THE EFFECT OF SOIL AERATION ON THE RECOVERY OF SOIL STRUCTURE IN THE NORTH OTAGO ROLLING DOWNLANDS FOLLOWING WINTER GRAZING OF SHEEP AND CATTLE

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Abstract
The North Otago Rolling Downlands (NORD) has undergone considerable land-use change and intensification following a greater use of irrigation and fertiliser, resulting in increased pasture production and subsequent stocking rates. A decline in soil physical quality associated with livestock grazing has been reported in a number of studies that have been based in this region. Once compacted, soil structure may be restored through a process of natural recovery facilitated by wetting and drying, freeze-thawing, pasture growth and earthworm activity. These processes however tend to be limited to the top 0-5 cm of soil where moisture fluctuations, pasture root growth and biological activity are often greater than at lower soil depths. Mechanical aeration has been used to ameliorate the adverse effects of soil compaction by loosening top-soils to greater depth within the soil profile. Here we report findings from a trial that was established in the NORD region to compare the rates of soil recovery (as determined by increases in soil macroporosity values) via natural or mechanical means. This assessment was made at a trial site where four years of winter forage cropping under cattle or sheep grazing had caused a significant amount of soil compaction.

Soil macroporosity levels at depths of 0-5 and 5-10 cm were significantly greater in aerated soils relative to the non-aerated treatment six months after mechanical aeration to 20 cm soil depth. This was apparent under both cattle and sheep grazed pastures. Significant differences between aerated and non-aerated plots were no longer evident eighteen months after aeration, however. Consistently higher pasture growth rates were evident in the aerated treatment during both years following aeration. Results indicate that mechanical aeration can provide an immediate improvement in porosity of compacted soils, although this benefit appears to be short-lived.

Introduction
Land use intensification has occurred at a rapid rate in recent years across New Zealand, in particular in water-scarce regions of the South Island where several large irrigation schemes have recently been established. The North Otago Rolling Downlands (NORD), for instance, has undergone considerable land-use change and intensification following a greater use of irrigation. This has seen an increase in pasture production, fertiliser input and animal stocking rates (Houlbrooke *et al.* 2008). A decline in soil physical quality associated with intensified livestock grazing has been reported in a number of studies based in the NORD region (Cournane *et al.* 2011; Houlbrooke *et al.* 2011). Regional pedology is dominated by Pallic soils with poorly structured subsoils and a pronounced Fragipan generally at a depth of c. 500 mm (Hewitt and Shepherd 1997). Impaired drainage characteristics mean these soils remain wet for extended periods of the year, making them highly susceptible to soil structural

damage when grazed intensively (Drewry and Paton 2000b; Hewitt and Shepherd 1997; Houlbrooke *et al.* 2008). Following four years of consecutive winter cropping at this trial site, Houlbrooke *et al.* (2009) reported an on-going decline in soil macroporosity (defined as pores > 30 µm) under cattle and sheep grazing, particularly where irrigation had been applied during the crop establishment phase. This occurred due to the increased amount of biomass grown with irrigation and the subsequent increase in stocking densities (Houlbrooke *et al.* 2009).

A reduction in total and macro porosity (i.e. compaction) has been shown to reduce the drainage capacity of soils and increase soil bulk density (Cournane *et al.* 2011; Houlbrooke *et al.* 2008; McDowell *et al.* 2003). A shift in pore size distribution towards greater microporosity will also affect the soil's water release characteristics (Miller *et al.* 2002). During wet conditions compacted soils will reach a point of saturation more rapidly than non compacted soils (O'Sullivan and Ball 1993). Greater incidence of surface run-off associated with lower infiltration rates and/or lower water holding capacity may lead to greater nutrient loss to surface waterways (McDowell *et al.* 2003), while poor drainage may increase the rate of compaction (Piwowarczyk *et al.* 2011). Furthermore, the distribution of pasture roots may also be affected by an increase in soil strength associated with compaction (Drewry *et al.* 2008).

