in sheep numbers nationally, from 57.9 million in 1990 to 26.8 million in 2019, with a corresponding rise in national dairy cow numbers from 3.4 million to 6.3 million (Stats NZ 2021). A significant proportion of the dairy cattle increase occurred in the Canterbury region, with an increase from 113 000 in 1990 to 1.2 million in 2019 (Stats NZ 2021). The area of irrigated agricultural land in New Zealand almost doubled between 2002 and 2019, from 384 000 to 735 000 ha (Ministry for the Environment, Stats NZ 2021; Stats NZ 2021). The majority of irrigated land is in the Canterbury region. There was a 203% increase in irrigated land area for Canterbury farms (that were dominantly dairy), from 89 000 to 269 000 ha, from 2002 to 2019 (Stats NZ 2021).

Suitable soils and water availability are key resources needed for agriculture but are under increasing pressure from the intensification of agricultural land and changing land use (Godde *et al.* 2018; Kopittke *et al.* 2019; Koppe *et al.* 2021). Intensification of agricultural land includes the irrigation of previously dryland areas to increase yields and, associated with this, often an increase in nutrient inputs, stock numbers, and changing grassland management practices or stock type (Cherubin *et al.* 2016; Drewry *et al.* 2021*b*; Koppe *et al.* 2021). Improved technologies and practices are being developed to use water more efficiently (Evett *et al.* 2020), and reduce the impacts of intensification on water quality (Chapman *et al.* 2021). With more intensive land use, changes to soil properties can occur, such as soil compaction and reduced soil pore space (Cherubin *et al.* 2016; Drewry *et al.* 2021*c*; Hu *et al.* 2021), greater available water capacity (Drewry *et al.* 2021*a*), and changes to soil biochemistry and biology (Lobry De Bruyn and Kingston 1997; Mayel *et al.* 2021). Knowledge of changes in soil physical properties is important as these changes affect crop and pasture yield (Drewry *et al.* 2008) and the ecosystem services that soil provides, such as production, regulation of water and gas flows, and filtering nutrients (Dominati *et al.* 2019; Hu *et al.* 2021).

Accurate measurements of soil water storage and other soil physical properties are important for optimising production and the use of soil resources by allowing an informed approach to irrigation water use, carbon and nutrient cycling, and the optimisation of plant yield (Minasny and McBratney 2018; Drewry *et al.* 2019; Gonçalves *et al.* 2020). Available water capacity (AWC) is important for accurately simulating crop yield in dry conditions (Gladish *et al.* 2021) and under irrigation (Brown *et al.* 2021). Underestimation of AWC was found to be more detrimental when modelling plant yield estimates than the same amount of its overestimation (Wu *et al.* 2019). Knowledge or representation of these is also important for modelling water and diffuse nutrient losses from agriculture (e.g. Kreiselmeier *et al.* 2019; Vogeler *et al.* 2019). Soil water storage attributes are also key information for irrigation management, both for water allocation and system design, as well as on-farm scheduling practice (Irrigation New Zealand 2013; El-Naggar *et al.* 2020).

Research on the effect of irrigation on soil physical properties has been focused on arid, semi-arid, or tropical environments and non-pastoral land use, often with furrow- or flood-irrigated systems (Singh *et al.* 2013; Drewry *et al.* 2021*b*). The effect of flood irrigation on soil physical properties was studied in New Zealand for a wide range of pastoral soils (Rickard and Cossens 1966, 1968; Cossens and Rickard 1969; Rickard and Cossens 1973). These irrigated soils generally showed an increase in bulk density, field capacity, and AWC, compared with soils without irrigation, but results reviewed in the wider literature vary (Drewry *et al.* 2021*b*). With the exception of a few studies (e.g. Houlbrooke *et al.* 2008; da Costa *et al.* 2014), the effects of modern sprinkler-irrigated pastoral farming on soil physical properties are not well quantified internationally, particularly for temperate climates (Drewry *et al.* 2021*b*).

There has been a trend in soil science studies to measure soil at shallow depths, rather than the deeper depths measured several decades ago (Yost and Hartemink 2020). Many of these previous irrigation effect studies have mainly researched topsoil depths, e.g. to 10 or 15 cm depth only, with deeper and subsoil depths being a knowledge gap. It is particularly important to better determine the effects of irrigation on drainage and water storage properties over a soil profile, including both topsoil and subsoil, to understand the potential effect on drainage and nutrient movement. Previous studies under pasture have also either compared dryland with irrigation between different paddocks and farms (Fu *et al.* 2021), which makes it difficult to separate the irrigation effect from other land management practices associated with intensification (Rickard and Cossens 1966; Drewry *et al.* 2021*b*), or have focused on the single paddock (Drewry *et al.* 2021*a*) or plot scale (Houlbrooke and Laurenson 2013).

The main objective of this study was to use paired sites within the same paddock to evaluate at the regional scale the effect of irrigation and dryland on soil physical properties in both the topsoil and subsoil, under modern pastoral grazing and sprinkler irrigation. A second objective was to determine if land use, or irrigation duration, influenced the irrigation effect on soil physical properties.

