MARLBOROUGH DISTRICT COUNCIL

Soil Compaction Pugging Survey Under Drystock Land Use

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Executive Summary

Soil structural degradation as a result of soil compaction/pugging is increasingly being recognised as an important issue at some grazing sites in New Zealand. This is because the effects of soil compaction/pugging are wide ranging, affecting not only soil and plant health but also the wider environment.

Currently we only have limited information on the extent and magnitude of soil compaction across some landuses in Marlborough. This is true for drystock pasture sites which are a landuse activity known to be susceptible to soil compaction.

In this study 117 soil samples were taken from 37 drystock pasture sites. Each soil sample was analysed for soil macroporosity and bulk density (two measures of soil compaction/pugging) and also available phosphorus (Olsen P).

It was found that the vast majority of sites (32 of 37) had soil macroporosity values within target ranges considered optimal for pasture production and environmental protection. The small number of sites with low macroporosity were ones which hadn't been subject to recent pasture renewal or sites that had been strip grazed. Remedial works to subsoil and re-sow these types of sites will reduce compaction and likely result in improved pasture production.

Olsen P concentrations in soils were all well below the upper limit considered to pose an environmental risk. In fact all but four sites had Olsen P values below the target range required to sustain near maximum pasture production for sheep and beef in sedimentary soils and would benefit from a capital P fertiliser application.

This study has shown that with the exception of a small number of sites, soils under drystock pasture are not showing evidence of widespread soil compaction.

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1. Introduction

Regional councils (and unitary councils) have a responsibility for promoting the sustainable management of the natural and physical resources of their region. One of the physical resources that we have a duty under Section 35 of the Resource Management Act (1991) to monitor and report on is soil; specifically to report on the "life supporting capacity of soil" and to determine whether current practices will meet the "foreseeable needs of future generations". The collection of detailed soil monitoring data is therefore vital because it provides information on what effects current land use activities are having on soil quality and whether we need to change or prioritise the way we manage the land environment. This is essential because not all soils are equal and some are fragile and if not carefully managed are at risk of degradation. This kind of information is becoming increasingly important as some land use activities e.g. dairying, viticulture are intensifying across New Zealand and putting pressure on our soils.

Several forms of soil degradation have been observed across New Zealand from national monitoring under the '500 Soils Project' (and subsequent regional council Soil Quality Monitoring Programmes). These have included loss of organic matter and soil structural stability under some cropping sites, a build up of nitrogen in soils under some dairy pastures coupled with high levels of available phosphorous and widespread moderate compaction under pasture and some cropping land uses (MfE, 2010).

To help determine what effect land use practices were having on soil quality in the Marlborough region a soil monitoring program began in 2000. The monitoring program involved collecting soil samples from a network of sites that represented the main land use activities and soil types within the region and analysing samples for a suite of soil physical, biological and chemical properties that have been shown to be robust indicators of soil quality. This data was then compared to national soil quality targets developed by Ministry for the Environment. To date 87 sites have been sampled as part of the Council's soil quality monitoring programme, and while these sites need to be sampled several times at 5 yearly intervals to give an indication of trends or changes over time, what the results of this monitoring do provide is a useful snapshot of soil quality at a point in time.

The results of monitoring to date indicate that on the whole soil quality is fairly good in Marlborough, although there are some potential issues. Notably there is a high proportion of soils that don't meet the desired target value for macroporosity - one of the soil physical measurements that is considered a sensitive indicator of soil compaction. This was evident in soils at cropping sites, soil in the inter-row at vineyards and in particular soils at dairy sites where a large number had macroporosity values below the 10% threshold thought to adversely affect pasture production (Figure 1). What was also apparent was that a number of the drystock pasture sites had low macroporosity values. This is something that has been reported nationally, where a third of the drystock pasture soil quality monitoring sites sampled between 1995 and 2009 didn't meet their target range for macroporosity (MfE, 2010).