Soils recover naturally through a number of processes including wetting and drying, freeze-thawing, pasture growth and earthworm activity (Drewry 2006). These processes however tend to be limited to the top 15 cm of soil where soil moisture fluctuates more frequently than subsoil (Drewry *et al.* 2000b). Mechanical aeration has been used to assist in reversing the adverse effects of soil compaction by loosening soils to greater depth within the profile, usually around 25 cm (Drewry and Paton 2000b). Greenwood and Cameron (1990) reported a 30% increase in macroporosity following mechanical aeration of a Pallic soil in North Otago previously damaged from on-going cattle grazing. Similarly, in Southland, New Zealand, Drewry et al. (2000b) reported a 27% increase in macroporosity of a Pallic soil used for winter grazing, however some re-compaction and settling occurred in the upper 18 cm of the soil profile following the re-introduction of cattle. Other work has shown that the benefits of mechanical aeration can be dependent on soil type. Some soils quickly revert back to their compacted state (Burgess *et al.* 2000; Hamilton-Manns *et al.* 2002; Houlbrooke 1996), particularly dispersive soils such as those found in the NORD (Adcock *et al.* 2007; Hewitt and Shepherd 1997).

There have limited studies dealing with the effect of winter grazing on soil compaction and the subsequent length of time required for soil to recover once damaged. If the period of soil damage is prolonged this is likely to have severe implications for pasture yields. Therefore, in an attempt to reverse the soil compaction evident after four years of winter forage cropping under cattle or sheep grazing, a trial was established in the NORD to monitor the rate of natural soil recovery (i.e. an increase in soil macroporosity without the use of mechanical aeration), and to assess the effectiveness of mechanical aeration on soil recovery.

Materials and Methods

Description of the study area

The experiment was conducted on a sheep and beef farm near Windsor, North Otago (170^{o}46'00.68"E, 45^{o}01'09.49"S), approximately 200 m above sea level. This region has a mean annual rainfall of 550 mm yr^{-1}, a mean January temperature of 15° C, and mean July temperature of 5° C. The trial paddock was north facing with a slope of c. 7-15°.

The soil is characterised 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). The site was historically used for dryland sheep and dairy support grazing, with a recent history of short rotation feed crops for two years (kale and barley silage), preceded by long-term permanent pasture. The research trial comprised of 16 fully fenced plots (approximately 10 m wide and 25 m long) running lengthways down the slope.

In December 2008, soil was mechanically loosened (aerated) in one half of each plot to a depth of 20 cm using a ‘Clough pan-aerator’ with winged tips. The ‘Clough pan-aerator’ was pulled through the soil by a tractor causing the winged tips to break up the soil to a depth of 25 cm. The remaining half of the plot left undisturbed (control). Points were identified within each plot to ensure that both aerated and control treatments had upslope and downslope sampling locations. A ryegrass (*Lolium perenne L.*) and white clover (*Trifolium repens L.*) pasture mix was sown by direct drilling at a rate of 20 kg ⁄ ha in January 2009.

Soil Management
In the 6 months after aeration, all plots were grazed once by sheep followed by two grazings by young cattleprior to normal treatments being imposed. This was to allow the newly sown pasture on aerated soils time to establish. Each plot was subsequently grazed by either sheep or cattle, and stocking rate was 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 range of cattle was 270 to 530 kg/animal, and the average lamb/hogget from 32 and 55 kg. Grazing rotations were 27 days long on average during the growing season (defined as 15 August - 15 May). All treatments were grazed at the same time when pasture cover across all plots reached 3500 kg DM ha^{-1}, with grazing down to approximately 1400 kg DM ha^{-1}.