Materials and methods

Sites, experimental, and sampling design

For this regional study, 24 paired sites were sampled across the Canterbury region of New Zealand, from Tekapo to Waiau (Fig. 1), to be representative of a range of pastoral farms (23 farms in total), soil types, management practices, and climates in the region. The climate of the Canterbury region is temperate. Examples of locations and mean annual rainfalls across the region, for the period 1981–2010, are Lake Tekapo 591 mm (south-Canterbury), Ashburton 681 mm (mid), and Culverden (576 mm) in north-Canterbury (Macara 2016).

Each site consisted of a paddock (grazed field) that was irrigated under modern spray irrigation, and another adjacent part of the same paddock that was dry, i.e. where the spray irrigator could not reach, such as the corner of a paddock left dry, as would typically occur beyond the reach of a centre-pivot-irrigator. The irrigated and non-irrigated sites otherwise had the same soil type, climate, land use, and paddock management. These were termed paired sites (i.e. a paired site containing both irrigated and

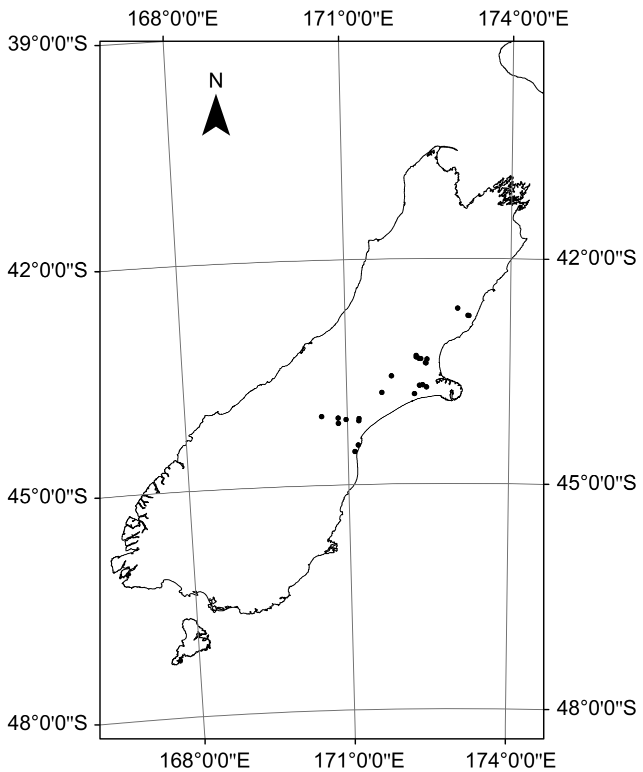

Fig. 1. Locations for sites sampled in Canterbury, South Island of New Zealand. Map outline from Land Information New Zealand.

dryland areas). Each paired site consisted of two sampled pits (one in the irrigated area and one in the dryland area); any measured difference between them was assumed to be the result of irrigation (Mudge *et al.* 2017, 2021).

At each sampling pit, soil samples were taken at six 10 cm depth increments (0–10, 10–20, 20–30 cm, etc.), resulting in six soil sampling increments per pit (i.e. 12 soil sampling increments per paddock). The 0–60 cm depth increments were chosen because 0–60 cm is used for irrigation scheduling in New Zealand, and is the depth modelled by the OVERSEER nutrient budget model (PCE 2018), which is widely used in New Zealand (PCE 2018; Monaghan *et al.* 2021). The 0–30 cm depth increments typically represented the A and AB topsoil horizons for soils sampled in this region (Manaaki Whenua-Landcare Research 2020).

Soils and land management

Possible sites were initially identified using aerial photography to identify irrigated farms across the region that had paddocks with possible irrigated and dry areas. Sites were selected to be on deep soils (>60 cm depth of stone-free soil) to enable sampling of soil cores for the complete suite of soil porosity measurements. The soils were checked prior to sampling using a test pit or auger to ensure the dryland and irrigated soils matched with similar morphological properties. When sampled, the soil profile was described (Milne *et al.* 1995) and classified to the subgroup level of the New Zealand soil classification (Hewitt 2010). The distribution of soil orders sampled (Table 1) was representative of the proportions of irrigated deep soils mapped by S-map (Lilburne *et al.* 2012; Manaaki Whenua-Landcare Research 2020) across the Canterbury region.

Site selection was also based on land management information obtained from the farmers, such as time in pasture and since cultivation, if there had been any previous irrigation on dryland, and whether dryland and irrigated land areas were managed in the same way. Land use was 13 dairy cattle paddocks ('milking-platform'), and 11 'non-lactating-dairy' or not-dairy (comprising five sheep and beef, four 'dairy support', and two beef sites). Dairy cows were grazed off the primary farm (or 'milking platform') during winter for 11 of the 13 dairy farms. This is common practice on New Zealand dairy farms, where cows are grazed on 'run-off blocks' (for winter grazing of cows or grazing young stock). In New Zealand, 'run-off blocks' are often owned or leased by the dairy farmer to have complete control over grazing. Alternatively, 'dairy support' has similar use but is often owned by another farmer to graze dairy cows on pasture or crops over winter only, with different land uses at other times of the year. See Dalley *et al.* (2014) for more information.

