Survey of Soil Compaction/Pugging in Some Marlborough Dairy Farm Soils

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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 especially true for dairy pasture sites which are a landuse activity known to be susceptible to soil compaction.

In this study soils were sampled from 51 dairy pasture sites under permanent pasture. At each site soils were analysed for soil macroporosity and bulk density (two measures of soil compaction/pugging) and also Olsen P.

It was found that all the sites sampled (with the exception of those samples taken from under fencelines) showed evidence of soil compaction/pugging. This is likely a result of animal treading on pastures that are too wet which has effectively reduced the large pore fraction in these soils. The degree of soil compaction/pugging found is likely to have a negative effect on spring pasture growth. While the evidence of compaction was not surprising, what was somewhat unexpected was the high proportion of sites that showed compaction and the severity of the compaction/pugging. However, there are several reasons for these findings including the timing of sampling and the effects of heavy rolling of pasture which is employed to reduce surface roughness and control pasture grubs at some sites.

Although available phosphorus (Olsen P) concentrations in soil were generally acceptable, soil compaction/pugging has the potential to exacerbate losses of P from other sources i.e. farm dairy effluent, dung and the pasture plants themselves through surface runoff.

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. While this study has shown that many sites show evidence of soil compaction/pugging, there are a number of potential mitigation methods that can be employed to prevent or minimise soil compaction/pugging in the future and also options to remediate sites already compacted/pugged.

Contents

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 75 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 3 - 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 are 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, some soils at dryland pasture sites and in particular soils at the dairy sites where all 10 sites sampled had macroporosity values below the 10% threshold thought to adversely affect pasture production (Figure 1).

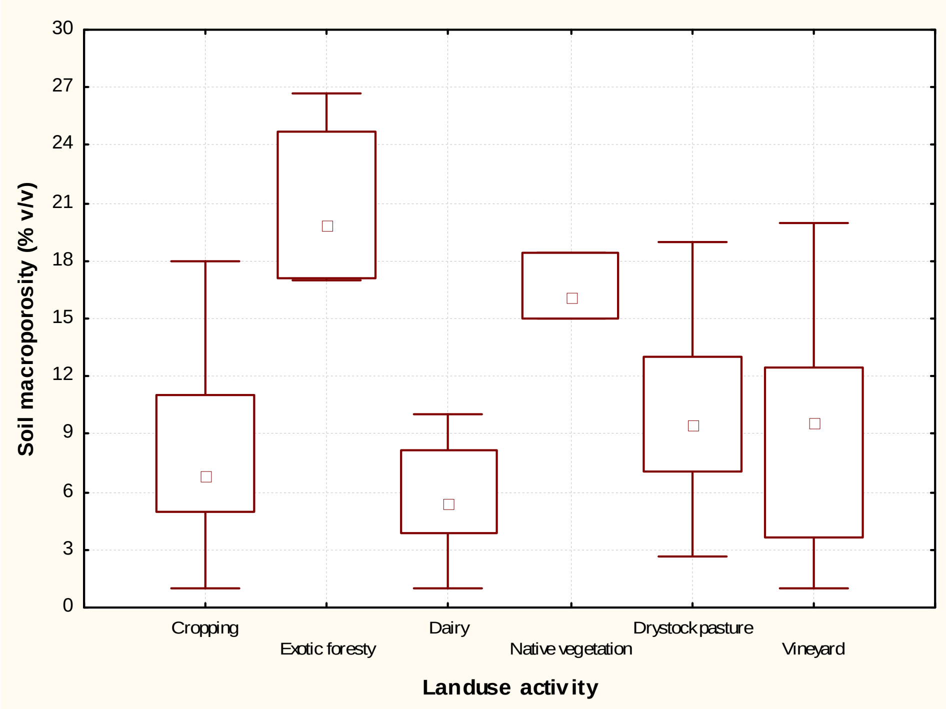

Figure 1 Box and whisker plot showing soil macroporosity values (% v/v) from different landuse activities from the soil quality monitoring sites (n=75)

So 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 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).