Urea (80 kg ⁄ ha) was applied in March and December, and 45 kg P ⁄ ha was applied as superphosphate in November 2009. Following soil aeration in December 2008, pasture was grazed twice by sheep (20 April and 18 May 2009) at a stocking density of ca. 1700 sheep ⁄ ha, to control pasture growth. Grazing treatments, i.e. cattle (yearlings) or sheep grazing, commenced on 23 July with each grazing lasting approximately 24 hours.

Irrigation water was applied using fixed low application rate (c. 2 mm hr^{-1}) sprinklers (K-Line pods) between September and April each year. Irrigation was applied when a trigger point of 50% available water capacity (as determined by an *in-situ* Aquaflex^{TM} SI.60 soil moisture tape; Streat Instruments Ltd, Christchurch) was reached.

The research site was fertilised throughout the three years of the trial in accordance with farm practice to ensure no limitation of nutrient supply for pasture growth. Dry land plots were fertilised according to irrigated plots to ensure no immediate differences in soil fertility levels occurred between the irrigated and dryland treatments over the four year experimental period.

Measurements
Soil sampling in late autumn each year measured percentage macroporosity (v/v), soil bulk density (Mg m^3) and structural condition score (SCS). Pore size distribution and bulk density were determined at 0-5 and 5-10 cm depth from three paired samples per plot, and measured in a manner previously described in detail by Drewy and Paton (2000a). Earthworms were removed using formaldehyde, then all cores equilibrated on a tension table to -1 kPa and -10

kPa to determine the percentage of soil pores > 300 μm diameter, and the percentage of soil pores > 30 μm diameter (macroporosity), respectively. Dry bulk density and total porosity were calculated from sample oven-dry weights. The SCS was a semi-quantitative assessment that was determined from three sub-samples of intact soil from each plot. Here, squares of soil (20 x 20 cm wide by 10 cm deep) were dug with a spade and brought back to the laboratory. Scores were determined after breaking-up and spreading each sample onto a rectangular tray, following the method from Peerlkamp (1967). The scale of SCS ranges from 1 to 5 in half unit increments, where a high value related to a well-structured soil and a low value to a poorly structured soil. This was judged by visual assessment of the size, shape and porosity of aggregates, and their cohesion and root development (Peerlkamp 1967). Pre- and post-grazing pasture mass was assessed using a locally calibrated rising plate meter (L'Huiller and Thompson 1988) to determine pasture growth rates from xxxx 2008 to yyyy 2011.

Data treatment and statistical methods

Soil physical data (bulk density and macroporosity) at each depth were analyzed by analysis of variance (ANOVA), with the block structure given by subsample within sample, within plot, and within block, and the treatment structure given by irrigation and stock treatments and their interaction. Significance in monthly pasture production was determined by a student t-test. All analyses were carried out using the statistical package GenStat 11 (2008). Unless stated otherwise, all reported changes in time or differences between treatments are significant at the 5% level.

Results and discussion

Prior to soil aeration in December 2008, macroporosity was less than 10% v/v in the surface soils (0-5 cm) where cattle had previously grazed winter forage crops (Figure 1). Interesting macroporosity under sheep grazing remained above 10% v/v and therefore was unlikely to have limited pasture growth. At a soil depth of 5-10 cm, macroporosity post forage crop grazing was less than 10% v/v under both sheep and cattle. A significant decline in pasture growth has been reported when soil macroporosity is less than 10% and is associated with restricted water and nutrient movement within the soil matrix (Burgess *et al.* 2000). Mechanical aeration of sheep and cattle plots was effective in raising soil macroporosity above this threshold for plant growth at depths of 0-5 and 5-10 cm. A significant increase in macroporosity also occurred in the non-aerated plots, once a shift from winter grazing of fodder crops to rotational grazing of pastures occurred. Improved macroporosity in non-aerated soils reflects the natural recovery of soil structure, and while significant, recovery was less than that achieved by mechanical aeration in the first year (i.e. July 2009).