All sites had been under pasture for a minimum of 18 months to avoid the disturbance of cultivation. The pasture was typically perennial ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*) mix, with pasture age since sowing ranging from 1.5 to 15 years (median 4.5 years). Irrigation duration at the sites were 2–9 years (nine sites), 10–19 years (13 sites), and 20+ years (two sites). The type of sprinkler irrigation was predominantly centre-pivot, with one site under linear-move irrigation. In

Table 1. Soil order (Hewitt 2010), site numbers, and USDA and FAO soil classification equivalents.

Soil order	Number of sites.	USDA equivalents (Soil Survey Staff 2014)	FAO equivalents (IUSS Working Group WRB 2015)
Gley	1	Aquents, Aquepts	Gleyic Fluvisols/Gleysols
Pallic	17	Aqualfs, Aquepts, Haplusteps, Fragiudalfs	Fragic Planosols/Luvic Planisols
Recent	6	Fluvents	Fluvisols

Canterbury, the irrigation season typically occurs from September to April. On the farms in this study, the irrigation return period for a complete revolution of the centre-pivot ranged from 1 to 10 days (median 3 days). Additional factors used in site selection included a minimum area of 50 m × 50 m for the dry part of the paddock; no previous irrigation applied (even prior to the current irrigation system installation); uniform grazing and fertiliser management; and sampling points located at least 10–20 m from shelterbelts, gateways, and water troughs.

Sample collection and soil analyses

At each site, a pit was dug underneath the irrigated area and the dry area within the same paddock. Sites were sampled from late November 2017 to early February 2019, with most sites sampled during November–February. Pits and sites were sampled once only during the study. The 24 paired sites were the replicates (i.e. 24 replicates). Soils were sampled in six 10 cm increments down to 60 cm depth, i.e. 0–10, 10–20, ... 50–60 cm. The inside wall of each core liner was smeared with a thin layer of Vaseline petroleum jelly to seal between the soil and liner. At each depth, a level surface was prepared. Undisturbed soil pedestals, slightly larger than the liner, were then hand carved down the depth increment, over which the soil core liners were then vertically inserted with care, and removed for later analysis.

Cores were sampled adjacent to each other to span the approximate mid-point of each depth increment, using large cores (10 cm diameter, 7.5 cm depth) for large pore size distribution (>30 μm diameter) and smaller soil cores (5 cm diameter, 3 cm depth) for smaller pore sizes (<30 μm diameter). Bulk density was measured on each core. Cores (wrapped in cling film) were stored at 4°C before laboratory analysis.

Soil physical analyses were measured at the Manaaki Whenua – Landcare Research soil physics laboratory. Full methods for the preparation of soil cores, bulk density, particle density, pore size distribution, and water retention are described elsewhere (Gradwell 1972; Gradwell and Birrell 1979). Particle density was measured for each core to calculate total porosity. Water retention of soil cores was measured under tensions of −10, −100, and −1500 kPa. The large cores (10 cm diameter) were equilibrated to −10 kPa on ceramic plates using a hanging column of water to measure the volumetric percentage of pores >30 μm. The smaller soil cores were equilibrated to −100 and −1500 kPa using pressure chambers (Gradwell and Birrell 1979).

Although terms vary in the literature (Drewry *et al.* 2021*b*), we report macroporosity as pores >30 μm drained at −10 kPa matric potential, volumetric water content at field capacity (−10 kPa), 'readily' available water capacity, RAWC (−10 to −100 kPa), stress point (−100 kPa), 'semi-available' water capacity, SAWC (−100 to −1500 kPa), AWC (−10 to −1500 kPa), and volumetric water content at permanent wilting point, PWP (−1500 kPa). The water content below PWP is considered unavailable to plants. Water release values are expressed as a percentage volume of pores per unit volume of soil (% v/v). Note that SAWC + RAWC = AWC. While RAWC and AWC are widely used in the literature (e.g. Román Dobarco *et al.* 2019), the water-holding pore space between stress point and wilting point does not appear to have a commonly used term, so we have used SAWC. RAWC is the water storage porosity that plants can access under minimal stress, whereas soil water stress increasingly restricts plant growth as the soil dries below stress point. We use the term SAWC to represent these pores.

Statistical analysis

Statistical analyses of soil properties (at six 10-cm-depth increments, and averaged over 0–30, 30–60 and 0–60 cm) were undertaken to compare soils under irrigation and dryland. Each set of irrigated and dryland soils was treated as a pair, and a paired samples *t*-test was used to determine the significance of the difference between irrigated and dryland.

A one-way analysis of variance was used to determine whether land use (dairy vs non-dairy sites) significantly affected response to irrigation. Regression analysis was used to determine the significance of the correlation between irrigation duration (number of years under irrigation) and response to irrigation. For each analysis, the model residuals were examined to ensure they conformed with the model assumptions. For one of the soil sites, the macroporosity, AWC, and RAWC values for the 40–50 cm depth increment for the irrigated pit were very unusual; this was ascribed to an unusually sandy lens, so the analyses involving these three variables were rerun omitting the depth increment from this site.