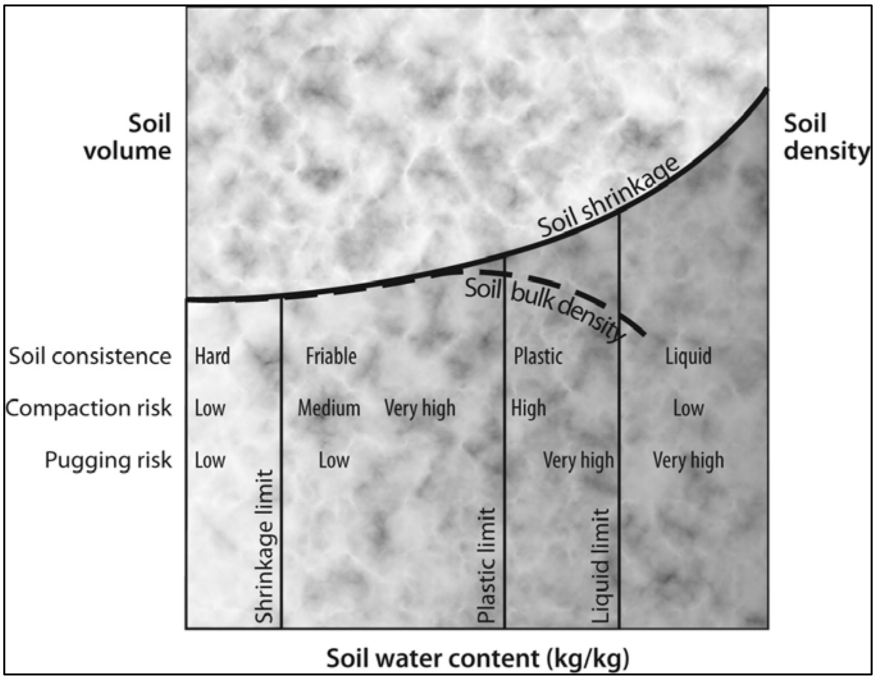

Figure 2 Relationship between soil water content and soil consistency (from Drewry et al., 2008, reprinted with permission from author).

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 Brown soil (NZSC) on a dairy farm in Marlborough

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). In contrast 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).

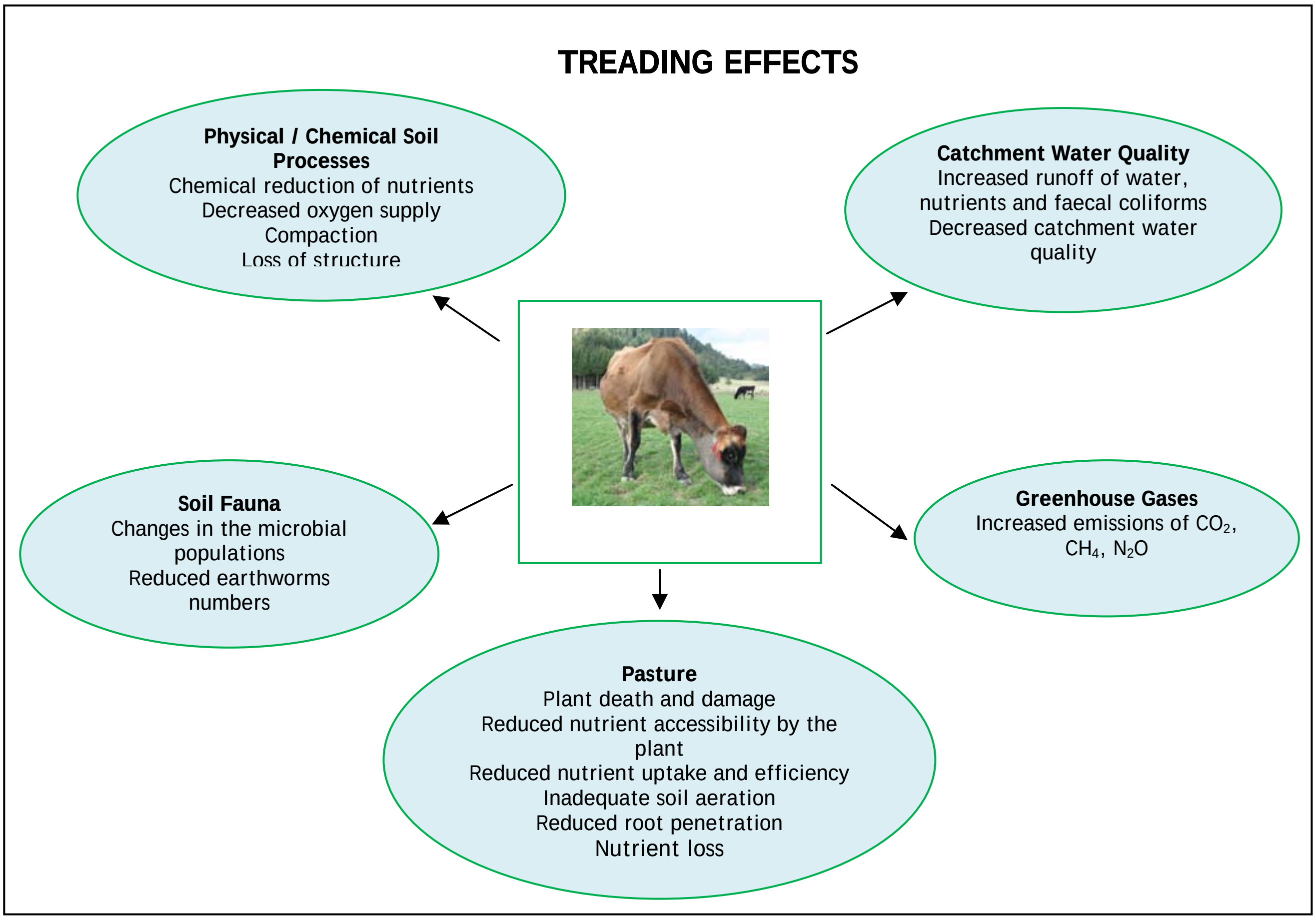

Figure 4 Potential on- and off-site effects of animal treading (adapted from Singleton et al., 2000)

Some of the effects of soil compaction/pugging on soil physical properties include decreased macroporosity, saturated (K_{sat}) and unsaturated (K_{unsat}) 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, K_{sat}, K_{unsat} 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. This objective of this study is therefore to find out the extent and effects of soil compaction for some dairy pasture sites in Marlborough. This landuse activity was selected as it appears to be susceptible to soil compaction as discussed earlier.

