Keyline Water Management: Field Research & Education in the Capital Region
Soil Indicators Monitoring Program

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Disclaimer

Executive Summary

Keyline Water Management is practiced around the world, and is promoted by farmers and farm system designers. Promoters report improvements in soil water storage and distribution, and rapid increase in topsoil depth. These results have typically been achieved in conjunction with other soil management best practices and there has been little scientific evidence to support keyline plowing specifically.

The 'Keyline Water Management: Field Research & Education in the Capital Region Project' was started to engage farmers and land managers in the Capital Regional District with the keyline water management concepts. Specifically, keyline water management as a tool for farm-scale climate change adaptation. The Soil Monitoring Program was designed as a pilot program to measure the changes in water storage and soil quality after keyline plowing on pasture. The results of the Soil Monitoring Program are intended to be used to determine whether Keyline plowing could be part of a wider regional water management and climate change adaptation strategy, and evaluate methods of assessing its use.

Our treatment/control sites were largely unused, mowed-only or seldom-grazed pastures prior to study. We chose these conditions to be able to isolate keyline plowing from other active management strategies and assess the benefit of keyline plowing on its own. We tested soil moisture and soil quality metrics that we expected to show change within the two-year (two full growing seasons) project timeframe. We installed permanent soil moisture probe arrays on two farms to collect year-round soil moisture content on the plowed and unplowed pastures. We also collected soil organic carbon samples, root depths and penetrometer measurements from three farms.

We found that the benefit of using a permanent soil moisture probe installation was that we were able to collect real-time response to rainfall and constant soil conditions throughout the year. The drawbacks were that to avoid damaging the equipment, we were not able to plow the 5-m x 10-m moisture probe zone again after the first pass when probes were installed. It is common among practitioners to plow progressively deeper over a three-year period, which was done on the surrounding pasture, but we were not able to evaluate the direct effect of these repeated passes.

We also found that the active carbon analysis method we used was low cost and repeatable, and would be useful for gathering larger datasets in the region. We worked with the B.C. Ministry of Environment & Climate Change Strategy's Analytical Laboratory in Victoria, BC to trial this potassium permanganate extraction method and it was considered a successful addition to their soil testing service.

The findings of the Soil Monitoring Program were that one pass of keyline plowing:

- Did not appear to affect the rate at which soils dry out at the start of growing season.
- Did not appear to increase water infiltration rate into the soil during typical (less than 4 mm in a 24-hour period) rainfall events during the summer.
- Did not appear to affect the overall rate at which soils absorb water during the fall months.
- Did not appear to increase water infiltration into the subsoils during the winter (saturated period between November and February).
- Did not appear to increase active carbon concentration in the topsoil on two out of three farms.

- May have increased soil moisture holding capacity in the topsoil, but not the subsoil, during the summer.
- May increase water infiltration rate during larger-than-average summer and fall rainfall events (at least 4 mm of rain in 24 hours, or 8 mm of rain in a 36-hour period on the monitoring sites)
- May result in a sustained decrease in soil penetration resistance and increase rooting depth on sites that have coarse soil textures, but not on sites with medium soil textures (no fine soil textures were tested).

Our results suggest that the benefits of the plow for soil decompaction may be dependent on soil texture, or use in combination with other soil quality improvements (e.g. compost tea injection), longer use of the technique, or seeding directly into the rip line. Keyline plowing did appear to increase active carbon on one farm, and total organic carbon on two of the three sites. However, a change in total organic carbon in only two years is an unexpected result based on the literature, so it is most likely that the apparent change in total organic carbon was because there were not enough replicates collected.

Table of Contents

List of Tables

List of Figures

List of Photos

List of Appendices (available upon request)

1 Introduction

Keyline Water Management is being practiced around the world, and has garnered support from agricultural system designers and farmers who report improvements in water retention, improved seasonal and spatial water distribution on pasture and silvopasture systems, and marked increase in topsoil depths (e.g. see: Permaculture Research Institute, February 22, 2013). However, most farmers using the technique also use other land improvement strategies such as organic soil amendments, liming, rotational grazing, perennial cropping, and no-till systems. These strategies have better documented quantitative benefits that may also be responsible for the improvements advocates attribute to the use of different aspects of keyline management.

The Keyline Water Management: Field Research & Education in the Capital Region project was implemented in 2015 with three primary objectives:

- **Education**: introducing farmers/professionals/practitioners to the keyline plow and design concepts; and whether they might be applicable to farming challenges in the Capital Region;
- **Testing and Demonstration**: allowing interested farmers, agricultural system designers and policy practitioners to see the plow in practice and familiarize themselves, evaluate and discuss in the field the practical application of keyline geometry and the Yeoman plow; and
- **Evaluating Claims:** pilot potential field-scale assessment methods to quantify the soil building and moisture distribution benefits of the keyline management system.

The educational and demonstration objectives were met with a series of free, publicly advertised field days and seminars each year, and website and social media outreach. The field days and seminars were aimed at farmers and professionals working on agricultural land management, but were approachable for the general public. Seminars focused on discussing the keyline design process and theory, and presenting the results of each year's monitoring, as well as additional permaculture concepts for water management on farm properties. The field days focused on demonstration and use of the Yeoman plow, describing the research design; as well as overall keyline design, and demonstration of soil quality monitoring techniques for farmers.

Besides the results of the monitoring program below, the two-year program (October 2015 to October 2017) yielded practical observations regarding the plow's functionality and the geometry of keyline on local farms.

This report describes the methods and results of the pilot study to evaluate methods to quantify the potential benefits of keyline plowing.

The two main components of Keyline Water Management are:

1. the use of keyline geometry to create off-contour subsoiling, swales or mounding patterns on complex topography landscapes, and
2. the use of a custom-designed Yeoman plow subsoiler.

We were not able to assess the claims regarding the farm or field-scale redistribution of water from keyline geometry use, as the farms enrolled in the study were too small to have an adequate control and treatment, and the topographic and soil diversity both on site and between farms prevented treating each farm as a replicate. Instead, we focused on potential soil building and soil moisture-holding benefits that could be measured on a site-specific, within-pasture basis: increase in rooting depths, decompaction, and water infiltration and holding due to the Yeoman plow subsoiler.

Soil monitoring data was collected from three farms within the Capital Regional District: Beetnik (Central Saanich), Raven Hill (Central Saanich) and Bullock Lake (Salt Spring Island). Each of these farms had an unimproved (minimal rotational sheep grazing, or unused and infrequently mowed) pasture available to isolate the effect of keyline plowing alone from other soil management strategies to improve pasture yield or condition.

The desired outcomes for the pilot-scale soil monitoring program were to:

- assist in narrowing down which of the hypothesized benefits of keyline design may be measurable when used on farms representative of the small-scale agriculture on diverse topography practiced in the Capital Region;
- develop an estimate of the level of on-site variation in soil moisture that would need to be accounted for in future studies (i.e. how many farms and replicates would be required to acquire statistically testable datasets); and
- test the sensitivity of potential measurable parameters/measurement equipment to measure the hypothesized effects of keyline land management on a small-scale farm.

2 Hypotheses

The three pasture attributes that should see improvements, if the Yeoman's plow has the effects promoters claim, are: 1) increased soil moisture, 2) decreased soil penetration resistance (decrease in compaction), and 3) increased soil organic carbon. Each hypothesis has one or more metrics that are assessed in the Results section (Section 4). Pasture attributes, associated hypotheses, metrics, and farm identification for each metric are shown in Table 2-1.

The soil building claims of keyline plowing have been methodically evaluated by two other studies we could find:

1. One conducted over two years (2010 to 2011) on four dairy cattle pastures in Vermont, USA, which did not find a statistically observable effect in any of the soil parameters measured (soil penetration resistance, active carbon, organic matter, bulk density, forage NDF (neutral detergent fiber); except for an increase in earthworm abundance (Gorres, Gilker and Colby, undated). They did not test soil moisture parameters.

2. One conducted on a sloped pasture in Ontario (2015 to 2016), which found keyline plowed pasture at the top of a slope had decreased water content compared to controls, but held moisture longer compared to the control; on the pasture at the bottom of the slope, plowed soils held more moisture during wet periods of the year (greater than 0.26 m^3/m^3 volumetric water contents), and less moisture during the dry season (RAIN, undated[a]). They did not find any increase in soil organic matter or improvement in grass yield (RAIN, undated[b]).

The testable hypotheses for the soil monitoring program were observations we expected to see within a two full growing seasons timeframe, and that had been previously tested by other researchers, where possible. In the case of the soil moisture effects, effects were those that could be expected to be seen after only one pass of the plow, since the probes were left in place to collect continuous data and re-plowing would damage the equipment. Soil carbon analyses and penetrometer measurements were taken from treated and control areas adjacent to the probe installation with up to two plow passes, as sampling for those parameters was not destructive. Root depth measurements were also restricted to areas with only one pass of the plow, as it was assumed that the plants would require time to recover from any root pruning that occurred during the plowing, and increases in rooting depth may only be observable after a second growing season.

The data collected from this soil monitoring program can be used to refine hypotheses about the magnitude of effects observable from Yeoman plow subsoiling, and provide information on how to design larger studies in the Capital Region to test those hypotheses.

Table 2-1   Keyline Plow Soil Moisture Program Testable Hypotheses and Metrics

Pasture Attribute	Hypothesis	Metrics	Farm Studied		
			Bullock Lake	Raven Hill	Beetnik
Soil Moisture	Increased moisture retention in the rooting zone in non-saturated conditions	1. Percent difference in average volumetric soil moisture (m^3/m^3) between control and treatment area moisture probes for the periods between rainfall events during the dry season. 2. Comparative rate of decrease in soil moisture measured by control and treatment probes during the dry-down period of the year when fall rains return.			
	More rapid infiltration of water into the soil during rainfall events during non-saturated conditions	1. Percent difference in volumetric soil moisture (m^3/m^3) between control and treatment area moisture probes during rainfall event days in the dry season. 2. Comparative rate of increase in soil moisture measured by control and treatment probes during the wet-up period of the year when fall rains return.			
	More water infiltration into the subsoil during saturated periods of the year	Percent difference in volumetric soil moisture (m^3/m^3) between control and treatment area moisture probes at any time during the wet season.			
Soil Penetration	Decreased soil penetration resistance, resulting in greater rooting depths, and	Absolute value difference in depth penetrometer can be pushed in control and treatment areas before reaching root			

Resistance	this decrease is sustained over time	restriction pressures (300 psi).			
		Absolute value difference in rooting depths observed in control and treatment areas, and increase in root abundance in treatment areas.			
Soil Carbon	Increase in soil carbon storage in the rooting zone	Increase in the average active carbon concentration in the rooting zone of treatment areas, as measured using the technique developed by Weil et al. (2003).			
		Increase in total organic carbon concentration in the rooting zone of treatment areas, as measured by LECO combustion.			

3   Methods

3.1 Site Selection

At each of Ravenhill and Bullock Farms, several soil pits were excavated at different landscape positions to investigate the variability of the soils within each proposed treatment area and to find a location with similar soil texture and drainage on both sides, and, in the case of Ravenhill, similar impervious pan layer depth.

3.1.1   Bullock Lake Farm

At Bullock Lake Farm, the probe installations were positioned to either side of a slope crest with a north-northwest aspect. There is a fence running the length of the crest, and sheep pasture on either side. The probes were placed where the slope had an approximately 2 degree slope; on the treatment side, there is a small gently sloping plateau, which then drops steeply beginning approximately 3 m from the probes, with the slope angle increasing to 14 degrees mid-slope, and 20 degrees for the lower third (see Photo 1). On the control side, the slope continues gently to the fenced property edge, with forest on the other side. The soil within the rooting depth is a silt loam, with approximately 25 percent coarse fragments over the field, comprised of boulders to fine gravel, with coarse fragment content increasing downslope. The soil pits within the soil moisture probe installation area were classified as a Gleyed Dystric Brunisol[1], and had no cobbles or stones, so had only approximately 15 percent coarse fragments. Auger refusal was variably encountered below 40 cm due to the presence of large boulders. The soil classification is consistent with the existing mapping from the Soils of the Gulf Islands soil survey, which is an imperfectly drained Suffolk soil formed on coarse glaciomarine and glaciofluvial deposits over compacted till (Van Vliet et al., 1987).

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[1] very thin or absent Ah or topsoil horizon, with prominent mottles indicating saturation for extended periods of the year, and a pH less than 5.5

Photo 1   Overview of Soil Moisture Probe Location at Bullock Lake Farm Prior to Probe Installation (Future Probe Location by Blue Tarp)

3.1.2   Ravenhill Farm

At Ravenhill Farm, the probe installations were positioned on either side of a small ridge approximately one-third of the way west from the western field edge, mid-slope and perpendicular to the dominant slope. The dominant slope is 9 degrees, with a south-southeast aspect (see Photo 2). The soil within the rooting depth around the probe installation is also in the silt loam texture class, but with approximately 10 percent less sand and 10 percent more silt than Bullock Lake. Coarse fragment content is approximately 15 percent, comprised almost entirely of gravel, but potentially overestimated due to many concretions present. The soil types across the farm are variable based on slope position, with better drained, reddish soils encountered near the top of the field, and imperfectly drained, gleyed soils near the toe of the slope. The soil pits within the soil moisture probe installation area were classified as an Eluviated Eutric Brunisol[2] , with a very thin topsoil (Ap) layer. Auger refusal was encountered at approximately 75 cm, and there is a clay pan approximately 2 cm thick that occurs between 20 and 28 cm below surface; when the soil is wet, this pan can be dug through by auger or shovel. The Vancouver Island Soil Survey describes the soil association here as an imperfectly drained Orthic Sombric Brunisol

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[2] evidence of eluviation (Ae horizon, movement of organic matter and clay from upper soil into the subsoil), and a pH greater than 5.5

formed on glaciomarine deposits (Jungen 1985); the original deep forest floor and topsoil layers would have been removed during the original clearing of the land for cultivation.

Photo 2   Overview of Soil Moisture Probe Location at Ravenhill Farm Prior to Probe Installation (Future Probe Location at Cooler Location)

3.1.3   Beetnik Farm

At Beetnik Farm, no soil moisture probes were installed, but the upper vegetable field was plowed in spring 2016, so soil data collection from Beetnik Farm was added to the data collection. The southern half of the field is in field vegetables, the northern half is mowed grass (see Photo 3, Photo 4). The field has an overall western aspect with a 10 degree slope. The soil is a sandy loam with up to 30 percent coarse fragments of cobble to gravel size, a shallow Ah horizon, with some slight eluviation (Ahe horizon). The soil survey for the area describes the soil as Somenos, a well-drained Duric Dystric Brunisol developed on coarse till. We did not excavate deep enough to encounter the duric horizon described for this soil association between 70 to 110 cm depth (Jungen 1985).

Photo 3   Overview of Soil Data Collection Area at Beetnik Farm Prior to Plowing – Study Area is Fallow Field in Top Left Above Greenhouse

Photo 4   Close-up of Soil Data Collection Area at Beetnik Farm (Summer 2015 Prior to Plowing)

3.2 Plowing Methods

Plowing was conducted after baseline soil characterization. In October 2015, two shanks approximately 1 m apart (3 feet) were pulled through the treatment areas at a depth of 25 to 35 cm, set to approximately 5 cm below the average rooting depth. Plow lines followed the keyline geometry established for each site (Photo 5).