Results

Comparisons of irrigated and dryland sites

AWC, RAWC, SAWC, and PWP

Comparisons of the water retention characteristics at irrigated and dryland sites at each depth increment are presented in Table 2. SAWC and PWP values were significantly greater in the irrigated sites than the dryland sites at the 0–10 and 10–20 cm depths (Table 2). In contrast, over the same depth increments, RAWC was significantly smaller under irrigation and at 40–50 cm depth (Table 2), and illustrated in Fig. 2. AWC values integrated the opposite trends in RAWC and SAW, resulting in AWC only being significantly greater under irrigation at the 10–20 cm depth (Table 2). For the remaining depths, there were few significant differences between the treatments, with no obvious trend except for SAWC (20–30 cm) which was

Table 2. Readily available water capacity (RAWC, % v/v), available water capacity (AWC, % v/v), semi-available water capacity (SAWC, % v/v), and water content at permanent wilting point (PWP, % v/v), for irrigated and dryland sites for six depth increments.

Indicator	Depth (cm)	Irrigated	Dryland	l.s.d. (5%)	Sig. of diff.
RAWC (%)	0–10	7.95	9.07	0.68	**
	10–20	7.41	8.69	0.86	**
	20–30	7.68	8.60	1.15	n.s.
	30–40	7.11	7.85	0.95	n.s.
	40–50	5.74	6.86	0.81	**
	50–60	5.38	6.07	0.81	n.s.
AWC (%)	0–10	23.71	22.92	1.90	n.s.
	10–20	20.57	18.87	1.25	**
	20–30	18.08	17.10	1.78	n.s.
	30–40	15.67	15.48	1.60	n.s.
	40–50	12.65	12.86	1.18	n.s.
	50–60	11.11	11.80	1.39	n.s.
SAWC (%)	0–10	15.75	13.85	1.74	*
	10–20	13.16	10.18	1.00	***
	20–30	10.40	8.50	1.54	*
	30–40	8.56	7.64	1.42	n.s.
	40–50	6.70	6.08	1.20	n.s.
	50–60	5.73	5.73	1.16	n.s.
PWP (%)	0–10	18.26	16.47	1.65	*
	10–20	18.01	16.38	1.16	**
	20–30	16.66	16.13	1.50	n.s.
	30–40	18.26	17.10	1.71	n.s.
	40–50	19.02	18.23	1.58	n.s.
	50–60	19.54	17.81	1.67	*

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.
l.s.d., least significant difference; n.s., not significant; Sig. of diff., significance of difference.

consistent with differences over the 0–20 cm depth. The site distributions for AWC, SAWC, and PWP are shown in the Supplementary material (Figs S1, S2).

AWC, RAWC, SAWC, and PWP for the irrigated and dryland sites, averaged over 0–30 cm (topsoil), 30–60 cm (subsoil), and 0–60 cm (soil profile), are presented in Tables 3 and 4. Both SAWC and PWP values were significantly greater in the irrigated sites than in the dryland sites when averaged over 0–30 cm; and also 0–60 cm for SAWC (Tables 3 and 4). In contrast, RAWC was significantly greater in the dryland sites when averaged over 0–30, 30–60, and 0–60 cm.

Management decision support tools often utilise soil water storage expressed as 'mm storage' for a specific profile depth, with water storage equivalent summarised in Table 3. For the water storage measurements with observed significant differences, summed over the 0–30 cm depth, and over the 30–60 cm depth, irrigated sites had an average of 3.3 and 2.5 mm less RAWC than dryland sites, respectively. Summed over the 0–60 cm depth, irrigated sites had 6.2 mm less RAWC than dryland sites (Table 3). Summed over the 0–30 cm depth, irrigated sites averaged 6.8 mm more SAWC than dryland sites, and over the 0–60 cm depth, irrigated sites had 8.2 mm more SAWC than dryland sites.

Soil bulk density, total porosity, and macroporosity

Soil bulk density, total porosity, and macroporosity for the irrigated and dryland sites are presented in Table 5. Macroporosity was significantly greater in the dryland sites at the 10–20 cm depth, but there were no significant differences for bulk density and total porosity (Table 5). When averaged over 0–30 cm, macroporosity was significantly greater in the dryland sites, but there were no significant differences for bulk density and total porosity when averaged over the depths (Table 4).

For individual sites in this study, 12 of the 24 irrigated sites had macroporosity (0–10 cm) <10%, with four sites <6%, indicating compaction (Drewry *et al.* 2008; Hu *et al.* 2021).