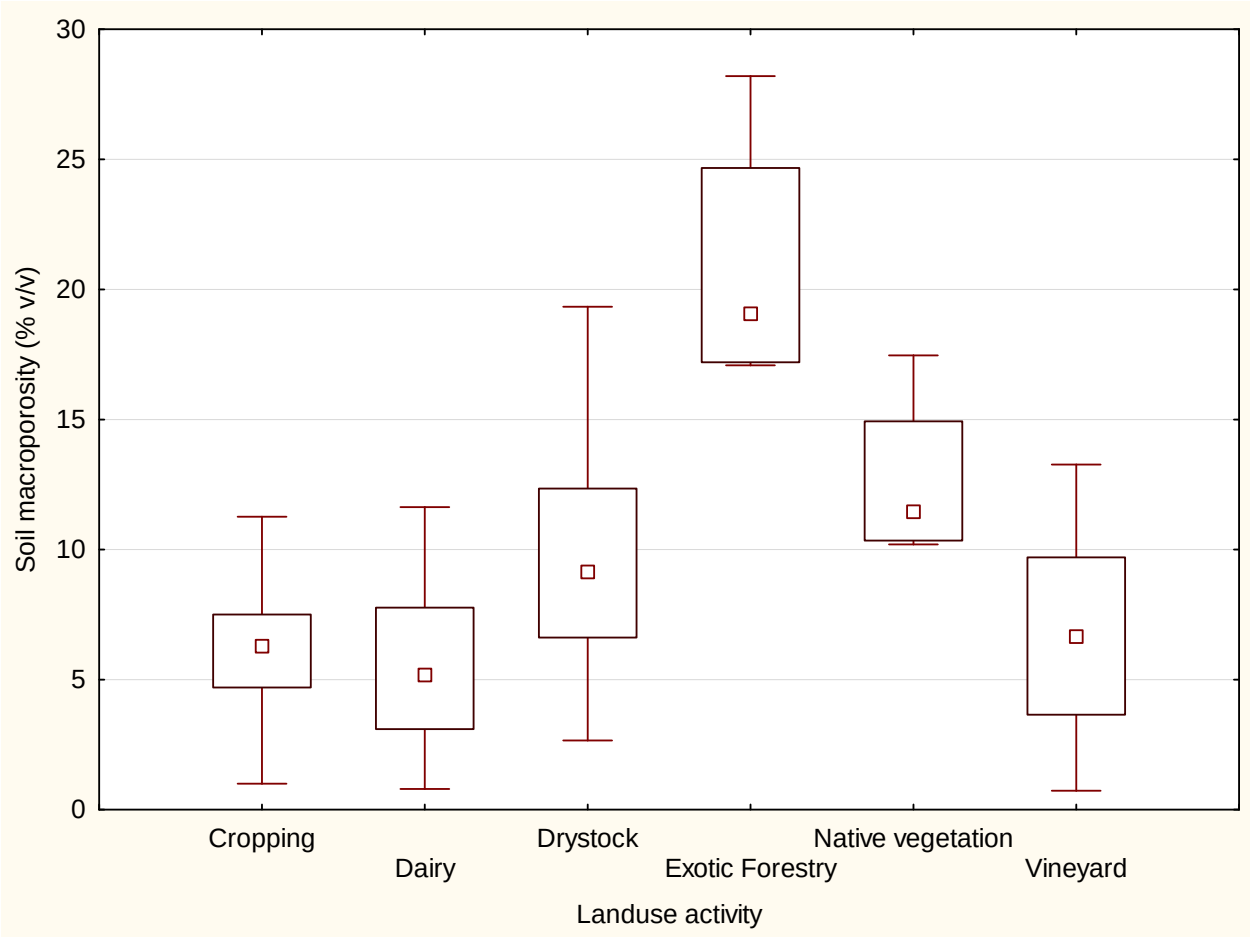

Figure 1 **Box and whisker plot showing soil macroporosity values (% v/v measured at -5kPa) from different land use activities from the soil quality monitoring sites (n=87)**

1.1. What is soil compaction and why is it important in terms of soil quality?

Soil compaction has been described as the compression of an unsaturated soil body resulting in a reduction of the volume of air (Hillel, 1980). In grazing situations it occurs when the load of a grazing animal imposed on an unsaturated soil is greater than the load-bearing capacity of the soil. During compaction particles are forced closer together by the applied load reducing the total pore space and permanently expelling air or water from the soil pores (Patto et al., 1978). Typically the volume of large inter-aggregate soil pores (i.e. macropores) are first to disappear. Hence a measure of soil macroporosity is often thought to be a sensitive indicator of soil compaction. What is important to note is that soil compaction is very dependent on the level of moisture in the soil. Very dry soils below the shrinkage limit are hard and resist deformation (Figure 2). In comparison, wetter soils up to the plastic limit have a very high risk of compaction (Figure 2).

Another term often used to describe soil structural deterioration, specifically due to livestock treading, and that is sometimes incorrectly used to describe soil compaction is soil pugging. Soil pugging describes the process whereby livestock tread in wet, soft soil and create deep hoof imprints (Figure 3). It is a type of plastic deformation and occurs on soils with medium to high soil water content (Figure 2) when the animal load exceeds the bearing capacity of the soil (Patto et al., 1978).

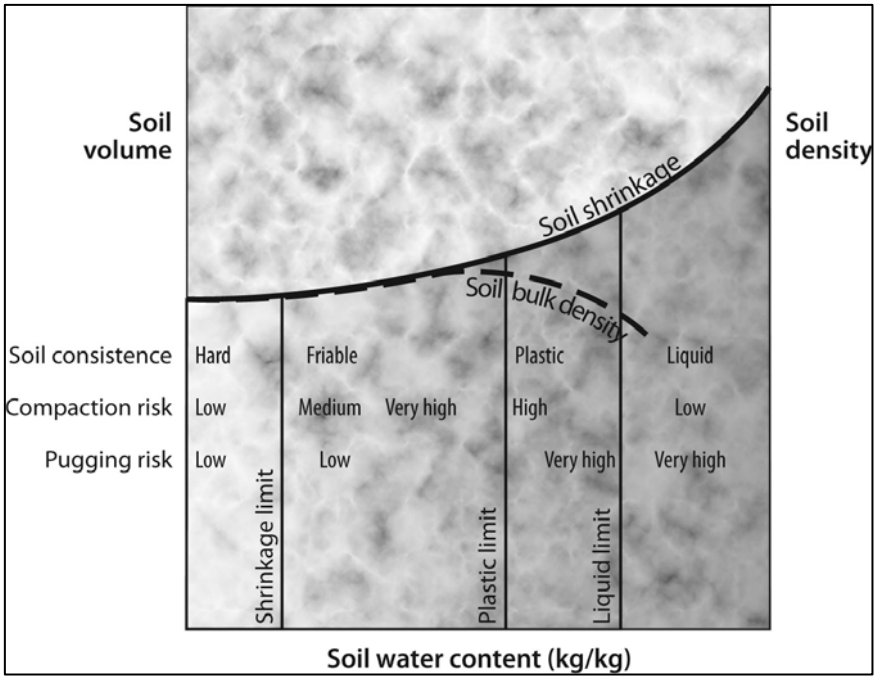

Figure 2 Relationship between soil water content and soil consistency (from Drewry et al., 2008, reprinted with permission from author).

When soils are pugged the air pores are generally water-filled and will not compress under the weight of the hoof. However the network of macropores in the soil can become distorted or disconnected, so that when the water dries out, the exchange of air and drainage of water is difficult even though the volume of the macropores is often unaffected.