Photo 5   Keyline Plowing at Ravenhill Farm, Fall 2015

On Bullock Lake farm, the control section was on the opposite side of a grazing fence, within an entirely unplowed pasture. The control section of the Ravenhill farm was within the plowed pasture, but plowing was avoided on a section of the pasture approximately 40-m wide running from top to bottom of pasture. See plan view images of Bullock Farm and Ravenhill Farm in Figure 3-1 and Figure 3-2, respectively.
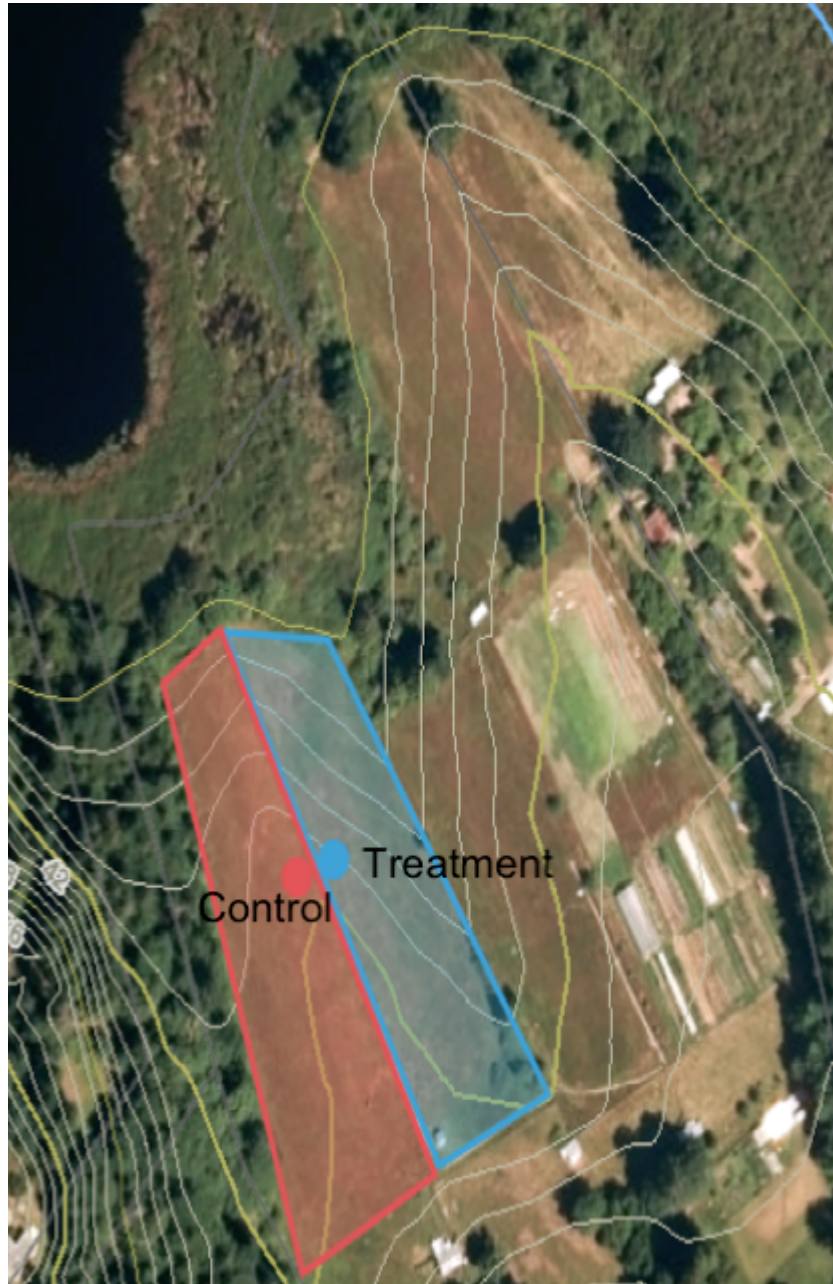
Figure 3-1 Plan View of Keyline Plow Treatment Areas on Bullock Lake Farm

Figure 3-2 Plan View of Keyline Plow Treatment Areas on Ravenhill Farm

Keyline pattern tree mounds were also used on the plowed pasture on Ravenhill Farm as part of the overall mixed farming system using keyline geometry during the second year of the program (fall 2016). *Pinus pinea* (Italian Stone Pine) and *Pinus koreansis* (Korean Stone Pine) were planted in 4-inch rotovated beds. The rotovated beds on the treated side were ripped with 3 tines spaced very close together to 50 cm depth, while the beds on the control side received no keyline plowing. Since we could not collect two full growing seasons of data, we excluded the tree mounds from monitoring for this project, but intend to observe over the next 5 to 10 years if significant differences are found in tree growth and condition between plowed and unplowed beds.

Plowing on Beetnik Farm was completed in mid-October 2015 (see plan view of study areas on Figure 3-3). We subsoiled to an average depth of 33 cm, plowing across the slope, using a contour guideline. An area to the north of the field was left for control measurements.
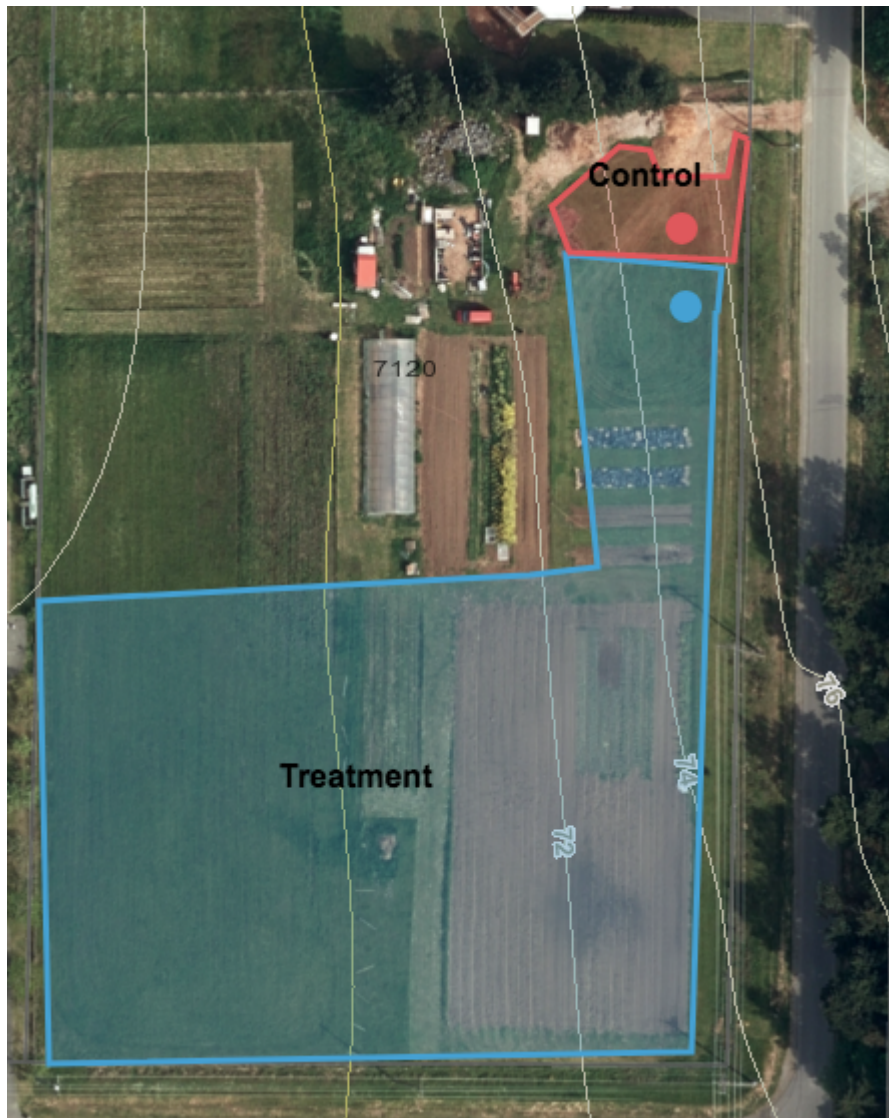
Figure 3-3 Plan View of Keyline Plow Treatment Areas on Beetnik Farm

3.3 Soil Data Collection

3.3.1   Soil Characterization

Baseline data collection and probe installation was conducted on October 7 and 8, 2015 at Ravenhill Farm, and October 9 at Bullock Farm, and baseline soil characterization and soil fertility data were collected on Beetnik Farm on October 10. Baseline data included soil pits for soil characterization, soil fertility and bulk density, root characterization, and penetrometer measurements on treatment and control areas. Probe installation was completed at Bullock Farm in late November 2015, as new probe attachments had to be ordered. All baseline data was collected from treatment and control areas prior to treatment, except for the penetrometer measurements, which were collected immediately following plowing.

Fertility and bulk density, root characterization and penetrometer measurements were repeated annually in fall 2016 and 2017; see Sections 3.3.2 through 3.3.4 for further descriptions of 2016 and 2017 data collection.

For soil characterization, one full soil pit within the control and treatment areas was excavated a couple metres away from the planned probe installation areas. At Ravenhill Farm, depth of excavation was to approximately 60 or 70 cm to ensure excavation past the hard pan and into the softer parent material; auger refusal occurs at 70 cm. At Bullock Farm, boulders or possible bedrock was encountered, and limited auger depth to approximately 40 cm. Each soil pit was described according to the Canadian System of Soil Classification (Soil Classification Working Group 1998). Information collected at each profile included:

- Slope and landscape position at pit location
- Depth of each horizon
- Colour, texture and texture of each horizon
- Coarse fragment[3] content and shape
- Rooting depth, size distribution and density
- Mottle and gleying[4] characteristics
- Field pH

No water table or seepage was observed on either site.

3.3.2   Soil Fertility Analysis

Within an approximately 5 m radius of the area selected for each treatment and control probe installation, composite samples for laboratory analysis was collected from five randomly placed subsamples of the upper soil horizons (approx. 0 to 20 cm depth; an Ap[5] at Ravenhill Farm and a Bg[6] at Bullock Farm). The composite samples were collected for a baseline fertility 'score card' adapted from the Cornell Soil Health Assessment Training Manual (Gugino et al. 2010). The analyses requested in 2015 were:

- pH ($CaCl_2$)
- pH (2:1 in water)
- Electrical conductivity
- Sodium adsorption ratio
- Available macro- and micronutrients (available nitrate-nitrogen [NO3-N], ammonium-nitrogen [NH4-N], potassium [K], phosphorus [P], calcium [Ca], magnesium [Mg], sodium [Na], copper [Cu], zinc [Zn], iron [Fe], manganese [Mn])
- Bulk density (defined core volume)
- Total organic carbon (by LECO® combustion analysis)
- Total nitrogen (by LECO® combustion analysis)
- Total organic matter (loss on ignition)

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[3] Rocks larger than sand

[4] Uniform dull grey, or bright red or light grey spots (reduced iron) in a darker soil colour background indicative of periods of the year when the amount of water in the soil prevents fresh oxygen reaching certain depths, and the bacteria present use it all up.

[5] Organic enriched topsoil horizon, modified by human activity

[6] Subsoil horizon, physically or chemically altered from the underlying parent material by high water tables (gleying characteristics present)

14

- Active carbon (Weil et al. [2003] permanganate method)

At Ravenhill Farm, samples of the Bm[7] horizon were also collected for pH in calcium chloride (2:1 CaCl)$_s$ for Brunisol[8] subgroup classification.

Laboratory analyses were conducted at Pacific Soil Analysis Inc. in Richmond, BC, except for active carbon, which was analysed at the Ministry of Environment laboratory in Victoria, BC.

Soil fertility analyses were repeated in 2017 for topsoil samples only, and did not include bulk density, pH or texture, as there were no interventions being conducted that would change those parameters . In 2015, one composite sample of five subsamples in each of the control and treatment areas was sent to the lab, and so no variability within the fields could be estimated. In 2017, the five subsamples were not composited, and were analysed separately at the laboratory. We also collected active carbon samples in May, July and October in 2017 (beginning, middle and end of the growing season, respectively). to determine what the magnitude of change in active carbon is throughout the growing season, and how strongly it varies due to soil temperature, moisture, and active growing status of the plants.

3.3.3 Root Data Collection

Root data was collected in fall 2015 prior to plowing for baseline on both treatment and control sides, and then adjacent to plow rips in 2016 and 2017 on treatment areas (randomly within unplowed pasture for control areas). At each of the five subsample plots in each control and treatment area, a 0.09 m^2 face (0.3 m by 0.3 m) was excavated. Rooting density, average and maximum depth (if encountered), root diameter and orientation was recorded. Density was initially recorded at Ravenhill Farm using the Field Manual for Describing Terrestrial Ecosystems (BC MOFR and MOE 2010) scale; however, the resolution of that scale obscured the variability of rooting in the fields, so roots/cm^2 within the majority rooting zone was estimated for subsequent plots at Bullock Farm, and repeat root measurements in 2016 and 2017.

3.3.4 Soil Penetration Resistance Data Collection

Penetrometer readings were taken on a 5 m long transect on each of the treatment and control areas on each farm. A reading was taken approximately every 50 cm, for a total of 10 measurements. On treatment areas, reading locations were adjusted so that they varied between 25 and 80 cm apart; one-third of the readings were taken between contour plow lines, equidistant between contours, and two-thirds of the readings were taken 10 cm above or 10 cm below the centre of a plow line. In 2017, measurements were taken on two-year-old plow lines and one-year-old plow lines.

To determine where the relative depth soils became too hard for roots to penetrate, the three-quarter inch penetrometer tip cone was used, and even pressure at a rate of one centimetre per second was applied (per manufacturer's directions) until a maximum pressure of 300 pounds per square inch (psi) was reached. The depth of the probe at maximum pressure was then recorded.

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[7] Subsoil horizon, physically or chemically altered from the underlying parent material by organic matter enrichment or weathering.

[8] Canadian System of Soil Classification, soil group denoting minimal development (subsoil development, weak topsoil development)

3.4 Soil Moisture Probe and Datalogger Installation

3.4.1 Bullock Lake Farm

The treatment and control sets of probes were installed within approximately 5 m^2 blocks (boundaries unmarked) on either side of the fence line demarcating the top of the ridge following plowing, with the western side of the fence left unplowed. Two posts for the datalogger mounts were installed, one each at the fence edge of each block (Photo 6). A total of three pits to 20 cm deep were excavated in each block; approximately 160 and 90 degrees from each datalogger station, approximately 2-m from each other. The sod was cut and removed in a single plug. The pits on the treatment side were excavated so that one edge of the pit was approximately 15 cm from the centre of a plow line, so that the 4 inch (approximately 10 cm) probe sensors would be within the 10 cm zone of decompaction next to each plow line, but would not be within it.

One Decagon GS1 volumetric water content sensor was installed in each pit (6 total; 3 on each of the treatment and control blocks) at 10 cm depths (see Photo 7). Probes were installed per manufacturer's directions: horizontally, using even pressure until the sensor mount was flush with the pit face. Pits were backfilled and tamped lightly with the shovel every few centimetres to prevent voids and replace all excavated soil to roughly the same bulk density. The sod was replaced over each pit and pressed into place, filling voids around the cuts.

Narrow trenches were cut with shovels and hand trowels to bury the probe cords between the pits and the dataloggers. Cords were buried approximately 5-cm below ground surface. Each probe cord was labelled with flagging, and run through a 50-cm length of narrow polyvinyl chloride plastic (PVC) tubing, two cords per tube. The PVC tubes were secured vertically to the datalogger post. Both the cord burial and PVC protection were intended to prevent chewing by rodents, though no vole holes were observed at the Bullock Farm. Each Decagon EM-50 datalogger had three probes attached. Dataloggers were strapped to the posts approximately 1.5 m above ground, and set to record a measurement every 30 minutes. Chicken wire was also wrapped in a tube around the datalogger posts to protect the posts from rubbing by sheep (Photo 8).

Photo 6   Soil Moisture Dataloggers at Bullock Lake Farm – Control Dataloggers in Foreground

Photo 7   Installed Soil Moisture Probe at 10-cm Depth at Bullock Lake Farm

Photo 8   Sheep Guard Around Control Datalogger at Bullock Lake Farm

3.4.2   Ravenhill Farm

The treatment and control sets of probes were installed within marked out approximately 5-m^2 blocks (boundaries unmarked) on either side of the mid-field ridge following plowing, with the western side of the ridge left unplowed. Three posts for datalogger mounts were installed, one on the centreline between the treatment and control block, and one each in the centre of each block. A total of three pits to 60-cm deep were excavated in each block; two pits were spaced approximately 1.5 to 2 m apart at approximately 120 degrees from the central datalogger station, and the third was placed approximately 1.5 m from the middle datalogger station, one on either side of the ridge, equidistant between the other two pits (see Photo 9). The pits on the treatment side were excavated as described for Bullock Lake. Each soil horizon was piled separately to the extent possible, and the sod was cut and removed in a single plug.

Two Decagon GS1 volumetric water content sensors were installed in each pit (12 total; 6 on each of the treatment and control blocks) at 10 cm and 40 cm depths. The lower probe at 40 cm was placed below

the hard pan, within an approximately 20 cm thick compact silty clay layer, which typically occurred between 20 and 30 cm. Below this layer, there was typically a very soft fine sand layer (see Photo 10). Probes were installed per manufacturer's directions; horizontally, using even pressure until the sensor mount was flush with the pit face. Pits were backfilled by layer, and tamped lightly with the shovel every few centimetres to prevent voids and replace all excavated soil to roughly the same bulk density. The sod was replaced over each pit and pressed into place, filling voids around the cuts. A six-inch nail labeled with flagging tape was set into the ground next to each set of probes.