3. Materials and Methods

3.1. Sites

Fifty-one sites under permanent pasture were sampled. A site represented an individual paddock within a dairy farm. This is because a paddock is normally grazed as a single unit, fertilized as a whole paddock etc. Sites represented four soil types i.e. Rai, Ronga, Manaroa and Kaituna which are some of the main soils in the dairying region of Marlborough and two soil orders i.e. Recent soils and Brown soils (Hewitt, 1993).

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 $NaHCO_3$ 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 (-5 kPa), air capacity (-10 kpa) and total porosity were calculated as described by Klute (1986). Particle density was measured by the pipette method. [1]

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]

5. Results and Discussion

5.1. Soil physical measurements

There was a wide range in soil macroporosity across the 51 sites sampled with values ranging from a low of 0.4 up to 18% with a median value of 3.6 % (Table 1 and Appendix A).

Table 1 Summary statistics for selected soil physical and chemical measurements across the 51 dairy sites

	minimum	maximum	median	Lower quartile (25%)	Upper quartile (75%)
Macroporosity (%)	0.4	18.0	3.6	2.1	5.6
Bulk density (t m^{-3})	0.763	1.346	1.045	0.973	1.167
AFP (%)	1.5	20.9	5.3	3.8	8.0
Total porosity (%)	49.5	68.7	59.4	55.5	62.3
pH	5.2	6.6	5.8	5.6	6.0
Olsen P (mg/L)	11	82	38	21	48
Organic matter (%)	5.2	16.3	8.7	7.5	11.5

[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 -5kPa and is a measure of pores in the soil that are 60µm or larger. It is worth noting that the general definition of macroporosity has recently been expanded to cover a slightly larger range of pores sizes than the original definition. Several regional councils have adopted macroporosity measurements based on volumetric water content at -10kPa (technically referred to as the Air Filled Porosity). However for comparison and consistency with older MDC soil data we use the -5kPa measurement, although the -10kPa data is included 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.

To determine the significance of these values, data were compared to target ranges for soil macroporosity that are considered optimal for 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 only nine sites had soil macroporosity values considered adequate for pasture production and environmental protection (Figure 5). Of these, eight of the sites were in fact sampled from under fencelines to try and get data for soils that were judged not to have been significantly impacted by animal treading. Two further sites were found to have low soil macroporosity values, while the remaining 40 sites have soil macroporosity considered very low.

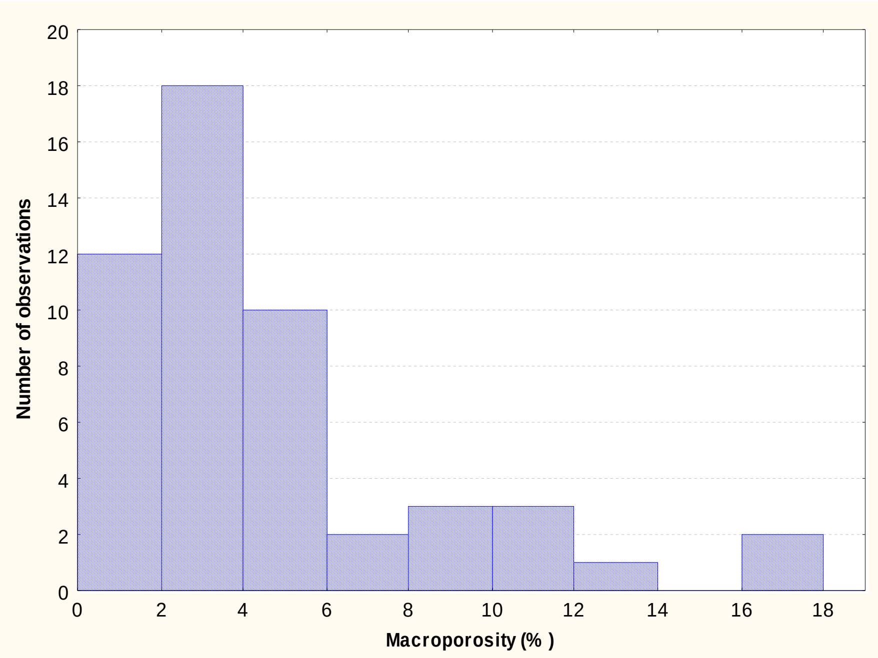

Figure 5 Frequency distribution for soil macroporosity (% v/v) for the 51 dairy pastures soils

Low macroporosity values have been observed in other regions of New Zealand. For example in the Auckland region, values for 21 dairy farm sites ranged between 0.6 – 8.6 % with a median value of 3.2% (Stevenson, 2010) and only one site had an 'adequate' macroporosity value. In the Northland region, values for 7 dairy sites ranged between 3.1 to 10.7% with a median value of 6.2% (Northland Regional Council, 2007) and like the Auckland study only one site had an 'adequate' macroporosity value. In the Wellington region macroporosity values ranged between 0.7 to 20.7 % with a median value of 6.8% across 23 different dairy pasture sites (Sorensen, 2009). However only 9 of the 23 sites sampled had soil macroporosity values considered 'adequate'. In the Tasman region macroporosity values ranged from 4.6 to 13.8 % with half the results in the very low category, 3 within the low category and only one site was within the adequate range. While in the Waikato region 50% of the dairy sites monitored in their programme were below the soil quality target value of 6% (Taylor et al., 2010).