Figure 3 Example of a highly pugged Recent Soil (NZSC) on a drystock farm in Marlborough

1.2. So what are some of the effects of soil compaction/pugging?

An overview of some of the potential soil, plant and environmental effects of soil compaction/pugging from animal treading is given in Figure 4.

One of the most important effects of soil compaction/pugging is what it can do to pasture production, with the effects being both direct and indirect. For example animal grazing and treading, particularly in wet conditions can affect pasture yield directly through leaf burial in mud, crushing, bruising and a reduction in dry matter production (Nie et al. 2001). Indirect effects include restriction of root penetration and radial growth of roots in dense soils, reduced aeration, increased water logging potential due to slower ability to drain, reduced nutrient availability and also compacted layers may impact on water infiltration and hence the amount of water storage in a soil.

A decrease in the proportion of large pores as a result of compaction/pugging can lead to reduced infiltration of water which increases the potential for surface runoff of water. If this runoff contains nutrients i.e. nitrogen (N), phosphorous (P) or contaminants i.e. bacteria, this may negatively impact on stream and lake water quality (Ngyen et a., 1998; McDowell et al., 2003; McDowell et al., 2008). Furthermore runoff can increase the potential for surface ponding and flooding (Taylor et al., 2009).

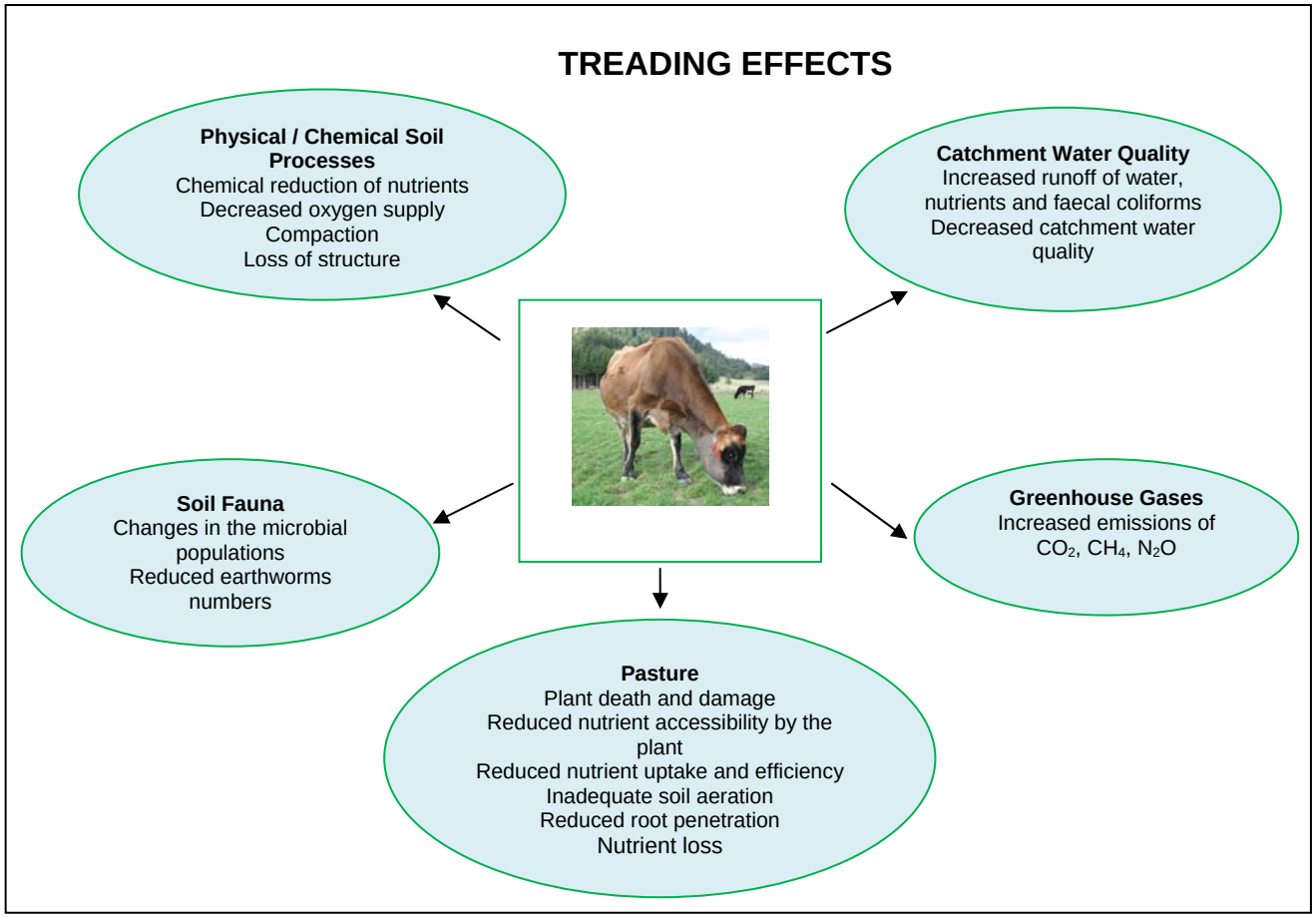

Figure 4 Potential on- and off-site effects of animal treading (adapted from Singleton et al., 2000)

Some of the effects of soil compaction/pugging on soil physical properties include decreased macroporosity, saturated (Ksat) and unsaturated (Kunsat) hydraulic conductivity, aggregate stability and increased bulk density (Kurz et al., 2006; Martinez and Zinck 2004; Drewry and Paton 2000). For example Singleton and Addison (1999) demonstrated a decline in macroporosity, Ksat, Kunsat and aggregate stability from soils that had never been treaded compared to soils that were normally grazed.

Badly pugged soil can also show evidence of poor soil structure such as surface caps, platy structure or an increase in massive soil clods and surface roughness.