Narrow trenches were cut with shovels and hand trowels to bury the probe cords between the pits and the dataloggers. Cords were buried approximately 5 cm below ground surface. Each probe cord was labelled with flagging, and run through a 50-cm length of narrow PVC tubing, two cords per tube. The PVC tubes were secured vertically to the datalogger post. Both the cord burial and PVC protection were intended to prevent chewing by rodents, as vole holes were numerous in the field, and burrows were excavated within the soil pits during baseline data collection. Each Decagon EM-50 datalogger had four probes attached; the middle datalogger was installed to log from one control and one treatment pit. Dataloggers were strapped to the posts approximately 1.5 m above ground, and set to record a measurement every 30 minutes (via the ECH2O utility software provided).
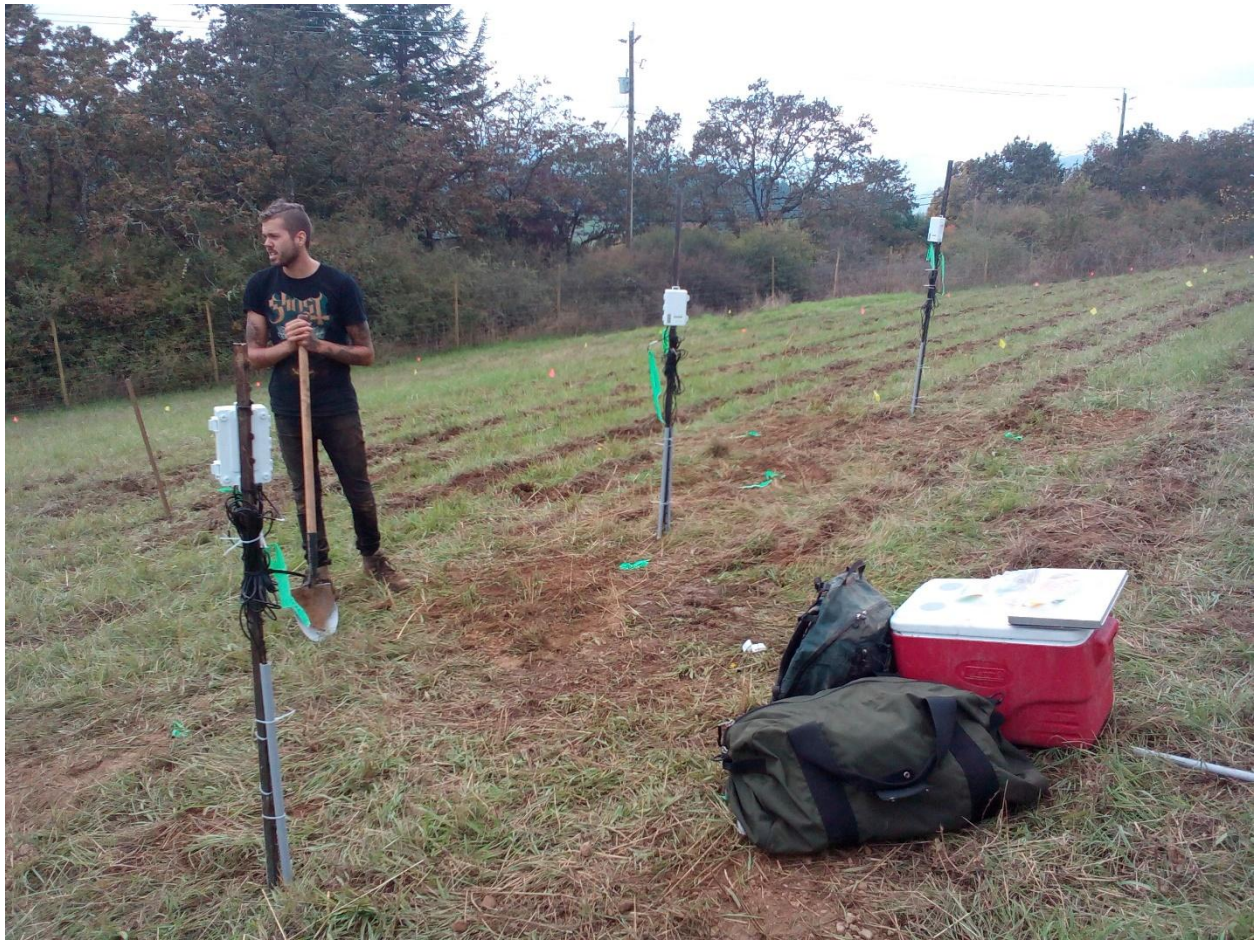
Photo 9   **Soil Moisture Dataloggers at Ravenhill Farm Treatment Datalogger in Foreground (middle datalogger has probes in both treatment and control plots). Green flagging marks and labels each probe pit.**

Photo 10   Installed Soil Moisture Probes at 10-cm and 40-cm Depths at Ravenhill Farm

3.5 Soil Moisture Probe Data Collection

Continuous soil moisture probe data was manually downloaded from each datalogger two to three times per year, when soil data was collected. Stored data was downloaded from the dataloggers by universal serial bus (USB) cable using the Decagon ECH2O Utility application. In summer 2017, the Bullock Lake dataloggers generated error messages when downloads were attempted, and the dataloggers had to be removed from site for the final download of data in October. Once back within Wi-Fi range, the downloads began automatically, so all data was collected by the end of the trial.

3.6 Data Analysis

3.6.1 Soil Moisture Probe Data

The dataloggers were programmed to collect a data point every 30 minutes; however, we found that moisture changes were mostly measurable over longer intervals of four to seven hours. To remove long periods of identical readings in between minor changes, while preserving the detail around abrupt wetting or drying trends, a subset of data was pulled for analysis that included a data point only every six hours. The data points selected were the first data point following equilibration on each site, and then every six hours after that point.

The data from each logger was then graphed to check for obvious error readings and to remove those readings. One of the control probes at 10 cm depth on Ravenhill appeared to have a malfunction or lost good soil contact in 2016, and again in 2017; the volumetric water content readings became improbably low (less than 0.044 m^3/m^3, lower than the driest readings obtained on any site) during May, and then became negative before slowly increasing back to within the typical range of variation for the control probe readings. As a result, all values from that probe between May 12 and October 6, 2016, and September 6 to October 17, 2017, were removed from the analysis.

The probe data analysed in Section 4.2 is the mean for all replicate probes on each site for each treatment depth, and the standard deviation or minimum and maximum of the mean probe value. The date range and rainfall characteristics of each data period examined is provided in the table summaries where applicable. Rainfall data is from the daily rainfall values obtained from the nearest school in the Victoria School-Based Weather Station Network (see: http://www.victoriaweather.ca/); Brentwood Bay Elementary for Ravenhill, and Fulford Elementary for Bullock Lake.

To evaluate whether keyline plowing resulted in improved water infiltration and retention during summer months, the percent difference in average soil volumetric water content (VWC) (m^3/m^3) between control and treatment probe groups was compared during rainfall event response days in summer (dry season). The beginning of summer was defined as the start of the period when the soil ceased to continue drying between rainfall events, and eventually plateaued at a low value that would be returned to within a few days of any rainfall; the end of summer was defined as the start of the period when the soil moisture would continue to rise and remain higher with each subsequent rainfall. The rainfall response period begins with a rapid rise in moisture that occurs on both sites one day after rain at the 10-cm depth, and ends approximately two days after last rain. If two rainfall events occur with less than three days between, they are counted as one continuous rainfall event. The saturated period of the year is defined as the plateau at which the soil remains at the approximately same moisture content throughout the winter.

3.6.2 Root Data

The average and maximum rooting depths for control and treatment samples observed in October of each year are compared, and the notes and photographs taken are discussed in the context of the results. There was no measurable difference in any of the other root data metrics collected (root size distribution, root orientation) over time, so these data are not presented for discussion.

3.6.3   Soil Penetration Resistance Data

The average and maximum penetrometer depths for each control and treatment site at each monitoring time (fall 2015; spring and fall 2016; spring, summer and fall 2017) were compared. The values from all 10 control measurements per transect were used to create the average. On the treatment transects, the between-rip and near-rip (within 10 cm) measurements were separated and averaged for comparison; between four and five measurements were taken between-rips on each transect, and eight to ten near-rips (one on either side of a rip) on each transect. The maximum of each of the between-rip or near-rip categories were presented.

In 2017, additional plow passes were completed within the pastures, but a minimum of 5 m from the soil moisture probe installations. Penetrometer measurements were also collected from transects in the newly plowed areas, and are analysed the same way, and presented with the data from the original treatment and control areas for discussion.

3.6.4   Soil Carbon Data

The trend between years for total organic and active carbon fractions, and within-year trends for active carbon, are compared. Total organic and active carbon fraction concentrations received from the laboratory from October 2015 and 2017 control and treatment samples on each site are used to compare between years; and the samples from May, July and October 2017 control and treatment samples are used to compare within year. Non-composited samples collected in 2017 are used to estimate the standard deviation of within-field samples.

4   Results and Discussion

4.1 Climate Context

The daily rainfall totals for each soil moisture probe site (Ravenhill and Bullock Lake) are provided for context in the soil moisture probe results section (see Section 4.3), based on the nearest weather station in the Victoria School-Based Weather Station Network (Brentwood Bay Elementary and Fulford Elementary, respectively).

The climate context for the Saanich Peninsula and surrounding area, including Salt Spring Island, is described here based on the Victoria International Airport weather station, which provides a 30-year climate normal dataset in addition to the monthly data presented for the duration of the trial.

Temperatures on the Saanich Peninsula are typically mild, ranging from monthly average lows around 5 degrees Celsius in the coldest months from December to February, and peaking in July and August around 17 to 18 degrees (Figure 4-1). Precipitation is typically highest from November to January, averaging 140 to 150 mm each month, mostly in the form of rain; then normally drops steadily from February to June, with the dry period lasting from late June to September, with the lowest average precipitation of approximately 18 mm in July. High fall rains usually return abruptly in October (Figure 4-2) (Government of Canada 1981-2010 Climate Normals & Averages).

The study period was from late October 2015 to the end of October 2017. Starting in 2014, and continuing through 2015 until approximately June 2016, was a strong El Niño event (NASA [blog], December 15, 2015), followed immediately by a weak La Niña that did not persist through the summer (NOAA [blog], February 7, 2017). The 2016 average temperature was higher that the 30-year (1981-2010) climate normal until November, up to 2 degrees higher in the late spring, and it was much drier than normal from April to August; rainfall typically decreases slightly month over month from February through July, but in 2016 dropped abruptly to dry season levels in April – a total of 10 mm of rain, compared to the normal 48 mm, was received at Victoria International Airport (YVR) - until the return of the rains in October. Once the rains returned, precipitation was higher than normal in the 2016 to 2017 winter (except for January, which was abnormally dry); the 2016 October was particularly wet, receiving 2.5 times the normal precipitation (233 mm versus the average October rainfall of 88 mm). The 2016-2017 December to February winter was also up to 2.5 degrees colder than normal, with a cold snap with average daily temperatures remaining below zero lasting for most of January (January 4 through 25).

Spring 2017 temperatures from March onward were near-normal, and peaking approximately 1 degree higher than normal during the late summer in August (average 18 degrees) and September; however, 2017 remained wetter than normal until June, and experienced a drought in July and August, with approximately 23.5 mm of rain received over the three months of July to September – none in July – equivalent to the typical total rainfall for the month of September.
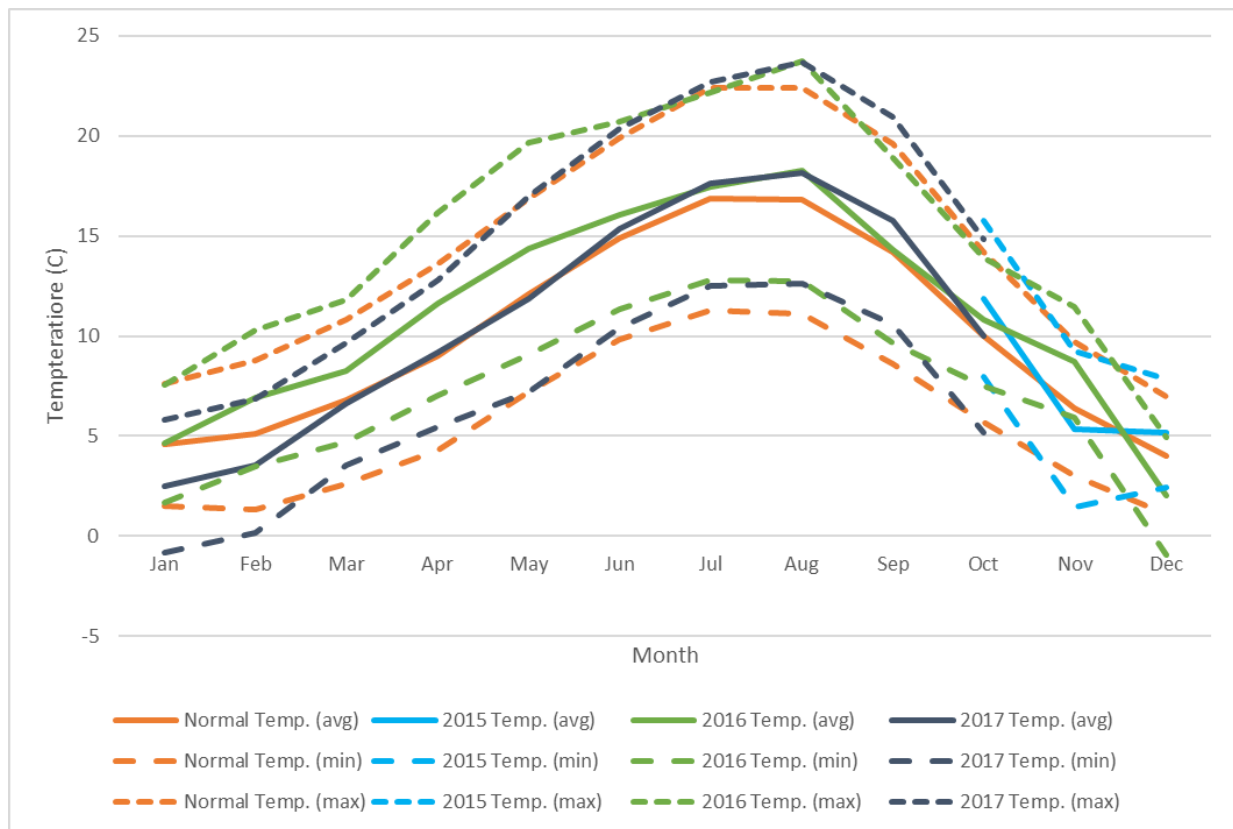
Figure 4-1 1981-2010 Climate Normals vs. 2015 - 2017 Study Duration Temperature
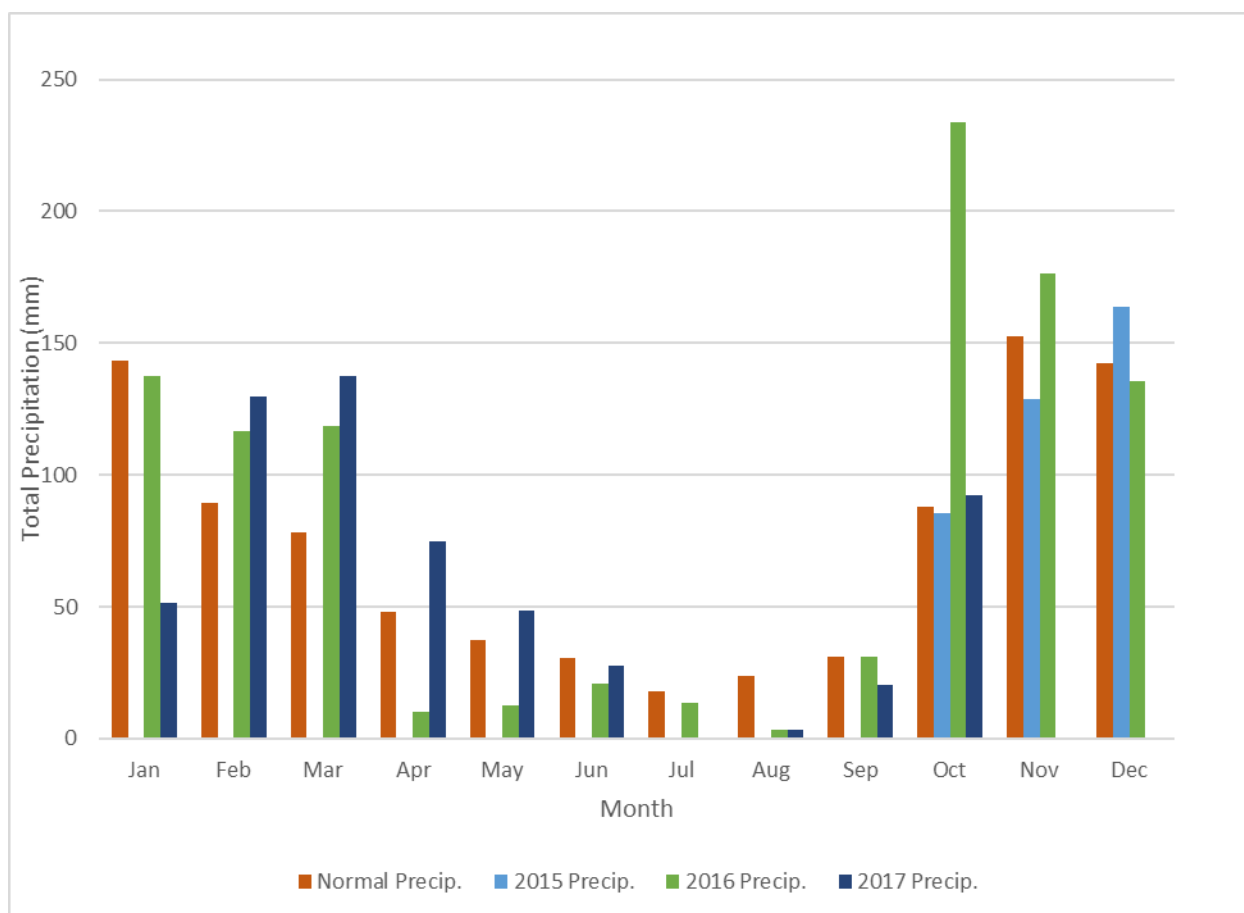
Figure 4-2   1980-2010 Climate Normals vs. 2015 - 2017 Study Duration Precipitation

4.2 Soil Moisture

4.2.1   Overview of Data

Overview graphs of the soil moisture probe data collected at each site are provided in Appendix E, upon request. The volumetric soil moisture content (m^3/m^3) data points are for four readings each day (every six hours). See Section 3.6.1 for a description of the moisture probe data processing methods. Figures E-1 and E-3 in Appendix E shows the results for each probe, and Figures E-2 and E-4 in Appendix E shows the mean treatment and control probe values for each site at each depth. Figure E-1 for Bullock Lake Farm shows that one of the three probes in each set is consistently much higher or lower than the other two throughout the year. The mean percent difference between the highest probe and the lowest probe reading in each treatment depth ranges from 15 percent (Bullock Lake Control) to 49 percent (Ravenhill Treatment at 40 cm depth), and most frequently is in the low 20 percent range (Table 4-1).