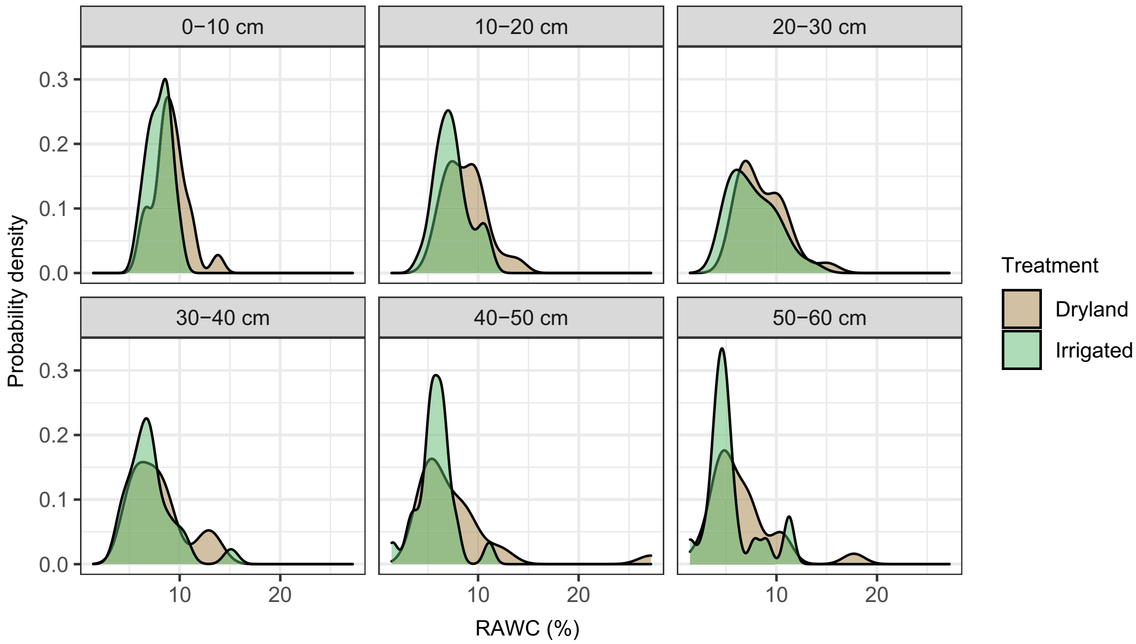

Fig. 2. Probability distributions for readily available water capacity (RAWC, % v/v) for irrigated and dryland sites for six depth increments.

Table 3. Mean readily available water capacity (RAWC, % v/v), available water capacity (AWC, % v/v), semi-available water capacity (SAWC, % v/v), and their water storage equivalent (mm), for irrigated and dryland sites, over 0–30 cm (topsoil), 30–60 cm (subsoil) and 0–60 cm (profile).

Indicator	Depth (cm)	Volumetric capacity				Water storage equivalent			
		Irrigated (% v/v)	Dryland (% v/v)	l.s.d. (5%)	Sig. of diff.	Irrigated (mm)	Dryland (mm)	l.s.d. (5%)	Sig. of diff.
RAWC	0–30	7.68	8.79	0.76	**	23.04	26.36	2.27	**
	30–60	6.01	6.86	0.70	*	18.04	20.57	2.09	*
	0–60	6.87	7.82	0.67	**	40.65	46.89	4.00	**
AWC	0–30	20.79	19.63	1.23	n.s.	62.36	58.90	3.69	n.s.
	30–60	13.12	13.23	1.28	n.s.	39.35	39.70	3.84	n.s.
	0–60	16.87	16.40	1.18	n.s.	101.25	98.38	7.07	n.s.
SAWC	0–30	13.13	10.85	0.97	***	39.32	32.54	2.90	***
	30–60	7.04	6.60	1.22	n.s.	21.11	19.80	3.65	n.s.
	0–60	10.11	8.75	0.97	**	60.68	52.53	5.81	**

0–30 cm typically represents topsoil, 30–60 cm subsoil, and 0–60 cm combined profile for the studied soils. Water storage equivalent (mm) is over the specified depth.
*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.
l.s.d., least significant difference; n.s., not significant; Sig. of diff., significance of difference.

Of the 24 sites, 10 and seven sites also had macroporosity <10% for the 10–20 and 20–30 cm depths, respectively. The site distributions for macroporosity are shown in Fig. 3. The distributions for bulk density are shown in the Supplementary material (Fig. S3).

Effect of land use and irrigation duration

The analyses of variance showed no significant differences in each of the soil physical property responses to irrigation between dairy and non-dairy pastoral land use. The regression analyses also showed no significant relationships between the soil physical property responses to irrigation and the duration (years) of the soil under irrigation.

Discussion

This study showed that while the total volume of pores (total porosity) did not change between irrigated and

Table 4. Mean water content at permanent wilting point (PWP, % v/v), bulk density (Mg/m^3), total porosity (% v/v), and macroporosity (% v/v) for irrigated and dryland sites, over 0–30 cm (topsoil), 30–60 cm (subsoil), and 0–60 cm (profile).

Indicator	Depth (cm)	Irrigated	Dryland	l.s.d. (5%)	Sig. of diff.
PWP (%)	0–30	17.64	16.33	1.26	*
	30–60	18.76	17.56	1.67	n.s.
	0–60	18.00	16.88	1.40	n.s.
Bulk density (Mg/m^3)	0–30	1.329	1.334	0.026	n.s.
	30–60	1.538	1.557	0.023	n.s.
	0–60	1.440	1.452	0.018	n.s.
Total porosity (%)	0–30	49.45	49.10	0.89	n.s.
	30–60	42.91	42.23	0.84	n.s.
	0–60	45.96	45.43	0.60	n.s.
Macroporosity (%)	0–30	11.02	13.14	1.34	**
	30–60	10.10	10.55	1.28	n.s.
	0–60	10.52	11.68	1.20	n.s.

0–30 cm typically represents topsoil, 30–60 cm subsoil, and 0–60 cm combined profile for the studied soils.
*$P < 0.05$; **$P < 0.01$.
l.s.d., least significant difference; n.s., not significant; Sig. of diff., significance of difference.