Two years after aeration macroporosity in the surface soil (0-5cm) of the aerated plots had reverted back to a state similar to that of the non-aerated soils with no significant difference between aeration treatments (Figure 1). While this trend was also apparent at the 5-10 cm soil depth where cattle had been grazed, macroporosity under sheep grazing remained significantly higher in 2010. As noted by Houlbrooke *et al.* (2008), the impact of cattle on soil macroporosity is substantially greater than sheep due to animal weight and therefore greater hoof pressure placed on the soil. Greater compaction under cattle grazing is likely to reflect differences in animal stocking class and the subsequent pressure on soils. By 2011 there was no difference between aerated and non-aerated soils regardless of soil depth or grazing class. These results support similar findings on this soil type whereby no significant differences in macroporosity between aerated and non-aerated plots were evident after six months (Curran Cournane *et al.* 2011). Structural improvements due to aeration decline more rapidly in soils with poor structure (Burgess *et al.* 2000). Due to their low carbon content, Pallic soils in the NORD are prone to soil slaking under moderate compactive force such as grazing. Structural changes achieved with aeration are therefore likely to be limited, particularly if on-going grazing events occur coincide with high SMC as was observed at this site (Adcock *et al.* 2007; Cournane *et al.* 2011).

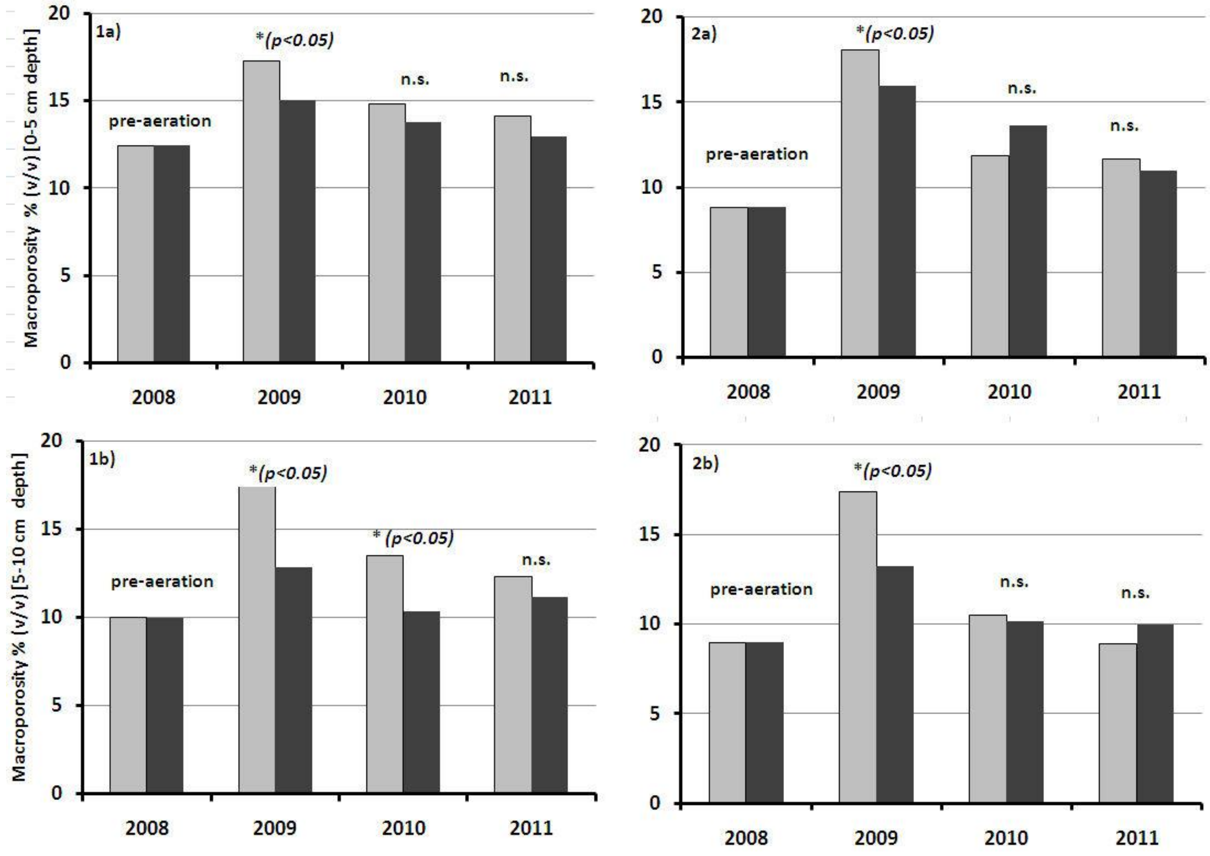

Figure 1. Soil macroporosity (v/v) in plots grazed by sheep or cattle with (■) or without (■) mechanical aeration [carried out between 2008 and 2009 sampling dates]. Macroporosity under sheep at a depth of (**1a**) 0-5 cm or (**1b**) 5-10 cm, and under cattle at depths of (**2a**) 0-5 cm or (**2b**) 5-10 cm are shown.