In addition, soil compaction also has the potential to increase the emission of several greenhouse gases including CO_2, CH_4 and N_2O (Oenema et al., 1997).

2. Objectives

Clearly the effects of soil compaction/pugging are wide ranging, both direct and indirect and the effects occur both on- and off-site. As indicated, we currently only have limited information on the extent and magnitude of soil compaction across some landuses in Marlborough. The objective of this study is therefore to find out the extent of soil compaction for some drystock pasture sites in Marlborough. This landuse activity was selected as it appears to be susceptible to soil compaction as discussed earlier, with a number of sites below threshold values for optimal pasture growth.

3. Materials and Methods

3.1. Sites

Thirty-seven sites under permanent pasture were sampled. A site represented an individual paddock within a farm. This is because a paddock is normally grazed as a single unit, fertilized as a whole paddock etc. Sites represented several different soil types i.e. Tuamarina Hill, Kaituna, Wither Hill, Flaxbourne Hill, Ugbrooke, Haldon and Broadbridge and two soil orders i.e. Pallic soils and Brown soils (Hewitt, 1993). Sites were located north and south of the Awatere valley, on the Northbank of the Wairau and also the Wither Hills.

3.2. Soil Sampling

Two types of soil samples were collected from each site. Firstly a composite sample comprising approximately 25 individual cores was taken across each paddock at a depth of 7.5 cm. These samples were used for soil chemical analysis. In addition, three undisturbed soil cores (100 mm diameter by 75 mm depth) were sampled at 10-, 30- and 60-m positions along a transect within a paddock avoiding gateways, areas of vehicle traffic access, recent excavation and stock camping. The soil cores were removed as one unit by excavation around the liner, bagged and loaded into padded crates for transport to the laboratory for analysis. These soil samples were used for physical soil analysis.

3.3. Soil Analyses

Total carbon (C) was determined by dry combustion of air-dry soil using a LECO 2000 CNS analyser (Blakemore et al., 1987). Soil pH was measured in water using glass electrodes and a 2.5:1 water to soil ratio (Blackmore et al., 1987). Olsen phosphorous (Olsen P) was determined by extracting soils for 30 min with 0.5 M NaHCO3 at pH 8.5 (Olsen, 1954) and measuring the phosphate concentration by the molybdenum blue method.

There are many soil physical measurements that can be used to give an indication of soil compaction/pugging. These include macroporosoity, air filled porosity, bulk density, aggregate size and stability and penetration resistance (Mackenzie, 2001). Of these measurements, macroporosity has been most often been identified as the most sensitive measure of structural change in soil (Ball et al 2007; Meneer et al., 2005; Drewry and Paton, 2000). Furthermore, along with soil bulk density it is also the measure that has been adopted by the New Zealand Land Monitoring forum for monitoring regional soil quality.

Dry bulk density was measured on soil samples extruded from cores and dried in an oven at 105°C until the weight remained constant and the sample was then weighed (Gradwell and Birrell, 1979).

Macroporosity (-10 kPa), pores >60 µm (-5 kpa) and total porosity were calculated as described by Klute (1986). Particle density was measured by the pipette method. 1

3.4. Statistical Analysis

Median, minimum, maximum and 25th and 75th percentiles were calculated for individual soil properties using STATISTICA. Where appropriate, summary data was presented as frequency distributions or Box and Whisker plots. 2

4. Results and Discussion

4.1. Soil physical measurements

There was a wide range in soil macroporosity across the 37 sites sampled with values ranging from a low of 3.7 up to 25.6% with a median value of 10.7 % (Table 1 and Appendix A).

Table 1 Summary statistics for selected soil physical and chemical measurements across the 37 drystock pasture sites

	minimum	maximum	median	Lower quartile (25%)	Upper quartile (75%)
Macroporosity (-10kPa) (% v/v)	3.7	25.6	10.7	9.1	15.0
Bulk density (t m^{-3})	0.9	1.4	1.1	1.1	1.2
Pores >60 µm (-5kPa) (% v/v)	2.4	20.1	8.5	6.8	11
Total porosity (%)	45.2	64.1	55.9	52.1	58.8
pH	5.3	7.1	5.7	5.5	5.9
Olsen P (mg/L)	4	34	10	7	14
Organic matter (%)	4.2	14	7.9	6.9	9.3

To interpret the significance of these values, data were compared to target ranges for soil macroporosity that are considered optimal for pasture production and environmental protection as set out in the National Land and Soil Monitoring Guidelines (Hill and Sparling, 2009). These target ranges suggest macroporosity values for pasture landuse between 8 – 30% are adequate, values between 6 and 8% are low and values less than 6% are very low. Using this as a guide, it was found that 32 of the 37 sites had

1 As described already macroporosity is a measure of the proportion of large pores in a soil – termed macropores. In this study macroporosity was measured at -10kPa (technically referred to as the Air Filled Porosity) and is a measure of pores in the soil that are 30µm or larger. Several regional councils have adopted macroporosity measurements based on volumetric water content at -10kPa. However historically macroporosity was measured at -5kPa, so for comparison and consistency with older MDC and national soil data we also included the -5kPa measurement in Appendix A for reference.

2 The length of each box shows the range within which the central 50% of the values fall, the centre square is the median value, with the box hinges (borders) at the 25th and 75th percentiles. The whiskers show the range of values that fall within the inner fences (but do not necessarily extend all the way to the inner fences). Values between the inner and outer fences are plotted with crosses. Values outside the outer fence are plotted with empty circles.

soil macroporosity values considered adequate for pasture production and environmental protection (Figure 5). In contrast only four sites are considered low with another one site with a very low soil macroporosity value.