Table 5. Bulk density (Mg/m^3), total porosity (% v/v), and macroporosity (% v/v) for irrigated and dryland sites for six depth increments.

Indicator	Depth (cm)	Irrigated	Dryland	l.s.d. (5%)	Sig. of diff.
Bulk density (Mg/m^3)	0–10	1.233	1.252	0.044	n.s.
	10–20	1.354	1.359	0.032	n.s.
	20–30	1.399	1.401	0.039	n.s.
	30–40	1.477	1.495	0.041	n.s.
	40–50	1.556	1.561	0.028	n.s.
	50–60	1.577	1.606	0.036	n.s.
Total porosity (%)	0–10	52.47	51.56	1.60	n.s.
	10–20	48.44	48.59	1.09	n.s.
	20–30	47.45	47.15	1.43	n.s.
	30–40	44.92	44.38	1.41	n.s.
	40–50	42.39	42.14	1.04	n.s.
	50–60	41.53	40.46	1.37	n.s.
Macroporosity (%)	0–10	10.51	12.17	2.35	n.s.
	10–20	9.85	13.34	1.79	***
	20–30	12.70	13.92	1.63	n.s.
	30–40	10.99	11.80	1.87	n.s.
	40–50	9.80	10.26	1.18	n.s.
	50–60	10.88	10.86	1.94	n.s.

***$P < 0.001$.
l.s.d., least significant difference; n.s., not significant; Sig. of diff., significance of difference.

dryland use, the pore size distribution was significantly affected, particularly in the topsoil (0–30 cm depth). Overall, our results showed a redistribution towards smaller pore sizes under irrigation, with the number of macropores (>30 μm) and readily available storage pores (30–3 μm) decreasing, while there was an increase in the abundance of smaller pores below stress point (pores <3 μm).

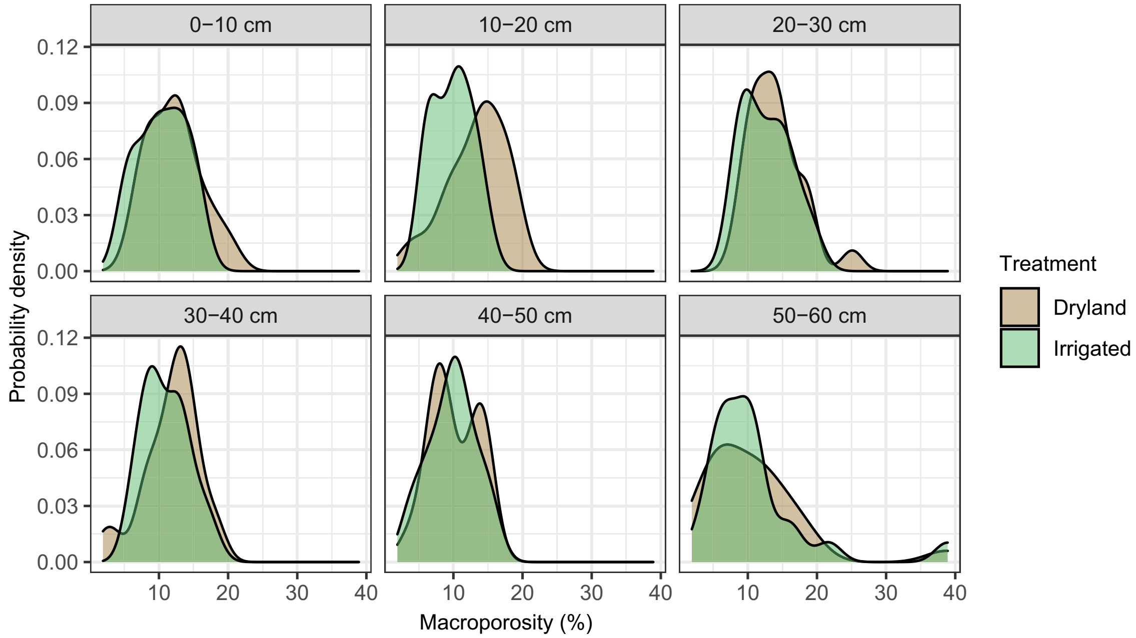

Fig. 3. Probability distributions for macroporosity (% v/v) for irrigated and dryland sites for six depth increments.

Effect of irrigation on soil water storage

In general, while AWC of the topsoil appeared to be slightly larger under irrigation, the difference was only significant at 10–20 cm depth. The plot study of Houlbrooke and Laurenson (2013) showed no significant difference when comparing AWC under the same cattle or sheep grazed land use, but for irrigated cattle grazing was significantly lower than both irrigated and dryland sheep-grazed pasture. The regional study of Fu *et al.* (2021) also found dryland sheep and beef to have significantly greater AWC than irrigated dairy at the 7.5–15 cm depth, but when individual depths were averaged over 0–30 cm there was no significant difference. In contrast, in the single paddock land use comparison of Drewry *et al.* (2021*a*), the AWC response varied between depth increments but was greater at the dairy site for 0–30 cm than at the dryland sheep site. Swanepoel *et al.* (2013) also reported water holding capacity was increased in a sandy soil under dairy-grazed irrigated pasture compared with natural vegetation, which was considered to be due to increased soil carbon content. Overall, this indicates that changes in AWC are not likely to show a consistent trend under irrigation when comparing between land uses, reflecting multiple differences in management such as stocking type, rate, and grazing regime (Drewry *et al.* 2021*b*). Although there are fewer comparisons where land use and management are the same, this study and that of Houlbrooke and Laurenson (2013) indicate AWC is not likely to significantly change under irrigation application in temperate pastoral grazing.