5.2. 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 0.76 to 1.35 t m^{-3} with a median value of 1.05 t m^{-3} (Table 1). With the exception of one site, 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 where all but a handful of sites showed evidence of compaction. 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 (Stevenson, 2010; Sorensen, 2009; Burton, 2009). 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.

5.3. Soil groups

There was no significant difference between the two soil groups i.e. Brown soil and Recent soils with respect to soil macroporosity (Figure 6). In comparison, soil bulk density values for the Recent soils were significantly lower than the Brown soils (Figure 7). The Recent soils also had significantly higher amounts of soil organic matter than the Brown soils on average i.e. 10.6% and 7.7% respectively. As discussed already, one possible reason for the Recent soils having lower bulk density values (higher porosities) than the Brown soil group maybe the higher organic matter status of these soils which while not preventing loss of large pores may have helped mitigate the loss of medium and smaller soil pores.

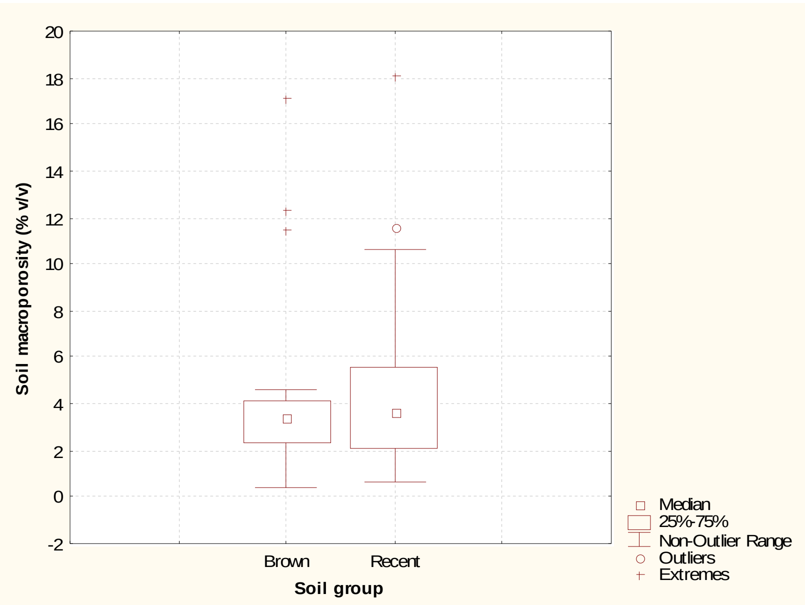

Figure 6 Comparison of soil macroporosity values between Brown and Recent soils

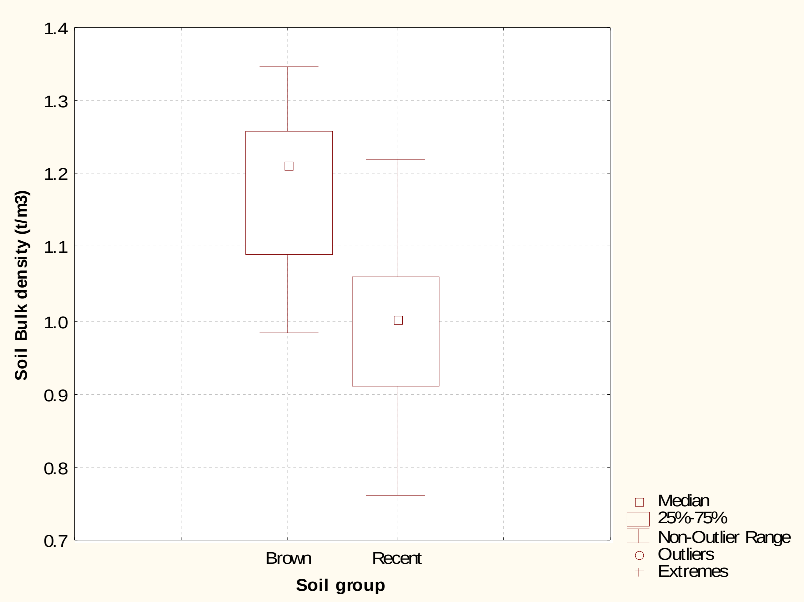

Figure 7 Comparison of soil bulk density values between Brown and Recent soils

5.4. Discussion of soil physical results

As shown all the sites sampled in this study with the exception of those soils taken from under fencelines showed evidence of moderate to severe soil compaction/pugging. As suggested this is likely a result of animal treading on pastures that are too wet which has effectively reduced the large pore fraction in soils. This was supported by the findings that median macroporosity values for soils sampled under fencelines, which are areas judged not to have been severely impacted by animal treading, were more than 3 times higher (i.e. 11.6%) compared to those soils sampled from within the paddock (i.e. 3.4%).

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 vales found in this study would indicate compaction is likely to have affected spring pasture growth in nearly all of the soils sampled. Furthermore, the evidence of widespread soil pugging (Figure 8) is also likely to have indirectly affected pasture production in these soils through damage to pasture plants and plant burial.