Low macroporosity values (measured at -10kPa % v/v) at drystock pasture sites have been observed in several other regions of New Zealand. For example in the Auckland region, values for 17 drystock sites ranged between 2.0 – 27 % with 11 of the 17 sites sampled having macroporosity values below the recommended range (Fraser and Stevenson, 2010). In the Northland region, values for 8 drystock sites ranged between 1.9 to 16.2% with a median value of 3.9%, with only 3 sites with 'adequate' macroporosity values (Ballinger, 2012). In the Wellington region macroporosity values ranged between 1.8 to 12.6% with a median value of 5.7% across 7 different drystock pasture sites (Milne et al., 2010). While in the Waikato region more than 50% of the drystock sites monitored in their programme were below the soil quality target value of 6% (Taylor et al., 2010).

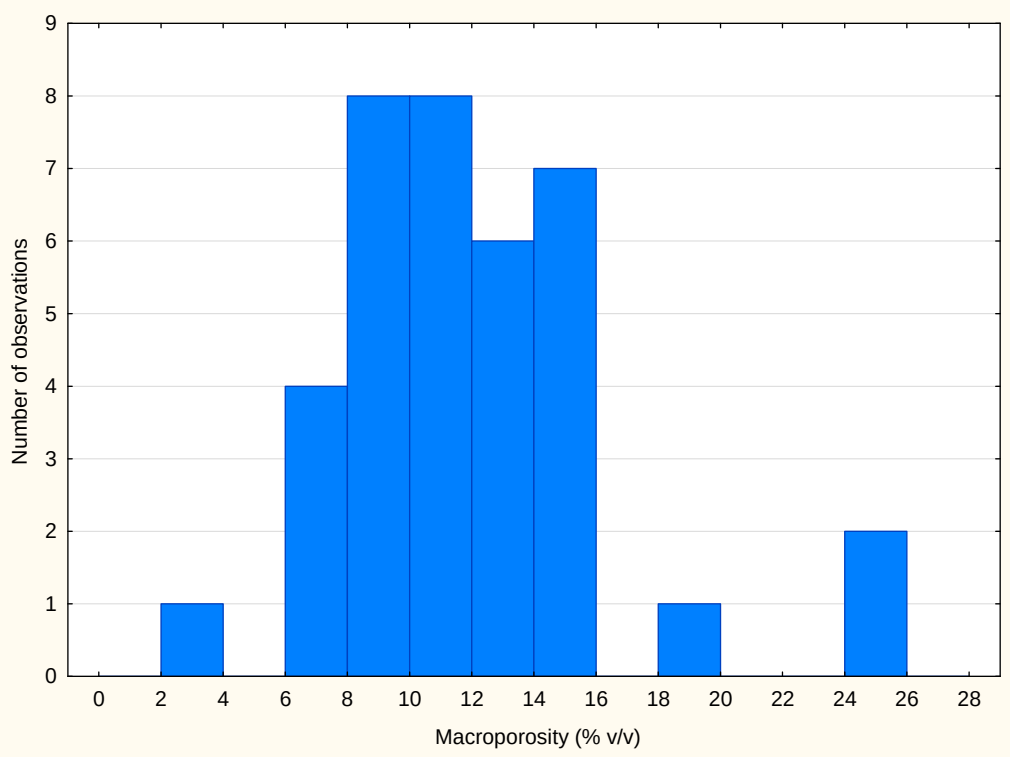

Figure 5 Frequency distribution for soil macroporosity (% v/v measured at -10kPa) for the 37 drystock pasture soils

4.2. Bulk density

The other common measure of soil compaction/pugging status in soil is bulk density. Bulk density is the weight of soil in a specified volume and provides a measure of how loose or compacted a soil is. Because it takes into account pore space in the soil it can give an indication of the level of soil compaction or conversely the porosity of the soil.

Bulk density values ranged between 0.9 to 1.4 t m^{-3} with a median value of 1.1 t m^{-3} (Table 1). All the bulk density values were generally considered adequate for production and environmental protection as set out in the Land and Soil Monitoring Guidelines (Hill and Sparling, 2009). Interestingly this contrasts with the findings for macroporosity. One explanation for bulk density not being such a sensitive measure of compaction is that while treading has reduced the volume of large pores i.e. macropores, the adequate organic matter contents in these soils (Table 1) is sufficient to help the soil resist overall compaction. This is because soil organic is well recognised as critical to the formation and stability of pores in soil (Ghani et

al., 2009). The net result is presumably a change in the pore-size distribution in the soils, with a decrease in the macropore volume and an increase in the volume of the medium and smaller pore sizes. Similar findings have been observed in studies in other regions where low soil macroporosity has been measured but there were adequate soil bulk density values (Fraser and Stevenson, 2010; Ballinger, 2012). This may indicate that soil bulk density might not be a particularly sensitive indicator of soil compaction in soils where organic matter status is adequate.

4.3. Discussion of soil physical results

Whilst the vast majority of the sites had acceptable macroporosity values, there were still several with low values. Some of these low values appeared to reflect how the sites were managed. For example, samples taken from one site that has never had the soil worked or undergone pasture renewal had a macroporosity value of 7%. This compares to the adjacent site which has had recent pasture renewal and had a macroporosity value of 16%.

Another site, which had been strip grazed with a forage crop (Figure 6) before being re-sown in pasture had the lowest macroporosity value (4%) of any of the sites sampled. In comparison, an adjacent site which had the soil worked prior to pasture sown has a value of 13%, while the same site sampled under a fenceline had a value of 18%.

Figure 6 Example a sheep break feeding a winter forage crop

Optimal plant growth requires soil with sufficient pores to allow them to drain, to facilitate gas exchange and allow plant roots to develop and gain access to plant nutrients etc. Loss of soil pores through compaction will affect these processes and therefore plant growth. Although there are many site specific variables, several studies have indicated that adequate plant growth requires minimum soil macroporosity of 10% (Drewry et al., 2008). Using this threshold value, the macroporosity values found in this study would indicate compaction is likely to affect spring pasture growth in a small number of the soils sampled.