The results showed a significant change in the distribution of pore sizes within the AWC. PWP can represent 'microporosity', being the small soil pores in which water is most tightly held, and unavailable to plants. SAWC represents the portion of plant-available soil water that is held below the stress point, where plants are required to expend increasing energy as the water content lowers towards PWP (Drewry *et al.* 2021*b*), or lead to failure of water conducting tissues (Rowland *et al.* 2015). Previous research has shown that irrigated pastoral soils can have greater microporosity compared with non-irrigated areas (da Costa *et al.* 2014). Similarly, Houlbrooke and Laurenson (2013) showed that soil water content at −100 and −1500 kPa matric potentials was higher under irrigated land than dryland for cattle-grazed pasture, while Fu *et al.* (2021) also found higher PWP and SAWC under dryland sheep and beef compared to irrigated dairy paddocks. This effect could be due to several factors, including the in-filling of pores with time from soil compaction (Houlbrooke and Laurenson 2013; Drewry *et al.* 2021*a*) as indicated from reduced pore and water storage indicators, and wetting and drying cycles (da Costa *et al.* 2014; Pires *et al.* 2017). Wetting and drying cycles also affect soil aggregate stability, cracking, and strength, and are closely associated with pore characteristics (Ma *et al.* 2015).

However, in contrast to the other water storage attributes, RAWC was significantly greater in the dryland sites than in the irrigated sites. This result is consistent with previous studies under temperate pastoral land use (Drewry *et al.* 2021*a*), which also showed that RAWC was significantly lower under irrigated cattle-grazed pasture to 30 cm depth. These studies attributed the reduction in RAWC to compaction arising from grazing of cattle at the high moisture contents that occur under regular irrigation return intervals. Houlbrooke and Laurenson (2013) noted that the water content of soil pores at −100 kPa was most affected by treading-induced compaction, which affects RAWC, while Drewry *et al.* (2021*a*) reported compaction of pores was associated with changes in volumes of pores across a wide range of sizes, consistent with that observed for water storage indicators in this study, e.g. RAWC, SAWC.

Soil compaction under irrigation

Regular soil quality monitoring in New Zealand shows soil macroporosity and bulk density at 0–10 cm depth are affected under dairy grazing land use, with many monitored sites having macroporosity values well below recommended targets (Drewry *et al.* 2021*c*; Hu *et al.* 2021; Ministry for the Environment, Stats NZ 2021). Results from this study showed at 10–20 cm depth, and averaged over the 0–30 cm depth, that macroporosity was significantly lower under irrigated grazed pasture. A similar trend was observed in the Otago (Houlbrooke and Laurenson 2013) and Canterbury regions (Drewry *et al.* 2021*a*; Fu *et al.* 2021), showing that soil physical quality is degrading under different land use beyond the commonly measured 0–10 cm depth that is typically used in soil quality monitoring. Compared to a national scale paired site study of carbon (Mudge *et al.* 2021), our paired site regional study was not designed to specifically examine differences from soil order.

Critical and optimum values of macroporosity for crops and pasture can vary with species, soils, and circumstances (Drewry *et al.* 2008; Pöhlitz *et al.* 2020; Hu *et al.* 2021). A commonly accepted critical value of 10% (Drewry *et al.* 2008) is used in New Zealand for environmental reporting (Ministry for the Environment, Stats NZ 2021). The results in our study showed half of the irrigated sites (which were dairy or dairy support land use) had low macroporosities (<10%), indicating compaction (Drewry *et al.* 2008; Hu *et al.* 2021). The results also indicated soil compaction is occurring at deeper depths. Low soil macroporosity values can indicate there is likely to be a potential limitation to pasture production, but there are few studies of critical values of soil physical properties under pastoral farming, as many studies are based on crop responses (Drewry *et al.* 2008; Hu *et al.* 2021). Pasture yield in New Zealand has been shown to decrease as macroporosity decreases (0–10 cm depth) (Drewry *et al.* 2004). Critical thresholds of 5% air capacity have been used to determine subsoil compaction (Horn and Fleige 2009; Mordhorst *et al.* 2021), but subsoil thresholds are not well defined in New Zealand. Although farm system modelling and grazing studies have been undertaken to assess the farm-system feasibility of restricting grazing during high compaction risk periods (Beukes *et al.* 2013; Laurenson *et al.* 2016; Laurenson *et al.* 2017; Christensen *et al.* 2019), the benefits vary with grazing management and farm system, so further whole-farm-system research under a wider range of soils, climates, and management practices is needed.