Given what has been observed from earlier soil quality monitoring in Marlborough and the findings in other regions across New Zealand, while some evidence of compaction was not surprising, what was somewhat unexpected was the high proportion of sites that showed compaction and its severity. There may be several reasons for these findings. Firstly 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 in the middle of a wet spring that followed a particularly wet winter. Hence results likely reflected a worst case where animals would have at some stage unavoidably been grazing on wet soils. The sampling data was supported by observations in the field where despite seemingly good pasture coverage there were numerous sites where there was evidence of recent pugging (Figure 8) with rough surfaces.

Figure 8 Evidence of previously pugged soils at sites that have now dried out

In addition, at several sites heavy rollers were employed as a means of reducing rough surfaces due to pugging (Figure 9).

Figure 9 Heavy roller being used to smooth the land surface of a previously pugged pasture soil

Heavy rolling was also used at some sites to control grass grub, presumably by reducing the volume of air in the soils by compaction. Typically rolling occurs in later autumn and winter when soils are wet. Both these practices obviously have the potential to increase in soil compaction.

5.5. Soil nutrients

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

5.6. 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 16 to 119 mg kg^{-1} with a median value of 49 mg kg^{-1} (Table 1) (Appendix B). These values, with the exception of two sites which had Olsen P values greater than 100 mg kg^{-1}, are all within the range which is generally considered adequate for production and environmental protection as set out in the National Land and Soil Monitoring Guidelines (Hill and Sparling, 2009). So it would appear potential negative offsite effects from soil P are relatively low.

However, there are other sources of P in soil, namely the land application of Farm Dairy Effluent (FDE) which is widely practiced in dairy farms in Marlborough and dung from animals. Like fertiliser derived P both of these have the potential to be lost from soils predominantly via overland flow. For example, McDowell et al., (2007) has indicated that dung is the source of 20 - 30% of the P lost from a typical dairy farm paddock. Therefore soil compaction also has the potential to exacerbate loss of these sources of P from soil through its effect on reduced infiltration and drainage.

Another potential loss of P from soil is from grazing animals smearing and compacting soils and exposing plant cell vacuoles and cytoplasm (Drewry, 2006; McDowell et al., 2007). The exposing plant cell vacuoles and cytoplasm has only been recently considered as a source of P lost from grazed paddocks but it has been estimated that this source could account for 10-20% of P losses from a paddock grazed by dairy cattle (McDowell et al. 2007). Given the degree of compaction and probably more importantly pugging, this may be an important source of P loss from these soils

5.7. 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. While this study has shown that many sites show 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:

- on/off grazing of animals
- 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
- use of feeding platforms
- standoff 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
- use tools like the AgResearch's penetrometer to predict the likelihood of pugging damage (Figure 10). This is a system for daily decision-making about pugging damage that involves a penetrometer and a graph on which to compare the results with predictions of probable pasture damage.

Figure 10 AgResearch penetrometer used to test soil strength before cows enter a paddock

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 to offset 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). Although 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.

6. Conclusions

- Soil macroporosity was shown to be a sensitive measure of soil compaction/pugging.
- With the exception of soils taken from under fencelines, all the soils sampled in this study showed evidence of soil compaction.
- The levels of compaction found potentially will have a negative effect on spring pasture growth.
- Available phosphorus was generally at concentrations unlikely to pose a significant environmental risk although there are other sources of P in soil which may be lost and their loss is exacerbated in compacted soils.
- While the evidence of compaction was not surprising, what was unexpected was the high proportion of sites that showed compaction and the severity of compaction/pugging.
- There are several reasons for these findings including the timing of sampling and the effects of heavy rolling of pasture.
- While this study has shown that many sites showed evidence of soil compaction/pugging, there are a number of potential mitigation methods that can be employed to prevent or minimise the affects.

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Appendix A: Soil physical Analysis from Landcare Research