Interestingly the results found in this study indicate there was a smaller proportion of sites that had low macroporosity than previously measured from Councils SoE monitoring and also what has been reported nationally. These differences could simply be related to the time of year of soil sampling. It has been recognised that seasonal variation can have a marked influence on the incidence and level of compaction in soils. For example Drewry et al. (2004) showed that soil compacted and deformed in spring due to

animals grazing on wet pasture soils recovered during summer and autumn due to drying and cracking of the soil i.e. natural amelioration. Soils in this study were sampled at the end of autumn compared to SoE monitoring in Marlborough and nationally which is typically undertaken in early spring. Hence results likely reflected a best case where animals would have been grazing drier pastures and therefore less damage.

A further complicating factor in interpreting macroporosity data is how it was measured i.e. at -5kPa or -10 kPa. As discussed, macroporosity data in New Zealand has historically been measured and reported using the two measurements and the difference in values can be several percent. For example, in this study macroporosity measured at -10kPa was 2% higher than that measured a -5kPa (Table 1). For consistency with national reporting and to allow comparison, macroporosity in this study was measured/reported at -10 kPa, which will to some extent explain the higher number of sites meeting their target vales for macroporosity.

4.4. Soil nutrients

As well as measuring some soil physical indicators of compaction, available P was also measured. This is because as discussed earlier compacted soil can in some circumstances exacerbate nutrient loses from some soils and this is particularly the case for soil P.

4.4.1. Phosphorous

It is recognised that the main loss pathway for P in grazed pasture systems is from overland flow. Overland flow occurs either as a result of infiltration-excess when the rainfall intensity exceeds the infiltration capacity of the soil or as a result of saturation-excess when rain falls on saturated soil and cannot infiltrate and therefore runs off. As described already, when soils are compacted there is a decrease in the larger pores and therefore a decrease in the soil water storage capacity. Compacted soils therefore can become saturated quickly and can be subject to saturation-excess overland flow which is considered the main pathway of P loss from soils (McDowell et al., 2003).

Fertiliser is applied to soils to replenish available P. This is often measured as Olsen P which provides an estimate of the amount of plant-available P in soil. Soils with a high Olsen P status have the potential for phosphorus losses which potentially can have a negative impact on water quality.

Olsen P values for the soils in this study ranged between 4 to 34 mg kg^{-1} with a median value of 10 mg kg^{-1} (Table 1) (Appendix B). These values are all well below the upper limit of 100 mg kg^{-1} generally considered an environmental risk (Hill and Sparling, 2009). In fact all but four sites had Olsen P values below the target range of 20 – 30 mg/kg required to sustain near maximum pasture production for sheep and beef in sedimentary soils (FertResearch, 2009). So while the potential negative offsite effects from soil P are low, sites would benefit from an application of P fertiliser to maximise pasture production.

4.5. Prevention and mitigation measures against soil compaction/pugging

To ensure sustained pasture production it is important that soil physical properties do not deteriorate to the degree that production, management and off-site environmental issues develop.

Whilst the vast majority of the sites had acceptable soil macroporosity values, there were a few sites that showed evidence of soil compaction/pugging. There are a number of potential mitigation methods that can be employed to prevent or minimise the affects of soil compaction/pugging, even on those soils not normally regarded as having a pugging problem. Practices could include:

- grazing wetter paddocks before the wet part of the season
- maintaining good pasture cover which gives better protection against pugging
- installing drainage in some areas
- decreasing winter stock numbers by moving stock onto well drained soil types off-site

- changing to lighter weight breeds
- using the farm bike rather than heavy tractors

While there are ways of preventing/minimising the effects of soil compaction/pugging, if there is already evidence on your property, the effects aren't necessarily permanent and there are several remediation options available. These can include:

Natural soil amelioration processes i.e. wetting and drying cycles, freeze and thaw cycles, plant root growth and decay and soil fauna and flora activity. Although the degree of recovery can vary from site to site depending on many factors such as previous land management practices, soil type, and climate and is often limited to a soil depth of about 10 cm and maximum of 15 cm (Drewry, 2006).

Mechanical loosening of soil (also called subsoling or aeration) can also be effective in offseting the effects of compaction/pugging (Drewry, et al., 2000; Burgess et al., 2000). In comparison to natural soil amelioration processes, mechanical loosening is effective to depths of up to 24 cm (McDowell, 2008). Again the effectiveness is specific to soil types with some soils quickly reverting back to their original state shortly after subsoiling (Houlbrooke, 1996).

Cultivation possibly involving growing a commercial fodder crop prior to re-sowing a new pasture is also shown to be effective.

5. Conclusions

- Soil macroporosity is a sensitive measure of soil compaction/pugging.
- All but 5 sites had soil macroporosity values within acceptable target ranges.
- The 5 sites with low values were ones which hadn't been subject to recent pasture renewal or sites that had been strip grazed. Remedial works to subsoil and re-sow these types of sites will likely decrease compaction and likely result in improved pasture production.
- Available phosphorus was found at concentrations unlikely to pose a significant environmental risk. In fact all but four sites had Olsen P values below the target range required to sustain near maximum pasture production for sheep and beef in sedimentary soils and would benefit from a capital P fertiliser application.