Table 4-1 Average Difference in Highest and Lowest Soil Moisture Probe Readings on Each Treatment Block

Probe Depth	Bullock Lake Farm	Ravenhill Farm	
	10 cm	10 cm	40 cm
Control	15	21	24
Treatment	23	35	49

The summer moisture plateau on Bullock Lake Farm in 2017 started a month later than in 2016, and so was only two months long compared to three months in 2016. The difference between 2016 and 2017 was not as great as could be expected, however, given that 2017 had less than 10 percent of the total rainfall of 2016, and only three rainy days. On Ravenhill Farm, the 2016 summer plateau started three weeks earlier than Bullock Lake, in the middle of May, but ended at approximately the same date, while the 2017 summer covered ended approximately one month later, in October. The difference between the rainfall received in 2017 versus 2016 was much less pronounced on Ravenhill than on Bullock Lake. there were approximately the same number of rainy days (20 compared to 22) and there was 60 percent less total rainfall in 2017 than 2016. The average water content on both control and treatment surface soils was approximately 20 to 30 percent lower in 2017 than in 2016 on both farms, despite the large difference in the change in rainfall experienced. Ravenhill Farm appeared to dry out faster than Bullock Lake, possibly due to higher evapotranspiration in the ungrazed fields, or greater shrinkage and exposure to air drying within the rip lines.

4.2.2   Effect on Soil Moisture Retention During the Dry Season

On Bullock Lake, the average soil moisture content at 10 cm during the summer when it was not raining was 15 percent higher on treatments than controls, and on Ravenhill, the soil moisture content on the treatment was on average 12 percent higher than the control (Table 4-2 and Table 4-3; Figures E-2 and E-4, Appendix E).

For the subsurface probes on Ravenhill (40-cm depth), the treatment was approximately 24 percent drier than the control when it was not raining in both years, possibly due to increased evaporation possible through the opened rip line. We based plow depth in 2015 on the standard practice of plowing 5 cm below the average rooting depth. It does not appear that this was deep enough to fully break through the clay pan, which would have resulted in greater moisture draining to the 40 cm depth in the summer (Table 4-4).

Table 4-2   Average Volumetric Water Content on Bullock Lake Farm Control and Treatment Between Rainfall Events in the Summer Months – 10 cm Depth

Year	Date Range	Control		Treatment		Average % Difference in VWC
		Average VWC (m^3/m^3)	St. Dev.	Average VWC (m^3/m^3)	St. Dev.	
2016	Jun 7 to Aug 31	0.109	0.031	0.124	0.024	13.7
2017	Jul 6 to Sept 7	0.094	0.015	0.109	0.013	15.8
Average		0.102	0.025	0.117	0.021	14.8

Table 4-3   Average Volumetric Water Content on Ravenhill Farm Control and Treatment Between Rainfall Events in the Summer Months – 10 cm Depth

Year	Date Range	Control		Treatment		Average % Difference in VWC
		Average VWC (m^3/m^3)	St. Dev.	Average VWC (m^3/m^3)	St. Dev.	
2016	Jun 7 to Aug 31	0.082	0.021	0.091	0.025	11.2
2017	Jul 6 to Sept 7	0.062	0.005	0.069	0.008	11.7
Average		0.072	0.013	0.080	0.016	11.5

Table 4-4   Average Volumetric Water Content on Ravenhill Farm Control and Treatment Between Rainfall Events in the Summer Months – 40 cm Depth

Year	Date Range	Control		Treatment		Average % Difference in VWC
		Average VWC (m^3/m^3)	Standard Deviation	Average VWC (m^3/m^3)	Standard Deviation	
2016	Jun 7 to Aug 31	0.161	0.029	0.125	0.026	-22.4
2017	Jul 6 to Sept 7	0.141	0.011	0.104	0.012	-26.4
Average		0.152	0.020	0.115	0.019	-24.2

The graph segments showing change in volumetric water content over time during spring, when volumetric water content changes from the saturated values over winter to the minimum values of the summer, are shown on Figure 4-3 through Figure 4-5 for the probe depths at each site. A linear equation was used to describe the slopes of each segment (goodness-of-fit, r^2, was usually between 0.6 and 0.9). The values of the slppes were compared for controls and treatments.

During dry down in the spring, the slope of the lines describing the treatment and control on Bullock Lake are not different, and are both very shallow (drying down happened slowly) (Figure 4-3, Table 4-5).
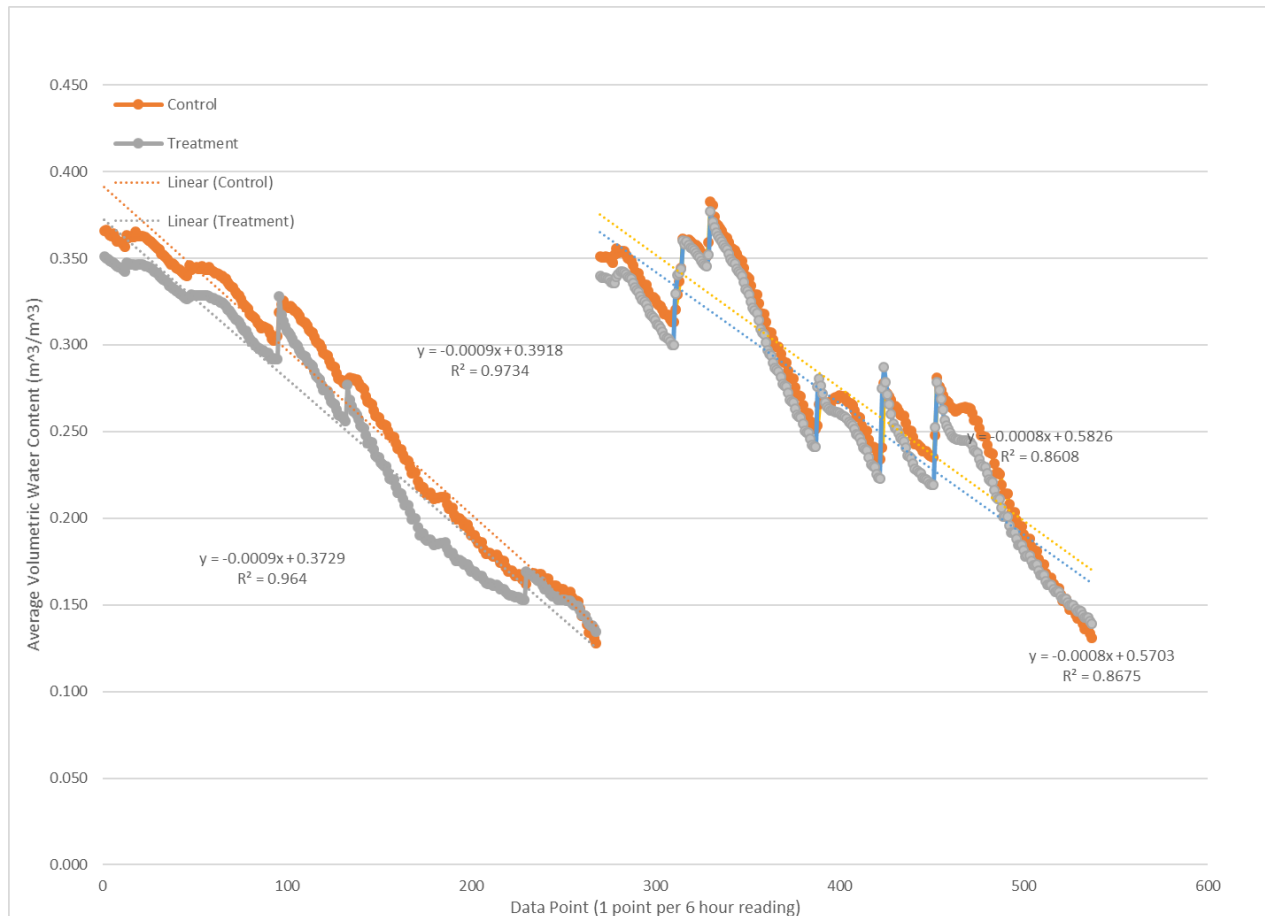
Figure 4-3 Drying Down Slopes of Volumetric Water Content Graphed Against Time for Control and Treatment for Bullock Lake, with Linear Equations

Table 4-5 Average Slopes of the Linear Equations Describing the Volumetric Water Content Graphed Against Time for Bullock Lake Farm Control and Treatment During Dry Down– 10 cm Depth

Year	Date Range	Control	Treatment	Average % Difference
2016	Apr 1 to Jun 6	-0.0009	-0.0009	0
2017	May 1 to Jul 5	-0.0008	-0.0008	0
Average		-0.0009	-0.0009	0

During dry down in the spring, the slope of the lines describing the treatment and control on Ravenhill are not different at either the 10 or 40 cm depth (Figure 4-4 and Figure 4-5), and are both shallow (drying down happens slowly) (Table 4-6 and Table 4-7).
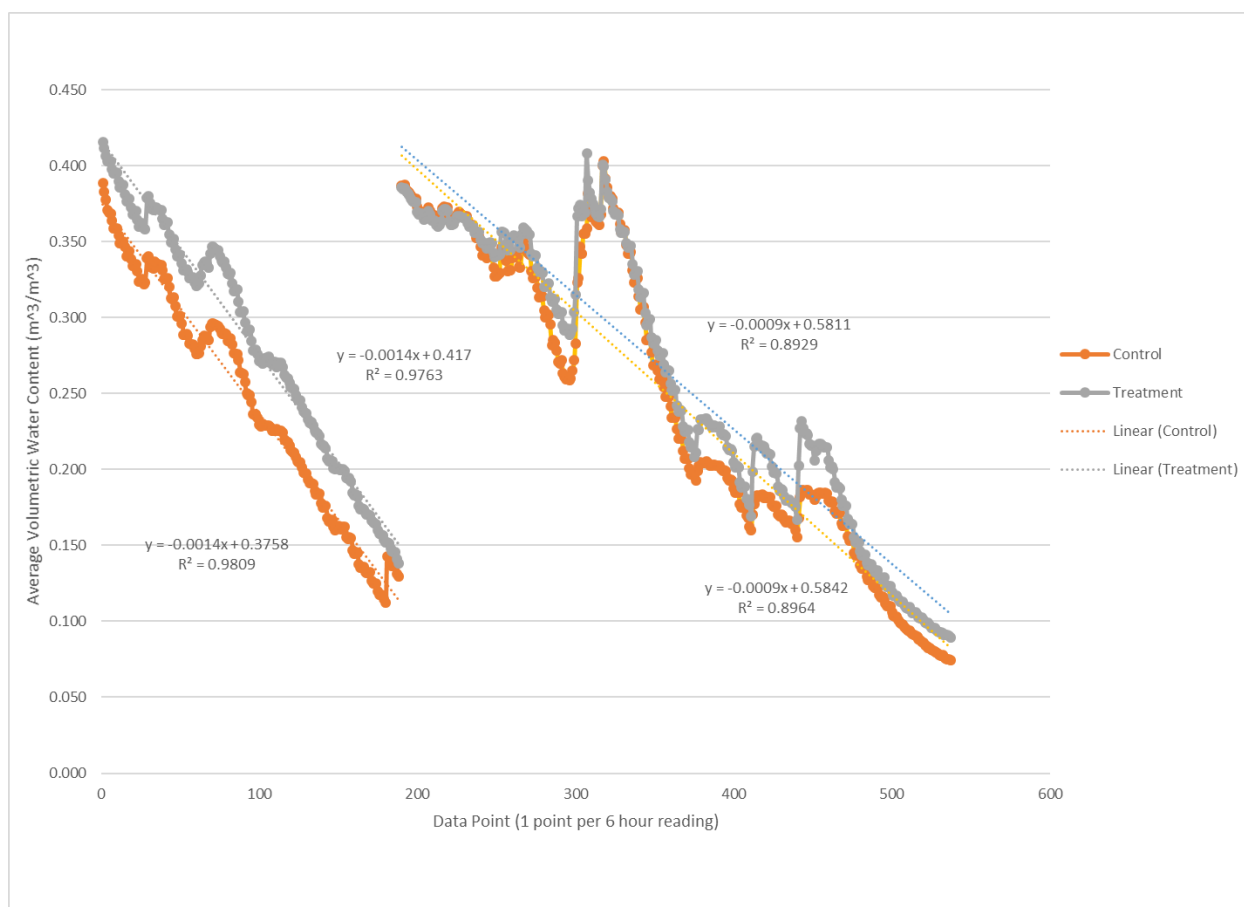
Figure 4-4 Drying Down Slopes of Volumetric Water Content Graphed Against Time for Control and Treatment for Ravenhill, with Linear Equations – 10 cm Depth

Table 4-6   Average Slopes of the Linear Equations Describing the Volumetric Water Content Graphed Against Time for Ravenhill Farm Control and Treatment During Dry Down– 10 cm Depth

Year	Date Range	Control	Treatment	Average % Difference.
2016	Mar. 28 to May 13	-0.0014	-0.0014	0.0
2017	Apr. 14 to Jul 9	-0.0009	-0.0009	0.0
Average		-0.0012	-0.0012	0.0
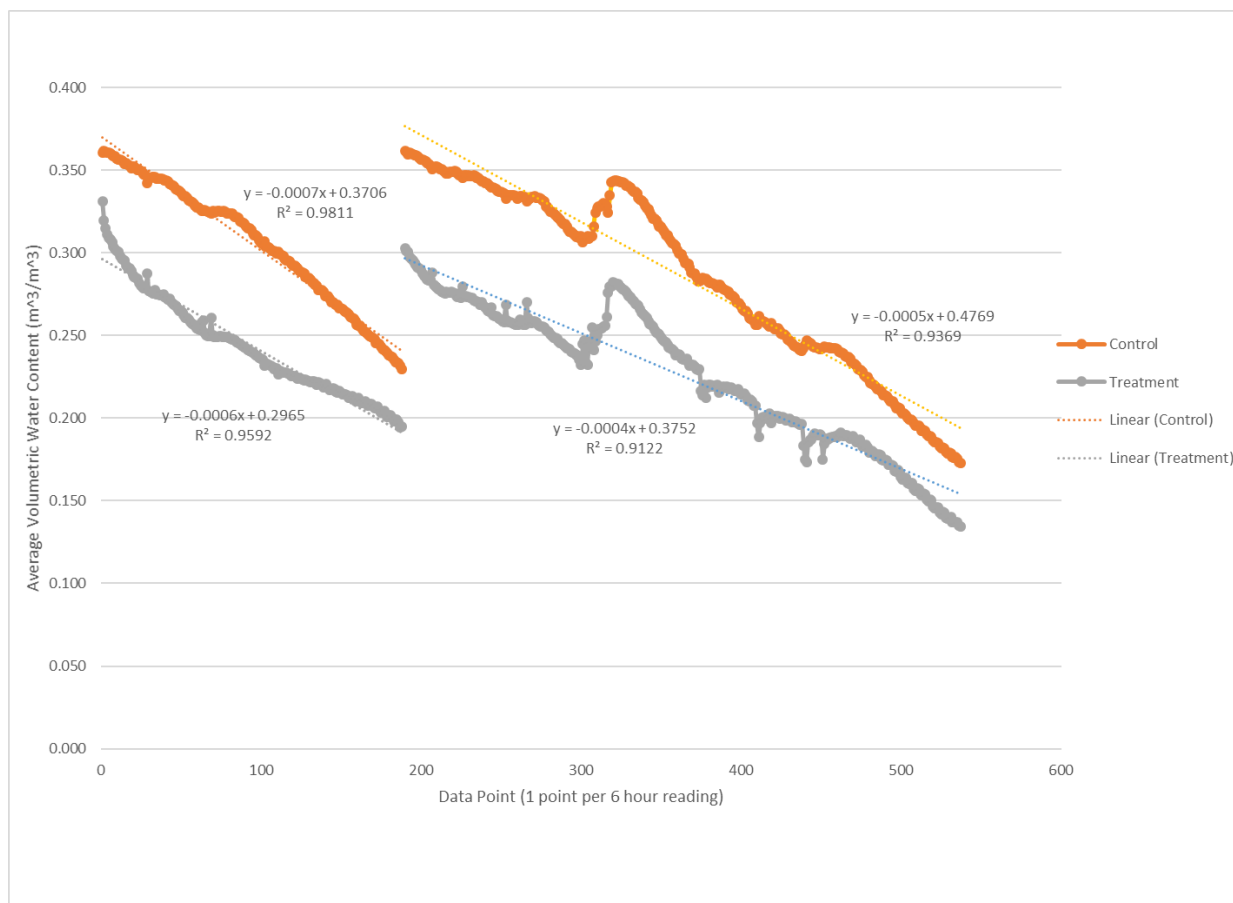
Figure 4-5 Drying Down Slopes of Volumetric Water Content Graphed Against Time for Control and Treatment for Ravenhill, with Linear Equations – 40 cm Depth

Table 4-7 Average Slopes of the Linear Equations Describing the Volumetric Water Content Graphed Against Time for Ravenhill Farm Control and Treatment During Dry Down– 40 cm Depth

Year	Date Range	Control VWC (m^3/m^3)	Treatment VWC (m^3/m^3)	Average VWC % Difference.
2016	Mar. 28 to May 13	-0.0007	-0.0006	-14
2017	Apr. 14 to Jul 9	-0.0004	-0.0005	25
Average		-0.0006	-0.0006	0

The Keyline plow treatment appears to increase soil moisture content over unplowed pasture throughout the dry season. However, the magnitude of the differences between the average treatment and control surface (10 cm) and subsurface (40 cm at Ravenhill) moisture contents were within the

magnitude of the variation between probes within treatments, and were within one standard deviation of each other.