Client ID	Initial WC	Dry Bulk density	Particle density	Total porosity	Macro-porosity	Air filled porosity	Vol. WC 5kPa	Vol. WC 10kPa
	(%, w/w)	(t/m3)	(t/m3)	(%, v/v)	(%, v/v)	(%, v/v)	(%, v/v)	(%, v/v)
MDC C1	24.7	1.20	2.53	52.5	3.8	5.0	48.7	47.5
MDC C2	32.6	1.16	2.53	54.1	2.4	4.7	51.6	49.4
MDC C3	26.7	1.22	2.54	52.0	4.3	5.7	47.7	46.3
MDC C4	21.0	1.25	2.54	50.9	4.0	5.6	46.9	45.3
MDC C5	29.6	1.20	2.55	53.0	5.5	7.2	47.5	45.8
MDC C6	23.5	1.20	2.53	52.8	4.4	5.7	48.4	47.1
MDC C7	27.4	1.20	2.57	53.4	4.5	6.3	48.9	47.1
MDC C8	27.6	1.18	2.54	53.6	5.7	7.5	47.9	46.1
MDC C9	30.8	1.27	2.56	50.5	2.1	3.4	48.4	47.1
MDC C10	31.2	1.16	2.54	54.3	5.8	7.5	48.4	46.8
MDC C11	24.0	1.29	2.54	49.1	1.4	3.1	47.8	46.0
MDC C12	22.8	1.29	2.55	49.3	2.6	4.1	46.7	45.2
MDC C13	31.7	1.19	2.59	54.2	7.1	9.2	47.0	45.0
MDC C14	22.0	1.35	2.61	48.2	0.6	2.4	47.6	45.8
MDC C15	20.9	1.27	2.59	51.2	3.3	5.2	47.8	46.0
MDC C16	26.8	1.00	2.53	60.4	12.8	15.4	47.6	45.0
MDC C17	35.7	1.03	2.59	60.3	13.1	14.3	47.3	46.0
MDC C18	23.3	1.09	2.60	58.0	10.9	13.1	47.1	44.9
MDC C19	32.6	1.33	2.64	49.5	2.5	3.8	47.1	45.7
MDC C20	41.4	1.22	2.62	53.3	>1	1.2	53.6	52.1
MDC C21	39.1	1.19	2.66	55.3	5.1	8.0	50.2	47.3
MDC C22	36.7	1.26	2.65	52.5	3.3	5.4	49.2	47.1
MDC C23	33.1	1.31	2.67	50.9	3.6	5.5	47.2	45.4
MDC C24	37.3	1.25	2.63	52.7	1.2	3.6	51.4	49.1
MDC C25	27.6	1.39	2.67	48.0	3.0	4.9	45.0	43.1
MDC C26	30.1	1.35	2.66	49.4	3.0	4.9	46.4	44.5
MDC C27	34.5	1.30	2.67	51.2	1.0	2.8	50.1	48.4
MDC C28	33.5	1.24	2.64	53.1	6.7	9.2	46.4	43.9
MDC C29	33.9	1.27	2.64	51.8	3.1	4.9	48.7	46.9
MDC C30	36.6	1.27	2.64	52.0	0.5	2.1	51.5	49.9
MDC C31	30.6	1.28	2.61	50.9	4.8	7.9	46.1	43.0
MDC C32	27.3	1.33	2.61	49.1	4.7	7.8	44.4	41.3
MDC C33	39.6	1.23	2.61	52.9	1.3	2.8	51.6	50.1
MDC C34	34.6	1.07	2.70	60.2	16.8	19.8	43.5	40.4
MDC C35	27.7	1.16	2.68	56.7	17.4	19.5	39.3	37.2
MDC C36	37.9	1.04	2.69	61.3	17.2	19.9	44.1	41.4
MDC - C37	58.9	0.97	2.59	62.4	2.7	6.1	59.8	56.3
MDC - C38	50.8	1.10	2.58	57.3	<1	1.0	58.9	56.3

Client ID	Initial WC	Dry Bulk density	Particle density	Total porosity	Macro-porosity	Air filled porosity	Vol. WC 5kPa	Vol. WC 10kPa
MDC - C39	56.3	1.02	2.62	60.9	1.2	3.8	59.7	57.1
MDC - C40	48.6	1.11	2.57	56.9	0.1	2.7	56.9	54.2
MDC - C41	47.0	1.13	2.59	56.2	0.1	2.1	56.1	54.1
MDC - C42	52.8	1.05	2.58	59.5	1.1	3.7	58.4	55.8
MDC - C43	48.6	1.14	2.60	56.3	<1	0.8	57.8	55.5
MDC - C44	42.3	1.21	2.63	53.8	<1	1.6	54.3	52.2
MDC - C45	48.6	1.12	2.62	57.3	<1	2.8	57.4	54.5
MDC - C46	43.5	1.20	2.62	54.2	<1	1.1	55.1	53.1
MDC - C47	34.0	1.29	2.65	51.4	1.6	4.1	49.7	47.3
MDC - C48	38.6	1.26	2.64	52.4	0.1	2.0	52.2	50.4
MDC - C49	52.3	1.10	2.61	58.0	<1	<1	59.5	58.8
MDC - C50	52.7	1.04	2.64	60.5	2.9	5.0	57.7	55.5
MDC - C51	56.3	1.00	2.62	62.0	2.3	4.6	59.7	57.4
MDC - C52	52.3	0.96	2.62	63.2	9.7	12.5	53.5	50.7
MDC - C53	46.2	1.00	2.62	61.9	13.2	15.4	48.7	46.5
MDC - C54	47.0	0.99	2.60	61.8	11.5	13.9	50.3	47.9
MDC - C55	62.7	0.85	2.41	64.7	6.8	9.8	57.9	54.9
MDC - C56	60.3	0.88	2.44	64.0	7.1	9.7	57.0	54.3
MDC - C57	60.2	0.84	2.43	65.4	10.5	13.4	54.9	52.0
MDC - C58	62.4	0.86	2.48	65.5	8.3	11.3	57.2	54.2
MDC - C59	60.7	0.88	2.50	64.8	7.3	10.0	57.5	54.8
MDC - C60	55.1	0.92	2.51	63.3	7.7	10.4	55.6	52.9
MDC - C61	65.5	0.83	2.48	66.6	9.8	11.9	56.8	54.7
MDC - C62	67.8	0.83	2.48	66.4	8.2	10.4	58.2	56.0
MDC - C63	62.0	0.84	2.48	66.2	9.6	11.9	56.5	54.3
MDC - C64	72.5	0.73	2.40	69.4	11.8	14.5	57.6	54.9
MDC - C65	65.3	0.90	2.41	62.6	0.0	2.5	62.7	60.1
MDC - C66	63.7	0.85	2.38	64.3	5.1	8.3	59.2	56.0
MDC - C67	64.3	0.87	2.43	64.3	3.6	6.0	60.7	58.3
MDC - C68	57.0	0.93	2.46	62.2	5.5	8.3	56.7	53.9
MDC - C69	64.1	0.87	2.37	63.2	1.9	4.5	61.3	58.7
MDC - C70	66.6	0.80	2.47	67.7	12.6	14.7	55.1	53.0
MDC - C71	57.7	0.76	2.43	68.8	20.4	23.6	48.3	45.2
MDC - C72	60.2	0.73	2.41	69.7	21.1	24.3	48.6	45.4
MDC - C73	53.9	0.95	2.52	62.1	5.8	7.8	56.4	54.3
MDC - C74	63.5	0.87	2.46	64.5	4.4	6.9	60.1	57.6
MDC - C75	59.4	0.91	2.49	63.4	5.3	7.4	58.1	56.0
MDC - C76	56.2	0.95	2.53	62.4	5.7	8.2	56.7	54.2
MDC - C77	54.0	0.99	2.53	60.7	3.5	5.9	57.2	54.8
MDC - C78	63.0	0.87	2.49	65.2	7.2	9.8	58.0	55.4
MDC - C79	51.9	1.07	2.56	58.2	<1	0.7	59.6	57.5