Pasture yield

Annual pasture production in the cattle and sheep grazed plots tended to be greater where aeration had been carried out (Table 2), however this was not significant (P>0.05) in the two years of monitoring. Pasture response to soil aeration was not evident in similar studies such as Burgess *et al.* (2000) and Drewry *et al.* (2000b) following one and two growing seasons respectively.

Table 2. Annual pasture production (tonnes dry matter per hectare) from plots grazed by sheep or cattle, with or without mechanical aeration.

	2009-10	**2010-11**	**Annual mean‡**
Sheep aerated	23.2	17.1	**20.2**
Sheep non-aerated	21.9	14.8	**18.4**
Cattle aerated	20.0	21.1	**20.5**
Cattle non-aerated	17.1	18.7	**17.9**

‡Not significant between aeration treatments for both cattle and sheep grazing

In general, differences in monthly dry matter production were not significant throughout the trial period, with the exception of two occasions under the cattle-grazed treatment. This included significantly greater monthly pasture production under aeration in May 2009 and again in March 2010 (Figure 3). Increased pasture production did not however correspond with abnormally wet conditions that might otherwise emphasise the benefit in soil aeration by improving soil drainage characteristics (Burgess *et al.* 2000). While aeration may, in some instances, decrease pasture production by causing greater moisture stress to the plant i.e. decreasing soil water holding capacity or damaging the root structure (Drewry *et al.* 2000b; Drewry and Paton 2000a), such factors did not appear to be influential in these soils. Monthly pasture production tended to be consistently higher under aeration, albeit in most cases this was not significant.