4.2.3 Effect on Rainfall Infiltration During the Dry Season

The average moisture content in the treatment at 10 cm on Bullock Lake was 13 percent higher than on the control side during rainfall events in all years.

Because the rainfall events that occurred were quite small, there was no discernible difference in moisture content during compared to between rainfall events in 2017, for any given depth (see Table 4-8, below, and Table 4-2 in Section 4.2.2).

In 2016, the average soil moisture content was 11 percent higher on treatments than controls; there are two large rainfall events/series in June and July that initially raise moisture content on treatments by 20 to 17 percent over the controls. However, the average moisture content during rainfall does not appear dramatically different as the controls eventually reach the same moisture content a few days later, i.e. the treatments peak faster, but dry out more rapidly during the high rainfall events. These peak events are visible only where at least 4 mm of rain was recorded at the nearest station within 24 hours (typical summer rainfall is less than 1 mm of rain in a 24-hour period). During the largest peaks where there was a total rainfall of at least 8 mm in 36 hours, the moisture content is raised to double the summer average moisture content (between 0.180 and 0.200 m^3/m^3 at the peaks, compared to typical averages of 0.112 to 0.127 m^3/m^3 for control and treatments, respectively).

Table 4-8   Average Volumetric Water Content on Bullock Lake Farm Control and Treatment During Rainfall Events in the Summer Months – 10 cm Depth

Year	Date Range	No. of Rainy Days	Total Rainfall (mm)	Control		Treatment		Average CWC % Difference
				Average VWC (m^3/m^3)	St. Dev.	Average VWC (m^3/m^3)	St. Dev.	
2016	Jun 7 to Aug 31	23	51.1	0.131	0.035	0.145	0.030	10.9
2017	Jul 6 to Sept 7	3	4.5	0.093	0.013	0.108	0.012	15.8
Average		13	27.8	0.112	0.024	0.127	0.021	13.4
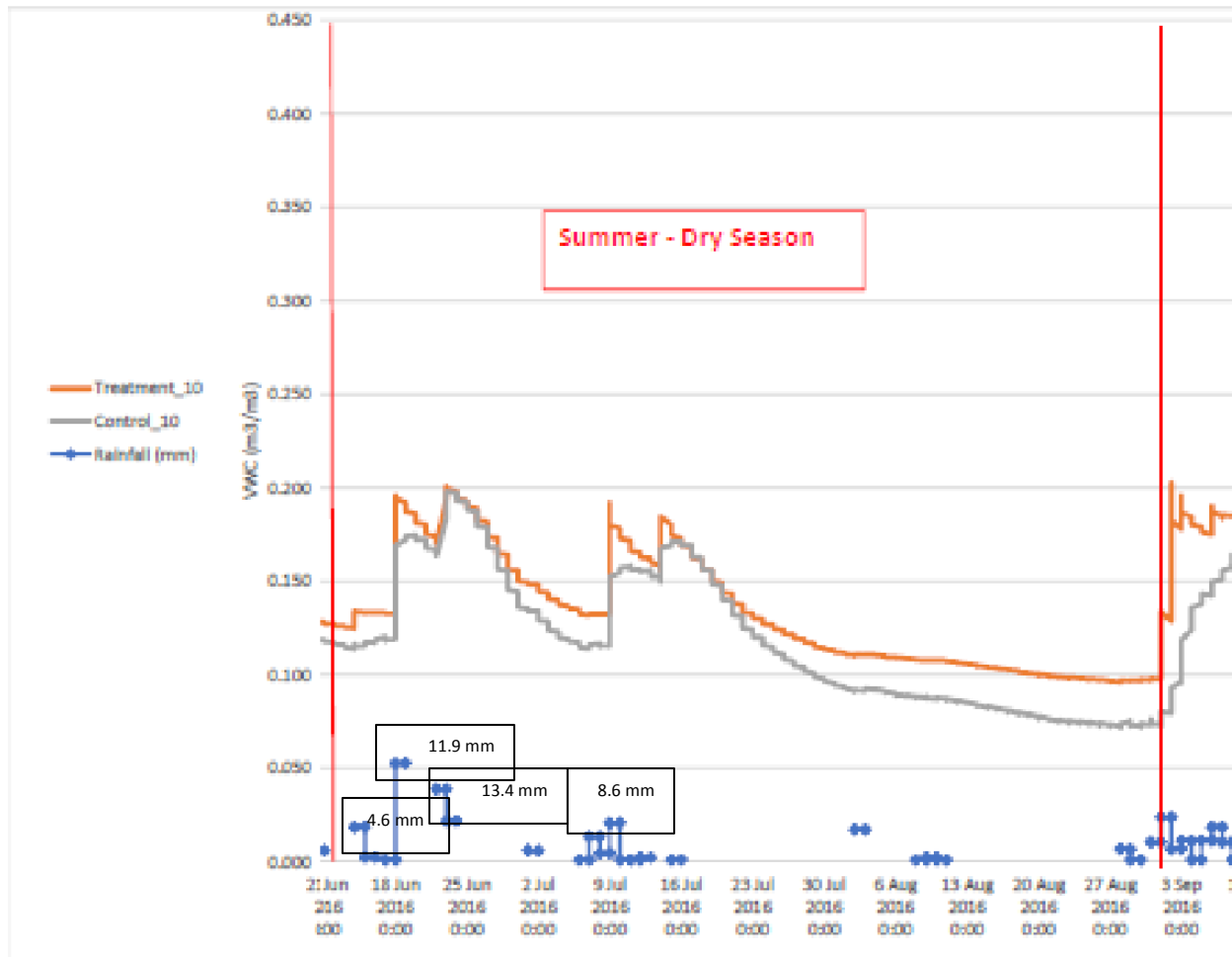
Figure 4-6 Bullock Lake Farm Mean Soil Moisture Probe Output - 2016 Summer Data Graph Subset

On Ravenhill, the average soil moisture content on treatments at 10 cm was 14 percent higher than on controls during rainfall events. However, in 2017, the average soil moisture content during rainfall events or between them was nearly the same within controls and treatments (0.072 and 0.073 m^3/m^3 for the control, and 0.084 and 0.080 m^3/m^3 for the treatment, respectively) (Table 4-9, below, and Table 4-3 in Section 4.2.2). As with Bullock Lake, the moisture content during rainfall events was the same as between rainfall events in 2017, because the rainfall events are so small.

In 2016, the average moisture content during rainfall events is 20 percent higher on the treatment than on the control; however, peak rainfall events in June and July do measurably increase the magnitude of the difference between the control and treatment. For each of the three rainfall events, which are visible only where at least 6 mm of rain within 24 hours was recorded at the nearest station, the peak soil moisture content increased by 0 to 33 percent over the summer average on controls, and between 25 to 55 percent over the summer average on the treatments. For the three large events, soil moisture content increased to between 0.084 to 0.108 on the control, and 0. 0.121 and 0151 m^3/m^3 at the peaks on the treatment, compared to typical averages of 0.081 and 0.097, respectively m^3/m^3) .

36

For the subsurface probes on Ravenhill (40 cm depth), the treatment was approximately 24 percent drier than the control in both years, even during rainfall events (Table 4-10).

Table 4-9   Average Volumetric Water Content on Ravenhill Farm Control and Treatment During Rainfall Events in the Summer Months – 10 cm Depth

Year	Date Range	No. of Rainy Days	Total Rainfall (mm)	Control		Treatment		Average VWC % Difference
				Average VWC (m^3/m^3)	St. Dev.	Average VWC (m^3/m^3)	St. Dev.	
2016	Jun 7 to Aug 31	23	51.1	0.081	0.016	0.097	0.024	19.9
2017	Jul 6 to Sept 7	3	4.5	0.066	0.005	0.071	0.006	9.0
Average		13	27.8	0.073	0.010	0.084	0.015	14.4

Table 4-10   Average Volumetric Water Content on Ravenhill Farm Control and Treatment During Rainfall Events in the Summer Months – 40 cm Depth

Year	Date Range	No. of Rainy Days	Total Rainfall (mm)	Control		Treatment		Average VWC % Difference
				Average VWC (m^3/m^3)	St. Dev.	Average VWC (m^3/m^3)	St. Dev.	
2016	May 14 to Sept. 1	22	49.3	0.156	0.021	0.120	0.019	-22.6
2017	Jul 10 to Oct. 16	20	28.5	0.128	0.002	0.096	0.004	-24.5
Average		21	38.9	0.142	0.012	0.109	0.011	-23.5
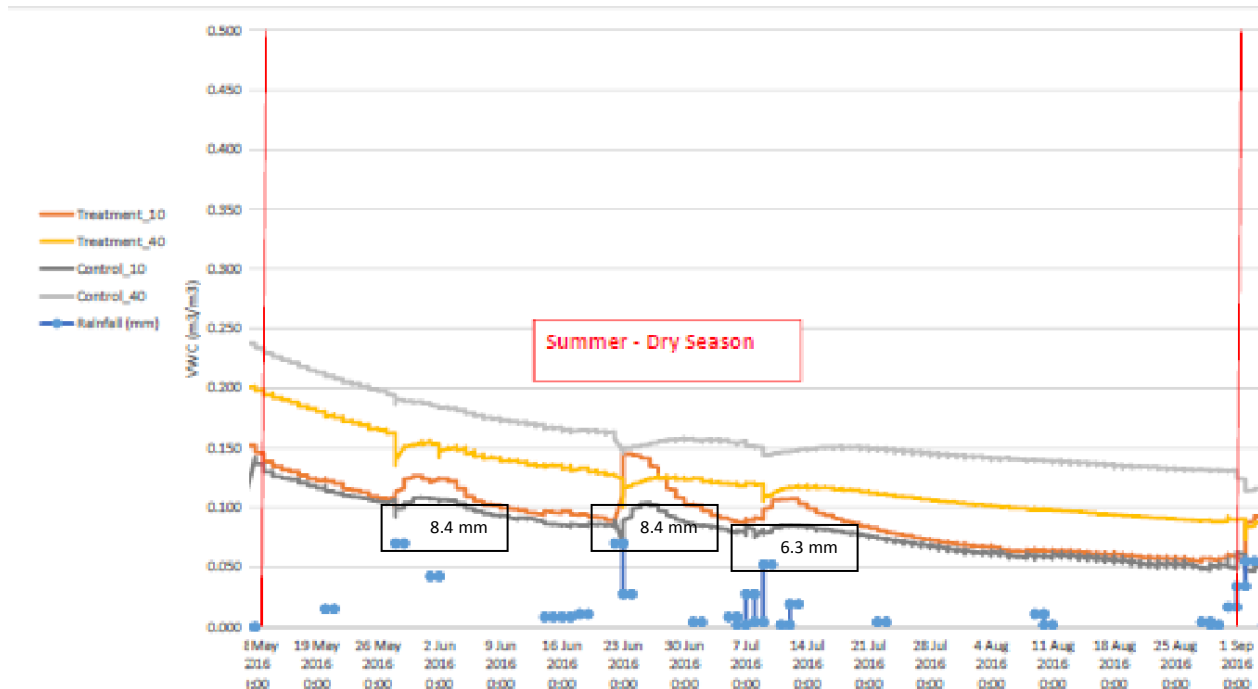
Figure 4-7 Ravenhill Farm Mean Soil Moisture Probe Output - 2016 Summer Data Graph Subset

During fall 2016, there were two distinct wet up events on Bullock Lake, with a plateau in the middle; the two wetting events were graphed separately. The treatment appeared to wet up an average of 33 percent more slowly than the control (Table 4-11); however, the treatment wet up more rapidly during the first few days of rainfall a large rainfall event (greater than 4 mm in 24 hours), then began to dry out while the control was still continuing to wet up (Figure 4-8). Thus, the overall shape of the fall wetting curve depends on the size of the initial rainfall events. A series of low volume rainfall events appears to result in no difference, or even a faster response by the control, but a large volume of rainfall infiltrated faster on the treatment side. Only the first half of the wet-up period was captured for 2017 before monitoring stopped; however the greater initial response of the treatments, followed by brief dry down during rainfall events greater than 4 mm in 24 hour and 8 mm in 36 hours, appears consistent with 2016 data.
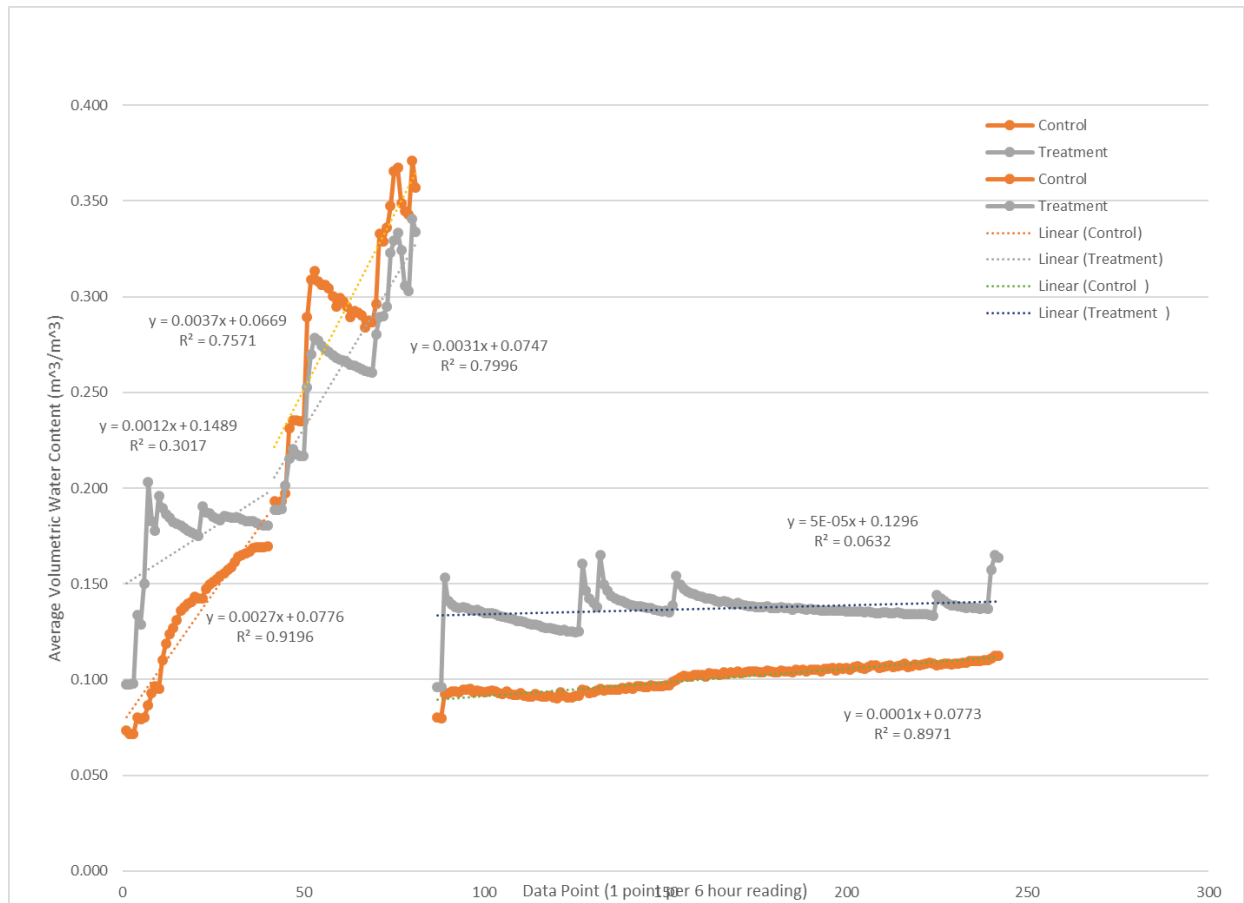
Figure 4-8   Wetting Up Slopes of Volumetric Water Content Graphed Against Time for Control and Treatment for Bullock Lake, with Linear Equations

Table 4-11 **Average Slopes of the Linear Equations Describing the Volumetric Water Content Graphed Against Time for Bullock Lake Farm Control and Treatment During Wet Up – 10 cm Depth**

Year	Date Range	Control Slope	Treatment Slope	Average Slope % Difference
2016	Sept 1 - Sept 10	0.0270	0.0120	-56
2016	Sept 11 - Oct 16	0.0370	0.0310	-16
2017	September 8 - October 17	0.0001	0.0001	0
Average		0.021	0.014	-33

The probe array was installed early enough in 2015 on Ravenhill to capture the 2015 wet up event, but the soil moisture content had not begun to increase for the fall wet up event in 2017 when monitoring finished that year. In the fall, the treatment appeared to wet up on average 38 percent faster at the 10 cm depth, and 52 percent slower than the control at the 40 cm depth (Figure 4-9 and Figure 4-10; Table 4-12 and Table 4-13). As with Bullock Lake, wetting up happens more rapidly than drying down at the 10 cm depth.

y = 0.0042x + 0.1967
$R^2 = 0.8523$

y = 0.0027x + 0.2036
$R^2 = 0.5728$

y = 0.0012x - 0.0004
$R^2 = 0.6769$

y = 0.001x - 0.0236
$R^2 = 0.6732$

Control
Treatment
Linear (Control)
Linear (Treatment)

Average Volumetric Water Content (m^3/m^3)