Client ID	Initial WC	Dry Bulk density	Particle density	Total porosity	Macro-porosity	Air filled porosity	Vol. WC 5kPa	Vol. WC 10kPa
MDC - C80	48.9	1.03	2.53	59.2	2.8	5.3	56.4	53.9
MDC - C81	49.5	1.06	2.56	58.8	2.8	5.0	56.0	53.8
MDC - C82	42.7	1.02	2.53	59.6	8.7	11.4	50.9	48.2
MDC - C83	41.5	1.07	2.55	57.9	7.4	9.5	50.6	48.4
MDC - C84	46.9	1.04	2.52	58.9	4.6	7.2	54.3	51.7
MDC - C85	47.6	1.02	2.56	60.2	3.8	6.5	56.3	53.7
MDC - C86	52.6	1.01	2.51	59.9	0.5	3.0	59.4	56.9
MDC - C87	53.7	1.00	2.51	60.1	1.2	3.3	58.8	56.8
MDC - C88	43.6	1.07	2.51	57.2	3.5	5.4	53.7	51.8
MDC - C89	44.8	1.08	2.52	57.3	1.4	3.4	55.9	53.9
MDC - C90	40.9	1.12	2.52	55.6	1.5	3.4	54.1	52.2
MDC - C91	55.6	0.95	2.50	62.2	2.5	4.2	59.7	58.0
MDC - C92	53.1	1.05	2.53	58.7	<1	0.9	59.7	57.8
MDC - C93	46.3	1.05	2.50	58.2	4.3	6.2	53.8	52.0
MDC - C94	46.4	1.04	2.52	58.7	5.4	7.2	53.3	51.5
MDC - C95	50.9	0.99	2.47	60.1	5.5	7.7	54.5	52.4
MDC - C96	52.8	0.98	2.51	60.8	3.4	5.7	57.4	55.1
MDC - C97	45.4	1.03	2.49	58.5	3.5	5.5	55.0	53.0
MDC - C98	42.3	1.04	2.53	59.0	6.2	8.1	52.8	50.9
MDC - C99	43.7	1.08	2.55	57.6	4.1	6.0	53.5	51.6
MDC - C100	43.2	0.98	2.52	61.3	11.7	13.8	49.6	47.5
MDC - C101	54.3	0.90	2.55	64.6	9.7	11.9	54.9	52.7
MDC - C102	50.6	0.91	2.51	63.9	10.5	13.3	53.4	50.6
MDC - C103	44.0	1.05	2.54	58.5	4.6	7.0	53.9	51.5
MDC - C104	45.6	1.07	2.52	57.4	0.6	2.4	56.8	55.0
MDC - C105	49.1	1.05	2.51	58.3	0.5	1.8	57.9	56.5
MDC - C106	47.7	1.01	2.52	60.0	6.2	8.2	53.8	51.8
MDC - C107	42.7	1.04	2.54	59.2	6.9	8.7	52.2	50.5
MDC - C108	49.8	0.96	2.52	61.9	3.6	5.2	58.3	56.7
MDC - C109	45.1	1.09	2.56	57.3	1.1	3.0	56.3	54.3
MDC - C110	42.8	1.14	2.61	56.4	1.0	3.2	55.3	53.2
MDC - C111	44.7	1.12	2.58	56.6	1.8	3.8	54.8	52.8
MDC - C112	39.6	1.16	2.63	55.8	3.8	6.2	52.0	49.6
MDC - C113	44.0	1.13	2.61	56.8	2.4	4.8	54.3	52.0
MDC - C114	44.4	1.10	2.59	57.6	1.6	4.1	55.9	53.5
MDC - C115	54.8	1.03	2.57	59.8	<1	1.6	60.7	58.2
MDC - C116	57.4	0.97	2.57	62.4	3.6	6.1	58.8	56.3
MDC - C117	53.6	0.98	2.57	61.9	5.7	8.1	56.3	53.8
MDC - C118	51.0	1.08	2.58	58.3	0.9	3.2	57.4	55.1
MDC - C119	57.5	1.00	2.57	61.0	0.6	2.9	60.4	58.1
MDC - C120	59.4	1.00	2.57	61.3	<1	1.1	62.6	60.2