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Appendix A: Soil physical Analysis from Landcare Research

Client ID	Initial WC	Dry Bulk density	Particle density	Total porosity	Pores >60 µm	Macro-porosity	Vol. WC 5kPa	Vol. WC 10kPa
	(%, w/w)	(t/m3)	(t/m3)	(%, v/v)	(%, v/v)	(%, v/v)	(%, v/v)	(%, v/v)
C1	51.7	0.97	2.62	62.8	9.6	11.8	53.2	51.0
C2	23.2	1.33	2.62	49.2	9.7	11.9	39.5	37.3
C3	48.6	1.09	2.57	57.8	4.9	7.7	52.9	50.1
C4	27.4	1.18	2.66	55.5	16.2	18.5	39.3	37.0
C5	36.9	1.10	2.63	58.1	12.4	16.3	45.6	41.8
C6	34.0	1.22	2.58	52.8	9.3	11.7	43.5	41.1
C7	39.3	1.22	2.58	52.8	4.1	5.9	48.7	46.9
C8	52.6	1.07	2.57	58.3	1.2	4.0	57.1	54.3
C9	48.0	1.05	2.56	58.9	6.8	9.6	52.1	49.3
C10	45.7	0.99	2.51	60.6	10.1	12.7	50.5	47.9
C11	40.8	1.05	2.52	58.2	9.6	11.9	48.6	46.3
C12	39.8	1.05	2.52	58.5	9.4	13.1	49.1	45.4
C13	35.1	1.16	2.56	54.8	7.2	9.7	47.6	45.1
C14	47.2	1.08	2.53	57.2	0.5	2.7	56.8	54.5
C15	40.3	1.13	2.58	56.3	6.1	8.7	50.2	47.6
C16	29.7	1.09	2.54	57.2	13.5	16.4	43.7	40.8
C17	42.2	1.02	2.56	60.2	7.7	12.7	52.4	47.5
C18	53.4	0.98	2.53	61.3	3.3	7.4	58.1	53.9
C19	39.7	1.10	2.61	57.7	9.9	12.3	47.8	45.4
C20	39.5	1.16	2.64	56.1	6.2	8.1	49.9	48.0
C21	39.3	1.12	2.65	57.8	9.3	11.7	48.5	46.1
C22	40.9	1.13	2.58	56.4	7.2	9.7	49.2	46.7
C23	45.6	1.06	2.57	58.7	7.2	10.0	51.5	48.7
C24	38.9	1.18	2.60	54.7	5.8	8.2	48.9	46.5
C25	41.9	1.07	2.58	58.4	8.4	11.2	50.0	47.2
C26	40.2	1.05	2.59	59.6	13.0	15.8	46.6	43.8
C27	40.2	1.05	2.56	59.0	11.3	14.1	47.7	44.9
C28	42.4	1.06	2.58	59.0	10.0	12.6	49.0	46.4
C29	40.6	1.04	2.60	59.9	12.6	15.2	47.3	44.7
C30	41.2	1.09	2.59	58.0	9.2	11.6	48.8	46.4
C31	43.9	1.03	2.58	60.2	10.5	13.2	49.8	47.0
C32	45.2	1.03	2.58	60.2	9.7	11.0	50.5	49.2
C33	41.5	1.11	2.57	57.0	7.8	10.2	49.2	46.8
C34	38.1	1.04	2.56	59.5	13.7	16.8	45.8	42.7
C35	36.5	1.04	2.59	59.9	15.8	19.0	44.1	40.9
C36	34.5	1.05	2.60	59.8	16.6	18.7	43.2	41.1
C37	34.7	1.27	2.61	51.4	0.9	3.0	50.5	48.4
C38	35.1	1.25	2.57	51.4	>1	1.9	52.5	49.5
C39	36.0	1.22	2.61	53.4	3.8	6.1	49.6	47.3
C40	41.3	1.09	2.58	57.8	5.5	9.7	52.3	48.1
C41	42.7	1.08	2.58	58.2	8.7	11.5	49.6	46.7
C42	49.6	1.02	2.58	60.5	6.3	10.2	54.2	50.3
C43	31.2	1.14	2.61	56.4	8.1	12.4	48.3	44.0
C44	45.2	0.90	2.54	64.4	13.8	17.8	50.7	46.6
C45	33.6	1.04	2.57	59.4	11.1	16.9	48.3	42.5
C46	32.5	1.19	2.63	54.9	7.8	11.4	47.1	43.5
C47	31.0	1.18	2.55	53.6	3.4	5.8	50.2	47.8
C48	31.3	1.16	2.54	54.4	6.7	9.9	47.7	44.5
C49	37.5	1.06	2.56	58.6	12.3	15.9	46.3	42.7
C50	36.5	1.07	2.54	57.9	6.9	10.1	50.9	47.8
C51	37.2	1.08	2.56	57.9	10.4	13.1	47.5	44.8