Data Point (1 point per 6 hour reading)
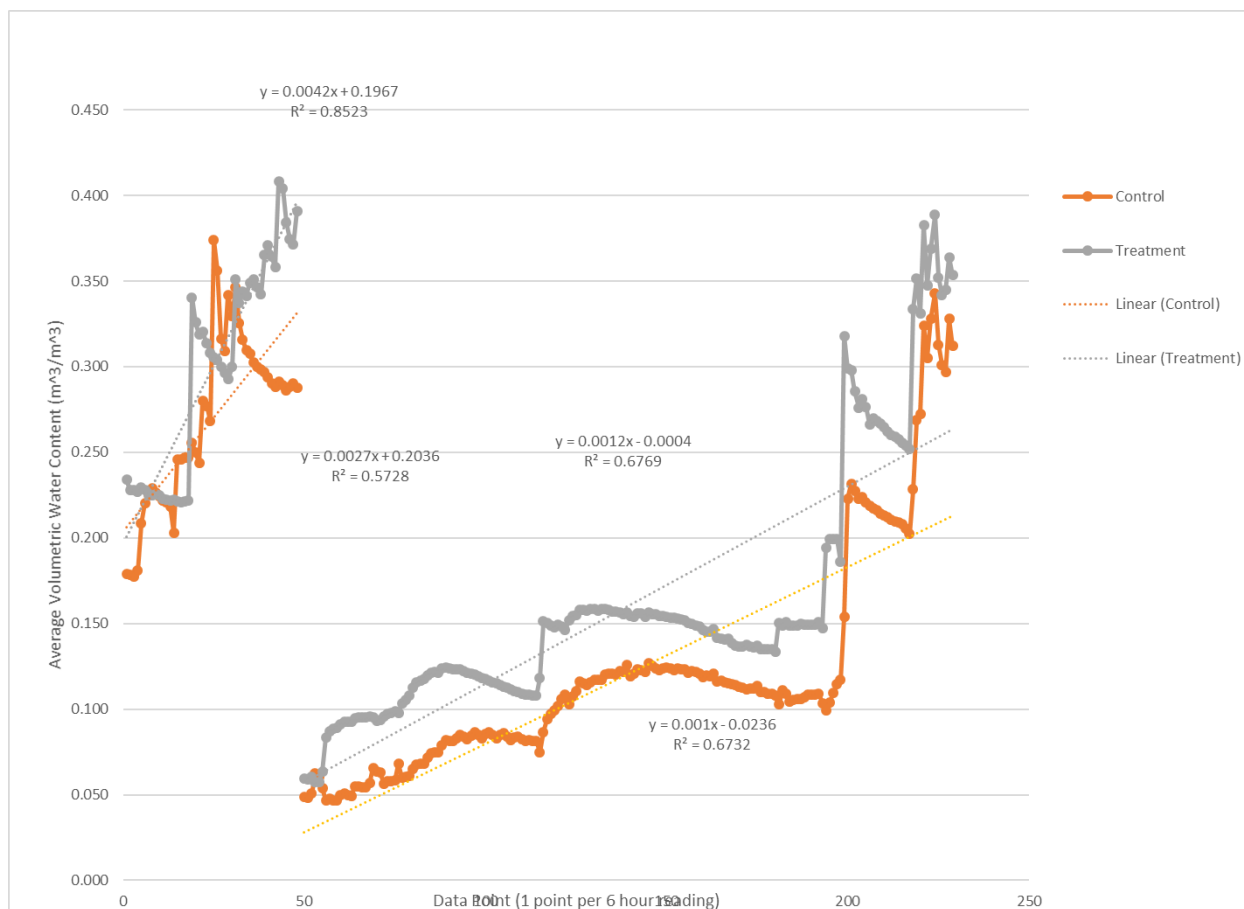
Figure 4-9   Wetting Up Slopes of Volumetric Water Content Graphed Against Time for Control and Treatment for Ravenhill, with Linear Equations – 10 cm Depth

Table 4-12   Average Slopes of the Linear Equations Describing the Volumetric Water Content Graphed Against Time for Ravenhill Farm Control and Treatment During Wet Up – 10 cm Depth

| Year	Date Range	Control Slope	Treatment Slope	Average Slope % Difference
2015	Oct. 25 to Nov. 5	0.0027	0.0042	56
2016	Sept. 1 to Oct. 14	0.0010	0.0012	20
2017	-	-	-	-
Average		0.0019	0.0027	38
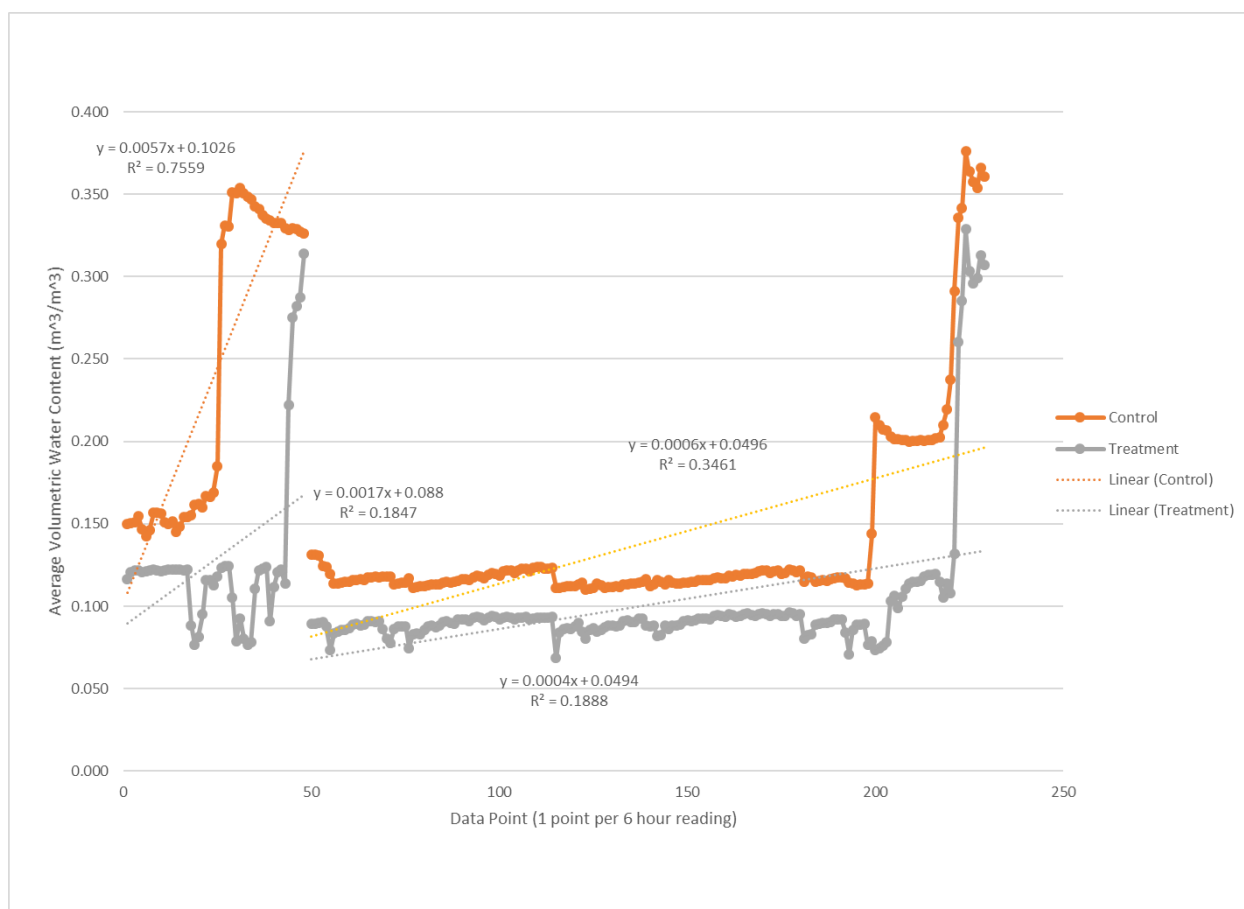
Figure 4-10   Wetting Up Slopes of Volumetric Water Content Graphed Against Time for Control and Treatment for Ravenhill, with Linear Equations – 40 cm Depth

Table 4-13 Average Slopes of the Linear Equations Describing the Volumetric Water Content Graphed Against Time for Ravenhill Farm Control and Treatment During Wet Up – 40 cm Depth

Year	Date Range	Control Slope	Treatment Slope	Average Slope % Difference
2015	Oct. 25 to Nov. 5	0.0057	0.0017	-70
2016	Sept. 1 to Oct. 14	0.0006	0.0004	-33
2017	-	-	-	-
Average		0.0032	0.0011	-52

The Keyline plow treatment appears to increase water infiltration during large rainfall events, compared to unplowed pastures. However, the differences between the average treatment and control surface (10

cm) and subsurface (40 cm at Ravenhill) moisture contents during rainfall events were within the variation between probes within treatments, and were within one standard deviation of each other.

4.2.4 Effect on Rainfall Infiltration During the Wet Season

On both Bullock Lake and Ravenhill, the soil reached saturation between mid-October and early November (on Bullock Lake, part of the early saturation period is missed, as probe data collection did not begin until late November of 2015). On Bullock Lake, the treatment was an average of 5 percent drier than the control, and the standard deviation was small, as there was little response to rainfall during the winter once the soil reached the initial saturation point. The exception was during January (Table 4-14), when apparent soil moisture dropped during the three weeks that temperatures stayed below 0 degrees at the Victoria Airport, and soil water was likely frozen; the treatment appeared to freeze more than the control.

On Ravenhill, the treatment was an average of 8 percent wetter than the control at 10-cm depth, and 14 percent drier at 40-cm depth (Table 4-15 and Table 4-16). There was no apparent difference in the soil moisture content during the cold snap in January on Ravenhill. The average soil moisture content at 10- and 40-cm depths on the control was similar, 0.356 m^3/m^3 and 0.360 m^3/m^3, respectively; while the 40-cm depth was much drier on the treatment than the 10-cm depth: 0.308 m^3/m^3 compared to 0.386 m^3/m^3. It is not clear what the mechanism for the drier subsoil on the treatment is, but may be greater moisture retention above in the rooting zone.

As with the dry season, the difference between the average treatment and control surface (10 cm) and subsurface (40 cm at Ravenhill) moisture contents in the winter were within the magnitude of variation in the readings between probes within treatments, and were within one standard deviation of each other.

Table 4-14 Average Volumetric Water Content on Bullock Lake Farm Control and Treatment During the Winter Months – 10 cm Depth

Year	Date Range	No. of Rainy Days	Total Rainfall (mm)	Control		Treatment		Average VWC % Difference.
				Average VWC (m^3/m^3)	St. Dev.	Average VWC (m^3/m^3)	St. Dev	
2015 - 2016	Nov. 21 to Mar. 31	110	804.2	0.377	0.011	0.358	0.011	-5
2016 - 2017	Oct. 16 to Apr. 30 (excl. Jan 4 to 25)	157	976.4	0.370	0.010	0.351	0.014	-5
	Jan 4 to 25			0.357	0.018	0.291	0.046	-18
Average		134	890.3	0.373	0.010	0.354	0.012	-5

Table 4-15 Average Volumetric Water Content on Ravenhill Farm Control and Treatment During the Winter Months – 10 cm Depth

Year	Date Range	No. of Rainy Days	Total Rainfall (mm)	Control		Treatment		Average VWC % Difference.
				Average VWC (m^3/m^3)	St. Dev.	Average VWC (m^3/m^3)	St. Dev	
2015 - 2016	Nov. 6 to Mar. 27	110	735	0.360	0.025	0.397	0.015	10
2016 - 2017	Oct. 15 to Apr.13	135	780	0.352	0.025	0.375	0.016	6
Average		123	757	0.356	0.025	0.386	0.015	8

Table 4-16 Average Volumetric Water Content on Ravenhill Farm Control and Treatment During the Winter Months – 40 cm Depth

Year	Date Range	No. of Rainy Days	Total Rainfall (mm)	Control		Treatment		Average VWC % Difference.
				Average VWC (m^3/m^3)	St. Dev.	Average VWC (m^3/m^3)	St. Dev	
2015 - 2016	Nov. 6 to Mar. 27	110	735	0.359	0.008	0.313	0.015	-13
2016 - 2017	Oct. 15 to Apr.13	135	780	0.361	0.005	0.303	0.013	-16
Average		123	757	0.360	0.007	0.308	0.014	-14

4.3 Soil Penetration Resistance and Rooting

Keyline plowing is a method of subsoiling, and so can be used to break up clay pans, increase vertical drainage channels in pastures, and to some extent mechanically lift and loosen soils at horizontal distance from the rip line with the Yeoman plow foot. We evaluated whether the decrease in soil penetration resistance observable after plowing persisted over time on our trial sites.

In fall 2015 after plowing on Bullock Lake, the penetrometer on the treatment reached nearly three times the depth on the control before meeting resistance within 10 cm to either side of the rip line (approximately 17.8 cm compared to 5.7 cm) (Figure 4-11). Halfway between the rip lines on the treatment, penetration up to twice the depth of the control was occasionally achieved, but there was a large standard deviation in that measurement. In the following year, spring 2016 through spring 2017, there was no consistent difference between the control, rip lines or between the rip lines, and no resistance was met with the penetrometer until well below the rooting zone, likely because the soil was wet. The volumetric water content at the subsequent sampling times was around 0.35 m^3/m^3 (maximum field capacity), compared to 0.10 to 0.15 m^3/m^3 when the plowing was completed in 2015. In summer 2017, when the soil was at its driest, reduced penetration resistance may have persisted near the rip lines, but there was large variation in the depths achieved along the transect. In fall 2017, a second pass with the plow was completely on most of the treatment pasture, leaving an area around the moisture probe installation. As with the first plow pass, maximum penetrometer depth near the rip lines on the second plow pass was reduced by approximately half compared to the control and treated area between the rips; however, variation between measurements was high.
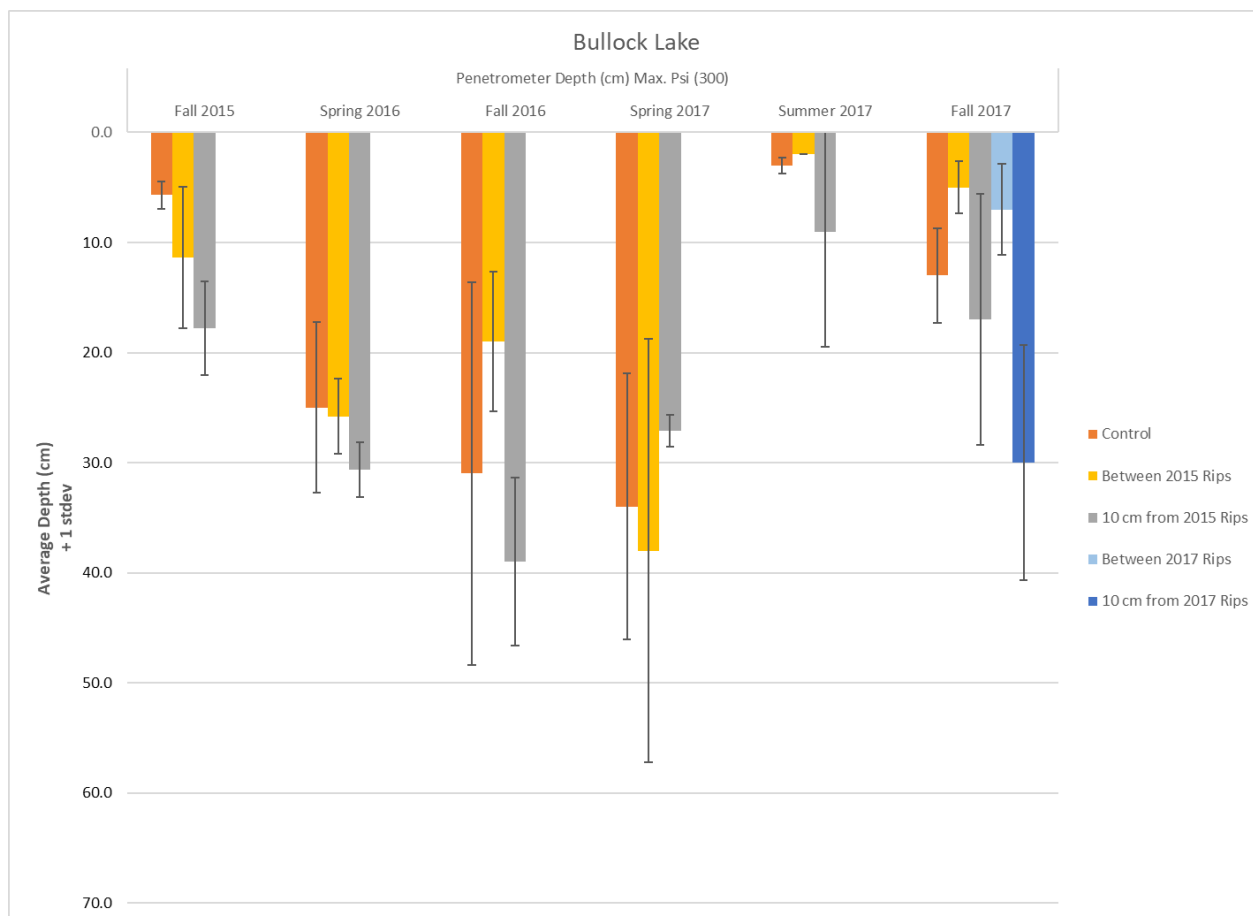
Figure 4-11   Maximum Penetrometer Depth Achieved on Bullock Lake from 2015 to 2017 on Control and Treatment Transects