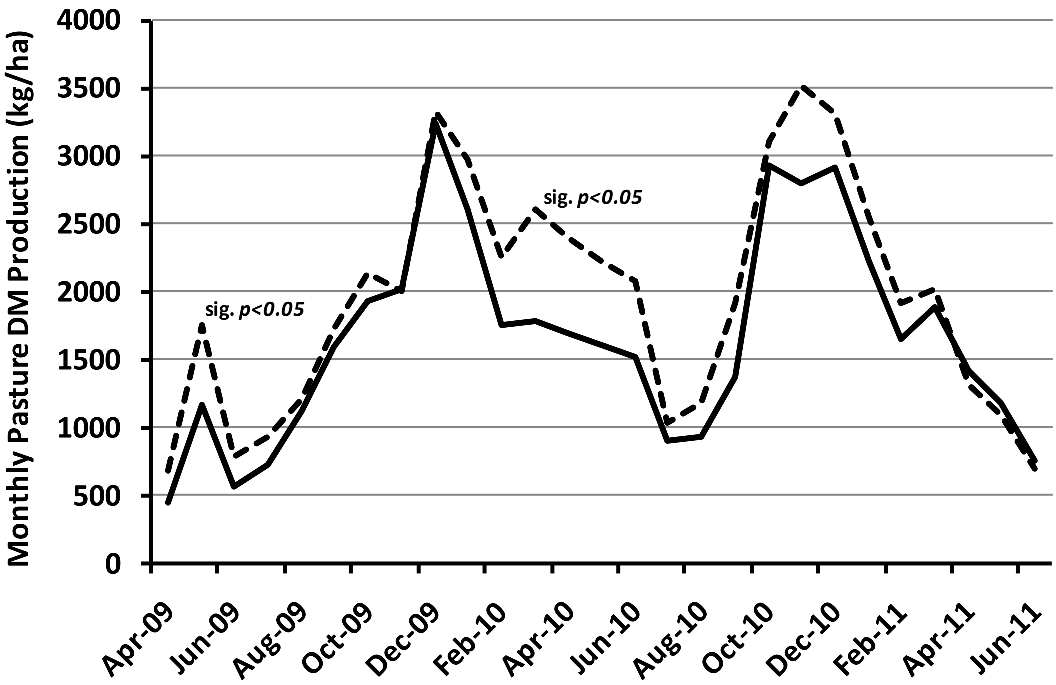

Figure 3. Monthly pasture production (kg dry matter per hectare) from plots grazed by cattle with (dotted line) or without (solid line) mechanical aeration. Difference in monthly pasture production were significant only where indicated by '*sig. p<0.05*'.

The formation of macro-aggregates involves the stabilisation of micro-aggregates into larger structural macro units, and is generally associated with improved pasture growth (Drewry *et al.* 2004). This process relies on carbon residues such as glomalin, an amino polysaccharide derived from plant roots and mycorrhizal fungi, to form cohesion between soil micro-aggregates (Wright and Upadhyaya 1996). Therefore long term improvements in soil macroporosity are only likely to be achieved in soils with an active biological community (Beylich *et al.* 2010). Better soil aeration intended through mechanical aeration may encourage a productive soil biological community, thereby catalysing the forming soil aggregates (Beylich *et al.* 2010). This process is suggested by Burgess *et al.* (2000) to increase, albeit over a short time frame (i.e. 40 weeks), with soil aeration whereby a greater abundance of small aggregates was observed by these researchers suggesting macro-aggregate formation. Soil macroporosity data suggests an initial 'loosening' of soils under mechanical aeration and subsequent increase in macroporosity. Improved soil structure however does rely on the on-going soil biological processes involved in soil aggregation (Wright and Upadhyaya 1996). Poorly timed grazing events, i.e. when soil moisture content is high, in both aerated and non-aerated soils is likely to have curtailed aggregate formation processes to a reconsolidation of the soil structure and depletion in soil oxygen (Drewry 2006). Therefore the initial benefit achieved with mechanical aeration is likely to be of limited duration if subsequent grazing management does not consider SMC at the time of grazing. In such a case, macroporosity and pasture growth in general will decline despite prior aeration treatment being carried out or not (Curran Courna *et al.* 2011).

Conclusions

Generally, soil macroporosity significantly improved in the first 6 months following mechanical aeration. In the mid-term (i.e. 2-3 years) however, the benefit of aeration on macroporosity was minimal when compared against natural soil recovery processes. Where cattle were subsequently grazed following soil aeration, re-compaction of soils back to a non-aerated state occurred rapidly. It should be noted however that although only slightly significant, soil aeration did increase pasture yield by approximately 10-15%. Despite this, we suggest improvements in macroporosity attained through repetitive aeration of soils (i.e. annually) are likely to be temporary and will fall short in building resilient soil aggregates unless soil biological processes are enhanced by improved drainage and aeration. Furthermore, natural recovery of soils was effective in rejuvenating soil structure. Preference should therefore be towards strategic management of animals, particularly cattle, in order to prevent grazing on soils with high SMC, particularly those soils that are prone to compaction such as the Pallic soils of NORD.

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