Implications for irrigation management

In New Zealand, soil water attributes are widely used to inform both on-farm management decisions, as well as water allocation and environmental compliance. The observation that RAWC was reduced in irrigated sites is significant for land management as it is within this range of soil water content that irrigation scheduling aims to operate, i.e. where pasture can access soil water under the least stress (Vogeler *et al.* 2019). Houlbrooke and Laurenson (2013) highlighted that this could mean shorter irrigation return periods will be needed to prevent plant water stress, but the plot-scale nature of that study may have limited the direct applicability to on-farm systems. Our study showed that this early finding appears to be the case across a wide range of farms in the Canterbury region. Summed over the 0–60 cm depth, irrigated soils had on average 6.2 mm less RAWC capacity than under dryland management (or 3.3 mm less RAWC over the 0–30 cm depth). This is significant for irrigation scheduling, meaning on average the need to irrigate 1 day earlier that if RAWC was similar to that under dryland, given the average Canterbury irrigation application of 4–5 mm/day (KC *et al.* 2018), and internationally ~5–7 mm/day applied (Denef *et al.* 2008; da Costa *et al.* 2014).

The lower RAWC on irrigated sites also potentially has a substantial effect at the farm and regional water planning level. On average, our data indicate that this potential RAWC storage capacity scales to 62 cubic metres per irrigated hectare, or 23 million cubic metres across the 377 000 ha of spray-irrigated dairy and sheep/beef land use in the Canterbury region in 2019 (Ministry for the Environment, Stats NZ 2021). Irrigation is the biggest user of freshwater resources within New Zealand (Ministry for the Environment, Stats NZ 2021). If the reduction in RAWC on irrigated pastoral farms could be addressed then there is potential to reduce the demand of irrigation on freshwater resources and increase freshwater availability for other ecosystem services. A limitation of the study is that it is confined to the Canterbury region, so evaluation in other areas would be worthwhile.

The soil moisture level is a critical factor in the compaction response of soil to grazing (or machinery), with the risk of soil structural damage increasing as water content increases with irrigation to field capacity or near a critical moisture content (Laurenson and Houlbrooke 2016). Given the average spray irrigation return interval, it is likely that grazing may often occur when the soil water content is near field capacity, at least for near-surface soil depths. The resulting compaction effects on the soil pore network that this study showed, further support the need to adopt deficit irrigation highlighted in several studies (Houlbrooke and Laurenson 2013; KC *et al.* 2018; Drewry *et al.* 2021*a*). The benefit of using deficit irrigation would be to avoid grazing when the soil moisture is above a critical limit for compaction risk (Betteridge *et al.* 1999; Drewry *et al.* 2008; Laurenson *et al.* 2016). This has been estimated in several New Zealand soils to be *c.* 10 mm deficit below field capacity, over the 0–300 mm depth (Laurenson and Houlbrooke 2016; Drewry *et al.* 2021*a*). In this study, irrigated soils had an average RAWC over this depth of 23 mm, which only allows for 13 mm application depth if adopting deficit irrigation. This is marginal for practical on-farm adoption, given the typically scheduled requirement in the region of 4–5 mm/day being applied on the average 3-day return interval will mean there is the risk of soils drying to near stress-point within the irrigation cycle. However, based on the dryland sites, there is potential RAWC that could be recovered if the deficit irrigation could minimise the impact of compaction, which is sufficient to provide a buffer in RAWC above the risk of drying to stress point. However, further research is required to quantify the practicality and benefits of this proposed strategy.

Conclusions

Land use change and intensification of agricultural land occurs through irrigation expansion and changing farm management practices, such as increased stocking rates and nutrient use. With more intensive land use, changes to soil physical (and biological and chemical) properties can occur, but the effects of modern irrigation and pastoral farming systems on soil physical properties have not been well quantified. A number of studies have also compared changes between land use, but this can make it difficult to separate land management effects such as irrigation, cultivation, stock type, and the grazing regime.

In this study, the approach meant consistency in land management, with just irrigation varying between paired sites. Although sampling occurred over the two years, the experimental design of paired sites accounted for any variation. The pore-size distribution significantly differed between dryland and irrigated management, particularly in the water storage pores. Under irrigation there was a shift towards a greater abundance of smaller pores. This is reflected in the macroporosity and RAWC being significantly lower under irrigation, while the SAWC and unavailable water held below the PWP both increased. Total porosity and bulk density can be less sensitive than pore size indicators. We conclude that these differences reflect increased compaction under irrigated grazed pasture, particularly under dairy grazed pasture, consistent with findings in similar studies. This study quantified changes in both the topsoil and subsoil but showed that most differences were confined to the topsoil.

In terms of irrigation management, our study indicates that the lower RAWC for the irrigated pasture is significant, both in terms of having to irrigate more frequently, and also potentially increasing allocation requirements when scaled across the region. There is potential to reduce these irrigation requirements if the compaction-induced reduction in RAWC on irrigated pastoral farms could be addressed. Our study also suggests that adopting deficit irrigation could minimise the impact of compaction, but further research is required to quantify the practicality and benefits of this strategy.

Supplementary material

Supplementary material is available online.

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Data availability. The data that support this study cannot be publicly shared due to ethical or privacy reasons and may be shared upon reasonable request to the corresponding author if appropriate.

Conflicts of interest. No potential conflicts of interest was reported by the authors.

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