On Ravenhill, there is a distinct 2 cm deep clay pan found at approximately 20 to 28 cm depth. The first plow pass in 2015 did not reach below that depth, and did not make a difference in the soil hardness on that site (Figure 4-12). In spring and fall of 2016 and 2017, when the soil was wet, there was also no difference in the hardness between treatment and control, and the clay pan was soft enough to penetrate with no resistance, on both two-year-old and one-year old (spring 2016 plowed) rip lines. In the summer of 2017, the ground was dry and very hard, and while maximum penetrometer depth appeared higher on the treatment compared to the control (4.8 cm vs. 2.5 cm), the depth of penetration possible was very low.
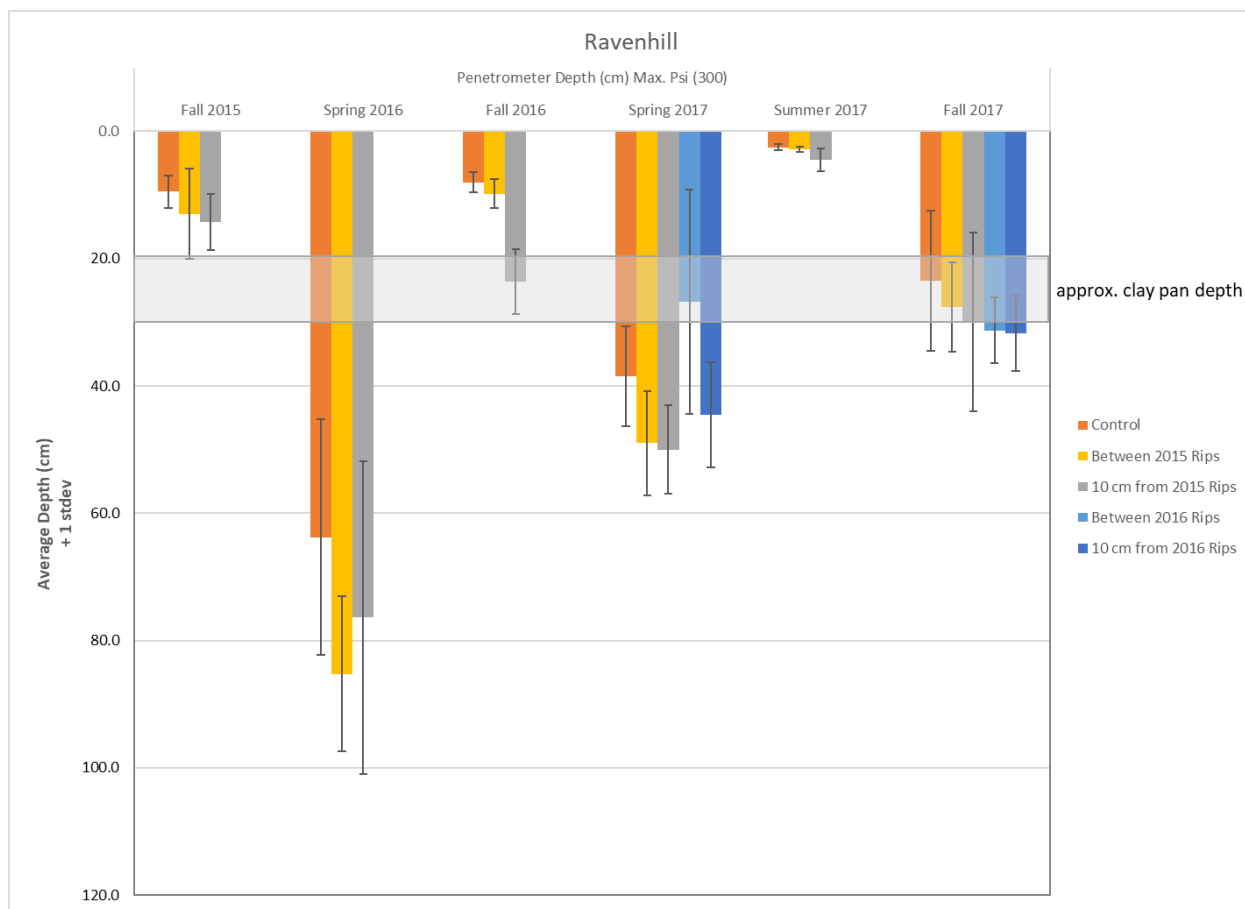
Figure 4-12   Maximum Penetrometer Depth Achieved on Ravenhill from 2015 to 2017 on Control and Treatment Transects

Beetnik Farm was the only site were there was a large and sustained difference in maximum penetration depth within 10 cm of the rip line that lasted the duration of the trial, through all seasons measured (Figure 4-11). Near the rip lines, the penetrometer was able to reach depths of 20 to 40 cm in the spring and fall, and 12.5 cm in the summer near the rip lines, compared to 8 to 15 cm in the spring and fall and 3.5 cm in the summer on the control transect (Figure 4-13).
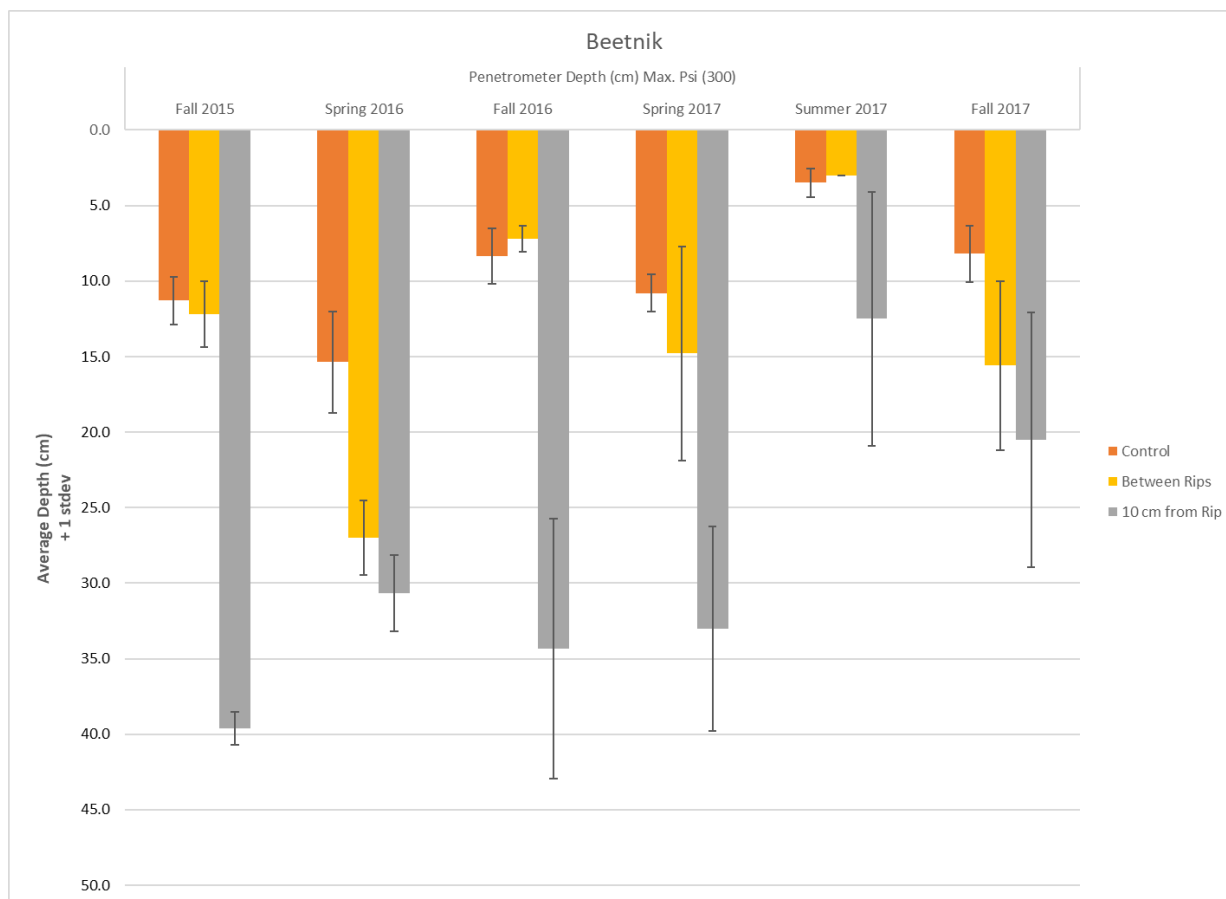
Figure 4-13 Maximum Penetrometer Depth Achieved on Beetnik from 2015 to 2017 on Control and Treatment Transects

Comparing rooting depths, there was no observable difference in the average or maximum rooting depths on excavated faces adjacent to the rip lines at any point in the trial on any site (Figure 4-14). One exception was that on Beetnik Farm in 2016, the rooting depth appeared to be three times deeper, 30 cm versus 10 cm, on the treatment compared to the control; however, that difference was not observed in 2017, so there may have been a skewed sample that year, such as measurement near a forb species within the pasture grasses. Alternatively, the plowing may have temporarily stimulated increased rooting depth in the pasture grasses, but it was not maintained by the plants. It is possible that if an annual pass with the plow had been done again in 2016 and 2017, as is typically done in keyline design, increased rooting depth would have been continually stimulated, and overall rooting depth in the pasture would have been increased.
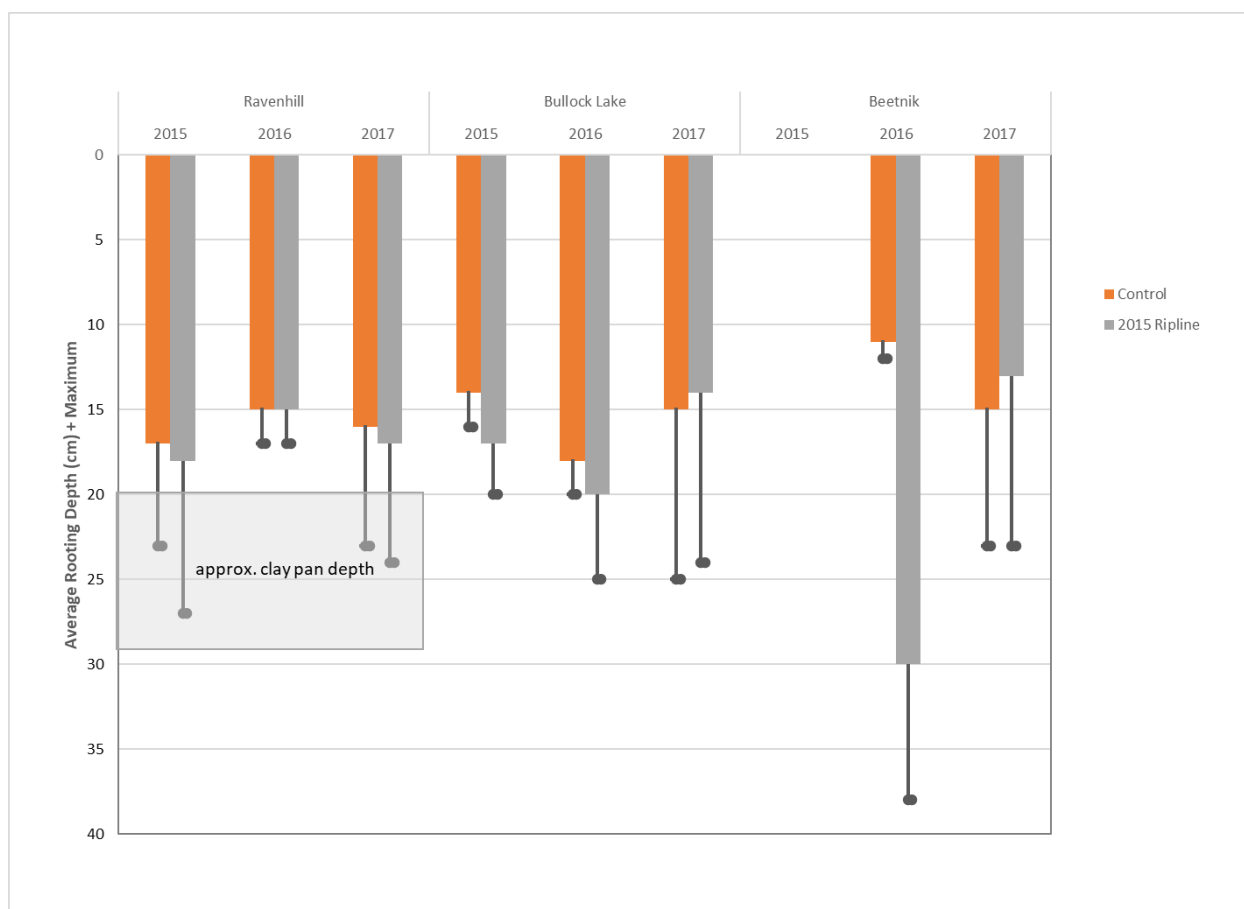
Figure 4-14 Average and Maximum Rooting Depth on Control and Treatment Plots from 2015 to 2017

4.4 Soil Carbon

Keyline plowing is hypothesized to increase soil organic carbon storage, presumably by increasing the biomass production on pastures, and increasing the rate of organic matter stabilization by soil microbial populations through improved soil moisture, increased rooting (and increased root exudates to feed soil bacteria) and better aeration.

Soil organic carbon increases slowly over time, and changes in tillage methods on agricultural croplands and pastures are not observed until possibly decades after the introduction of new practices (Brady and Weil 1999, Moulin et al. 2002; Weil et al. 2003). The active carbon fraction, which is that fraction of the carbon in the soil that is associated with biological activity, e.g.bacterial cells and their metabolic products, may be measurably responsive to differences in management practices before total organic carbon (TOC) (Weil et al. 2003).

TOC values typically range from 0.06 to 6.0 for Brunisols and Regosols (Brady and Weil 1999). The active carbon values from the laboratory standards were 330 to 584 mg/kg, and the University of Minnesota soil test score card suggests that an active carbon value greater than 850 mg/kg is desired in a biologically active agricultural field (Gugino et al. 2010). The TOC values on the control and treatment areas ranged between 3.0 and 5.3 percent, while active carbon values ranges from 355 to 671 mg/kg;

TOC values are within the range expected for with young, cultivated soils, while the active carbon values are lower.

The active carbon fraction apparently decreased for both treatment and control on Bullock Lake and Ravenhill between 2015 and 2017, and did not change for Beetnik between 2015 and 2017, and (Table 4-18 and Figure 4-13); unexpectedly, the TOC values increased on both controls and treatments for all sites between 2015 and 2017, with the largest increases on the treatments (Table 4-14 and Figure 4-15). In 2015, however, the active and TOC concentrations were nearly identical between the control and treatment areas (samples were composited, no standard deviation was calculated), whereas in 2017 the treated areas all had higher active and TOC concentrations than their respective controls; on Ravenhill the treatment area had active carbon and TOC concentration higher than the control by more than one standard deviation, but Bullock Lake control and treatment sites were within one standard deviation of each other. The Beetnik control site had a higher TOC concentration in 2017 than in 2015, but both sites were within one standard deviation of each other.

The highest concentrations of active carbon in the rooting zone of the control areas was found in May, with values decreasing over the growing season by 100 to 200 mg/kg (20 to 30 percent). On the plowed areas, the active carbon concentration decreased slightly between May and July, but increased again to the May values in October (Figure 4-16). This meant that while the control areas had slightly higher active carbon than plowed areas in May and July (but within one standard deviation), plowed areas typically had higher active carbon concentrations in October (though still within a standard deviation). Ravenhill was an exception, as the plowed area had an average active carbon concentration approximately 150 mg/kg higher than the control, with no overlap in the standard deviations between the control and treatment area.

The results of the seasonal analysis suggest that the time of sampling during the year may make a difference when trying to assess whether active carbon fractions increase due to keyline plowing; the highest overall pasture active carbon will likely be measured in May, but whatever effect the plowing may have will not be measurable, or may even be negative at that time. The treatment areas all had higher active carbon contents than the controls in October, which could indicate that plowing extends the active period for soil microbes or plants, and that would be the best time to test for early changes in soil carbon; however, the size of the standard deviation in active carbon on the study areas was also highest at that time, and control and treatment areas were within one standard deviation of each other on two of the three farms.