C52	30.0	0.90	2.52	64.2	19.5	23.0	44.6	41.2
C53	26.3	0.94	2.54	63.0	16.3	22.8	46.7	40.2
C54	22.3	0.88	2.54	65.2	24.6	28.7	40.6	36.5
C55	21.9	1.12	2.55	56.0	13.6	17.7	42.4	38.3
C56	27.7	1.13	2.49	54.7	3.4	10.2	51.3	44.5
C57	23.9	1.04	2.56	59.3	13.8	18.0	45.5	41.3
C58	29.4	0.67	2.41	72.1	22.1	34.2	50.0	37.9
C59	24.9	0.99	2.52	60.9	13.4	19.0	47.5	41.9
C60	22.2	1.05	2.54	58.9	17.3	23.6	41.6	35.3
C61	26.2	1.24	2.58	51.8	6.5	7.9	45.3	43.9
C62	22.0	1.25	2.59	51.9	7.7	9.8	44.3	42.1
C63	24.6	1.21	2.59	53.5	7.2	9.5	46.3	44.0
C64	19.4	1.15	2.57	55.4	13.3	15.1	42.1	40.3
C65	21.8	1.11	2.59	57.2	15.7	18.1	41.5	39.1
C66	23.2	1.15	2.57	55.1	12.4	14.6	42.7	40.5
C67	20.8	1.24	2.57	51.7	10.1	12.6	41.6	39.1
C68	23.4	1.19	2.58	54.1	11.1	13.1	43.0	41.0
C69	17.8	1.37	2.60	47.4	7.4	9.6	40.1	37.8
C70	25.0	1.17	2.57	54.3	7.2	9.9	47.1	44.4
C71	25.3	1.27	2.60	51.2	7.9	10.2	43.3	41.0
C72	26.3	1.20	2.55	52.8	6.3	8.9	46.4	43.9
C73	27.1	1.11	2.59	57.2	12.8	15.7	44.5	41.5
C74	30.8	1.10	2.59	57.4	12.1	14.7	45.3	42.7
C75	31.6	1.06	2.54	58.3	12.4	14.7	45.9	43.6
C76	20.7	1.27	2.60	51.2	10.8	13.7	40.4	37.5
C77	20.9	1.37	2.62	47.7	8.2	10.1	39.6	37.6
C78	19.0	1.45	2.61	44.5	5.6	7.0	38.9	37.5
C79	36.7	1.21	2.63	54.1	6.9	9.0	47.2	45.1
C80	41.4	1.14	2.58	55.8	5.6	8.2	50.1	47.6
C81	40.9	1.16	2.59	55.4	5.1	8.0	50.3	47.4
C82	36.4	1.19	2.64	54.9	8.6	10.9	46.3	44.0
C83	39.8	1.15	2.60	55.9	7.9	10.3	48.0	45.6
C84	37.5	1.23	2.62	53.2	4.6	7.1	48.6	46.1
C85	45.2	1.00	2.58	61.4	13.9	16.8	47.5	44.6
C86	42.1	1.05	2.58	59.2	12.2	14.9	47.0	44.3
C87	43.3	1.05	2.58	59.3	11.9	14.6	47.4	44.7
C88	37.8	1.11	2.56	56.6	10.3	11.1	46.3	45.5
C89	38.7	1.11	2.52	55.9	9.9	11.1	46.0	44.8
C90	34.8	1.15	2.52	54.5	11.4	13.6	43.1	40.9
C91	25.7	1.34	2.68	50.2	5.2	7.1	45.0	43.1
C92	17.2	1.35	2.64	48.9	6.9	8.1	42.0	40.8
C93	15.0	1.42	2.69	47.3	9.7	10.7	37.5	36.6
C94	37.2	1.06	2.57	58.8	11.2	14.5	47.6	44.3
C95	34.0	0.94	2.55	63.1	16.0	23.6	47.0	39.5
C96	42.9	1.02	2.57	60.2	6.9	7.3	53.3	52.9
C97	25.9	1.29	2.58	50.1	3.0	5.9	47.2	44.2
C98	24.2	1.27	2.62	51.6	4.9	8.2	46.7	43.4
C99	23.2	1.27	2.62	51.4	4.7	7.0	46.7	44.4
C100	21.4	1.19	2.62	54.6	8.3	8.6	46.3	46.0
C101	20.9	1.20	2.60	53.8	10.6	11.8	43.2	42.0
C102	26.3	1.23	2.60	52.9	8.4	9.7	44.4	43.2
C103	20.9	1.24	2.64	53.1	14.2	17.9	38.8	35.2
C104	11.1	1.50	2.65	43.5	7.6	9.8	35.9	33.7
C105	21.5	1.23	2.64	53.3	10.0	12.3	43.3	41.0
C106	19.5	1.44	2.63	45.3	7.1	9.8	38.3	35.5
C107	17.7	1.42	2.65	46.6	5.5	7.7	41.1	38.9
C108	16.3	1.44	2.64	45.5	7.6	9.4	37.9	36.1

C109	22.0	1.16	2.59	55.4	15.2	18.3	40.2	37.1
C110	15.8	1.36	2.60	47.8	12.4	13.7	35.4	34.1
C111	19.2	1.44	2.62	45.0	8.1	9.7	36.9	35.3
C112	23.4	1.40	2.63	46.8	5.8	7.8	41.1	39.0
C113	24.7	1.41	2.62	46.1	6.1	8.1	40.1	38.0
C114	19.1	1.53	2.67	42.6	3.9	5.6	38.7	37.0
C115	22.2	1.34	2.64	49.2	9.4	11.7	39.8	37.5
C116	22.1	1.25	2.62	52.3	11.0	14.6	41.3	37.7
C117	24.4	1.44	2.62	45.1	3.5	4.8	41.6	40.3

Appendix B: Soil Chemical Analysis

Site	pH	Olsen P	Organic matter
		mg/L	%
C1	5.7	14	7.2
C2	5.4	8	5.6
C3	5.6	9	8.5
C4	5.8	6	11
C5	6.2	9	8.4
C6	5.4	4	9.3
C7	5.8	13	7.8
C8	5.9	13	7
C9	5.9	27	8.6
C10	5.6	6	8
C11	5.6	12	6.9
C12	5.8	5	12.9
C13	5.6	6	10
C14	5.9	11	8.8
C15	5.5	9	8.4
C16	5.6	10	12.7
C17	5.5	17	9.5
C18	5.4	15	14
C19	6.3	16	7.1
C20	6.2	8	7
C21	5.9	13	6.8
C22	5.5	27	11.9
C23	5.9	12	9.5
C24	6	30	6.9
C25	5.6	14	6.1
C27	5.7	6	6.7
C28	6	15	8.5
C29	5.5	10	7.5
C30	5.3	11	9.4
C31	5.5	7	7.7
C32	7.1	34	8
C33	5.7	6	5.3
C34	5.3	7	6.1
C35	5.4	7	4.6
C36	5.7	4	4.2
C37	5.5	8	5.4