Client ID	Initial WC	Dry Bulk density	Particle density	Total porosity	Macro-porosity	Air filled porosity	Vol. WC 5kPa	Vol. WC 10kPa
MDC - C121	51.8	1.09	2.58	57.8	<1	<1	59.9	58.3
MDC - C122	47.7	1.13	2.62	57.1	1.0	3.0	56.1	54.1
MDC - C123	53.2	1.08	2.57	58.0	<1	<1	60.8	58.6
MDC - C124	56.3	1.00	2.59	61.2	0.1	2.4	61.1	58.8
MDC - C125	52.3	1.04	2.61	60.3	1.9	4.8	58.4	55.5
MDC - C126	53.4	1.04	2.60	60.0	1.0	3.5	59.0	56.5
MDC - C127	56.0	0.96	2.44	60.6	2.7	4.9	57.8	55.7
MDC - C128	59.1	0.96	2.47	61.0	<1	2.2	61.1	58.8
MDC - C129	53.1	0.99	2.46	59.6	3.7	5.8	56.0	53.8
MDC - C130	50.2	0.98	2.58	62.1	9.9	12.9	52.2	49.2
MDC - C131	54.4	0.97	2.57	62.4	7.6	10.6	54.8	51.8
MDC - C132	49.2	0.99	2.55	61.2	9.4	11.9	51.8	49.3
MDC - C133	56.5	0.94	2.49	62.2	4.5	7.5	57.8	54.7
MDC - C134	61.9	0.91	2.49	63.4	3.3	6.4	60.1	57.0
MDC - C135	70.4	0.86	2.46	64.9	0.0	3.0	65.0	61.9
MDC - C136	69.0	0.89	2.43	63.4	<1	1.3	64.2	62.1
MDC - C137	59.4	0.91	2.44	62.8	4.8	7.1	58.0	55.7
MDC - C138	71.7	0.83	2.38	65.0	<1	1.7	65.6	63.3
MDC - C139	39.5	1.20	2.64	54.5	1.3	4.3	53.2	50.2
MDC - C140	35.9	1.22	2.66	54.3	5.9	8.5	48.4	45.8
MDC - C141	39.7	1.25	2.68	53.5	<1	3.0	53.6	50.5
MDC - C142	46.2	1.10	2.60	57.5	2.4	4.9	55.1	52.6
MDC - C143	47.2	1.11	2.61	57.3	<1	1.9	58.6	55.4
MDC - C144	49.6	1.02	2.58	60.4	4.7	7.2	55.7	53.2
MDC - C145	55.6	1.02	2.61	60.9	<1	0.6	62.4	60.3
MDC - C146	47.9	1.11	2.60	57.1	<1	1.2	58.2	55.9
MDC - C147	46.6	1.11	2.61	57.4	0.6	2.6	56.8	54.8
MDC - C148	43.3	1.15	2.63	56.3	1.3	4.1	55.0	52.2
MDC - C149	44.1	1.19	2.61	54.4	<1	<1	56.4	54.6
MDC - C150	45.1	1.16	2.62	55.7	<1	<1	57.6	56.0
MDC - C151	52.4	0.90	2.61	65.5	13.0	16.6	52.5	48.9
MDC - C152	56.4	0.90	2.62	65.7	10.0	12.8	55.7	52.9
MDC - C153	49.2	0.96	2.61	63.3	11.9	14.8	51.4	48.5

Appendix B: Soil Chemical Analysis

Site	pH	Olsen P	Organic matter
		mg/L	%
Site 1	6.2	57	7.3
Site 2	6.1	46	7.8
Site 3	6.0	82	9.7
Site 4	6.0	47	7.5
Site 5	5.4	35	6.1
Site 6	5.5	47	8.4
Site 7	5.7	59	6.9
Site 8	5.7	67	8.1
Site 9	5.7	46	8.6
Site 10	5.7	66	9
Site 11	5.7	80	7.2
Site 12	5.2	27	5.8
Site 13	5.6	16	8.8
Site 14	5.9	17	8.2
Site 15	6.0	11	6.8
Site 16	5.9	26	6.2
Site 17	6.0	13	8.5
Site 18	6.0	21	7.8
Site 19	5.6	38	13.5
Site 20	5.8	21	10.4
Site 21	5.6	18	12.7
Site 22	5.3	58	16.3
Site 23	5.5	45	15
Site 24	5.6	21	14.5
Site 25	5.7	22	11.4
Site 26	5.7	19	11
Site 27	6.0	66	10.1
Site 28	5.8	46	9.2
Site 29	5.8	56	11.6
Site 30	5.4	67	10.8
Site 31	5.8	62	12.1
Site 32	5.3	44	12
Site 33	5.7	56	11.6
Site 34	5.8	33	10.9
Site 35	5.6	44	11.5
Site 36	5.6	48	11.2
Site 37	5.5	43	9.9
Site 38	5.6	38	7.7

Site	pH	Olsen P	Organic matter
Site 39	5.8	31	8
Site 40	6.0	36	8.3
Site 41	5.9	34	7.3
Site 42	6.0	34	8.7
Site 43	6.0	35	13.9
Site 44	5.5	20	7.8
Site 45	6.1	44	12
Site 46	6.2	15	14.4
Site 47	6.6	18	5.2
Site 48	6.5	22	7.3
Site 49	6.6	35	7.8
Site 50	6.6	46	6.9
Site 51	6.5	18	7.4

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