Table 4-17 Total Organic Carbon Contents on All Farms in 2015 and 2017 – 10 cm Depth

| | 2015 | | | | 2017 | | | |
| | Control | | Treatment | | Control | | Treatment | |
Farm	Average TOC (%)	ST. Dev.	Average TOC (%)	St. Dev.	Average TOC (%)	St. Dev.	Average TOC (%))	St. Dev.
Beetnik	3.2	-	3.2	-	4.6	0.8	4.1	0.4
Ravenhill	4.0	-	4.4	-	4.1	0.5	5.3	0.4
Bullock Lake	3.1	-	3.0	-	3.6	0.3	4.1	0.7

Table 4-18 Active Carbon Contents on All Farms in 2015 and 2017 – 10 cm Depth

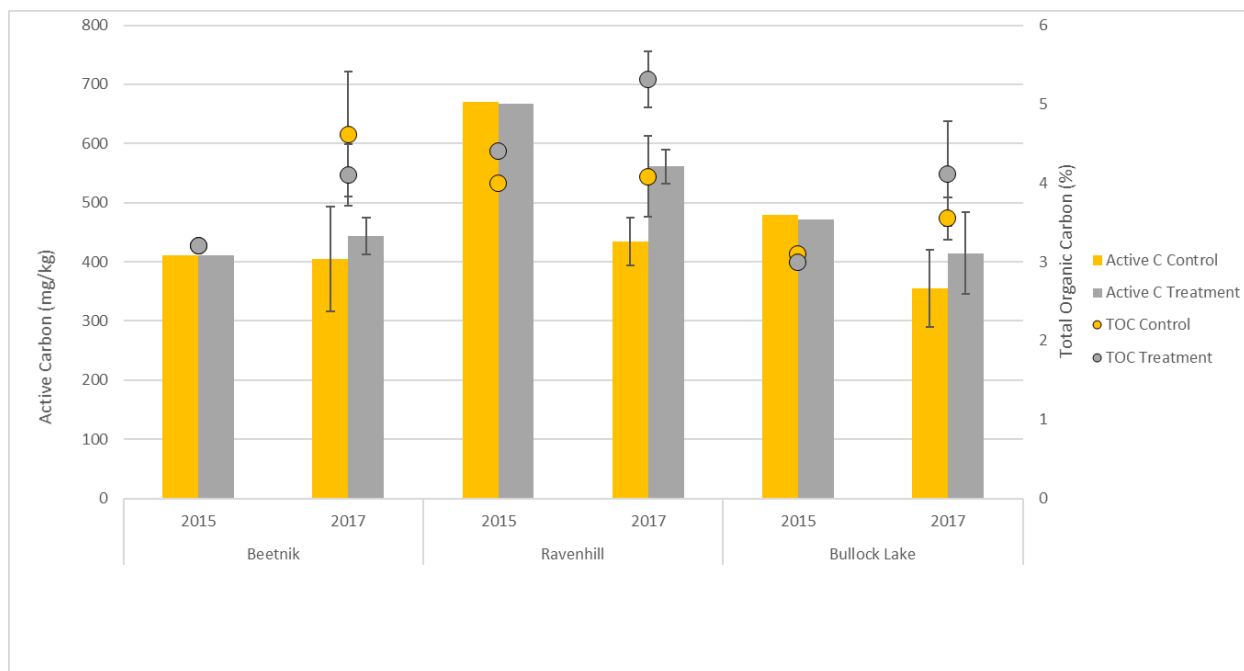| | 2015 | | | | 2017 | | | |
| | Control | | Treatment | | Control | | Treatment | |
Farm	Average Active C (%)	ST. Dev.	Average Active C (%)	St. Dev.	Average Active C (%)	St. Dev.	Average Active C (%)	St. Dev.
Beetnik	411	-	411	-	405	88	444	31
Ravenhill	671	-	667	-	435	41	561	29
Bullock Lake	480	-	472	-	355	65	415	69

Figure 4-15 Change in Total Organic Carbon and Active Carbon on Treated and Control Areas for All Sites between October 2015 to October 2017
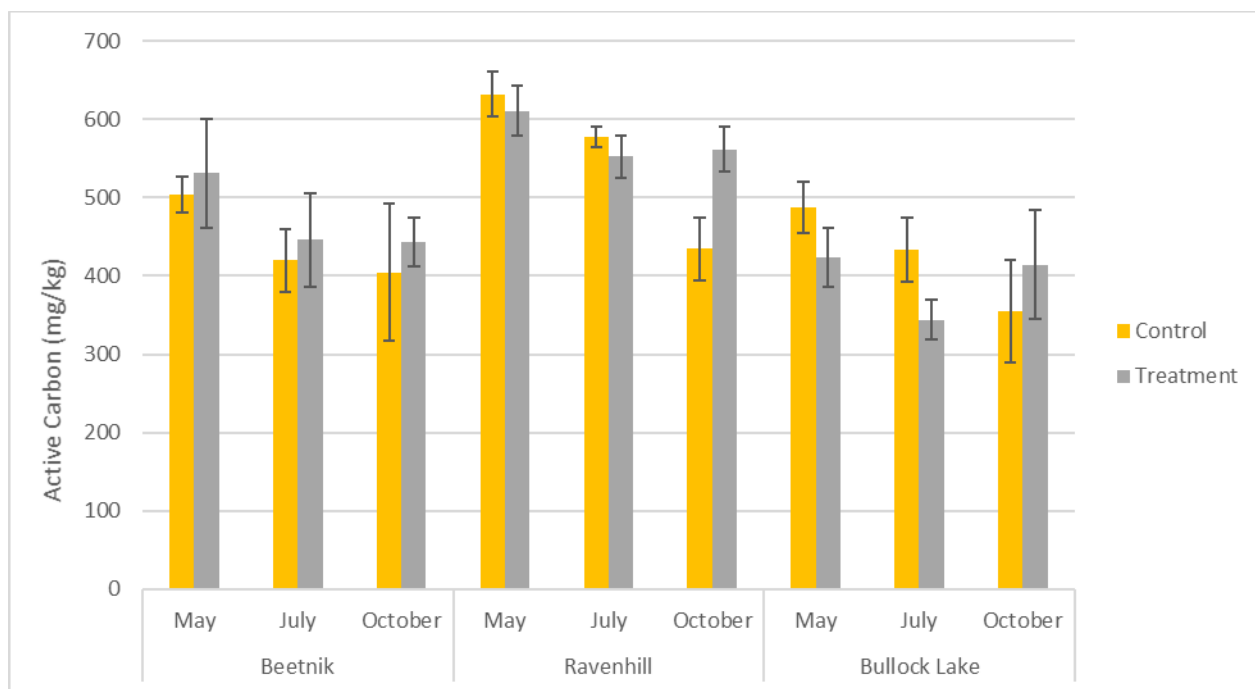

Figure 4-16 2017 Seasonal Active Carbon Values for Treated and Control Areas on All Sites

5 Summary and Conclusions

5.1 Summary of Results

The use of a permanent soil moisture probe installation to evaluate the effect of the keyline plow on soil moisture had benefits in that we were able to collect real-time response to rainfall and constant soil conditions throughout the year; however, the drawbacks were that to avoid damaging the equipment, we were not able to evaluate the effect of the typical plow use, which is to make annual passes with deeper plow depths on the same area.

The main findings of the soil moisture monitoring program, for one pass of the keyline plow, are summarized below:

1) **Effect on Soil Moisture:**
The mean annual percent difference between the highest probe and the lowest probe reading in each treatment depth ranges from 15 percent (Bullock Lake Control) to 49 percent (Ravenhill Treatment at 40 cm depth), and most frequently is in the low 20 percent range. The treatment probes on Bullock Lake and Ravenhill Farms installed within 10 cm from a rip line, at 10 cm depth, show on average 9 to 19 percent higher soil moisture content over the year than the control probes at 10 cm depth (average difference of 13 percent on Bullock Lake and 14 percent on Ravenhill, respectively). For the subsurface probes on Ravenhill (40 cm depth), the treatment was approximately 24 percent drier over the study duration than the control.

a. **Retention During the Dry Season:**
Keyline plowing may increase soil moisture retention in the topsoil, but not the subsoil, during the dry season; however, itt did not appear to slow the rate at which soils dry out during seeding time.

   - Soil moisture content was measurably higher (15 and 12 percent, for Bullock Lake and Ravenhill, respectively) on treatments than controls at 10 cm depth on both farms between rainfall events throughout the dry (summer) season.
   - Soil moisture content was measurably lower (24 percent) between rainfall events on treatments compared to controls at the 40-cm depth on Ravenhill.
   - There was no measurable difference on either farm in the rate at which soil dried out during the spring at the 10-cm depth.

b. **Infiltration During the Dry Season:**

Keyline plowing appears to increase the rate and volume of water infiltration into the topsoil during rainfall events of at least 4 mm over 24 hours; however, infiltration was not increased for lower volume rainfall. On Ravenhill, the greater water infiltration during high rainfall events resulted in an overall faster rate of soil moisture increase on the treatment during the fall. The increased water infiltration into the topsoil did not appear to reach the subsoil (40 cm depth) on Ravenhill.

   - Soil moisture content was measurably higher (13 to 14 percent for Bullock Lake and Ravenhill, respectively) on treatments compared to controls at 10 cm depth on both farms during large rainfall events. However, the magnitude of the overall effect was

nearly the same as between rainfall events because most rainfall events were small, less than 4 mm of rain in 24 hours.

- Soil moisture content was measurably lower (24 percent) during rainfall events on treatments compared to controls at the 40-cm depth on Ravenhill.
- The treatment wetted up measurably more slowly than the control on Bullock Lake at the 10-cm depth (33 percent) over the entire fall season, and on Ravenhill at the 40-cm depth (52 percent), during the fall.
- The treatment on Bullock Lake wettd up more rapidly during rainfall events where greater than 4 mm of rain was received in 24 hours, or 8 mm of rain in 36 hours; but then began to dry out more rapidly after the rain stopped, while the control continued to wet up. The treatment wet up more quickly (38 percent) than the control on Ravenhill at the 10-cm depth during the fall.

c. **Infiltration During the Wet Season:**

Keyline plowing did not appear to increase water infiltration rates in the topsoil or subsoil during the wet season.

- Soil moisture content was measurably lower on treatments compared to controls throughout the wet (winter) season at 10 cm on Bullock Lake (5 percent) and 40 cm on Ravenhill (14 percent), and higher on treatments compared to controls at 10 cm on Ravenhill (8 percent).
- The differences between the average treatment and control surface (10 cm) and subsurface (40 cm at Ravenhill) moisture contents were measurable, but were within one standard deviation of each other, and within the magnitude of the variation between probes within treatments.

Keyline plowing may have a beneficial effect on moisture retention in the rooting zone during the dry season, and improved moisture retention during rainfall events during summer and fall. This increased moisture retention may also decrease surface runoff from the site. With only one 6 inch (10 cm) pass, there was no likely increase in drainage into subsoils during winter and spring.

Adequate replication over many fields or farms with similar soil and management characteristics will be necessary to determine if the difference in soil moisture resulting from keyline plowing is statistically significant. The 2017 monitoring year was drier than the 2016 year, with 90 percent less rainfall during the summer dry months on Bullock Lake Farm, and 60 percent less rainfall on Ravenhill Farm; the average water content on both control and treatment surface soils was approximately 20 to 30 percent lower in 2017 than in 2016 on both farms. Variation in the average magnitude of the difference between the controls and treatments between the two monitoring years may be a result of the difference in rainfall pattern and volume, or it may also be due to settling of the soil around the rip lines as the trial progressed.

2) **Effect on Soil Penetration Resistance and Rooting:**
Keyline plowing resulted in a sustained decrease in soil penetration resistance and increase in rooting depth on the site that has coarse soil texture, but not on the sites with medium soil textures (no fine soil textures were tested).

- One pass of the keyline plow resulted in a sustained decrease in soil penetration resistance and potentially an increase in rooting depth, on one site, Beetnik Farm. This site is well-drained, with a sandy loam soil texture.
- There was no sustained decrease in soil penetration resistance or any change in rooting depth due to the keyline plow past the initial treatment on the other two farms, Bullock Lake and Ravenhill. These sites are imperfectly drained, with silt loam soil texture**.**

Our results suggest that the benefits of the plow for soil decompaction may be dependent on site soil texture. The improvements in rooting depth observed by other plow practitioners on their sites may be limited to plants seeded or planted immediately within the rip line itself, taking advantage of that microsite. A general improvement in rooting on the pasture may not be seen except with many years of successive plow passes. More importantly, the pastures used for the project were also unused or lightly used, and did not experience regular machine traffic, so plow or animal traffic compaction within the rooting depth was not likely to have been a limitation in the first place.

The effect of seeding or planting directly into the rip line was not done on this trial, so we could not assess that claim. We were also not able to evaluate how several years of annual passes with deeper plow depths could have contributed to improvement in soil moisture over time, as we could not plow within the soil moisture probe installation area.

Soil penetration resistance on the medium textured soils was most strongly determined by the moisture content of the soils, with minimum resistance achieved in the fall once soils reached between 20 and 30 percent volumetric water content. On these sites, any root restrictions due to soil penetration resistance would likely be best reduced by substantially increasing soil moisture through the growing season by either irrigating or increasing mulch and organic matter to increase water retention. On the coarse textured soils of Beetnik Farm, soil penetration resistance may be decreased by plowing, though it was not clear that resistance in the upper soil profile posed a restriction for effective rooting depth at baseline.

3) **Soil Carbon:**
Keyline plowing appeared to increase total organic carbon, but had no effect on active soil carbon. Given that an observable change in total organic carbon in only two years is an unexpected result based on soil carbon literature, it may be premature to conclude that keyline plowing does increase soil carbon storage; it is most likely that keyline plowing had no effect on either carbon measurement.

- The monitoring program farm soils all have TOC values between 3.0 and 5.3 percent, indicative of cultivated soils. Published values for soils are typically between 0.06 and 6 percent (Brady and Weil 1999).
- The TOC concentrations appeared to increase by approximately 1 percentage point over the length of the trial on the treatments on two of the farms (Bullock Lake and Ravenhill); however, it also increased by approximately 1.5 percentage points on the controls on Beetnik (and 0.5 percentage points on the controls on Bullock Lake).

- The active carbon fractions did not appear to increase over the length of the trial, and on Bullock Lake and Ravenhill appeared to decrease by approximately 100 mg/kg.
- The active carbon fraction concentration may fluctuate 20 to 30 percent over the growing season. The maximum active carbon concentration was recorded in May samples, but the greatest measurable difference between a plowed area and control was at the end of the growing season (October samples).
- Replicates of soil carbon samples were not collected in 2015, so it is not certain whether the data for each treatment between years would have been within one standard deviation, but it is likely; the controls and treatments were within one standard deviation of each other for total and active carbon values in 2017.
- The standard deviation in the active carbon in soil samples on each treatment/control area is between 5 to 20 percent of the mean (up to 100 mg/kg). The standard deviation in the total organic carbon in soil samples on each treatment/control area is between 7 to 17 percent of the mean (up to 0.8 percent).
- The Ministry of Environment laboratory found that the Weil method for active carbon analysis was simple, quick and easy to calibrate, so it would be useful for gathering larger active carbon datasets in the region. Average active soil carbon fractions for soils in the CRD Region (and the rest of BC) may commonly vary between 350 to 600 mg/kg depending on soil texture and land use; the trial area samples all had active carbon concentrations within the range of the laboratory standards collected in BC.

5.2 Conclusions

We knew that the diversity of topography, microclimates, and crops that are an opportunity and challenge of farming in the Capital Regional District would make scientific replication and proper controls difficult if not impossible for this trial. We intended for the data collected from this soil monitoring program to be usable to refine hypotheses about the magnitude of effects observable from Yeoman plow subsoiling, provide information on how to design larger studies in the Capital Region to test hypotheses about the benefits associated with the plow equipment specifically, and evaluate the suite of practices within keyline water management theory more generally.

Our study results suggest that keyline plowing may be useful as a component of pasture management strategies to improve water infiltration and increase soil moisture storage during the more frequent high intensity rainfall events and drier summers predicted for the region as the climate changes. However, based on the relative difference between plowed versus unplowed areas, compared to the variability between probes within each area, the magnitude of the benefit to water storage and infiltration specific to keyline plowing appears small. After two growing seasons, there is no evidence of increased rooting depth near the plow rip lines on lightly used pastures. An increase in total organic carbon was observed on two out of three pastures, but it is more likely that low replication and sampling error (e.g. slight difference in depths collected between samplers and sampling events) would explain this unlikely occurrence. Higher numbers of probes and soil samples (pseudoreplicates) within farms and higher replicates of participating farms could increase the power to find the true effect size. More probes would also help determine whether the effects are statistically significant.

The monitoring equipment and techniques used for this study would be appropriate for large scale soil moisture monitoring studies; the moisture probe arrays were relatively easy to deploy, robust and largely problem-free to operate. Their cost is low when amortized over their potential field life of five to ten years. The potassium permanganate extractable active carbon fraction used is a promising metric for assessing changes in the active carbon due to the availability of interpretive literature for the results, and the ease of use for collection and laboratory analysis.

The potential role for keyline water management in climate change adaptation may be most strongly associated with the education and outreach activities. Farmers and land managers may be encouraged to think about farms as whole systems embedded in a surrounding watershed, and in the introduction of perennial cropping and other management activities that emphasize the long-term resilience of the farm.

6 Questions for Further Investigation

1. Keyline plow versus standard subsoiling on compacted pastures: The limited benefits we observed with the use of the keyline plow for decompaction may be in part because the pastures were not severely compacted in the first place – further research using pastures with high traffic or demonstrable root restriction due to a shallow plow pan layer may be warranted. Investigation of the relative benefits of the keyline plow (namely, decreased surface disturbance) relative to more commonly available subsoiler types would be useful.

2. Full use of keyline plowing suite of techniques: keyline plow users typically do three annual passes with the plow to progressively deeper depths. We were not able to evaluate whether this practice would have created larger benefits due to permanence of the soil moisture equipment. Beginning a study with a baseline data collection prior to plowing, and then installing soil moisture probes after year three of plowing may better capture the intended effects. In addition, land managers may combine plowing with drill seeding within the rip lines, or include compost tea injection; both practices could increase the rooting depth and effect on soil carbon.

3. Holistic cost-benefits of keyline water management: given the variability of farms in the CRD, it may be most useful to evaluate the keyline plow and land management approach within the context of the recorded financial and time costs of implementing these techniques compared to more conventional ones. The farm-scale quantifiable results (e.g. changes in soil fertility measures, yields, irrigation requirements, runoff measurements) could be evaluated against the costs, and the estimated costs of more conventional techniques that would have been required to achieve the same results. A longer time frame may be required to capture the true costs and benefits, as upfront costs for installing perennial agricultural systems are known to be higher, but the purported benefits should accrue over time compared to annual cropping.

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